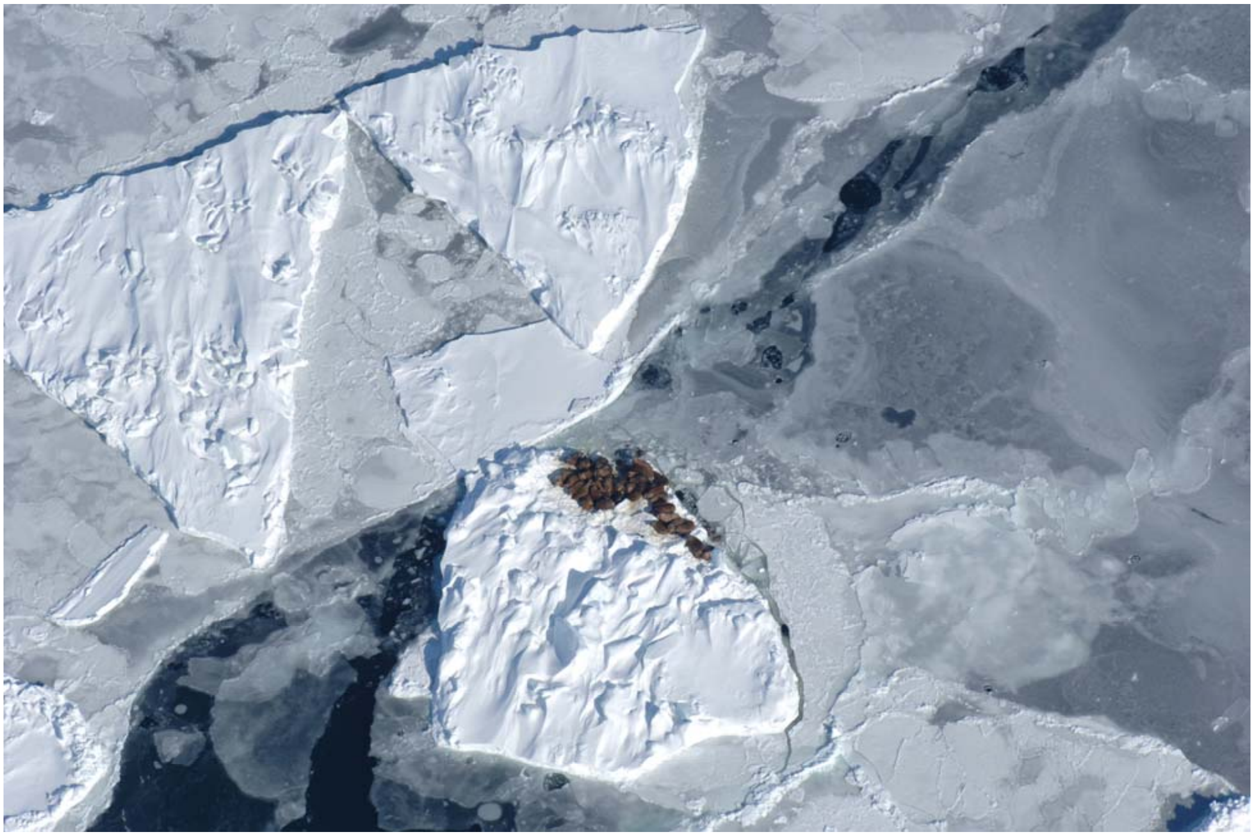
Progress Report

Range-wide Survey of Pacific Walruses in 2006: Estimated Number of Walruses on Sea Ice



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ABSTRACT

In spring of 2006, a range-wide survey of the Pacific walrus (*Odobenus rosmarus divergens*) was conducted as a collaboration among the U. S. Fish and Wildlife Service, U.S. Geological Survey, and the Russian institutes Giprorybflot and ChukotTinro. The goal of the survey was to estimate the size of the Pacific walrus population across its spring range, the ice-covered continental shelf of the Bering Sea. U.S. and Russian scientific crews coordinated aerial survey efforts on their respective sides of the international border. The Bering Sea was partitioned into survey blocks, and a systematic sample of transects within a subset of the blocks was surveyed with airborne thermal scanners using standard strip-transect survey methodology. An independent sample of scanned walrus groups was aerially photographed with digital cameras. Counts of walruses in photographed groups were used to model the relation between the thermal signature and the number of walruses in a group and to estimate the probability of thermally detecting a walrus group as a function of its size. These models were then used to estimate the number of walruses in groups that were not photographed but were detected by the thermal scanner, and to estimate the number of walruses in groups that were not detected by the scanner. Thermal imagery is capable only of detecting walruses that are hauled out on the pack ice. Adjustment of the on-ice estimate to account for walruses in the water and unavailable for detection will be addressed in a later publication. During the course of the survey, the size of the study area, i.e., the area of Bering Sea pack ice over waters less than 200 m deep, ranged from about 576,000 km^2 to 742,000 km^2 and averaged about 660,000 km^2. Transects covering a total of 96,423 km^2 of sea ice were surveyed, representing 9-45% of the area in each of 26 survey blocks. The area of the blocks surveyed by the U.S. and Russia was 318,204 km^2, representing about 48% of the available walrus habitat, based on average study area size. The total number of Pacific walruses hauled out on sea ice within the surveyed area was estimated to be about 22,000 individuals, with a 95% confidence interval of 8,453 to 45,439 individuals. Estimation of the total population size for the Pacific walrus will require additional analysis, including estimation of the number of walruses in the water and in areas not represented by surveyed blocks.

All literature cited in this report, including unpublished reports and Russian-language literature, are available in Portable Document Format from the U.S. Fish and Wildlife Service, 1011 E. Tudor Road, Anchorage, Alaska, 99503, USA. Telephone 800 362-5148.

Cover photo: Group of 35 Pacific walruses in the Bering Sea, 13 April 2006. Photo taken from 647 m by R. Bradley Benter, USFWS.

INTRODUCTION

The Pacific walrus (*Odobenus rosmarus divergens*) is an important ecological component of the Bering and Chukchi seas, and an irreplaceable cultural and economic resource for the Native peoples who inhabit this region (Fay et al. 1997). The U.S. Marine Mammal Protection Act (MMPA) recognizes the important role that marine mammals play in marine ecosystems, and directs that marine mammal species, including Pacific walruses, are maintained at an "optimum sustainable population." The current size and trend of the Pacific walrus population are unknown (U.S. Fish and Wildlife Service 2002), and the environmental changes that are occurring in walrus habitat make it increasingly important that reliable methods for monitoring this species are developed. A precise estimate of Pacific walrus population size is critical for successfully fulfilling the U.S. Fish and Wildlife Service's mandate under the MMPA for conservation and management of this species. In the Russian Federation, quotas for the hunting of walruses for the needs of Native peoples are determined annually, based on forecasts by ChukotTINRO of the number of walruses that can be removed from the population. Such a calculation is possible only with a precise and accurate estimate of population size. Pacific walruses inhabit sea ice habitats and terrestrial haulouts in both the U.S. and Russia, and management of this species therefore becomes an international challenge.

Based on large, sustained harvests in the 18th and 19th centuries (Fay 1957), Fay (1982) speculated that the pre-exploitation population of Pacific walruses was represented by a minimum of 200,000 animals. Since that time, population size is believed to have fluctuated markedly in response to varying levels of human exploitation (Fay et al. 1989). Large-scale commercial harvests reduced the population to an estimated 50,000-100,000 animals in the mid-1950s (Fedoseev 1962, Fay et al. 1997). The population is believed to have increased rapidly in size during the 1960s and 1970s in response to reductions in hunting pressure (Fay et al. 1989).

