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Estimates of Detection Probability for BWASP Bowhead Whale, Gray Whale, and Beluga Sightings Collected from Twin Otter and Aero Commander Aircraft, 1989 to 2007 and 2008 to 2011

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ABSTRACT

The Bowhead Whale Aerial Survey Project (BWASP) database is a long-term (1979-2013) database on the distribution, relative abundance, and behavior of marine mammals in the northern Bering, northeastern Chukchi, and western Beaufort seas. Data from the BWASP database are analyzed to produce separate detection function models using multiple covariates distance sampling methods for each combination of species (bowhead whale (*Balaena mysticetus*), gray whale (*Eschrichtius robustus*), and beluga (*Delphinapterus leucas*)), aircraft (Twin Otter and Aero Commander), and time period (1989-2007 and 2008-2011) in the northeastern Chukchi and western Beaufort seas. The line-transect survey protocols used to collect the data have been remarkably consistent across the years; however, changes in protocol that could affect detection probability are discussed and accounted for in the analyses. Potential covariates evaluated for inclusion in the detection function models included group size, depth of the sea floor at the location of the sighting, Beaufort Sea State, longitude of the sighting, sea ice percentage, and observer effects. Group size variables tended to increase effective strip width (*ESW*) in the bowhead whale models for Twin Otters, and sea state and sea ice variables decreased *ESW* for beluga models for Twin Otters. *ESW* decreased with increasing depths and more westerly longitudes for some bowhead whale and beluga models; this result could be due to spatial heterogeneity in either animal behavior or unmeasured or unmodeled environmental conditions. Beaufort Sea State positively affected *ESW* for bowhead whale models for Twin Otters in the early years and gray whale models for Aero Commanders; this relationship is difficult to explain.

CONTENTS

INTRODUCTION

The Bowhead Whale Aerial Survey Project (BWASP[1]) database contains a long-term dataset (1979-2013) on marine mammal distribution, relative abundance, and behavior collected during aerial surveys conducted in the spring, summer, and autumn in the northern Bering, western Beaufort, and northeastern Chukchi seas. BWASP was initiated by the Bureau of Land Management, and later supported by the Minerals Management Service and Bureau of Ocean Energy Management, Regulation and Enforcement. Currently, the Bureau of Ocean Energy Management supports the continuation of BWASP, which is conducted by the National Oceanic and Atmospheric Administration. BWASP data were collected during line-transect surveys that have used remarkably consistent protocols since 1982 and, therefore, represent a valuable resource for examining spatiotemporal patterns in the distribution and relative density of arctic marine mammals, and the interannual and interdecadal variability therein.

Several researchers have examined the BWASP data to investigate habitat associations (Moore 2000, Moore et al. 2000) and patterns in relative density of marine mammals in the western Arctic (Clarke et al. 2011a; 2011b; 2011c; 2011d; 2012). Those analyses assumed that the probability of detecting animals during the aerial surveys was constant in space and time. If the probability of detection varies due to environmental conditions, animal behavior, survey platform, observer, or other factors, and if that variability is heterogeneous in space or time, analyses based on the BWASP dataset might be biased if they do not account for the variability in detection probability. Givens et al. (2010) analyzed a subset of the BWASP database to examine which factors influenced the detection of Western Arctic bowhead whales during the aerial line-transect surveys conducted in the western Beaufort Sea from 1982 to 2006. We build on the Givens et al. (2010) analysis by estimating detection functions for bowhead whales (*Balaena mysticetus*), gray whales (*Eschrichtius robustus*) and belugas (*Delphinapterus leucas*) in the northeastern Chukchi and western Beaufort seas from 1989 to 2011. In addition, by taking

[1] "BWASP" has been used to refer specifically to the aerial surveys conducted in the western Beaufort Sea and, simultaneously, to the entire database, which contains data from surveys conducted in the northern Bering and northeastern Chukchi seas, in addition to the western Beaufort Sea. To avoid confusion, we will use "BWASP" to refer only to the database.

into account the known evolution in survey protocols over the years, we determine whether and, if so, how, the changes in protocol affected detection probabilities.

METHODS

Study Area

The core study area spans approximately 230,000 km^2 across the western Beaufort and northeastern Chukchi seas, from 140°W to 169°W, 68°N to 72°N (Fig. 1); surveys were conducted farther north and south during some years, but those data were excluded from this analysis in order to focus on how the environment of the core study area might affect detection probabilities. The study area incorporates active offshore oil and gas lease areas. The western Beaufort Sea was surveyed annually from 1979 to 2013, with consistent coverage in September and October, and additional survey effort in July and August of some years. The northeastern Chukchi Sea was surveyed from 1982 to 1991 and 2008 to 2013; September and October were consistently surveyed in this region, although in some years surveys began in June, July, or August. The 2012 and 2013 data were not available to be included in this analysis.

Field Methods

The surveys followed basic aerial visual line-transect protocols and were designed to study the broad-scale distribution, relative density, and behavior of all marine mammals observed, although the bowhead whale was the target species prior to 2008. In the western Beaufort Sea, transect lines were established within a fixed set of 12 survey blocks, with transect endpoints randomly generated within 0.5° intervals on the northern and southern boundaries of the survey blocks, resulting in transect lines oriented along a north-south axis. In the northeastern Chukchi Sea, a similar survey design with transects oriented north-south in 10 survey blocks was used until 2008. Beginning in 2009, the survey design in the northeastern Chukchi Sea was modified to consist of long transects stretching from the coastline to the offshore boundaries of the study area, spaced approximately 19 km apart and oriented perpendicular to the general trend in bathymetry, prevailing currents, and expected gradients in marine mammal density. In addition, in 2009 a coastal transect located approximately 1 km offshore from Point Barrow to Point Hope was added to the survey design. Survey flights were flown every day, weather permitting; survey flights were not typically launched, and were typically aborted, when sea states (Chapman 1971) were consistently above Beaufort Sea State 5.

Surveys were flown at a target airspeed of 110-140 kts and target altitude of 305 to 458 m (1,000 to 1,500 ft). Lower altitudes were occasionally flown in situations where weather dictated for flight safety. Surveys have been conducted from three types of aircraft. Surveys were flown in a Grumman Turbo Goose Model G21G aircraft from 1979 to 1991, a de Havilland Twin Otter Series 300 aircraft from 1986 to 2011, and an Aero Commander 690A twin turbine aircraft from 2009 to 2011. The Twin Otters and Aero Commanders were equipped with bubble windows on both sides of the plane, allowing observers a complete view of the trackline; the Grumman Goose did not have bubble windows.

The survey flights were partitioned into five different flight types: deadhead, transect, connect, search, and circling. Deadhead referred to the portion of the flight that occurred while the aircraft was over land or transiting through poor weather conditions that severely obscured or prevented downward visibility. Transect referred to the systematic search for marine mammals that was conducted during prescribed linear or coastal transects. The transits between transects were designated as connect legs from 1979 to 2008; the term connect was eliminated in 2009 and replaced with search, with no loss of information. Search was also used to refer to transits between the airport and the study area. Observers actively engaged in scanning for marine mammals during transect, connect, and search, and a common set of data were collected during these three flight types. The use of the term circling was introduced in 2009 to identify directed search effort conducted in a small area; circling could occur while on transect or search and typically involved the aircraft banking, pitching, rolling, and changing altitude. The only way to determine whether the aircraft was circling in the data collected prior to 2009 is to plot the locations or examine the rate of change in the aircraft headings.

Three types of data were collected during the surveys, including automatic time and location data, environmental data, and sighting data. The geographic position of the aircraft was obtained from a Global Navigation System from 1979 to 1991 and a Global Positioning System (GPS) from 1992 to 2011 at temporal intervals ranging from 5 minutes to 30 seconds (beginning in

2009). Survey altitude was taken from the aircraft altimeter until 1992, when it began to be recorded from the observers' handheld global positioning system (GPS) unit. The latitude and longitude of sightings refer to the actual position of the animal if the side of the plane on which the sighting occurred, aircraft heading, and angle of declination to the sighting were available; otherwise, they refer to the position of the aircraft. Environmental data were collected every 5 minutes or whenever conditions changed and included the following: sky conditions (overcast, partly cloudy, or clear), Beaufort Sea State, left and right visibility in kilometers (unlimited, 5-10 km, 3-5 km, 2-3 km, 1-2 km, < 1 km, 0 km), average percent ice cover, ice type (USDOD, Navy, Naval Hydrographic Office 1956), and impairment to visibility (fog, haze, low ceiling, glare, precipitation, or none). Sighting data included observer (starting in 1989), species, angle of declination from the horizon to the sighting, side of plane on which the sighting occurred, group size, number of calves, sighting cue, behavior, habitat, whether the sighting was a known repeat, and whether the animals exhibited a response to the aircraft. Prior to 2009, only the best estimate of group size was recorded. Starting in 2009, additional group size data could be collected to record the initial best estimate of group size, the final best estimate of group size (usually determined during circling initiated after the initial sighting), and the maximum and minimum group size estimates. Furthermore, starting in 2009, the number of calves sighted after diverting from a search or transect leg to circle the sighting was recorded separately from the total number of calves in the sighting.

The survey crew always consisted of a pilot, co-pilot, data recorder, and left and right observers (the "primary" observers). The data recorder entered data onto hand-written data sheets from 1979 to 1981 and onto a portable computer from 1982 to 2011, and served as a secondary observer. The primary observers scanned for marine mammals from the trackline (or as far as downward visibility allowed in the Grumman Goose) to the horizon, and measured the angle of declination from the horizon to the sighting using handheld clinometers. Pilots and data recorders often did not have access to handheld clinometers and, therefore, were unable to reliably measure the angle of declination.

It is not possible to distinguish which sightings in the original BWASP database were made by primary observers prior to 1989 because the observer field associated with each sighting was not populated in the early years of the surveys. From 1989 to 2006, observer was recorded as either initials or an identification number of the observer who first observed the sighting. Starting in 2007, the full name of the observer was entered. In 2008, ObsLeft and ObsRight were differentiated; therefore, any sightings in which the observer matched ObsLeft or ObsRight were sightings made by a primary observer. In 2011, all survey crew initials in the BWASP database were replaced with full names, based on information contained elsewhere (primarily annual survey reports, such as Treacy et al. 1990). Initials that remain in the observer field are those that could not be identified to individual based on available information. In this analysis, for cases in which it was not known for certain whether a sighting was made by a primary observer, we made the conservative assumption that the sighting was not made by a primary observer. This assumption eliminates the risk of including the less accurate data from secondary observers that, if included, could potentially increase the uncertainty of, or add bias to, the analysis.

Analytical Methods

Analyses of the line-transect data proceeded by parameterizing the detection function, $g(x)$, which defines the probability of detecting an object or cluster of objects at distance x from the trackline (Buckland et al. 2001). This step required data on the distance perpendicular to the trackline at which sightings were detected, and other variables, referred to as covariates below, potentially affecting the sighting process. The effective strip width (*ESW*; strictly speaking, the effective strip half-width) is the distance on either side of the transect that would contain the same expected number of detected objects if detection probability were equal to 1.0 as were actually detected during the survey, when detection probability varied with distance and possibly other covariates. Effective strip width is equal to the integral of (equivalently, the area under) the detection function over the range w of the distance surveyed on each side of the trackline (Buckland et al. 2001):

$$ESW = \int_0^w g(x)dx \quad . \tag{1}$$

ESW is also equal to the product of w and P_a, where P_a is the probability of detecting an object, given that it is within w of the trackline (Buckland at al., 2001):

$$ESW = w \cdot P_a \quad . \tag{2}$$

Following Buckland (1992), the detection function comprises two components, a key function and a series expansion:

$$g(x) = \text{key}(x)[1 + \text{series}(x)] \quad . \tag{3}$$

The key function is a function of the perpendicular distance x from the transect to the sighting:

$$\text{Half-normal key function: } exp\{-x^2/2\sigma(\boldsymbol{z})^2\} \tag{4}$$

$$\text{Hazard-rate key function: } 1 - exp\{-[x/\sigma(\boldsymbol{z})]^{-b}\} \quad . \tag{5}$$

In multiple covariates distance sampling (MCDS), covariates $\boldsymbol{z}$ relating to the environment, sighting, observer, or survey platform can be included in the scale parameter $\sigma(z)$ of the key function, thereby affecting the width of the detection function (Marques and Buckland 2003). Specifically, $\sigma(z)$ can be modeled as an exponential function of the covariates,

$$\sigma(\boldsymbol{z}) = exp\left(\beta_0 + \beta_1 z_1 + \cdots + \beta_q z_q\right) \ , \tag{6}$$

where

z_i : covariate i;

β_0 : intercept; and

β_i : parameter to be estimated.

Positive values of β_i increase the *ESW*, whereas negative values of β_i decrease the *ESW*.

Detection function models were built separately for bowhead whales, gray whales, and belugas because differences in sighting characteristics, such as coloration, body size, behavior, habitat, and group size range, likely affect detection probabilities. Data from surveys conducted on the Grumman Goose, which did not have bubble windows, were excluded from this analysis. The analysis was restricted to sightings made by primary observers because other crew members likely did not have a way to accurately measure the angle of declination to the sightings, and species identification and group size estimates made by primary observers were likely the most reliable; therefore, the analysis was limited to data collected from 1989 to 2011. Only sightings collected while on search (from 2009 to 2011) or transect (all years) were included in order to exclude sightings made while the aircraft was circling. Data from all available months, June through October, were used in the analysis, and it was assumed that the environmental covariates would account for potential effects of seasonal environmental variability on the detection process. Seasonal and temporal variability in behavior was not addressed explicitly in this analysis because it is often difficult to identify specific behaviors in the brief amount of time the observers have to view the animals; in addition, a variety of behaviors, including swimming, feeding, and milling, have been observed for all species throughout the June through October time period. Additional criteria for a sighting to be considered valid for this analysis were that information on group size, Beaufort Sea State, and percent sea ice cover must be present.

An additional level of stratification was required due to apparent differences in observer search strategies. There was a notable emphasis in searching near the trackline prior to 2008, as evident from the spike in sighting frequencies near the trackline in perpendicular sighting distance distributions derived from the 1989-2007 data (Appendix Fig. A1). Therefore, the data were also stratified by time period (1989-2007; 2008-2011) prior to building the detection function models.

Preliminary examination of the distribution of perpendicular sighting distances revealed apparent differences in detectability of marine mammals near the trackline for Twin Otters compared to Aero Commanders. There appeared to be fewer sightings than expected of all marine mammals within the 300 m strip located directly beneath the Aero Commander (Appendix Fig. A2), so all data from the Aero Commander were truncated to omit sightings within 150 m of the transect. The distribution of perpendicular sighting distances of bowhead whales during surveys conducted on the Twin Otter after 2007 exhibited a shoulder near the trackline, suggesting that this species was reliably detected on the trackline from this aircraft (Appendix Fig. A3a). The beluga and gray whale data collected on the Twin Otter after 2007 suggested that strips 200 m and 300 m, respectively, located directly beneath the aircraft had fewer than expected sightings (Appendix Figs. A3b, c), so these data subsets were left-truncated by 100 m and 150 m, respectively. It is unlikely that a single detection function could fit data for each species collected on both aircraft; therefore, separate detection function models were built for each combination of species (Bm = bowhead whale, Dl = beluga, Er = gray whale), aircraft (otter or cmdr), and time period (07 = 1989-2007, 08 = 2008-2011).

Multiple covariates distance sampling methods from the Mark-Recapture Distance Sampling (*mrds*) package version 2.0.5 (Laake et al. 2012) were used to build the detection function models in *R* version 2.15.2 (R Development Core Team 2012), using half-normal and hazard-rate key functions. Second order cosine series adjustments were also considered. Models were evaluated via forward selection based on Akaike's Information Criterion (AIC), with the model having the lowest AIC value selected as the final model, except as noted below for specific cases where the model with the minimum AIC had an unrealistic detection function and high standard errors for some parameter estimates, suggesting failure of the model to converge. In these atypical cases, the minimum AIC model with an acceptable detection function was selected as the final model. The data were binned into intervals unique to each data subset, as noted in Table 1, because there was evidence of rounding in the measurements of sighting angles. Each data subset was truncated to omit the farthest 5% of sightings (Buckland et al. 2001). Trackline detection probability ($g(0)$) was assumed to be 1.0 for all models.

The set of potential covariates (Table 1) that were evaluated for inclusion in the detection function models varied by species, time period, and aircraft combination (Table 2). Group size could affect detection probability because larger groups could be easier to detect than smaller groups. Three group size variables were considered: *size*, which is simply the observed group size; *loggs*, the $\log_{10}$ of the observed group size; and *catSize*, a categorical variable for group size. The range in gray whale group sizes was very small, so *size* was evaluated for this species. In addition, natural breaks were apparent in the distribution of group sizes for the Er08otter data subset, so *catSize* was evaluated for these data, with bins representing gray whale group sizes of 1 and 2 or more individuals per sighting. The range in bowhead whale group sizes varied by 1 to

2 orders of magnitude, so *loggs* was evaluated for this species. Belugas have not been a priority species for these surveys until relatively recently. The data suggest that group sizes for beluga sightings located farther from the trackline were underestimated; due to this apparent measurement error, no group size variables were included in the beluga models. The depth of the sea floor at the location of the sighting could affect detection probability if, for example, there were differences in behavior or environmental conditions associated with depth. Two depth variables, derived from the International Bathymetric Chart of the Arctic Ocean database (IBCAO; Jakobsson et al. 2012), were considered: *log10IBCAOz*, the $\log_{10}$ of the depth; and *catZ*, a categorical variable used to differentiate habitats in the coast (0-20 m), inner continental shelf (20-50 m), outer continental shelf (50-200 m), continental slope (200-2,000 m), and ocean basin (>2,000 m). In many line-transect surveys for cetaceans, Beaufort Sea State affects detection probability because it is more difficult to sight animals in rougher waters. The bowhead and gray whale analyses were limited to sightings made in sea states ranging from 0 to 5; belugas are smaller and more difficult to detect in higher sea states, so analysis of this species was limited to sightings made in sea states 0 to 4. For this analysis, Beaufort Sea State was evaluated as an integer-valued numeric variable (*iBeauf*) for every species, year, and aircraft combination, with the exception of the Dl08cmdr data subset, which had very low sample sizes in some sea states. In addition, Beaufort Sea State was considered as a binary categorical variable (*f4Beauf* for belugas; *f5Beauf* for gray and bowhead whales) to distinguish Beaufort Sea State 0 to 2 from the higher sea states in which whitecaps are present. The longitude of the sighting could affect detection probability if differences in behavior or environmental conditions were associated with longitude. Essentially all of the gray whale data were collected in a band along the northeastern Chukchi Sea with relatively small variation in longitude, so longitude was not evaluated for the gray whale models. Two longitude variables were evaluated for all bowhead whale and beluga models: *Long100*, the longitude of the sighting, scaled by -1/100; and *catLong*, a categorical variable defining separate strata for the eastern Beaufort Sea (140°W-148°W), western Beaufort Sea (148°W-154°W), survey block 12 (“Block 12,” 154°W-157°W), and northeastern Chukchi Sea (157°W-169°W). Sea ice cover, particularly broken floe sea ice, could affect detectability by making it more difficult for observers to filter cetacean sightings from the background of sea ice. Sea ice was prevalent in the study area only prior to 2008; therefore, only detection function models built on data prior to 2008 incorporated percent sea ice cover as a potential covariate.

The sea ice cover data were right-skewed, with the majority of sightings in 0% ice cover and very low sample sizes in higher ice concentrations. Approximately 12% of all valid sightings (pooled across all species) were found in > 10% sea ice. Therefore, percent sea ice cover entered the models as the binary variable *catIcePct*, with *catIcePct* equal to 0 if percent cover was less than 10%; otherwise, *catIcePct* equaled 1. Finally, the binary variable *obs0* was evaluated to capture the notable spike in bowhead whale and beluga sightings on the trackline by one observer ("Observer Zero") who participated in the surveys from 1999 to 2007 (Appendix Fig. A4); *obs0* = 0 for sightings made by Observer Zero and equaled 1 for all other observers' sightings. Determination of which depth, longitude, and group size variable to use for a specific combination of species, time period, and aircraft was made during the univariate selection stage: the variable resulting in the model with the lowest AIC value among the set of related variables was carried forward throughout the remaining model selection steps. Caution should be used when making conclusions about the effects of variables on cetacean detectability based on the parameterization of the final models because some variables are correlated; for example, *catIcePct* is correlated with *iBeauf* and depth.

RESULTS

Bowhead Whales

The Bm07otter model with the lowest AIC was a hazard-rate model with a 2nd order cosine series adjustment term, but the model was unrealistically complex and there was evidence in the parameter estimates for lack of convergence. The model selected as the final Bm07otter detection function model (n = 880 observations) was a hazard-rate model; it suggested that *loggs* and *iBeauf* increased *ESW*, whereas *log10IBCAOz* reduced it (Table 3; Appendix Fig. A5). Furthermore, *catLong* was included in the model, with *ESW* increasing towards the east across the Block 12, western Beaufort Sea, and eastern Beaufort Sea strata (there were no observations in the Chukchi Sea). The average *ESW* for this model was 1,335 m. All of the eight models within two AIC units of the final model included *iBeauf* and *loggs*, five included *log10IBCAOz*, three included *catLong*, three included *obs0*, and two included *catIcePct* (Table 4). The sign of the parameters for all variables included in the final model did not change in any of the alternate models; however, the rank of the categories in *catLong* varied.

The Bm08cmdr detection function models with the lowest AIC values that were built using the hazard-rate key function resulted in relatively high estimates of the coefficient of variation for the average *ESW*, so the hazard-rate models were no longer considered. The model selected as the final Bm08cmdr detection function model (n = 78 sightings) was built from a half-normal key function and included only *Long100* as a covariate, with narrower *ESW* toward the west (Table 3, Appendix Fig. A6). The average *ESW* for this model was 1,150 m. Three of the four models within two AIC units of the final model included *Long100*, and one replaced *Long 100* with *catLong*; one model included *loggs*, one included *f5Beauf,* and one included *log10IBCAOz* (Table 4). The sign of *Long100* was consistent among the final and alternate models.

The final Bm08otter detection function model (n = 243 sightings) was a hazard-rate model that showed *ESW* increasing with increasing *loggs* and decreasing with *log10IBCAOz* (Table 3, Appendix Fig. A7). The average *ESW* for this model was 1,193 m. All of the three alternate hazard-rate models included *loggs*, two included *log10IBCAOz*, one included *iBeauf*, and one included *Long100* (Table 4). The sign *loggs* and *log10IBCAOz* did not change in any of the alternate models.

Summary statistics for detection function models constructed using conventional distance sampling (CDS) methods, in which the scale parameter is assumed to be a constant, are listed in Table 5. Among the final bowhead whale models, the percent difference in average *ESW* for models built using MCDS methods compared to CDS methods ranged from 0.235 to 3.527%, and the percent difference in the coefficient of variation for the average *ESW* (CV(avg *ESW*)) ranged from -1.069 to 9.092%. One out of the three final bowhead whale detection function models constructed using MCDS methods had a higher CV(avg *ESW*) than analogous models built using CDS methods.

Belugas

The best Dl07otter detection function model (n = 766 sightings) was a half-normal model, with *iBeauf* and *catIcePct* as negative covariates, indicating that *ESW* decreased as the values of these variables increased (Table 3, Appendix Fig. A8). In addition, *catLong* entered the model, with *ESW* increasing towards the east across the Block 12, western Beaufort Sea, and eastern Beaufort Sea strata (there were no observations in the Chukchi Sea). The average *ESW* for this model was 616 m. All six of the alternate models within two AIC units of the final model included *catLong*, four included *iBeauf*, three included *obs0*, two included *catIcePct*, and one included *log10IBCAOz* (Table 4). The sign of the parameters for all variables included in the final model did not change in any of the alternate models.

The detection function model with the lowest AIC value created from the Dl08cmdr subset of data (n = 226 sightings) was a hazard-rate model (Table 3, Appendix Fig. A9). Under this model, the values of *catZ* resulted in the widest *ESW* in the coastal stratum, with *ESW* generally decreasing at greater depths (Table 3). In addition, the final model incorporated *catLong*, with *ESW* increasing towards the east across the Chukchi Sea, Block 12, western Beaufort Sea, and eastern Beaufort Sea strata. The average *ESW* for this model was 614 m. The only alternate model within two AIC units of the final model also included *f4Beauf* (Table 4). The sign or rank of the parameters for both variables included in the final model did not change in the alternate model.

The detection function model with the lowest AIC value built on the Dl08otter subset of data (n = 70 sightings) was a hazard-rate model; however, the function was unrealistically complex and had a relatively high coefficient of variation for the average *ESW*, suggesting that the model failed to converge (Table 3). Therefore, the final model selected was the half-normal model with the minimum AIC value. In the final model *ESW* decreased at greater depths (*log10IBCAOz*) and higher sea states (*f4Beauf*) (Table 3, Appendix Fig. A10). The average *ESW* for this model was 623 m. All three of the alternate models within two AIC units of the final model included *log10IBCAOz*, one included *f4Beauf*, and one included *catLong* (Table 4). The sign of *log10IBCAOz* was negative in both of the alternate models.

Among the final beluga models, the percent difference in average *ESW* for models built using MCDS methods compared to CDS methods ranged from 1.530 to 14.821%, and the percent difference in the coefficient of variation for the average *ESW* (CV(avg *ESW*)) ranged from

-8.407 to -0.457%. All three of the final beluga detection function models constructed using CDS methods had a lower CV(avg *ESW*) than analogous models built using MCDS methods.

Gray Whales

Gray whales are predominantly found in the northeastern Chukchi Sea region of the study area and are rarely sighted in the Beaufort Sea. There were very few gray whale sightings between 1989 and 2007 in aircraft with bubble windows because most of the surveys in the northeastern Chukchi Sea during this time period were conducted in the Grumman Goose. Therefore, detection function models were not made for gray whale sightings collected during the early time period.