In the former Soviet Union, fall aerial surveys of walruses on terrestrial haulouts and hauled out on ice in the Chukchi Sea were begun in 1960 and were continued periodically, about once every five years (Fedoseev 1962). Similar aerial surveys were conducted in the United States in the 1960s and early 1970s (Kenyon 1960, Kenyon 1972, Fay 1982). Between 1975 and 1990, cooperative contemporaneous visual aerial surveys were carried out by the U.S. and the former Soviet Union at five year intervals, producing population estimates ranging from about 170,000 to 250,000 individuals (Estes and Gilbert 1978, Gol'tsev 1976, Krogman et al. 1979, Estes and Gol'tsev 1984, Johnson et al. 1982, Fedoseev 1981, Fedoseev 1984, Fedoseev and Razlivalov 1985, Gilbert 1986, Gilbert 1989, Gilbert et al. 1992, Udevitz et al. 2001). Observers counted or estimated numbers of walruses hauled out on pack ice and land, but could not accurately detect or enumerate walruses that were swimming in the water. Surveyed areas included all known terrestrial haul out sites, but were limited to less than 5% of available ice habitat. The population estimates generated from these surveys are considered minimum values that cannot be used for detecting trends in population size (Hills and Gilbert 1994, Gilbert et al. 1992). Efforts to survey the Pacific walrus population were suspended by both countries after 1990 due to unresolved problems with survey methods that produced population estimates with unknown bias and unknown, but presumably large, variances that severely limited their utility (Gilbert et al. 1992, Gilbert 1999). In Russia, fall aerial surveys of walruses at terrestrial haulouts and on ice in the Chukchi Sea were suspended after 1990 for political and economic reasons as well.

An international workshop on walrus survey methods, hosted by the U.S. Fish and Wildlife Service (USFWS) and U.S. Geological Survey (USGS) in 2000, concluded that it would not be possible to obtain a population estimate with adequate precision for tracking trends using the existing visual methodology and any feasible amount of survey effort (Garlich-Miller and Jay 2000). Workshop participants recommended investing in research on walrus distribution and haul-out patterns, and exploring new survey tools, including remote sensing systems and development of satellite transmitters, prior to conducting another aerial survey. Remote sensing systems were viewed as having great potential to address many of the shortcomings of visual aerial surveys by sampling larger areas per unit of time (Garlich-Miller and Jay 2000), objectively detecting and quantifying walruses (Udevitz et al 2001), and reducing observer error (Burn et al. 2006).

To explore the feasibility of using airborne thermal imagery to detect and enumerate walrus groups on sea ice, Burn et al. (2006) conducted a pilot study in 2002, which successfully demonstrated that walrus groups can be detected at a variety of spatial resolutions. A second pilot study was conducted in the area of St. Lawrence Island in the Bering Sea in 2003 (Udevitz et al. 2008). This study collected thermal infrared images of nearly 30,000 km^2 of sea ice habitat, an area larger than that covered in any previous visual aerial survey of Pacific walruses. This was the first time that thermal imagery was used to estimate numbers of walruses hauled out on ice within a specific region (Udevitz et al. 2008).

In March 2004, two USFWS biologists traveled to Murmansk, Russia, to participate in an aerial survey of harp seals (*Pagophilus groenlandicus*) in the White Sea. This survey used a thermal imaging and digital camera system similar to the one used for Pacific walrus surveys in the Bering Sea. Based on this experience, as well as follow-up discussions with the Russian survey team, it was determined that technology and expertise existed in both countries to make a range-wide survey of the walrus population using airborne thermal imagery feasible. In April 2005, the Russian survey team conducted field trials using the methods of Burn et al. (2006) to survey Pacific walrus in the Gulf of Anadyr, Russia. At the same time, USFWS biologists conducted field trials with a new, high-resolution thermal detector array. In December 2005, both survey teams met in San Diego, California, to finalize plans for a complete survey of the Pacific walrus population in spring 2006 using airborne thermal imagery.

Study design included use of the methods developed by Burn et al. (2006, in prep.), Chernook et al. (in prep.), and Udevitz et al. (2008) to estimate the number of walruses hauled out on ice in the Bering Sea. The study also used satellite transmitters to collect information on haul-out status of individual walruses, which can be used to estimate the proportion of the population in the water (Jay et al. 2006). Analysis of haul-out behavior will be presented in a later publication. In this progress report, we present the estimated number of Pacific walruses hauled out on sea ice in the areas that were surveyed in spring 2006. This estimate provides the essential foundation for development of a total population estimate that will also account for the number of walruses in the water and in areas not represented by surveyed blocks.

METHODS

Study Area

In late winter and early spring, Pacific walruses are found in the Bering Sea pack ice where open leads, polynyas, or thin ice allow access to water (Fedoseev 1982, Fay et al. 1984). Pack ice in the Bering Sea is almost exclusively single-year ice that forms and melts annually (Fay 1974, Plotnikov 1999). Walruses use floating ice floes as substrate for birthing and nursing calves, resting, and for passive transport to new feeding areas. Although capable of diving to deeper depths, walruses usually feed in shallow waters of 100 m or less (Fay 1982, Fay and Burns 1988). In April 2006, we sought to survey the extent of Bering Sea pack ice, which typically does not extend beyond the 200 m continental shelf. Under these criteria of ice and depth, all potential spring walrus habitat would have been included in the survey. During this time of year, walruses do not generally use terrestrial haulouts (Fay 1982).

To estimate ice extent in the study area, we used daily ice edge data provided by the National Ice Center (http://www.natice.noaa.gov/). Daily ice edge is a product with approximately 25 km resolution that integrates data from a variety of sources with resolutions ranging from 200 m to 25 km (RADARSAT 2, DMSP OLS, AVHRR, ENVISAT, SSMI, and QUIKSCAT). The ice edge is a boundary line defined by a set of latitude/longitude pairs that extends across the Bering Sea, beyond which no sea ice can be detected in satellite imagery. Estimated extent of the pack ice over waters less than 200 m in depth was measured in ArcMap (ESRI, Leica Geosystems GIS Mapping, LLC). The study area therefore includes expanses of open water where ice coverage may have been very low, but still usable by walruses. It is known that walruses use sparse ice if the floes can support their weight (USFWS and USGS unpublished data). The ice edge is a dynamic metric, fluctuating greatly with wind speed, wind direction, temperature, and other environmental conditions. In Russia, the study area extended from the Bering Strait south to just north of Karaginskiy Island, depending on ice conditions. In the U.S., the study area extended from the Bering Strait past St. Matthew and into Bristol Bay, also depending on ice conditions.

Study Design

The ice-covered Bering Sea was partitioned into survey blocks, and study design called for surveying a systematic sample of transects within each block with airborne thermal scanners using standard strip-transect survey methodology (Figure 1). Survey blocks were defined as the contiguous area covered by one crew in single day of surveying and study design indicated that each block would be surveyed once. Thermal (infrared) imagery of walruses hauled out on pack ice was the primary type of data collected. Walruses are generally warmer than the background environment of ice and snow, and groups of walruses hauled out on ice are therefore detectable with thermal imagery, whereas walruses in water cannot be detected (Burn et al. 2006, Chernook et al. 1995, 1999). The amount of heat produced, or thermal signature, was recorded for each walrus group that was detected by a thermal scanner. Infrared radiation cannot penetrate cloud cover or fog, and therefore thermal scanning could only take place during periods when skies were clear between the ice and the scanner aircraft. Pilot studies indicated that walrus groups are less likely to be thermally detected under very cold conditions. Therefore, we planned to conduct surveys at 4 m resolution only when the ambient air temperature was above -12º C (10º F), and the wind chill factor was above -18º C (0º F). If temperatures were cold, we planned to decrease the altitude to increase data resolution. An independent sample of the thermally-detected groups was aerially photographed with high-resolution digital cameras. Counts of walruses in photographed groups were used to estimate the probability of thermally detecting walrus groups on the ice and to model the relationship between thermal signatures and the number of walruses in a group.

U.S. Data Collection

U.S. thermal imagery was collected from an Aero Commander 690B turbine twin-engine aircraft. This aircraft contained the thermal infrared (8.5-12.5 µm) scanner with a 0.625 milliradian instantaneous field of view. The system, built by Argon ST (Ann Arbor, Michigan) was equipped with a 3,000 pixel detector array and had 12-bit radiometric resolution, a 90° angle of view, and absolute sensitivity of 0.12 degrees Celsius. The system also included a position and orientation system (POS) to georeference the thermal imagery into the Universal Transverse Mercator (UTM) coordinate system (Applanix Corp., Richmond Hill, Ontario, Canada).