The best half-normal and hazard-rate models fitted to the Er08cmdr data (n = 284 sightings) were within one AIC unit of each other (Table 3). The hazard-rate model was selected as the final model because it had the lowest AIC value (Fig. A11). The final model was a function of *catZ*, with largest *ESW* on the inner continental shelf, smaller *ESW* on the outer continental shelf, and smallest *ESW* in the coastal stratum. The average *ESW* for this model was 1,201 m. Three of the six alternate models within two AIC units of the final model included *catZ* and *iBeauf*, two included *f5Beauf*, and two included *size* (Table 4). The rank of the parameters for the *catZ* variable did not change in any of the alternate models.

Similarly, the half-normal and hazard-rate models fitted to the Er08otter data (n = 184 sightings) were within two AIC units of each other and neither incorporated covariates into the scale parameter of the key function (Table 3). The half-normal model had the lowest AIC value and, therefore, was selected as the final model (Appendix Fig. A12). The average *ESW* for this model was 895 m. There were six univariate models and one null model within two AIC units of the final model (Table 4). The univariate models included *catZ*, *f5Beauf*, *catSize*, *log10IBCAOz*, *iBeauf*, and *size.*

Among the final gray whale models, the percent difference in average *ESW* for models built using MCDS methods compared to CDS methods was -0.155% and 0.000%, and the percent difference in the coefficient of variation for the average *ESW* (CV(avg *ESW*)) was 0.000% and

0.047%. One of the two final gray whale detection function models constructed using CDS methods had a CV(avg *ESW*) that was equal to the analogous model built using MCDS methods; in the other case, the CDS model had a higher CV(avg *ESW*).

DISCUSSION

This is the first analysis to derive detection function models for the BWASP gray whale and beluga aerial line-transect survey data, which allowed estimation of *ESW* and examination of the effects of covariates on the sighting process involved in collecting these data. In addition, this re-analysis of the BWASP bowhead whale data is the first to account for the effects of different survey platforms and observer search strategies on the detection function models and subsequent inference, while capitalizing on the amount of information in the database.

This multiple covariates distance sampling analysis confirmed several hypothesized relationships between *ESW* and the group size, sea state, *obs0*, and *catIcePct* variables for some data subsets. Group size was found to have a positive effect on *ESW* in the final bowhead whale models for Twin Otters in both the early (1989-2007) and late (2008-2011) time periods. Increasing values of *iBeauf* and *f4Beauf* reduced *ESW* in the final beluga model for Twin Otters in the early and late time periods. The reduction in *ESW* due to limiting the area searched to a narrow strip centered on the trackline was evident in the best half-normal bowhead whale model for Twin Otters in the early time period because *obs0* entered this model as a positive covariate (*obs0* = 1 for any observer other than “Observer Zero”); however, the hazard-rate model had the lowest AIC value for this subset of data, and it did not incorporate *obs0*. Sea ice cover was evaluated using the binary variable *catIcePct* for only the bowhead whale and beluga models for the early time period; *catIcePct* entered only the beluga model, showing a reduction in *ESW* when sea ice cover was ≥ 10%.

The *iBeauf* variable unexpectedly increased *ESW* in the final bowhead whale model for Twin Otters in the early years, and the best half-normal model for gray whale sightings from Aero Commanders in the later years, although the final Er08cmdr model (a hazard-rate model) did not incorporate *iBeauf*. Although it is difficult to explain these results, it is possible that observers may have adjusted their search effort by focusing further away from the trackline during high sea states.

Depth and longitude variables were incorporated into two final bowhead whale models and two final beluga models. Complex associations undoubtedly exist between depth, longitude, and unmeasured environmental or behavioral variables that might affect the sighting process. For example, whales engaged in feeding activity may spend greater amounts of time at the surface or be seen in association with other sighting cues (mud plumes, birds) that could positively affect detection probability. Bowhead whales are known to feed in late summer through autumn in some years southeast of Point Barrow (Mocklin et al. 2011), gray whales are reliably observed feeding from June through September between Point Barrow and Point Franklin (Clarke et al. 2012), and belugas molt and may feed during summer in the shallow water passes of Kasegaluk Lagoon, located along the northwestern Alaskan coast (Suydam et al. 2005). It may be important to account for this spatial heterogeneity in detection probabilities throughout the northeastern Chukchi Sea and western Beaufort Sea study areas when examining spatial patterns in bowhead whale and beluga density or relative density.

Givens et al. (2010) analyzed a subset of the BWASP data to examine factors that affected bowhead whale detection probabilities. There are notable differences between Givens et al.'s (2010) methods and those used in this analysis. Givens et al. (2010) limited their analysis to bowhead whale transect sightings from flights conducted between 28 August to 23 October 1982-2006, in only the western Beaufort Sea. Givens et al. (2010) did not limit their analysis to data from primary observers, and they did not exclude the data from the Grumman Goose, which had only flat windows. Aero Commander data were also not included in Givens et al.'s (2010) analysis because the Aero Commander was not used as a survey platform until 2009. The collection of covariates that Givens et al. used included: categorical sea state (*BSS*, defined as "Low" for Beaufort 0-1, "Medium" for Beaufort 2-3, and "High" for Beaufort 4 and beyond); categorical visibility (*VIS*, defined as "Low" for visibility on the side of the plane that was ≤5 km, and "High" for visibility >5 km); percent ice cover (*ICE*); waiting distance (*WAIT*, defined as the total distance along the flight path from the previous sighting or start of the survey until the present sighting); location of sighting along an idealized shoreline (*DAS*, correlated strongly with longitude); water *DEPTH* at sighting; *DAY* of year; and *YEAR* since 1982. Givens et al.

(2010) initially excluded group size from the collection of potential covariates because it exhibited a skewed distribution, and later found that incorporation of a categorical group size variable (corresponding to 1, 2, or 3+ whales) did not improve model fit. In total, Givens et al.'s (2010) analysis was based on 1695 sightings. In comparison, the current analysis used bowhead whale, gray whale, and beluga transect and search (after 2009) sighting data from flights conducted from June through October 1989-2011, in the northeastern Chukchi and western Beaufort seas. The current analysis was limited to sightings made by primary observers on Twin Otters and Aero Commanders, the two platforms that had bubble windows for the primary observers. Analyses into estimating *ESW* and the effects of covariates on the detection process for data collected aboard the Grumman Goose are underway. The current analysis examined the effects of group size (*size*, *loggs*, and *catSize*), depth (*log10IBCAOz* and *catZ*), sea state (*iBeauf*, *f4Beauf*, and *f5Beauf*), longitude (*Long100* and *catLong*), percent ice cover (binary variable, *catIcePct*), and observer (*obs0*). Both analyses relied on forward stepwise selection using AIC as the model selection criterion. The current analysis did not incorporate a covariate similar to Givens et al.'s (2010) *VIS* variable because it is likely correlated with perpendicular sighting distance, which violates one of the primary assumptions in multiple covariates distance sampling (Marques and Buckland, 2003). The sample sizes for the present analysis range from 70 to 880 sightings (Table 3).

Similar to the present analysis, Givens et al. (2010) found a negative relationship between *ESW* for bowhead whales and depth, and a positive relationship with sea state. In contrast to this analysis, Givens et al. (2010) did not find a relationship between east-west position and *ESW*. Additional covariates that entered into Givens et al.'s (2010) model were *WAIT* and *YEAR*, both of which were negative. They noted that incorporating *WAIT* into the detection function is one way to account for variability in encounter rate. They suggested that increasing waiting distances could be associated with poor sighting conditions, which could result in observers focusing their scan closer to the aircraft. Furthermore, noting that this bowhead whale population's abundance has increased dramatically over the survey time period, Givens et al. (2010) states, "thus, the results presented here confirm again that encounter rate affects the detection function." However, increased population abundance would likely result in increased encounter rate. If *YEAR* is a proxy for encounter rate, increased encounter rates as measured by *YEAR* appear to have the opposite effect on *ESW* compared to encounter rates measured by *WAIT*. Another potential explanation for the effect of *YEAR* is that the decreasing trend in *ESW* over time could be due to differences in observer search strategies, as addressed in this analysis using the *obs0* covariate, which relates to an observer who participated in the surveys from 1999 to 2007, the latter part of Givens et al.'s (2010) time series. Regardless of the apparent differences in the two analyses, the resulting estimates of *ESW* for bowhead whales are similar: 1,300 m (Givens et al.'s (2010) analysis with 2.896 km truncation distance); 1,108 m (Givens et al.'s (2010) analysis with 1.609 km truncation distance); 1,335 m (this analysis, 1989-2007, Twin Otter); 1,150 m (this analysis, 2008-2011, Aero Commander); 1,193 m (this analysis, 2008-2011, Twin Otter).

CONCLUSIONS

The BWASP database is a valuable resource for investigating patterns and spatiotemporal variability in marine mammal distribution and relative density in the northeastern Chukchi and western Beaufort seas. Users of the data should be aware of the limited but potentially significant changes in survey protocol over time that could affect detection probabilities. We analyzed the BWASP data to produce separate detection function models for each combination of species (bowhead whale, gray whale, and beluga), aircraft (Twin Otter and Aero Commander), and time period (1989 to 2007 and 2008 to 2011). Current efforts are focused on estimating the trackline detection probability, $g(0)$, for the species sighted during survey flights on Aero Commanders and revising the *ESW* analysis by including data from the 2012 and 2013 field seasons.

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Table 1. -- Definition of covariates considered for inclusion in detection function models.

Covariate Name	**Definition**	**Categories**
size	observed group size	
loggs	$\log_{10}$ of the observed group size	
catSize	categorical variable for group size	{1, 2+}
log10IBCAOz	$\log_{10}$ of the depth of the ocean floor at the location of the sighting	
catZ	categorical variable for depth	{0-20 m, 20-50 m, 50-200 m, 200-2000 m, >2000 m)
iBeauf	Beaufort Sea State, as an integer-valued numeric variable	
f4Beauf	Beaufort Sea State, as a categorical variable	{0 to 2, 3 to 4}
f5Beauf	Beaufort Sea State, as a categorical variable	{0 to 2, 3 to 5}
Long100	longitude of the sighting, scaled by -1/100	
catLong	categorical variable for longitude	{140°W-148°W, 148°W-154°W, 154°W-157°W, 157°W-169°W}
catIcePct	categorical variable for percent sea ice cover	{0-10%, >10%}
obs0	categorical variable for "Observer Zero"	*obs0*=0 for sightings made by "Observer Zero"

Table 2. -- Covariates evaluated in detection function models for bowhead whales (Bm), belugas (Dl), and gray whales (Er) in 1989-2007 ("07") and 2008-2011 ("08") surveyed on the Aero Commander (cmdr) and Twin Otter (otter). x*: group size categories {1, 2+}.

Model	*size*	*loggs*	*catSize*	*log10IBCAOz*	*catZ*	*iBeauf*	*f4Beauf*	*f5Beauf*	*Long100*	*catLong*	*catIcePct*	*obs0*
Bm07otter		x		x	x	x		x	x	x	x	x
Bm08cmdr		x		x	x	x		x	x	x		
Bm08otter		x		x	x	x		x	x	x		
Dl07otter				x	x	x	x		x	x	x	x
Dl08cmdr				x	x		x		x	x		
Dl08otter100				x	x	x	x		x	x		
Er08cmdr	x			x	x	x		x				
Er08otter150	x		x*	x	x	x		x				

Table 3. -- Detection function model summary for bowhead whales (Bm), belugas (Dl), and gray whales (Er) in 1989-2007 ("07") or 2008-2011 ("08") surveyed on the Aero Commander (cmdr) or Twin Otter (otter). HN = half-normal key function (Key Fcn). HR = hazard-rate key function. Scale parameters are listed as the parameter estimate followed by the standard error of the estimate in parentheses. *int* = intercept. *ESW* = average effective strip width. CV = coefficient of variation. *Model selected as the final model.

	Key Fcn	**AIC**	**Scale Parameters**	**Shape Parameter Intercept**	**ESW (km)**	**CV(ESW)**
Bm07otter						
# Observations: 880 Range (km): 0.00 - 2.80 Bin Width (m): 200	HN	4196.047	*int* 0.208 (0.151); *loggs* 0.271 (0.120); *log10IBCAOz* -0.169 (0.085); *obs0* 0.135 (0.068)		1.363	0.024
	HR*	4183.981	*int* -0.161 (0.282); *iBeauf* 0.095 (0.039); *loggs* 0.422 (0.170); *log10IBCAOz* -0.231 (0.140); *catLong/eBeauf* 0.246 (0.117); *catLong/wBeauf* 0.200 (0.134); *catLong/Blk12* included in *int*	0.826 (0.086)	1.335	0.040
Bm08cmdr						
# Observations: 78 Range (km): 0.15 - 2.55 Bin Width (m): 300	HN*	286.263	*int* 4.331 (1.959); *Long100* -2.838 (1.238)		1.150	0.078
	HR	278.407	*int* 15.560 (7.103); *Long100* -10.452 (4.675)	0.499 (0.265)	0.797	0.243
Bm08otter						
# Observations: 243 Range (km): 0.00 - 2.75 Bin Width (m): 250	HN	970.458	*int* -0.263 (0.051); *loggs* 1.504 (0.358)		1.118	0.045
	HR*	967.699	*int* 0.206 (0.355); *loggs* 1.406 (0.341); *log10IBCAOz* -0.297 (0.250);	1.202 (0.140)	1.193	0.060

Table 3. -- Continued.

	Key Fcn	AIC	Scale Parameters	Shape Parameter Intercept	ESW (km)	CV(ESW)
Dl07otter						
# Observations: 766 Range (km): 0.00 - 1.35 Bin Width (m): 150	HN*	2905.514	*int* -0.722 (0.109); *catLong/eBeauf* 0.292 (0.081); *catLong/wBeauf* 0.238 (0.078); *catLong/Blk12* included in *int*; *iBeauf* -0.074 (0.036); *catIcePct* -0.123 (0.073)		0.616	0.029
	HR	2917.668	*int* -0.604 (0.124); *catLong/eBeauf* 0.399 (0.093); *catLong/wBeauf* 0.328 (0.092); *catLong/Blk12* included in *int*; *iBeauf* -0.095 (0.036); *catIcePct* -0.148 (0.072)	1.234 (0.106)	0.704	0.032
Dl08cmdr						
# Observations: 226 Range (km): 0.15 - 1.35 Bin Width (m): 100	HN	1012.432	*int* -0.511 (0.272); *catLong/Chk* -0.211 (0.204); *catLong/eBeauf* 0.791 (0.344); *catLong/wBeauf* 0.757 (0.360); *catLong/Blk12* included in *int*; *catZ/0.to.20* included in *int*; *catZ/20.to.50* -0.250 (0.241); *catZ/50.to.200* -0.600 (0.199); *catZ/200.to.2000* -0.402 (0.323); *catZ/2000* -1.119 (0.493)		0.575	0.061
	HR*	1006.278	*int* -0.125 (0.275); *catLong/Chk* -0.425 (0.237); *catLong/eBeauf* 0.753 (0.233); *catLong/wBeauf* 0.661 (0.239); *catLong/Blk12* included in *int*; *catZ/0.to.20* included in *int*; *catZ/20.to.50* -0.303 (0.213); *catZ/50.to.200* -0.910 (0.215); *catZ/200.to.2000* -0.661 (0.296); *catZ/2000* -1.254 (0.387)	1.249 (0.190)	0.614	0.067

Table 3. -- Continued.

	Key Fcn	AIC	Scale Parameters	Shape Parameter Intercept	ESW (km)	CV(ESW)
Dl08otter						
# Observations: 70 Range (km): 0.10 - 1.35 Bin Width (m): 125	HN*	293.670	*int* 0.633 (0.564); *log10IBCAOz* -0.434 (0.213); *f4Beauf/0.to.2* included in *int*; *f4Beauf/3.to.4* -0.375 (0.264)		0.623	0.093
	HR	294.425	*int* 1.508 (0.806); *log10IBCAOz* -0.744 (0.314); *f4Beauf/0.to.2* included in *int*; *f4Beauf/3.to.4* -0.576 (0.333)	0.960 (0.323)	0.623	0.153
Er08cmdr						
# Observations: 284 Range (km): 0.15 - 3.15 Bin Width (m): 200	HN	1338.373	*int* -0.182 (0.129); *iBeauf* 0.084 (0.042)		1.291	0.045
	HR*	1338.134	*int* -0.820 (0.292); *catZ/0.to.20* included in *int*; *catZ/20.to.50* 0.776 (0.286); *catZ/50.to.200* 0.585 (0.293);	0.804 (0.136)	1.201	0.072
Er08otter						
# Observations: 184 Range (km): 0.15 - 2.25 Bin Width (m): 150	HN*	838.050	*int* -0.333 (0.053)		0.895	0.051
	HR	839.084	*int* -0.309 (0.107)	1.086 (0.175)	0.953	0.071

Table 4. -- Detection function models for bowhead whales (Bm), belugas (Dl), and gray whales (Er) in 1989-2007 (07) and 2008-2011 (08) observed on the Aero Commander (cmdr) and Twin Otter (otter). The final model and all models within two AIC units of the final model are shown. HR = hazard-rate key function. HN = half-normal key function. *int* = intercept.

Data Subset	Key Function	Covariates in Scale Parameter	ΔAIC
Bm07otter	HR	*int + iBeauf + loggs + log10IBCAOz + catLong*	0.00
	HR	*int + iBeauf + loggs + log10IBCAOz*	0.30
	HR	*int + iBeauf + loggs + log10IBCAOz + catLong + obs0*	0.68
	HR	*int + iBeauf + loggs + catLong*	0.71
	HR	*int + iBeauf + loggs*	0.95
	HR	*int + iBeauf + loggs + log10IBCAOz + obs0*	1.08
	HR	*int + iBeauf + loggs + log10IBCAOz + catLong + catIcePct*	1.79
	HR	*int + iBeauf + loggs + log10IBCAOz + catIcePct*	1.84
	HR	*int + iBeauf + loggs + obs0*	1.93
Bm08cmdr	HN	*int + Long100*	0.00
	HN	*int + catLong*	0.38
	HN	*int + Long100 + f5Beauf*	0.43
	HN	*int + Long100 + loggs*	0.66
	HN	*int + Long100 + log10IBCAOz*	1.60
Bm08otter	HR	*int + loggs + log10IBCAOz*	0.00
	HR	*int + loggs*	0.60
	HR	*int + loggs + log10IBCAOz + iBeauf*	1.67
	HR	*int + loggs + log10IBCAOz + Long100*	1.95
Dl07otter	HN	*int + catLong + iBeauf + catIcePct*	0.00
	HN	*int + catLong + iBeauf + catIcePct + obs0*	0.02
	HN	*int + catLong + iBeauf*	1.16
	HN	*int + catLong + iBeauf + obs0*	1.75
	HN	*int + catLong*	1.93
	HN	*int + catLong + obs0*	1.94
	HN	*int + catLong + iBeauf + catIcePct + log10IBCAOz*	1.99
Dl08cmdr	HR	*int + catLong + catZ*	0.00
	HR	*int + catLong + catZ + f4Beauf*	1.98
Dl08otter	HN	*int + log10IBCAOz + f4Beauf*	0.00
	HN	*int + log10IBCAOz*	0.27
	HN	*int + log10IBCAOz + catLong*	0.62
	HR	*int + log10IBCAOz + f4Beauf*	0.75

Table 4. -- Continued.

Data Subset	Key Function	Covariates in Scale Parameter	ΔAIC
Er08cmdr	HR	*int + catZ*	0.00
	HN	*int + iBeauf*	0.24
	HN	*int + iBeauf + size*	0.81
	HR	*int + catZ + f5Beauf*	1.19
	HN	*int + iBeauf + catZ*	1.42
	HN	*int + f5Beauf*	1.80
	HR	*int + catZ + size*	2.00
Er08otter	HN	*int*	0.00
	HN	*int + catZ*	0.22
	HR	*int*	1.03
	HN	*int + f5Beauf*	1.24
	HN	*int + catSize*	1.50
	HN	*int + log10IBCAOz*	1.53
	HN	*int + iBeauf*	1.92
	HN	*int + size*	1.95

Table 5. -- Comparison of detection function models created using conventional distance sampling (CDS) and multiple covariates distance sampling (MCDS), for bowhead whales (Bm), belugas (Dl), and gray whales (Er) in 1989-2007 ("07") and 2008-2011 ("08") surveyed on the Aero Commander (cmdr) and Twin Otter (otter). HN = half-normal key function (Key Fcn). HR = hazard-rate key function. The scale parameter is listed as the estimate of the intercept (*int*), followed by the standard error of the estimate in parentheses. *ESW* = effective strip width. CV = coefficient of variation. Δ = 100*(CDS - MCDS)/CDS.

	# Obs	Distance Range (km)	Bin Width (m)	Key Fcn	AIC	Scale Parameter	Shape Parameter Intercept	***ESW***			**CV(*ESW*)**		
								CDS	**MCDS**	**Δ (%)**	**CDS**	**MCDS**	**Δ (%)**
Bm07otter	880	0.00 - 2.80	200	HN	4201.229	*int* 0.103 (0.027)		1.373	1.363	0.724	0.024	0.024	-0.489
				HR	4191.478	*int* -0.053 (0.068)	0.773 (0.089)	1.338	1.335	0.235	0.040	0.040	1.314
Bm08cmdr	78	0.15 - 2.55	300	HN	288.799	*int* -0.037 (0.085)		1.192	1.150	3.527	0.077	0.078	-1.069
				HR	286.063	*int* -0.668 (0.375)	0.385 (0.286)	0.913	0.797	12.670	0.196	0.243	-24.184
Bm08otter	243	0.00 - 2.75	250	HN	996.209	*int* -0.047 (0.044)		1.192	1.118	6.214	0.042	0.045	-5.211
				HR	992.890	*int* -0.095 (0.100)	0.999 (0.145)	1.213	1.193	1.715	0.066	0.060	9.092
Dl07otter	766	0.00 - 1.35	150	HN	2915.967	*int* -0.688 (0.031)		0.625	0.616	1.530	0.029	0.029	-0.457
				HR	2935.538	*int* -0.563 (0.052)	1.166 (0.112)	0.712	0.704	1.099	0.033	0.032	1.856
Dl08cmdr	226	0.15 - 1.35	100	HN	1038.413	*int* -0.647 (0.065)		0.642	0.575	10.415	0.056	0.061	-9.207
				HR	1042.068	*int* -0.545 (0.101)	1.082 (0.233)	0.721	0.614	14.821	0.062	0.067	-8.407

Table 5. -- Continued.

Dl08otter	70	0.10 - 1.35	125	HN	298.324	*int* -0.596 (0.101)		0.674	0.623	7.596	0.086	0.093	-7.084
				HR	296.332	*int* -1.234 (0.433)	0.308 (0.324)	0.522	0.623	-19.409	0.217	0.153	29.564
Er08cmdr	284	0.15 - 3.15	200	HN	1340.302	*int* 0.041 (0.041)		1.301	1.291	0.763	0.040	0.045	-12.562
				HR	1340.258	*int* -0.212 (0.122)	0.737 (0.141)	1.200	1.201	-0.155	0.072	0.072	0.047
Er08otter	184	0.15 - 2.25	150	HN	838.050	*int* -0.333 (0.053)		0.895	0.895	0.000	0.051	0.051	0.000
				HR	839.084	*int* -0.309 (0.107)	1.086 (0.175)	0.953	0.953	0.000	0.071	0.071	0.000