Thermal imagery data were viewed in real time and continuously written to a storage disk as the aircraft flew along transect lines within a survey block. Survey transects were oriented north-south and ranged in length from 60-225 km in length. Scanning of a transect resulted in a single "thermal image." Initial survey operations for the scanner aircraft were conducted at 6,400 m above ground level (AGL), producing imagery with 4 m pixel size. On 19 April, surveys were conducted at both 6,400 m and 3,200 m AGL to collect imagery with both 4 m and 2 m pixel sizes, which correspond to 12 km and 6 km wide strip widths, respectively. Survey operations on 21 April and 22 April were also conducted at 3,200 m AGL. Transects were spaced with 24 km between strips in the 6,400 m surveys and with 12 km between strips in the 3,200 m surveys.

A second aircraft, an Aero Commander 680 twin-engine piston aircraft equipped with bubble windows and a vertical camera port, was used for aerial photography. Because of its slower speed and the limited area that could be searched using visual observations, the photography plane was directed to areas with walrus groups by the thermal scanning aircraft crew. This increased efficiency by reducing the time necessary to search for walrus groups to photograph. Once in an area with walruses, both pilots and two additional scientific crew in the aerial photography aircraft assisted with finding walrus groups. All walruses seen were photographed to obtain an independent sample of walrus group sizes. Walrus groups were photographed in high resolution with a digital single lens reflex Nikon D2X 12.4 megapixel camera that produces images with dimensions of 4,288 x 2,848 pixels. Photographs were taken from a nominal altitude of 700 m AGL using an image-stabilized 200 mm f2.8 Nikon camera lens and 1.4x Nikon teleconverter, giving an overall focal length of 280mm. Walruses very rarely reacted to the aircraft at this flight altitude.

Aerial photographs were georeferenced with a dedicated Global Positioning System (SGPS) unit. A Garmin 3 GPS was linked to the camera through a dedicated port, and aircraft position (latitude and longitude coordinates, altitude) and exposure time were annotated to the metadata of each photograph. Position was based on the location of the aircraft at the time the photographs were taken. The camera was connected to a notebook computer equipped with Nikon Capture software via an IEEE 1394 (firewire) port. The ability to review photos within seconds after collection greatly improved our efficiency, as we could quickly determine if a photo pass was successful and repeat the pass if necessary. The objective was to photograph as many walrus groups as possible within the strip surveyed by the thermal scanner within one hour of scanning, to minimize the effect of changes in group size over time. Additional areas were thermally scanned while the scanner aircraft was in transit to and from survey transects and additional "off-transect" walrus groups in these areas were photographed opportunistically to acquire additional data for calibration.

Russian data collection

All Russian thermal imagery and photography data were collected simultaneously from a single aircraft, a twin-engine Let L-410 specially equipped for scientific surveys. This aircraft accommodated a crew of 6, including 2 pilots and 4 scientific crew. Thermal imagery was collected with the Malakhit-M thermal scanner, which had an angle of view of 120°, radiometric resolution of 12 bits and sensitivity of 0.1°Celsius. The system had a 1.3 milliradian instantaneous field of view providing a resolution of 1.3 m at 1000 m AGL, with a strip width of 3.4 km. Surveys were conducted below cloud cover at altitudes from 500 to 1000 m AGL, yielding strip widths ranging from 1.4 to the full width of 3.4 km. Transects were usually spaced with 15.6 km between strips. On 18 and 24 April, when walrus densities were high, the distance was reduced to 7.8 km between transects. As the aircraft flew along transect lines within a survey block, thermal imagery data were viewed in real time by the scanner operator and temporarily stored in a buffer. When walruses were identified and verified by the scientific crew using thermal and/or visual observations, thermal data were written to the storage disk. If scientific crew did not see any walruses, then thermal data for that area were not saved, which may have resulted in the loss of some small walrus groups.

Three high-resolution digital Nikon D70s cameras with focal length of 50 mm were used to photograph walrus groups within the scanned area. Each camera had an angle of observation of 25°. Cameras were mounted on the aircraft so that one photographed directly below the aircraft, along the transect line, and the other two photographed the areas to either side, giving total coverage of about 75°. The cameras were managed using computer software so that all three cameras were fired simultaneously by the thermal scanner operator if walrus signatures were detected in thermal imagery or if requested by visual observers. Each photograph included exposure time and location (latitude and longitude coordinates) determined by a GPS. A fourth camera, a Nikon D70 with focal length of 18 to 200 mm, was used to manually photograph broader areas (F = 18 mm) when walrus groups were abundant, to record orientation among groups in relation to one another, and also to obtain more detailed photos of walrus groups (F = 200 mm). The objective was to photograph as many walrus groups as possible within the strip surveyed by the thermal scanner as scanning was occurring. Additional off-transect walrus groups were photographed opportunistically.

Data Processing

U.S. thermal infrared imagery was imported using a custom software application (Rapid Mapper) developed by Argon ST (Ann Arbor, Michigan). This program integrated the thermal data and position (POS) information to create georeferenced thermal images in Universal Transverse Mercator (UTM) coordinate system. ERDAS Imagine (Leica Geosystems, Atlanta, Georgia) software was used for initial data visualization and export to ASCII format. Sensor artifacts (i.e., temperature values that were impossibly high or low) were re-coded to missing values before the data were processed (Burn et al. 2006, Burn et al. in prep.). The same procedures were used for processing both the 2 m and 4 m resolution thermal images (Burn et al. in prep.). Thermal images were used to define walrus groups (Burn et al. 2006). A walrus group was considered distinct from other groups if their corresponding thermal signatures were separated by one or more pixels (2 – 4 m, depending on resolution). Geo-referencing made it possible to overlay each photograph on its corresponding thermal image so that each walrus group could be matched with its corresponding thermal signature. The unique patterns and features of the ice in the background, visible in both the photographs and thermal images, assisted in making final matches.

Russian thermal imagery was processed by a multifunctional program called "BinC" that was developed specifically for viewing and processing thermal imagery data files (Giprorybflot, St. Petersburg, Russia). This program allowed for the correction of geometric and temperature distortion of thermal images, and enabled selection and attachment of positional coordinates to groups of walruses and subsequent export of corrected data to the software package Surfer (Golden Software, Colorado), which was used to calculate the thermal index. Data were processed separately for each group of walruses and exported into this program as a GRID file in ASCII format in absolute temperature. Walrus groups were considered separate from neighboring groups if, between thermal spots, the temperature became equal to the temperature of ice for a distance of more than 3 to 4 meters.

Counting walruses in photographed groups

Each photograph was overlaid on its corresponding thermal image to match each walrus group with its thermal signature (Figure 2; Burn et al. 2006). Visual inspection of the ice field around each walrus group, which tended to have unique features that could be used for orientation, facilitated fine scale matching of photographed features with the thermal images. The number of walruses in each photographed group was counted using ERDAS Imagine software. Each photographed walrus group was counted three times by the same analyst (U.S. data) or three different analysts (Russian data), who marked each walrus with a uniquely colored symbol. If the three counts were not identical, the symbols for all three counts were simultaneously displayed and a fourth count was made to rectify differences. To ensure that groups of walruses in photographs reflected the same groups that were recorded by the thermal scanner, only walruses hauled out completely on the surface of an ice floe were counted; walruses clearly in the process of hauling out or leaving the ice were not counted. Counting error for photographs is assumed to be unbiased and small relative to other sources of variation.

Detecting walrus groups

The procedure for detecting walrus groups in U.S. thermal imagery data is reported in more detail in Burn et al. (in prep.). Each thermal image (one transect line) was subdivided into a series of 200 x 200 pixel "tiles," which covered an area 800 m on a side in 4 m imagery, and 400 m on a side in 2 m imagery. The temperature value for each pixel was rounded to the nearest tenth of a degree Celsius to create a temperature histogram for the pixels in each tile.