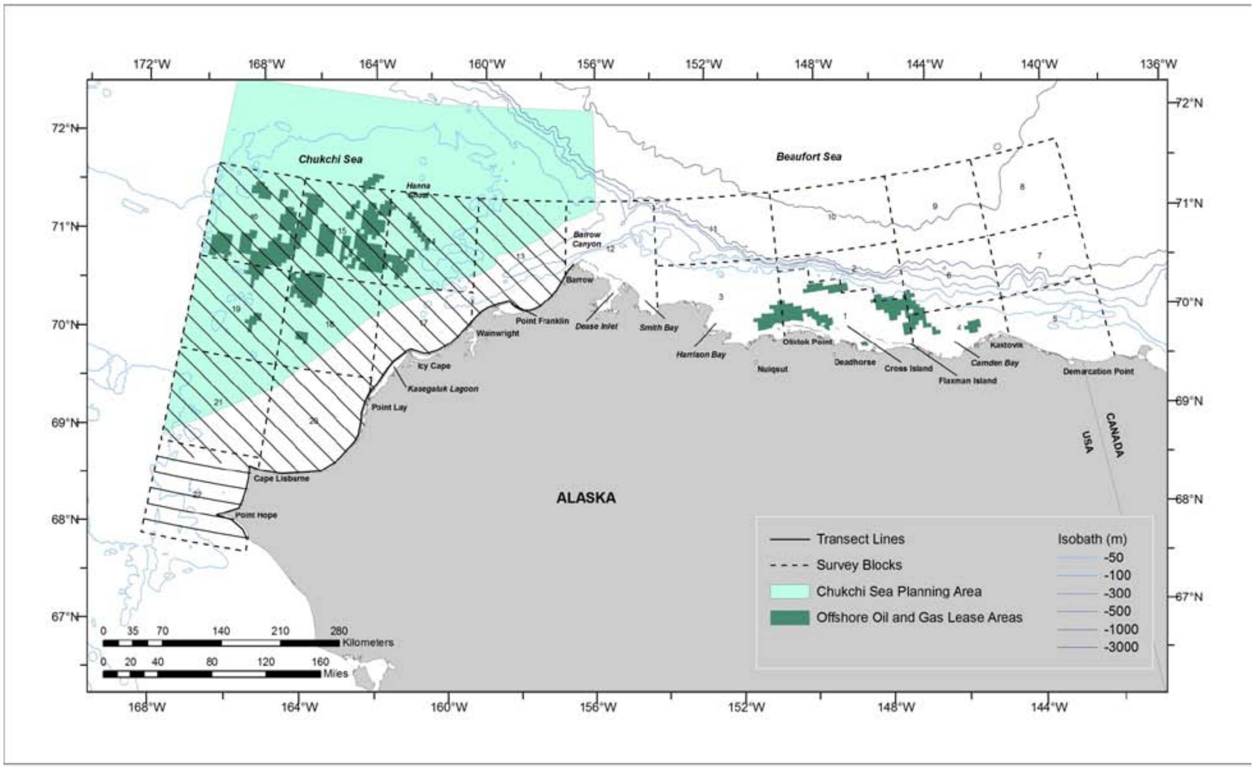
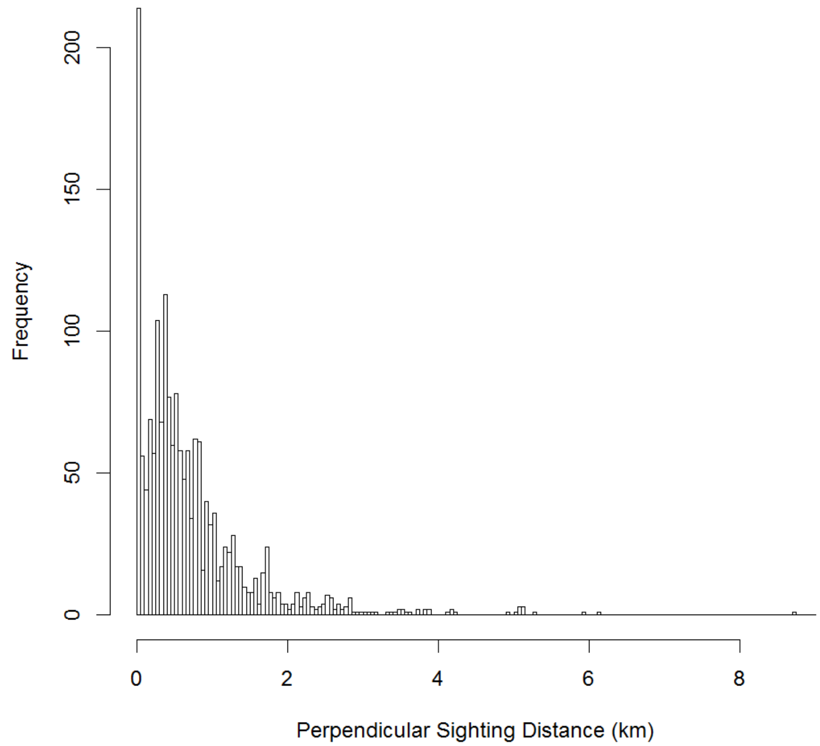
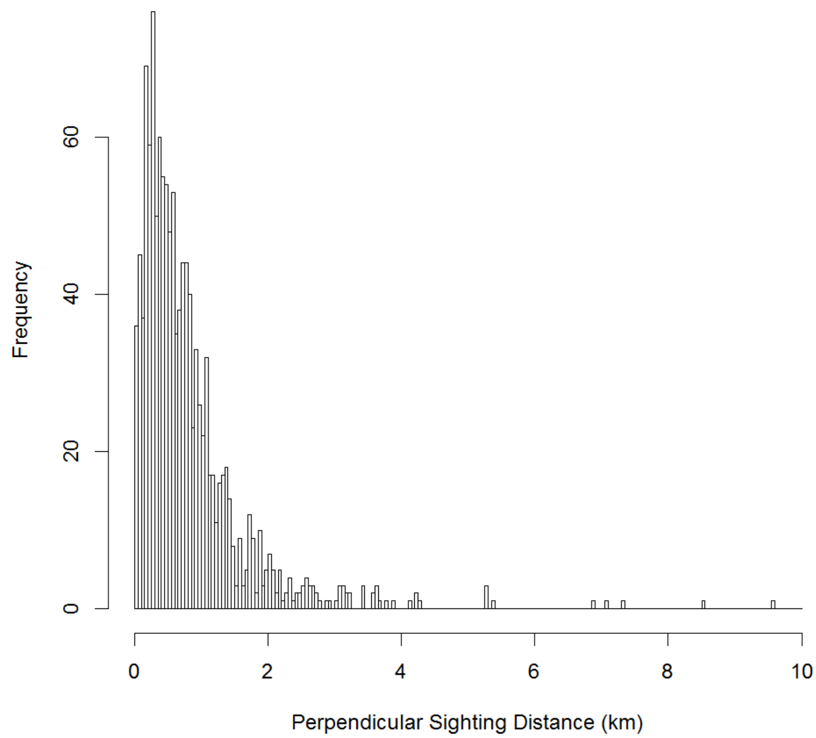


Figure 1. -- Study area for the subset of the BWASP dataset used in the current analysis, showing survey blocks, Chukchi Sea transect lines, Chukchi Sea Planning Area (CSPA), lease areas, and isobaths. Transect lines in the Beaufort Sea are generated daily and, therefore, not shown.

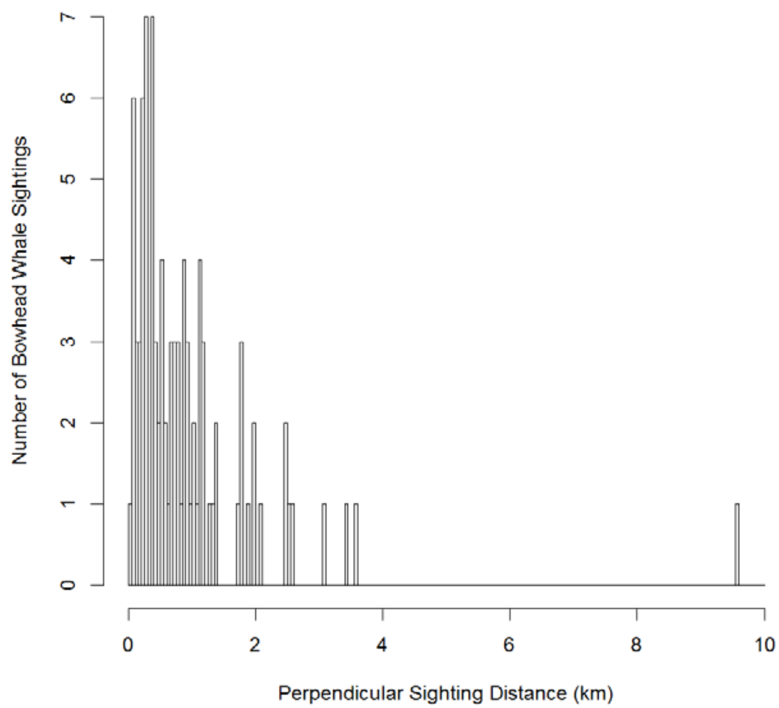
APPENDIX



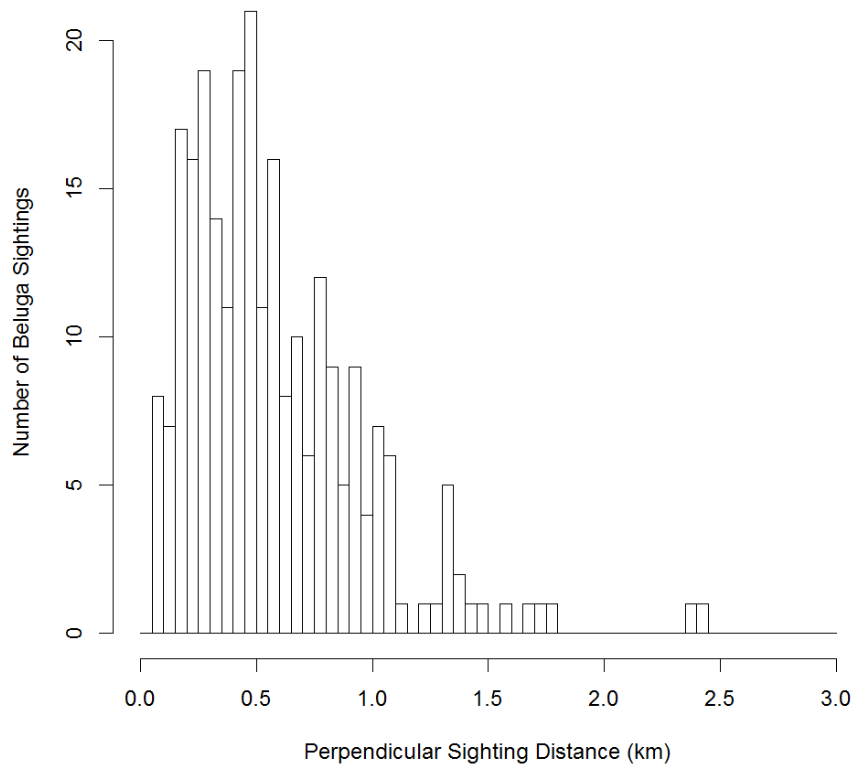
Appendix Figure A1a. -- Histogram (50 m bin width) of perpendicular distances (km) of bowhead whale, beluga, and gray whale sightings made by primary observers during BWASP aerial surveys conducted on the Twin Otter, 1989-2007, during Beaufort Sea States less than or equal to 5 (n = 1,745 sightings).



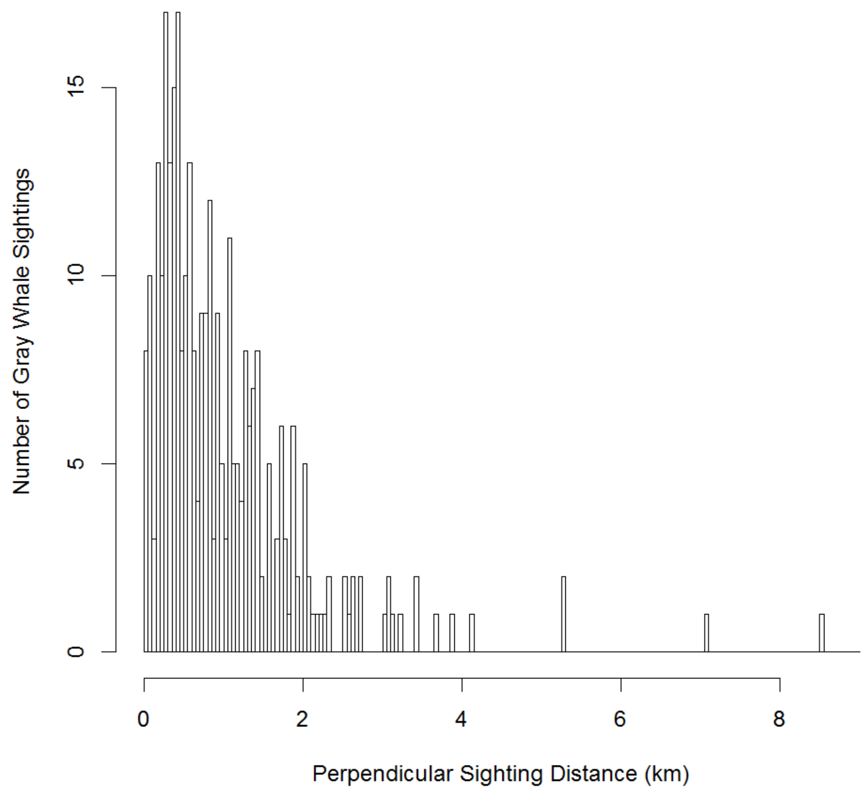
Appendix Figure A1b. -- Histogram (50 m bin width) of perpendicular distances (km) of bowhead whale, beluga, and gray whale sightings made by primary observers during BWASP aerial surveys conducted on the Twin Otter and Aero Commander, 2008-2011, during Beaufort Sea States less than or equal to 5 (n = 1,242 sightings).



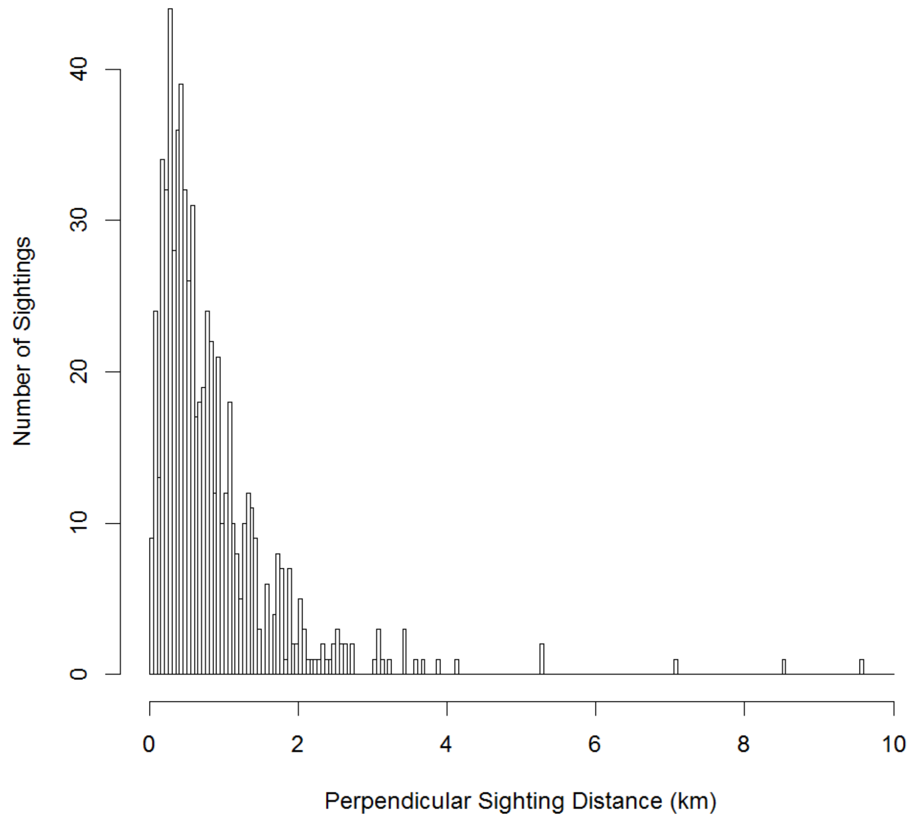
Appendix Figure A2a. -- Histogram (50 m bin width) of perpendicular distances (km) of bowhead whale sightings made by primary observers during BWASP aerial surveys conducted on the Aero Commander, 2008-2011, during Beaufort Sea States less than or equal to 5 (n = 93 sightings).