Three statistics were derived from the temperature histogram for each tile in each thermal image: 1) maximum temperature; 2) length of right-hand tail, calculated as the difference between the maximum temperature and the warmest histogram bin with a frequency of 10 or more pixels; and 3) maximum gap between histogram values (Figure 3). Temperatures near maximum for a tile are characteristic of thermal signatures of walrus groups because walruses are typically the warmest objects in their immediate environment. Long right-hand tails and large gaps are also characteristics of walrus thermal signatures because walruses are relatively rare features, typically present in less than 0.1% of the pixels in a tile (Burn et al. in prep.).

Lower threshold values for each of these three parameters were determined based on tiles that contained photographed walrus groups. Tiles were then assigned a set of three scores based on the values of these parameters relative to their threshold values. Tiles with a maximum temperature that exceeded the threshold value were given a score of 4. Tiles with a right-hand tail value that exceeded the threshold value were given a score of 2, and those that had a maximum gap value that exceeded the threshold were given a score of 1. Scores were set to 0 for each parameter that did not exceed its threshold value. The three scores were then summed to give a total score, which could range from 0 to 7 for each tile.

Tiles with total scores of 0 were eliminated from further consideration at this point. Data for remaining tiles were then examined in detail for the spatial arrangement of the warmest pixels and their degree of contrast with adjacent pixels. Warm pixels that corresponded to features such as open leads and rock faces along the shoreline could be eliminated easily based on visual inspection of the images. Walrus groups are typically located on thicker ice floes that register colder temperatures and therefore tend to be represented by pixels that have a high degree of contrast with adjacent pixels. These characteristics were used to identify which of the remaining tiles contained pixels that corresponded to walrus groups (Burn et al. in prep.).

Initial recognition of walrus groups in Russian thermal imagery was done in real time aboard the survey aircraft. The high resolution (1.3 m) of the thermal scanner made visual recognition of walrus thermal signatures possible, and the low survey altitude allowed real-time confirmation by visual observers. Recorded thermal images were later examined more closely using a method similar to that described in Burn et al. (2006) for final detection of walrus groups. To determine the threshold value for the Russian data, defined as the difference between the temperature of walruses and temperature of the surrounding environment, the frequency histogram of temperature values from the entire thermal image was used. In each thermal image, the point at which the columns of the histogram rapidly decreased from thousands of elements to less than ten elements, defined the threshold temperature value. The area where temperature was higher than the threshold value was considered to be occupied by walruses.

Calculating walrus thermal index values

Once a walrus group was identified, the correct number of pixels needed to be assigned to the group. Edges of walrus groups were not always distinct, given the averaging of temperatures over 4 m intervals in the U.S. data. Determination of which pixels belonged to each detected walrus group was accomplished with a disjoint cluster analysis relative to pixel locations within the tile (row and column coordinates) and temperatures (Burn et al. in prep.). This procedure assigned each pixel into 1 of 10 clusters by minimizing Euclidian distances, relative to these three normalized variables, among pixels in the same cluster (Anderberg 1973). By definition, the warmest cluster in a tile was always included as part of a group. However, in some cases, walrus groups consisted of more than one contiguous cluster. Clusters were ranked in order of their mean temperatures. Additional clusters were added to walrus groups until a cluster was more similar to the next coldest cluster (background) than it was to the next warmest cluster (previously designated as belonging to a walrus group). The temperature value for each pixel in a walrus group was normalized by subtracting the modal temperature for all non-walrus pixels in the tile. The thermal index was then calculated for each walrus group as the sum of these normalized temperatures. Normalizing with the modal temperature of each tile had the effect of standardizing the index relative to the local ambient temperature, thereby reducing overall variability of the relation between the index and the number of walruses in a group.

Calculation of the thermal index for Russian data for a group of walruses was implemented using the built-in function "Volume" in the program Surfer. In Surfer, there are three methods for calculating volume over an area: the trapezoid method (Trapezoidal Rule), Simpson's method (Simpson's Rule), and Simpson's 3/8 method (Simpson's 3/8 Rule). We calculated the thermal index for each group by taking the average of the three calculated volumes.

Statistical Analysis

Estimating group detection probabilities

Logistic regression models (Hosmer and Lemeshow 2000) developed by Burn et al. (in prep.) were used to estimate probabilities of detecting walrus groups in the U.S. thermal imagery. A separate analysis was conducted for 2 m and 4 m resolution data, and data for all photographed groups, including those photographed off-transect, were used. Group size, the log of group size, modal ice temperature for the tile (ice temperature), and the log of ice temperature were considered as possible predictors. At each resolution, models were fit that contained all combinations of the predictors, except that both transformed and untransformed versions of a predictor were not used in any single model. Models were fit with maximum likelihood. Akaike's Information Criterion (AIC, Burnham and Anderson 2002) was used to select the final detection model at each resolution. Fit of the final models was evaluated with the Hosmer-Lemeshow goodness-of-fit test (Hosmer and Lemeshow 2000).

The Russian data included only one photograph of an undetected group, which was not sufficient for formally estimating a detection function. However, the undetected group consisted of just a single walrus. There was one additional photograph of a single walrus that was detected and there were six photographed groups of two walruses that were all detected. Thus, it is likely that almost all groups containing more than one walrus, as well as some individual walruses, were detected. Based on this, we assumed that the number of walruses undetected in the Russian thermal imagery was a very small proportion of the population and did not attempt to account for them.

Calibrating thermal index values

Calibration models were developed to estimate the number of walruses in each group detected in thermal imagery based on its thermal index value. Models used for the U.S. data were developed by Burn et al. (in prep.), and separate analyses were conducted for both 2 m and 4 m resolution data. The same methodology was used to develop calibration models for the Russian data, using photographs of walrus groups that were detected in the Russian thermal imagery.

For all calibration models, only observations of groups that were detected in thermal imagery were used because the calibration models were conditional on groups being detected. Data for all thermally detected and photographed groups, including those photographed off-transect, were used. For the Russian data, we considered only linear functions of the thermal index for calibration. We did not attempt to use more complex functions of the index because plots of the data indicated the relation was, at least, approximately linear and there were too few photographs of larger groups to reliably estimate any curvature. Calibration functions were estimated using generalized linear models (McCullagh and Nelder 1999) with identity links. For each calibration model, Normal, Poisson, negative binomial, and gamma distributions were considered for fitting the error distribution. In addition to these model structures considered by Burn et al. (in prep.), for the Russian data we also considered generalized linear models with log-normal errors and identity links. For the log-normal models, the log of the thermal index was used as the predictor, to maintain the approximate linearity of the relation that was evident on the untransformed scale. All models were fit with maximum likelihood. AIC (Burnham and Anderson 2002) was used to select the final calibration model and deviance and deviance residuals were used to assess the fit to the data for each model (McCullagh and Nelder 1999).

Estimating numbers of hauled-out walruses

The basic approach described by Udevitz et al. (2008) was used to estimate the total numbers of walruses on the sea ice in each survey block, for both U.S. and Russian data. However, survey conditions encountered by Udevitz et al. (2008) likely resulted in a negligible number of undetected walruses hauled out on surveyed transects, and they made no attempt to account for them in their pilot study. Here, we extended this approach to incorporate detection functions to account for hauled-out walruses that were not detected on surveyed transects in U.S. blocks.

Calibration models were used to estimate the number of walruses in each group that was thermally detected on a survey transect, but not photographed. For thermally detected groups that were photographed, the group size was determined directly from the photographic count. The detection models were used to estimate the probability of thermally detecting a group as a function of its size. We used these estimated detection probabilities in Horvitz-Thompson estimators (Thompson 2002) of the number of hauled-out walruses on each surveyed transect:

$$\hat{Y}_{tb} = \sum_{g=1}^{G_{tb}} \left(\frac{\hat{Y}_{gtb}}{\hat{d}_{gtb}} \right),$$

where $\hat{Y}_{gtb}$ is the group size and $\hat{d}_{gtb}$ is the estimated detection probability for the g'th detected group, $g = 1, \ldots, G_{tb}$, on transect t in block b. For Russian transects, we assumed $\hat{d}_{gtb} = 1$.

The total number of walruses hauled out on sea ice in the surveyed blocks was estimated as a sum of separate ratio estimators (Thompson 2002) of the totals for each block:

$$\hat{N} = \sum_{b=1}^{B} \left(\hat{R}_b \sum_{t=1}^{T_b} A_{tb} \right) = \sum_{b=1}^{B} \hat{N}_b ,$$

where

$$\hat{R}_b = \frac{\sum_{t=1}^{t_b} \hat{Y}_{tb}}{\sum_{t=1}^{t_b} A_{tb}},$$

A_{tb} is the area of transect t in block b, T_b is the number of transects in block b, t_b is the number of surveyed transects in block b, and B is the number of blocks. For blocks that were surveyed more than once, the average of the estimated totals from the replicates was used in place of $\hat{N}_b$.

Udevitz et al. (2008) estimated variances and confidence intervals with a bootstrap procedure based on the general approach of Booth et al. (1994) for finite populations. The procedure involved generating a series of simulated populations, estimating statistics of interest by resampling from each simulated population, and then averaging these statistics over the simulated populations. We extended this approach to account for the additional component of variation due to estimation of the detection functions.

We generated simulated populations of transects (with associated walrus observations) for each block by first replicating the complete set of surveyed transects in the block as many times as possible without exceeding the total number of potential transects in the block. A random sample without replacement was then added from the surveyed transects to complete the population of potential transects. Bootstrap survey samples were obtained by drawing random samples without replacement from the simulated populations to give the same number of transects as in the original survey.

For each bootstrap survey sample, we also obtained a bootstrap sample of photographic counts for fitting the calibration and detection models. A bootstrap sample of photographed groups included all of the photographed groups in the bootstrap sample of surveyed transects if the number of those groups was ≤ the number on surveyed transects in the original sample. Otherwise, we sampled without replacement from the photographed groups in the bootstrap sample of transects to obtain the same number as in the original survey. We then completed the bootstrap sample of photographed groups by sampling with replacement from the original sample of groups photographed off survey transects to obtain the same total sample size (i.e., number of groups photographed on transects + number of groups photographed off transects) as in the original survey. This resampling strategy was designed to approximate the survey protocol which supplemented data from walrus groups photographed on survey transects with additional off-transect photographs.

Estimation for each bootstrap sample followed the same procedure as for the original sample. We obtained 100 bootstrap samples and associated estimates of population size for each simulated population and then calculated the standard error and 2.5 and 97.5 percentiles of those estimates. We repeated this process for 1,000 simulated populations and took the average of the standard errors and 2.5 and 97.5 percentiles as our estimates of standard errors and 95% confidence limits (Manley 1991) for the estimates from the original survey. We checked for convergence of estimates to ensure the numbers of bootstrap samples and simulated populations were sufficient.

We assessed the relative contributions of variance components by repeating the bootstrap procedure, using the originally estimated calibration and detection functions rather than resampling from the photographic counts and re-estimating the functions for each replicate. This provided variance estimates that accounted for sampling variation, but not the estimation of calibration and detection functions. We compared these to the full variance estimates to obtain the proportion attributable to sampling variation.

RESULTS

Airborne thermal infrared surveys of Pacific walrus in the Bering Sea were conducted from 04 to 22 April 2006 in the U.S. and from 03 to 23 April 2006 in Russia, Alaska Standard Time. Unseasonably cold temperatures and abundant fog across the Bering Sea in 2006 reduced the number of days suitable for surveying to 9 days in the U.S. and 10 days in Russia. For most of the survey period, temperatures were 2.8 to 8.3 °C colder than ten-year averages in Nome and Gambell, Alaska (National Weather Service, Nome, Alaska).

U.S. and Russian scientific crews coordinated survey efforts on their respective sides of the border. In the U.S., flight operations were conducted south of the Bering Strait and north of Nunivak Island (Figure 4). In Russia, the surveyed area extended from the Bering Strait to Cape Navarin (Figure 4). During the course of the survey, the size of the study area, i.e., the area of the Bering Sea where detectable sea ice was present over waters less than 200 m deep, ranged from about 576,000 km^2 on 09 April to 742,000 km^2 on 20 April, and averaged about 660,000 km^2. Southerly winds in late March pushed the pack ice to the north, reducing the size of the ice field, and cold temperatures throughout April resulted in additional freezing and expansion of ice along the southern edge of the ice pack. All surveys were conducted over pack ice concentrations ranging from about 50-100% total concentration.

During the survey, a total of 63 thermal images at 4 m resolution were collected in the U.S, covering 61,582 km^2. When cold weather conditions persisted, flight altitude was reduced to 3,200 m AGL, yielding a resolution of 2 m, and an additional 21 images were collected, covering 12,996 km^2. A total of 91 transects were thermally scanned in Russia with about 1.3 m resolution, covering 21,845 km^2. The area represented by the surveyed transects was less than the area covered by ice during the duration of the survey (Figure 4). We defined surveyed blocks as the minimum area that included the transect strips covered by a crew in a single day plus a distance equal to half the transect spacing on either side (Figure 4). The area of these surveyed blocks, combined for both Russia and the U.S., was 318,204 km^2, representing 48% of the available walrus habitat, based on an average study area size of about 660,000 km^2.

In the U.S., 124 unique walrus groups (91 on survey transects + 33 off-transect) were photographed in areas that were scanned at 4 m resolution and 85 walrus groups (33 on survey transects + 55 off-transect) were photographed in areas that were scanned at 2 m resolution (Figure 4, Table 1). Sizes of the U.S. photographed groups ranged from 1 to 168 walruses (mean = 22) for the 2 m imagery and from 2 to 446 walruses (mean = 27) for the 4 m imagery. There were 14 photographed walrus groups that could not be detected in the 2 m imagery, and 57 photographed groups that could not be detected at 4 m resolution. A total of 154 walrus groups were detected in U.S. thermal imagery on survey transects. Photographs were obtained of 90 walrus groups (50 on survey transects + 40 off-transect) within areas corresponding to Russian thermal images (Figure 4, Table 1), with sizes ranging from 1 to 150 walruses (mean = 20). All but one of these groups were detected in the corresponding thermal imagery. Two hundred eighteen groups of walruses were detected in thermal imagery on Russian survey transects. See Appendix A for daily summaries of survey effort and sightings.

Detection probabilities

Larger walrus groups were more likely to be detected using thermal imagery than smaller groups when resolution was coarser than the approximate scale of walrus body size (about 2-4 m). Detection models were used to account for groups on U.S. surveyed transects that were not detected. Final detection models developed by Burn et al. (in prep.) for the U.S. data had the form

$$E(Y_i) = g^{-1}(\beta_0 + \beta_1 X_i), \ \mathrm{var}(Y_i) = E(Y_i)\left(1 - E(Y_i)\right) ,$$

where Y_i is 1 if group i was detected and 0 otherwise, X_i is the size of group i, β_0 and β_1 are estimated coefficients, and

$$g(x) = \ln[x/(1-x)]$$

is the link function. Parameter estimates are given in Table 2. The models indicated that groups were always detected in the 2 m imagery if they contained more than about 10 walruses and in the 4 m imagery if they contained more than about 34 walruses (Figure 5). For smaller groups, detection probabilities decreased with group size to a value of 0.06 for single walruses in the 2 m imagery and 0.02 for single walruses in the 4 m imagery (Figure 5). As noted above, it was apparent that essentially all walrus groups were detected on Russian surveyed transects and we did not attempt to account for any undetected groups on Russian transects.

Thermal index calibration

Final calibration models developed by Burn et al. (in prep.) for the U.S. data were negative binomial (Figure 6A and B), with the form

$$E(Y_i) = \beta_0 + \beta_1 X_i, \ \mathrm{var}(Y_i) = E(Y_i) + k\ E(Y_i)^2 ,$$

where Y_i is the size of group i, X_i is the thermal index value for group i, β_0 and β_1 are estimated coefficients, and k is the estimated dispersion parameter. Parameter estimates are given in Table 3.