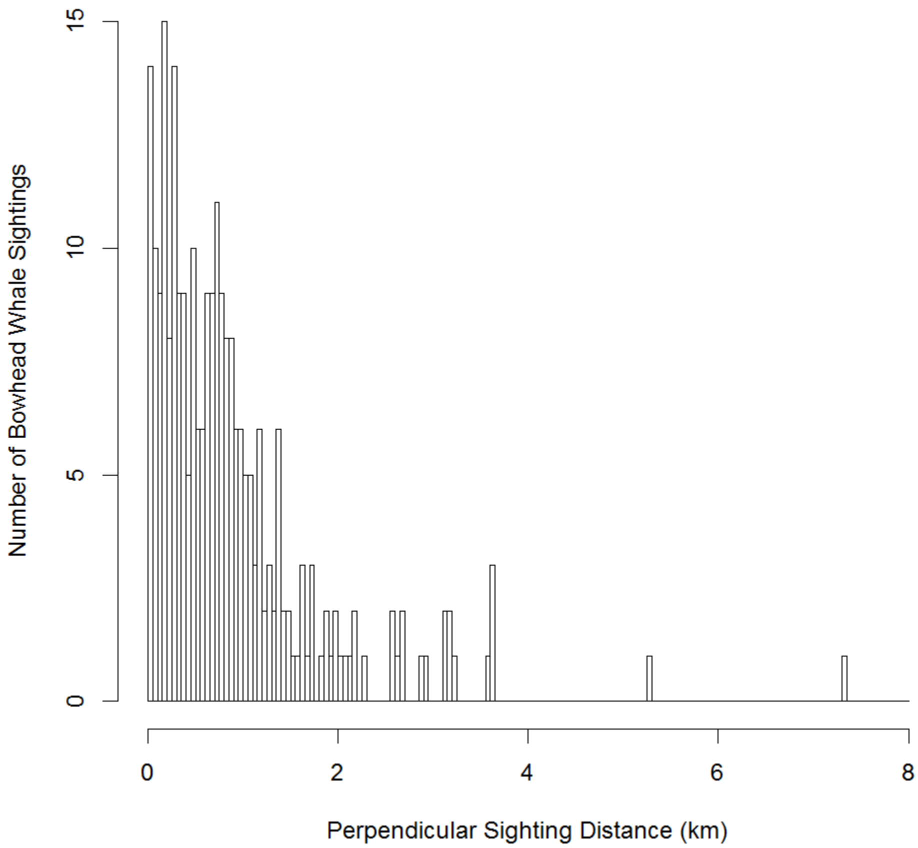
Appendix Figure A2b. -- Histogram (50 m bin width) of perpendicular distances (km) of beluga sightings made by primary observers during BWASP aerial surveys conducted on the Aero Commander, 2008-2011, during Beaufort Sea States less than or equal to 4 (n = 263 sightings).



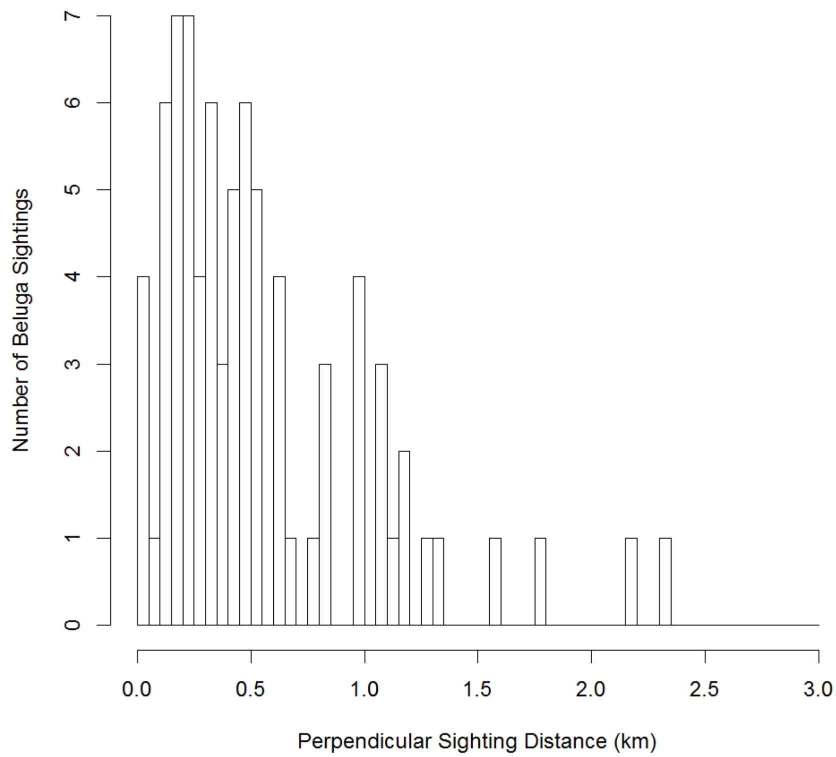
Appendix Figure A2c. -- Histogram (50 m bin width) of perpendicular distances (km) of gray whale sightings made by primary observers during BWASP aerial surveys conducted on the Aero Commander, 2008-2011, during Beaufort Sea States less than or equal to 5 (n = 315 sightings).



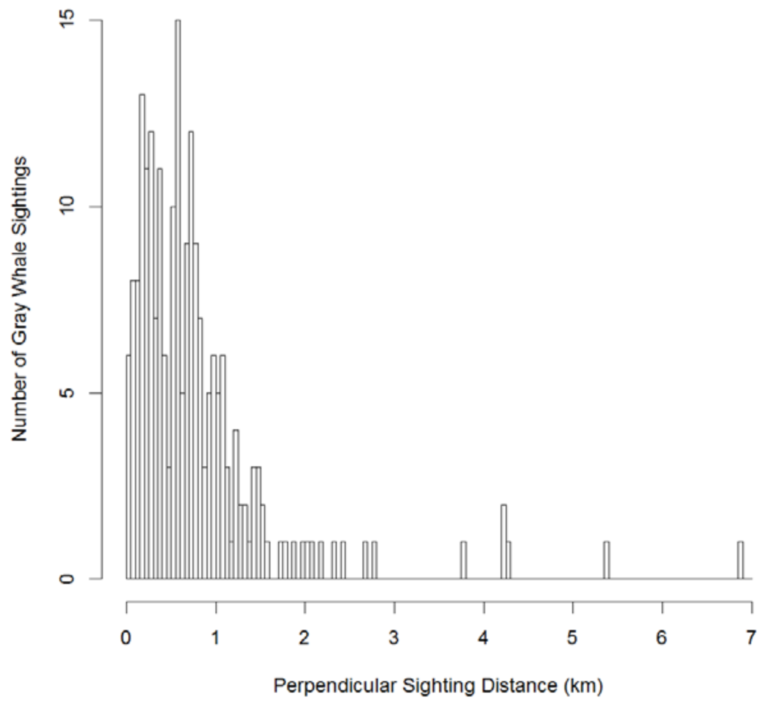
Appendix Figure A2d. -- Histogram (50 m bin width) of perpendicular distances (km) of bowhead whale, beluga, and gray whale sightings made by primary observers during BWASP aerial surveys conducted on the Aero Commander, 2008-2011, during Beaufort Sea States less than or equal to 5 (n = 671 sightings).



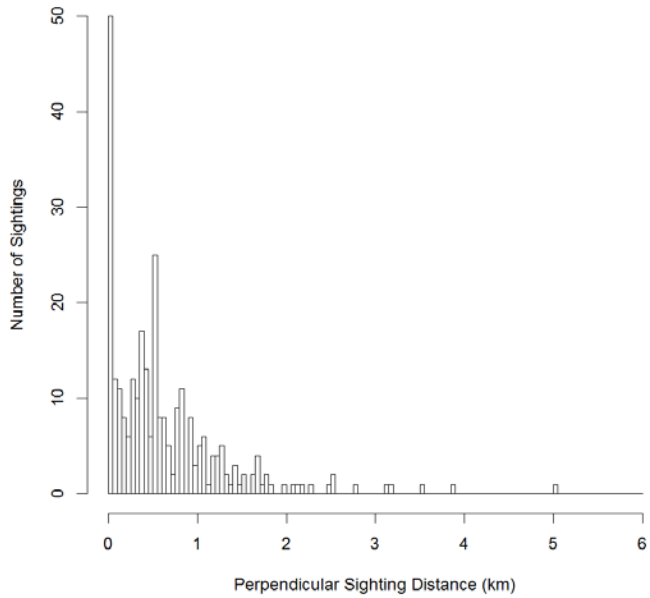
Appendix Figure A3a. -- Histogram (50 m bin width) of perpendicular distances (km) of bowhead whale sightings made by primary observers during BWASP aerial surveys conducted on the Twin Otter, 2008-2011, during Beaufort Sea States less than or equal to 5 (n = 256 sightings).

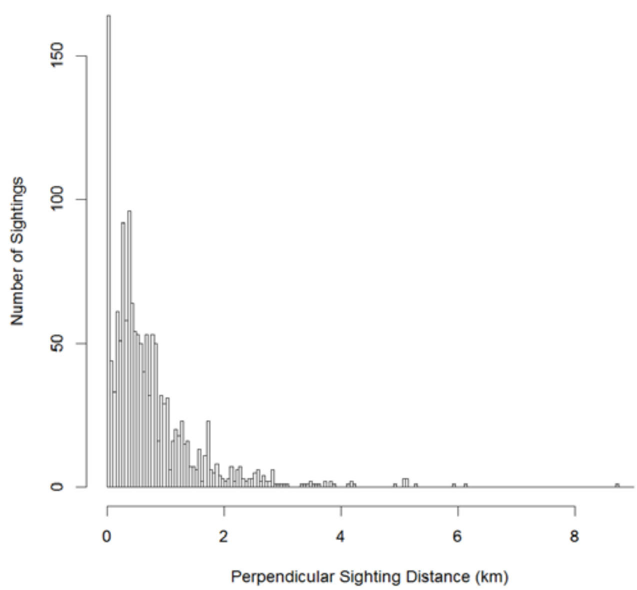


Appendix Figure A3b.-- Histogram (50 m bin width) of perpendicular distances (km) of beluga sightings made by primary observers during BWASP aerial surveys conducted on the Twin Otter, 2008-2011, during Beaufort Sea States less than or equal to 4 (n = 79 sightings).

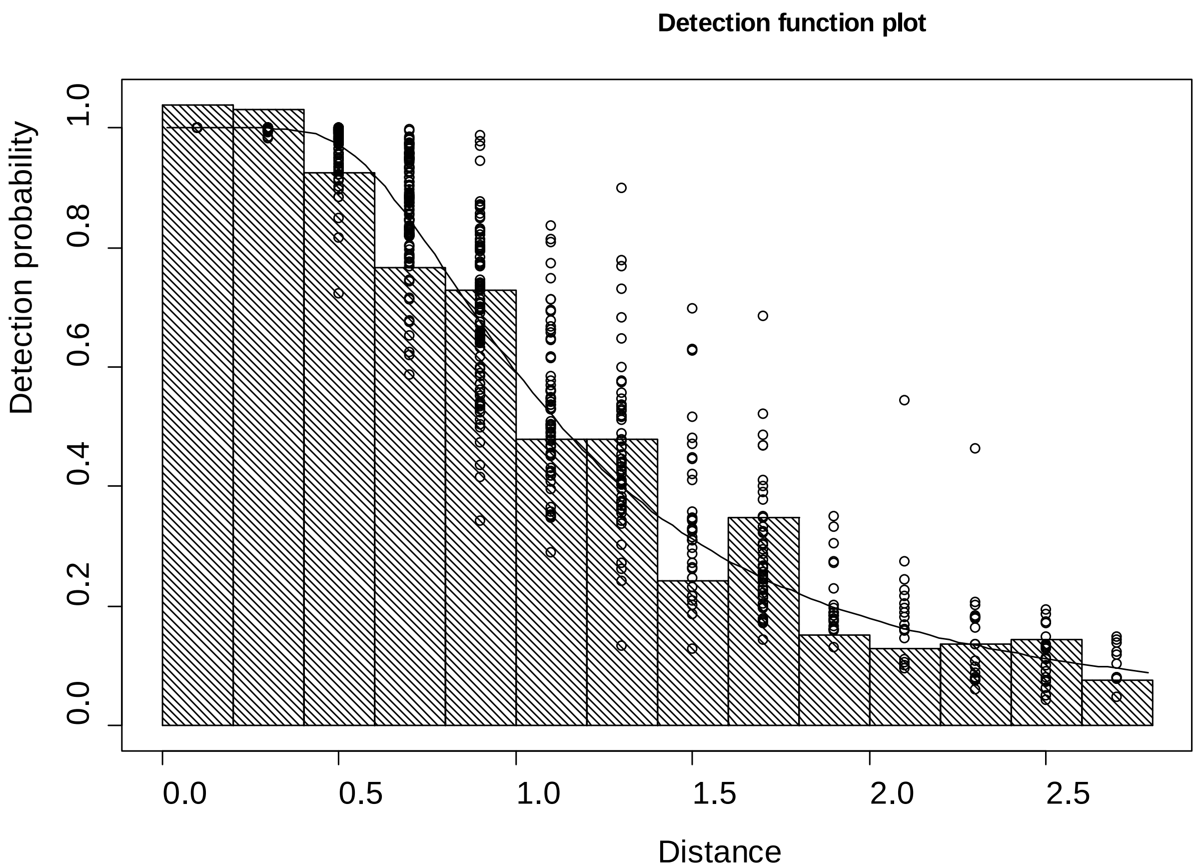


Appendix Figure A3c. -- Histogram (50 m bin width) of perpendicular distances (km) of gray whale sightings made by primary observers during BWASP aerial surveys conducted on the Twin Otter, 2008-2011, during Beaufort Sea States less than or equal to 5 (n = 216 sightings).

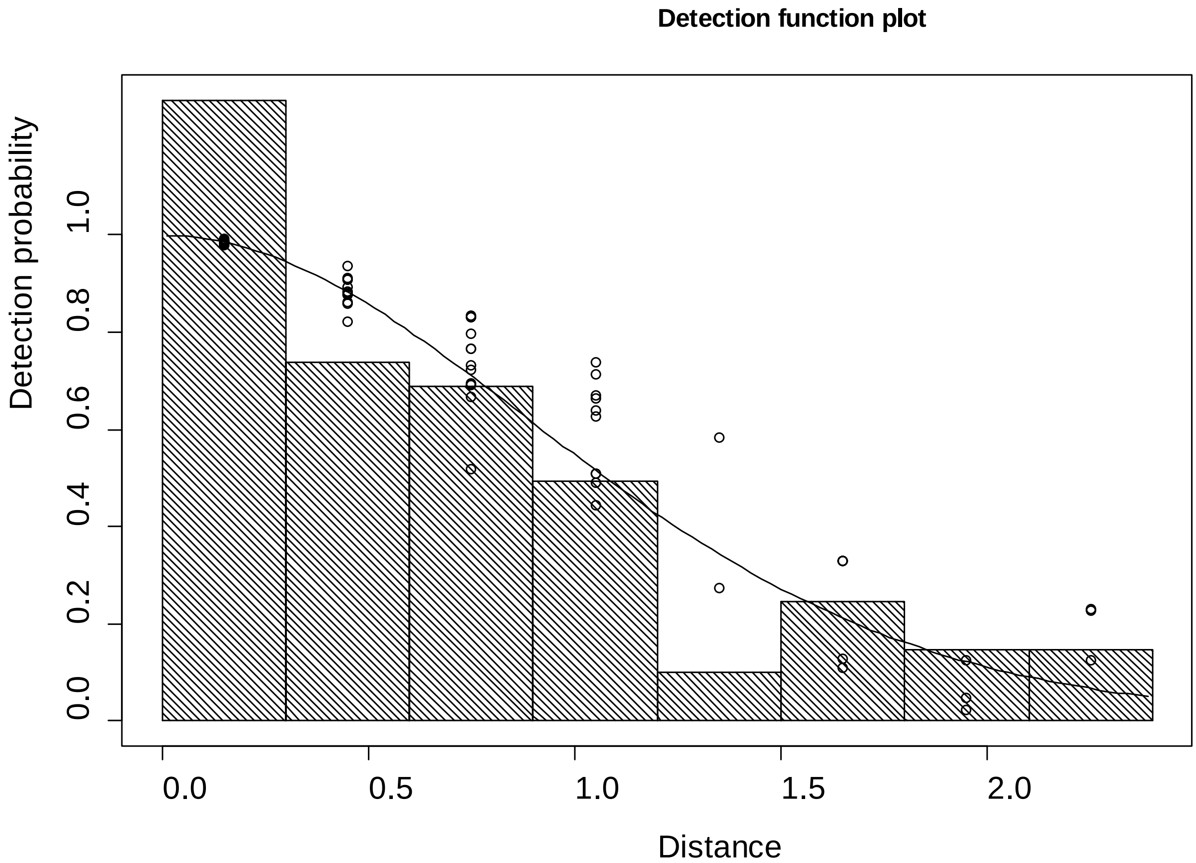




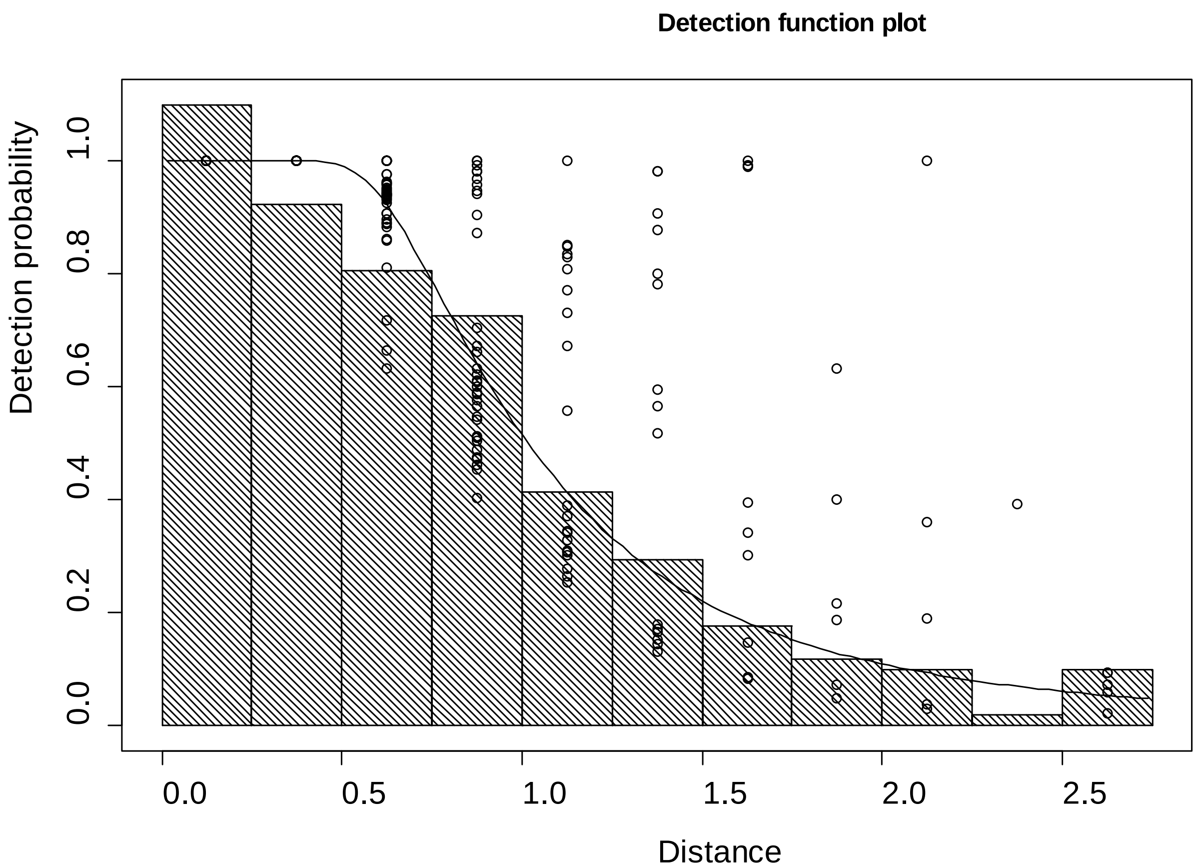
Appendix Figure A4. -- Histograms (50 m bin width) of perpendicular distances (km) of bowhead whale, beluga, and gray whale sightings made by "Observer 0" (top, n = 282 sightings) and all other observers (bottom, n = 1,463 sightings) during BWASP aerial surveys conducted on the Twin Otter, 1989-2007, during Beaufort Sea States less than or equal to 5.



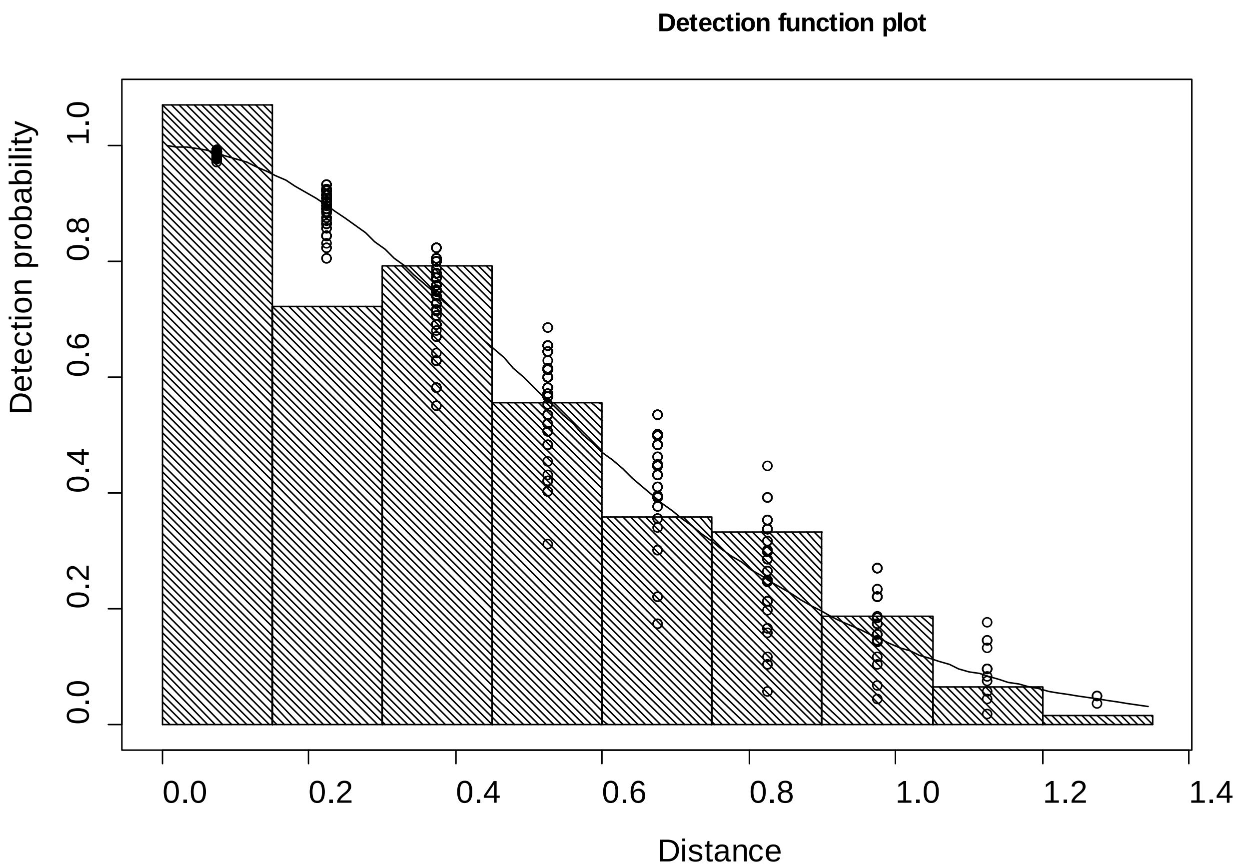
Appendix Figure A5. -- Final detection function model for bowhead whale sightings made during aerial surveys conducted on the Twin Otter, 1989-2007.