For the Russian data (Figure 6C), as with the U.S. data (Figures 6A and B), the thermal index had a strong linear relation to group size (Table 4) and variation increased with values of the thermal index. The negative binomial model fit this variance structure substantially better than models with other error distributions (Table 4). Therefore, the negative binomial model was selected for calibrating the Russian thermal index. This model had the same structure as the final calibration models selected by Burn et al. (in prep.) for the U.S. data. Examination of deviance and deviance residuals did not indicate any lack of fit for this final model. Parameter estimates for the final Russian calibration model are given in Table 3.

Estimated numbers of hauled-out walruses

Transects covering a total of 96,423 km^2 of sea ice were surveyed, representing from 9 to 45% of the area in 26 survey blocks (Figure 7, Table 5). However, this total includes transects in 6 blocks that substantially overlapped previously surveyed blocks (Figure 8). Survey blocks were originally defined as the contiguous area covered by one crew in single day of surveying and the intent of the original design was to survey each block once. However, three areas were surveyed twice and one small area was surveyed four times (Figure 8). Block A-217, north of St. Lawrence Island, was successfully surveyed on 17 April at 4 m resolution. On 19 April, we tried to survey south of St. Lawrence Island but were unable to do so due to low cloud cover. Satellite imagery showed an opening on the north side of St. Lawrence Island, and we returned to that area to scan a different systematic sample of transects and to obtain additional scanner calibration data (block A-219). The uppermost corner of A-217 and A-219 (A-217T and A-219T) was also scanned twice by the Russian survey team (R-900T and R-1000T; Figure 8). Blocks R-100 and R-1100, and R-900 and R-1000 also overlapped on the Russian side. These repeated surveys occurred when weather conditions or equipment malfunctions prevented us from surveying in new areas. Previously scanned areas were then re-surveyed in an effort to supplement data for areas that did currently have suitable conditions.

In most of these cases, the later blocks did not completely overlap the earlier blocks. However, based on the areas that did overlap and the distribution of detected walruses within these blocks, we assumed they constituted replicate surveys of the same portions of the population. This resulted in a partition of a 318,204 km^2 survey area into 20 blocks, now redefined based on area covered, without reference to the time of coverage. For blocks that were surveyed on more than one occasion, we estimated totals by averaging the estimated number of walruses from each occasion. For three of the four blocks that were surveyed multiple times, estimated totals differed substantially between replicates (Table 6).

No walruses were detected in 9 survey blocks (Table 5). Three hundred and seventy-two walrus groups were detected using thermal imagery from surveyed transects in the remaining 11 blocks (Table 5). Estimated sizes of groups detected on surveyed transects ranged from 1 to 446 walruses (Figure 9). Mean estimated group sizes within individual blocks ranged from 8 to 54 walruses (Figure 9). In U.S. blocks with detected walruses, estimated detection probabilities averaged $\geq$ 0.83 except for one block (block A-500) with an average detection probability of 0.28 (Figure 10). Average detection probabilities were lower in this block because it was surveyed at 4 m resolution and all of the detected groups were relatively small (maximum group size = 14, Figure 9).

Combining totals from all blocks, we estimated there were approximately 22,000 (95% confidence limits = 8,453 – 45,439) walruses hauled out on the sea ice in the surveyed area (Table 7). The precision of the estimates was relatively low, with coefficients of variation for individual block totals all $\geq$ 0.33 (Tables 5 and 6). This low precision was almost entirely due to the highly variable distribution of walruses among transects, as reflected in the sampling component of variation (Tables 5 and 6). The variance components associated with estimating calibration and detection functions contributed relatively little to the overall variance of the estimates.

DISCUSSION

This study is the first attempt to use thermal imagery to estimate the number of Pacific walruses hauled out on ice across their spring range, the ice-covered continental shelf of the Bering Sea, a critical first step in development of an estimate of the total population size. Due to logistical constraints and weather, the area covered by the 2006 survey included only about 48%

of the available habitat of the Pacific walrus population at the time of the survey, specifically, ice-covered waters less than 200 m deep (Fay 1982, Fay and Burns 1988). This estimate of total habitat, however, is a preliminary approximation that will be refined to account for ice thickness and other ice characteristics when the estimate of the proportion of walruses in the water is incorporated into the population estimate.

Persistent cloud cover prevented us from surveying an area southwest of St. Lawrence Island, the area south of Nunivak Island, and the nearshore area south of Cape Navarin (Figure 4). Large aggregations of walruses have been documented to the southwest of St. Lawrence Island during April surveys in other years (Fedoseev 1979, Fay 1982, Braham et al. 1984, Fay et al. 1984, Fedoseev et al. 1988, Burn et al. 2006, Burn et al. in prep.). Large aggregations of walruses are intermittently present in April to the south of Nunivak Island (this study, unpubl. data, Fay 1982, Braham et al. 1984, Fay et al. 1984) and smaller numbers have been documented to the south of Cape Navarin (Fay 1957, Fedoseev 1979, Fedoseev 1988). Given the high variability in walrus distribution, it is not known how many walruses may have been in areas not covered by the 2006 survey.

Our estimate of the number of walruses hauled out on ice in the area that was covered by the survey, about 22,000 individuals, does not account for the proportion of the population that was in the water at the time of the survey. Previous studies have indicated that walruses using terrestrial haul-outs spend approximately 75% of their time in the water (e.g., Jay et al. 2001, Lydersen et al. 2008). Thus, it is likely that most of the walruses in the area we surveyed were in the water at the time of the survey and were therefore not recorded in thermal imagery (Burn et al. 2006). Estimation of the total number of walruses in the surveyed area, adjusted to account for the number of walruses in the water, is still in progress and will be reported at a later date.

The goal of the 2006 survey was to estimate population size with high precision, so that additional surveys in the future would allow tracking of trends in abundance over time (U.S. Fish and Wildlife Service and U.S. Geological Survey 2006). The coefficients of variation reported in this study are larger than those in the trial survey conducted by Udevitz et al. (2008). This is likely because the 2003 survey used smaller blocks confined to a region around St. Lawrence Island, where walrus distribution may have been more uniform. Two of the three lowest coefficients of variation for U.S. blocks in our survey were for blocks in this region. Temporal variation was not assessed in the 2003 trial survey (Udevitz et al. 2008), but was a substantial component of variation in our blocks with replicate surveys.

Differences in estimated numbers from replicate surveys of the same block may have been caused by several factors. First, high variability in walrus distribution may have resulted in the presence of very few walruses on survey transects on some days but large numbers on others (Estes and Gilbert 1978, Gilbert 1989, Hills and Gilbert 1994). This type of variability is reflected in the large estimated standard errors, most of which is attributable to sampling variation. Second, the proportion of walruses in the block that was hauled out on the ice and available to be counted may have varied between replicates (USGS unpublished data). Finally, walruses may have moved in or out of the block between replicates. The replicate surveys we obtained for some blocks provide estimates of the average number of walruses hauled-out on the ice in those blocks over the period of time spanned by the replicates. The associated variance estimates account for the temporal as well as spatial components of sampling variation.

Differences in equipment and strategy accounted for differing probabilities of detecting small walrus groups in Russian and U.S. thermal imagery. With an integrated thermal scanning and photography system that operated from a single aircraft, the Russian team was required to fly at an altitude low enough to acquire high resolution digital photographs in which individual walruses could be discriminated. The low altitude limited the strip width of the thermally scanned area, and hence the total area that could be scanned, but resulted in high resolution thermal imagery in which even single walruses could be detected. With the option of using a second aircraft for photography, and with a larger area to survey, the U.S. team chose to maximize strip width of the thermally scanned area and the total area that could be scanned by flying at a higher altitude. This reduced resolution of the thermal images and the likelihood of detecting small groups, which had been shown to comprise a small proportion of the total number of walruses (Estes and Gilbert 1978, Burn et al. 2006, in prep.).