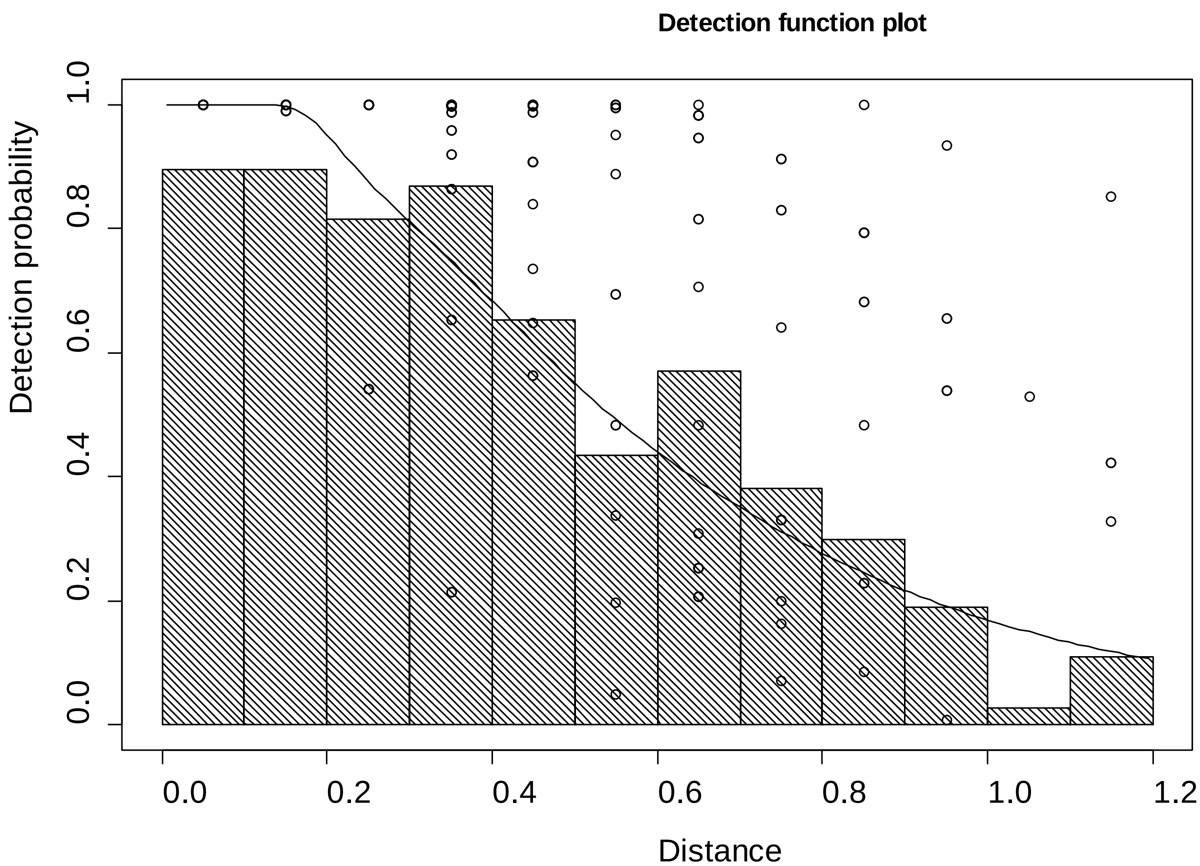
Appendix Figure A6. -- Final detection function model for bowhead whale sightings made during aerial surveys conducted on the Aero Commander, 2008-2011.



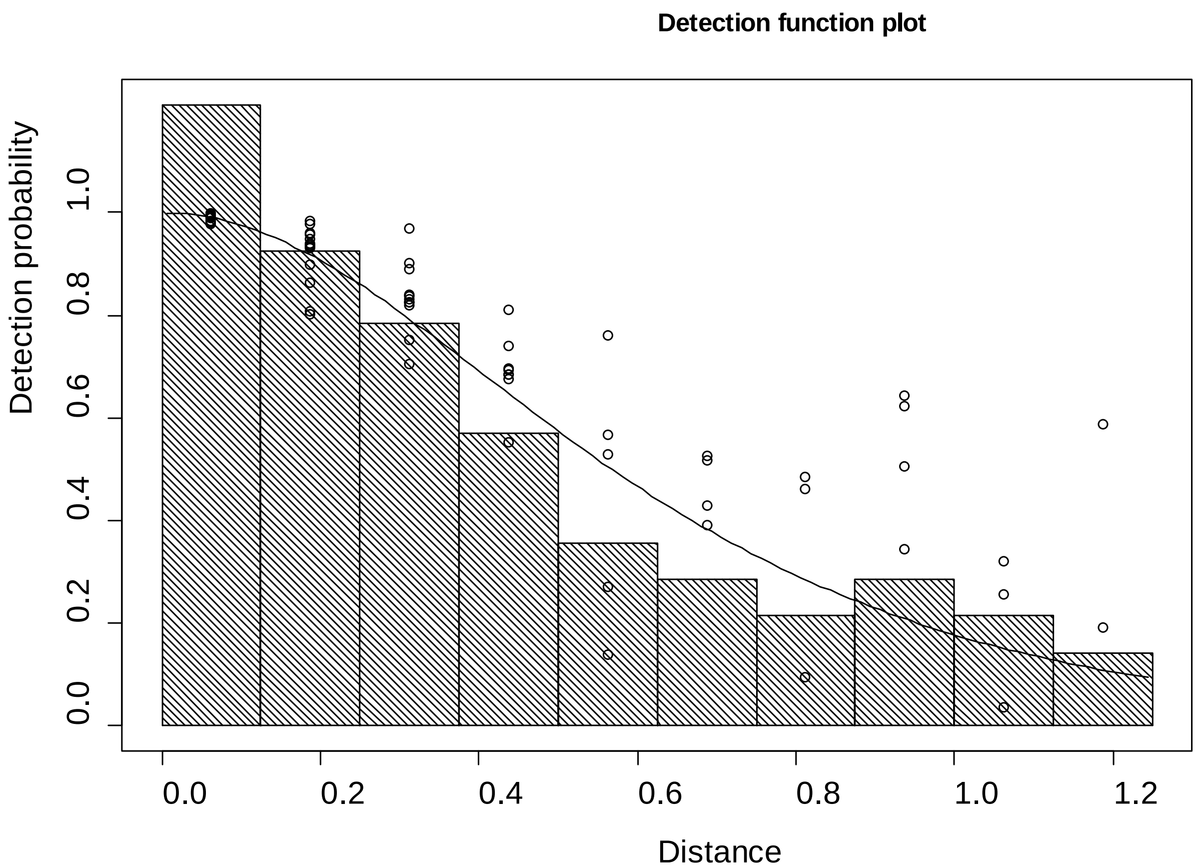
Appendix Figure A7. -- Final detection function model for bowhead whale sightings made during aerial surveys conducted on the Twin Otter, 2008-2011.



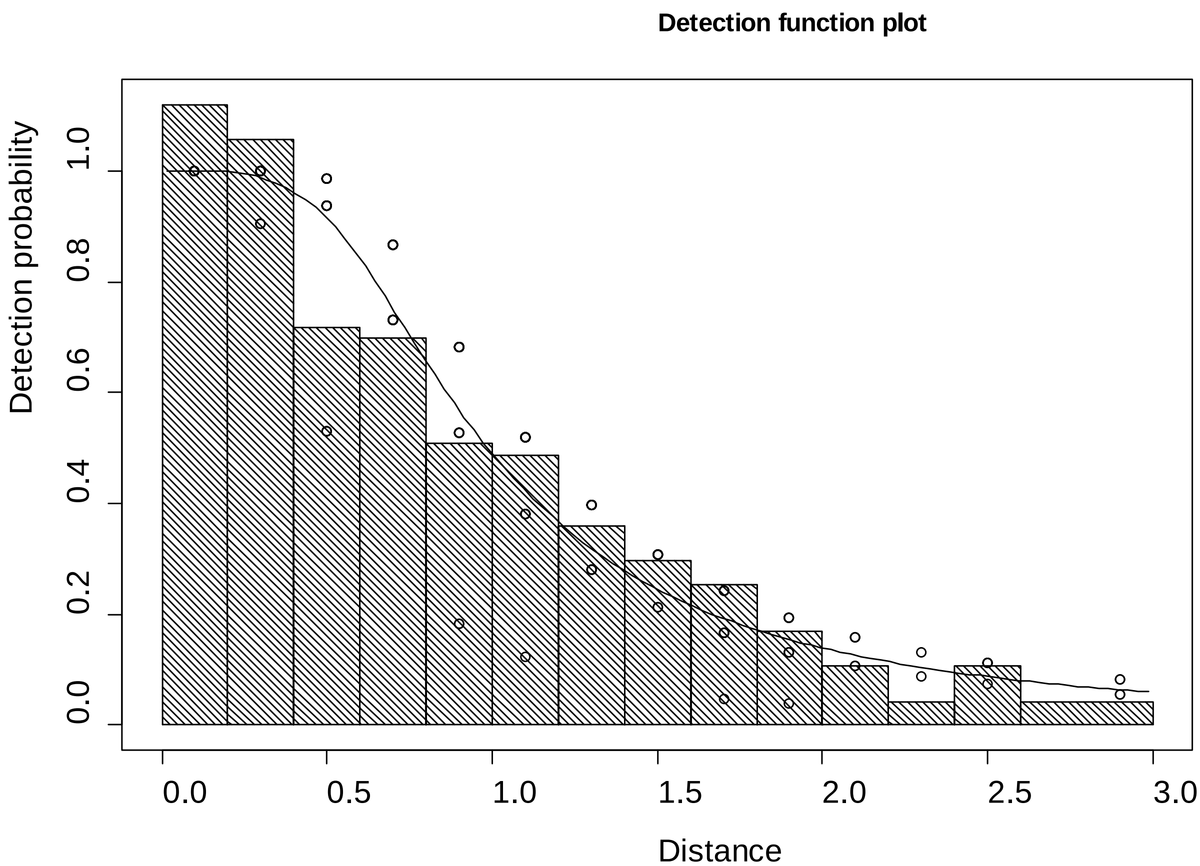
Appendix Figure A8. -- Final detection function model for beluga sightings made during aerial surveys conducted on the Twin Otter, 1989-2007.



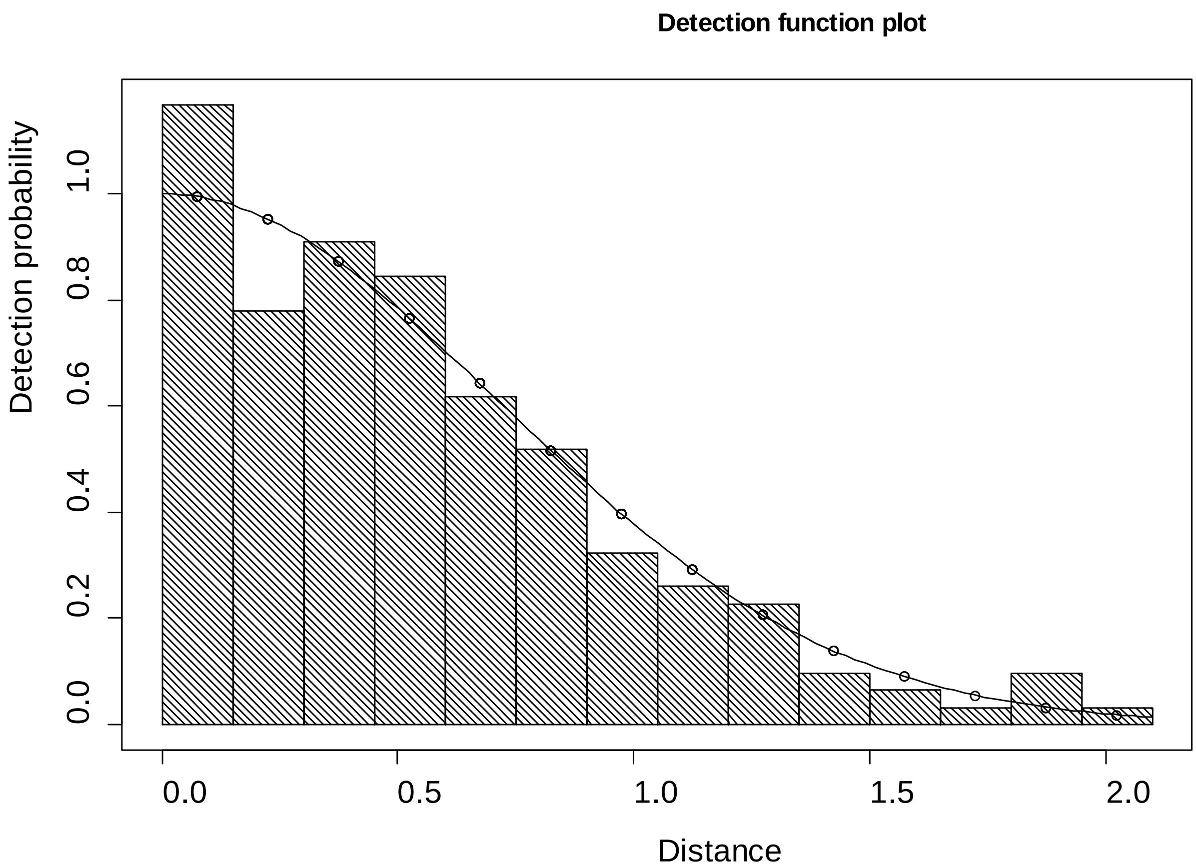
Appendix Figure A9. -- Final detection function model for beluga sightings made during aerial surveys conducted on the Aero Commander, 2008-2011.



Appendix Figure A10. -- Final detection function model for beluga sightings made during aerial surveys conducted on the Twin Otter, 2008-2011.



Appendix Figure A11. -- Final detection function model for gray whale sightings made during aerial surveys conducted on the Aero Commander, 2008-2011.



Appendix Figure A12. -- Final detection function model for beluga sightings made during aerial surveys conducted on the Twin Otter, 2008-2011.

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