Adult female walruses reach 3 m in length and weigh from 580-1,039 kg; males reach 3.6 m and weigh as much as 1,560 kg (Jefferson et al. 2008). The largest seal within the study area, the bearded seal (*Erignathus barbatus*), is substantially smaller than adult walruses, ranging up to 2.5 m in length and weighing up to 360 kg (Jefferson et al. 2008). Bearded seals typically haul out solitarily, rather than in groups or dense concentrations. No single walruses were detected in either the U.S. 2 or 4 m thermal imagery; it is therefore extremely unlikely that seals on ice could be counted as "false positive" walrus groups.

At about 1.3 m, Russian thermal imagery was of much higher resolution, making it more likely that individual animals could be detected. However, surveys dedicated to harp seals are conducted at much lower altitudes (200 m) than the 2006 walrus survey (1,000 m) specifically to increase resolution of thermal imagery and increase detection probability of this much smaller species (Chernook et al. 1999). Furthermore, walrus and bearded seals tend to be segregated in their distribution across suitable habitat due to competition for prey or predation interactions (Burns 1970, Lowry and Fay 1984, Simpkins et al. 2003). Absence of bearded seals from areas with concentrations of walrus groups further reduced the likelihood of confounding their thermal signatures. Although the detection of bearded seals in thermal imagery from Russia cannot be ruled out, it is highly unlikely that single bearded seals contributed significantly to our estimate of the total number of walruses.

Increasing sampling intensity (area sampled) has long been recognized as a way to reduce high variances in aerial marine mammal surveys, including surveys for walruses (Estes and Gilbert 1978, Gilbert 1999). However, Gilbert (1999), in a summary of efforts to understand the relationship between increased sampling intensity and coefficient of variation for aerial walrus surveys, cautioned that "the only effect of increasing sampling effort has been increasing the chance of sampling an area with a large group." Gilbert (1999) noted that for past walrus surveys, both estimates and coefficients of variation seem unrelated to improvements in survey design or attempts to increase sampling effort. In the 2006 walrus survey, sampling intensity (9 to 45%; mean 27%) was far greater than that achieved in earlier survey efforts, yet still was insufficient to substantially reduce coefficients of variation so that power to detect trends in abundance would be high. The extreme spatial and temporal aggregation of this species, combined with the vast ice-covered area it inhabits (Estes and Gilbert 1978, Hills and Gilbert 1994), continue to make survey design and execution a challenge.

Unseasonably cold temperatures and abundant fog across the Bering Sea in 2006 limited the number of days during which surveys could successfully be conducted. Reducing the altitude at which the U.S. thermal imagery was collected increased the resolution of the data to 2 m, thereby increasing the probability of detecting smaller walrus groups (Burn et al. in prep.), but this also decreased the sampling intensity.

Initial analysis of U.S. thermal infrared imagery with image processing techniques developed by Burn et al. (2006) revealed that a large number of photographed walrus groups were not detected in the thermal imagery. In addition, many of the groups that were detected appeared to have spatial footprints that were much smaller than their corresponding aerial photographs, suggesting that only a portion of the walruses in these groups were being detected. The initial calibration models for these data had large variances that would have decreased precision of population estimates. These unexpected results forced a re-examination of the image processing methodology and development of the more robust procedure for detecting walrus groups on sea ice in airborne thermal imagery under extremely cold environmental conditions presented by Burn et al. (in prep.) and used here.

Even with the improved detection method, colder temperatures resulted in lower detection probabilities for walrus groups in U.S. thermal imagery than for similarly sized groups in the pilot survey conducted by Udevitz et al. (2008). Estimates of detection probabilities were therefore incorporated to account for undetected groups on surveyed transects. The proportion of the variance associated with estimation of the detection function contributed relatively little to the overall variance of the estimates. High-resolution data collected by the Russian team were minimally affected by the cold temperatures.

The spring 2006 walrus survey was ground-breaking in many ways. New technology was developed to address issues that have long plagued attempts to estimate the size of the Pacific walrus population. We reported here on development and performance of thermal imagery as a tool for surveying large areas of sea ice for walruses quickly and accurately, without the biases that have accompanied past visual survey efforts. Analyses of walrus haul-out behavior based on data from satellite-linked radio tags, and adjustment of the population estimate to account for walruses in the water, will be reported elsewhere. Some long-standing issues, however, were still problematic. We were unable to survey all available walrus habitat due to logistical constraints and unfavorable weather, and precision was lower than we expected, and likely too low for accurate detection of trends in population size. We continue to analyze our data to more fully understand the sources of variation affecting the survey and to estimate the proportion of the population that was in the water. When all analyses are completed, we will evaluate the 2006 walrus survey and make recommendations for future work.

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Table 1. Summary of photographed walrus groups detected in U.S. and Russian thermal imagery.

Region	Image resolution	Number of photographed groups	Number of photographed groups detected/not detected	Size of smallest detected group	Size of largest undetected group
U.S.	2 m	85	71/14	2	6
	4 m	124	67/57	7	24
Russian	1 m	90	89/1	1	1

Table 2. Parameter estimates for U.S. detection models (Burn et al., in prep.).

Image resolution	Coefficient (SE)	
	Intercept	Group size
2 m	-3.65 (1.32)	0.85 (0.27)
4 m	-4.14 (0.77)	0.27 (0.05)

Table 3. Parameter estimates for final models selected for calibrating U.S. (Burn et al., in prep.) and Russian thermal indices.

Region	Image resolution	Coefficient (SE)		Dispersion parameter (SE)
		Intercept	Thermal index	
U.S.	2 m	5.34 (0.83)	0.09 (0.007)	0.08 (0.02)
	4 m	9.91 (1.70)	0.33 (0.032)	0.09 (0.02)
Russia	1 m	3.97 (0.44)	0.03 (0.002)	0.04 (0.02)

Table 4. AIC values for considered Russian calibration models.

Model structure[a]	Error distribution	Number of parameters	AIC	ΔAIC[b]
Linear	Negative binomial	2	517.73	0.00
Linear	Gamma	2	522.33	4.60
Linear	Poisson	2	536.79	19.06
Linear	Log-normal	2	551.00	33.27
Linear	Normal	2	582.37	64.64
Null	Negative binomial	1	720.20	202.47

[a]Null model includes only an intercept. All other models include an intercept and the thermal index or log(thermal index).

[b]ΔAIC is the difference between the AIC value for the specified model and the model with the lowest AIC value.

Table 5. Area covered and number of walrus groups hauled out on sea ice that were detected on surveyed transects in Bering Sea, April 2006.

Block[a]	Pixel size (m)[b]	April 2006 Date	Scanned area (km^2)	Block area (km^2)	Sampling intensity[c]	Detected Groups
R-200	1	3	2,741	16,292	0.17	0
R-300	1	5	2,650	14,817	0.18	4
R-400	1	18	3,003	20,344	0.15	0
R-500	1	11	1,470	12,551	0.12	0
R-600	1	12	1,113	12,077	0.09	0
R-700	1	13	2,457	14,321	0.17	0
R-800	1	23	703	4,638	0.15	7
R-100	1	4	2,838	15,498	0.18	61
R-1100	1	17	3,196	11,555	0.28	81
R-900	1	23	296	1,610	0.18	2
R-1000	1	19	954	7,287	0.13	26
A-100	4	15	6,734	15,006	0.45	1
A-304	4	4	4,824	14,272	0.34	0
A-313	4	13	3,616	11,403	0.32	10
A-314	4	14	5,224	12,826	0.41	0
A-400	4	4	11,235	31,616	0.36	0
A-500	4	10	7,775	21,506	0.36	12
A-800	4	12	8,973	29,823	0.30	0
A-221	2	21	7,812	28,985	0.27	4
A-321	2	21	5,184	18,200	0.28	33
A-217	4	17	6,542	15,042	0.43	0
A-219	4	19	5,097	15,042	0.34	94
R-900T	1	23	229	1,188	0.19	37
R-1000T	1	19	195	1,632	0.12	0
A-217T	4	17	1,116	2,212	0.50	0
A-219T	4	19	446	2,212	0.20	0

[a]Prefix R indicates block surveyed by Russian crew. Prefix A indicates block surveyed by U.S. crew.
[b]Size of pixels on the infrared image produced by the scanner (i.e., image resolution).
[c]Sampling intensity is the proportion of the block covered by the scanner (= Scanned area/Block area).

Table 6. Estimated numbers of walruses hauled out on sea ice during repeated surveys of blocks in the Bering Sea, April 2006.

Block	Replicate	Date	Number of walruses	95% confidence limits Lower	95% confidence limits Upper	Coefficient of variation	Sampling component of variance[b]
R-100	1	4	3,159	727	6,457	0.46	0.94
R-1100	2	17	4,170	502	8,957	0.51	0.99
R-100,1100	All		3,665[a]	611	8,191	0.52	0.98
R-1000	1	19	4,741	0	16,553	0.93	1.00
R-900	2	23	257	0	999	0.95	0.97
R-900,1000	All		2,499[a]	0	13,947	1.52	1.00
A-217	1	17	0	–	–	–	–
A-219	2	19	11,802	4,340	18,824	0.33	0.90
A-217,219	All		5,901[a]	0	17,750	1.10	1.00
A-217T	1	17	0	–	–	–	–
A-219T	2	19	0	–	–	–	–
R-1000T	3	19	0	–	–	–	–
R-900T	4	23	10,268	396	26,405	0.73	1.00
R-900T,1000T, A-217T,219T	All		2,567[a]	0	20,244	2.25	1.00

[a]Average of estimates for the indicated blocks. These are blocks that covered essentially the same region on different dates and are therefore assumed to represent repeated surveys of the same portion of the population.

[b]Proportion of the variance due to sampling only a portion of each block. The remaining portion is due to estimation of the calibration function and, for U.S. blocks, the detection function. Values of 1.00 indicate that the proportion due to estimation of calibration and detection functions was less than 0.01.

Table 7. Estimated numbers of walruses hauled out on sea ice in surveyed blocks in the Bering Sea, April 2006. The average of the replicate estimates (Table 6) is presented for blocks with repeated surveys.

Block	Number of walruses	95% confidence limits		Coefficient of variation	Sampling component of variance[c]
		Lower	Upper		
R-200	0	–	–	–	–
R-300	274	56	554	0.46	0.96
R-400	0	–	–	–	–
R-500	0	–	–	–	–
R-600	0	–	–	–	–
R-700	0	–	–	–	–
R-800	871	155	1,805	0.48	0.96
R-100,1100	3,665[a]	611	8,191	0.52	0.98
R-900,1000	2,499[a]	0	13,947	1.52	1.00
A-100	93	0	196	0.66	1.00
A-304	0	–	–	–	–
A-313	1,865	0	3,487	0.60	0.97
A-314	0	–	–	–	–
A-400	0	–	–	–	–
A-500	1,430	359	2,846	0.46	0.80
A-800	0	–	–	–	–
A-221	126	0	330	0.85	0.98
A-321	2,319	1,975	6,726	0.49	0.70
A-217,219	5,901[a]	0	17,750	1.10	1.00
R-900T,1000T, A-217T,219T	2,567[a]	0	20,244	2.25	1.00
Total	21,610[b]	8453	45,439	0.44	0.99

[a]Average of estimates for the indicated blocks. These are blocks that covered essentially the same region on different dates and are therefore assumed to represent repeated surveys of the same portion of the population.

[b]Total for the entire surveyed region, obtained by summing estimates for blocks surveyed once and averages of estimates for blocks surveyed more than once.

[c]Proportion of the variance due to sampling only a portion of each block. The remaining portion is due to estimation of the calibration function and, for U.S. blocks, the detection function. Values of 1.00 indicate that the proportion due to estimation of calibration and detection functions was less than 0.01.

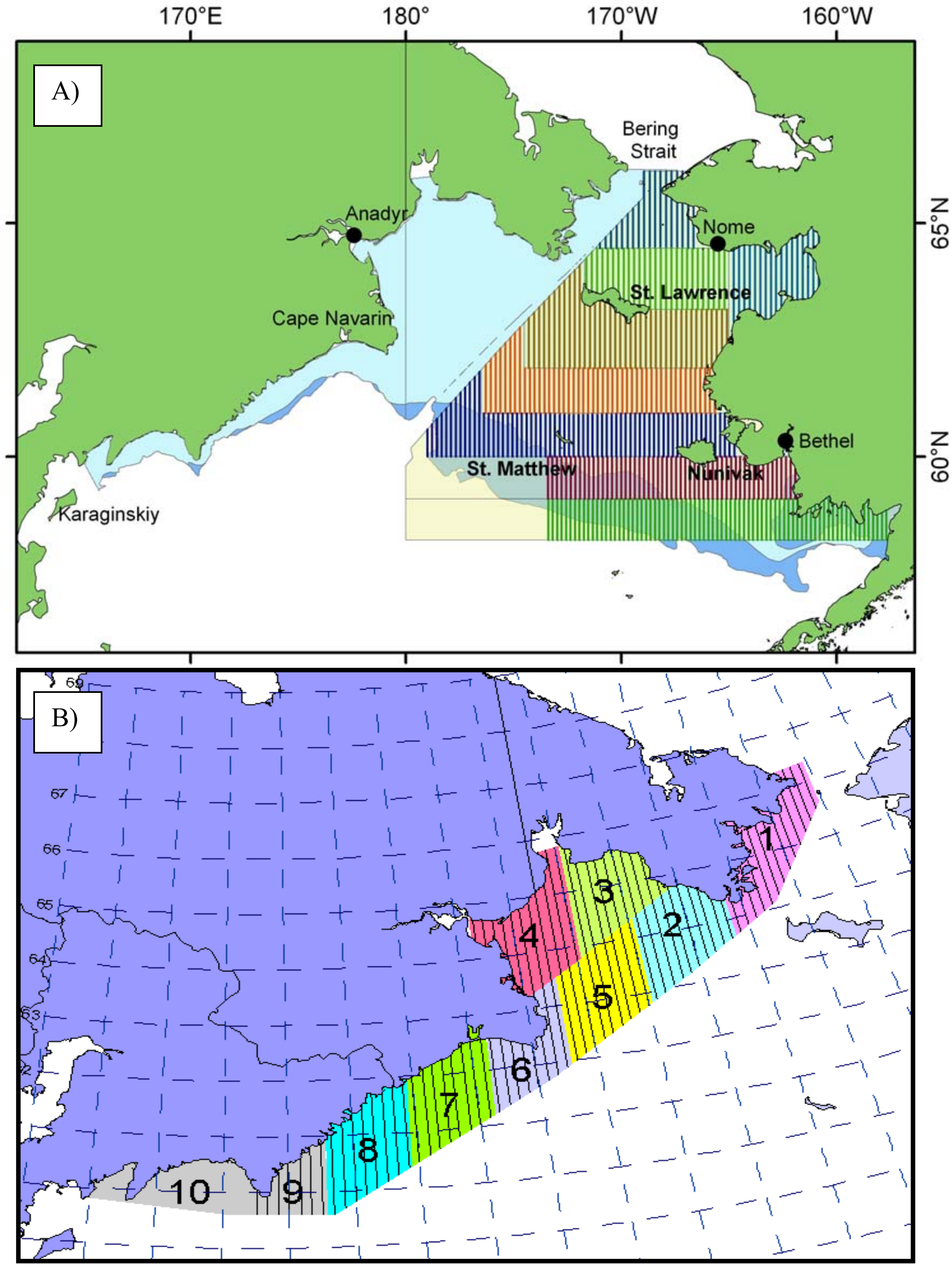


Figure 1A) Transect lines and study blocks indicate original design for the U.S. Dark blue indicates the maximum ice extent on 20 April (maximum study area size, 742,000 km^2); light blue indicates the minimum ice extent on 09 April (minimum study area size, 576,000 km^2); B) transect lines and study blocks indicate original study design for Russia.

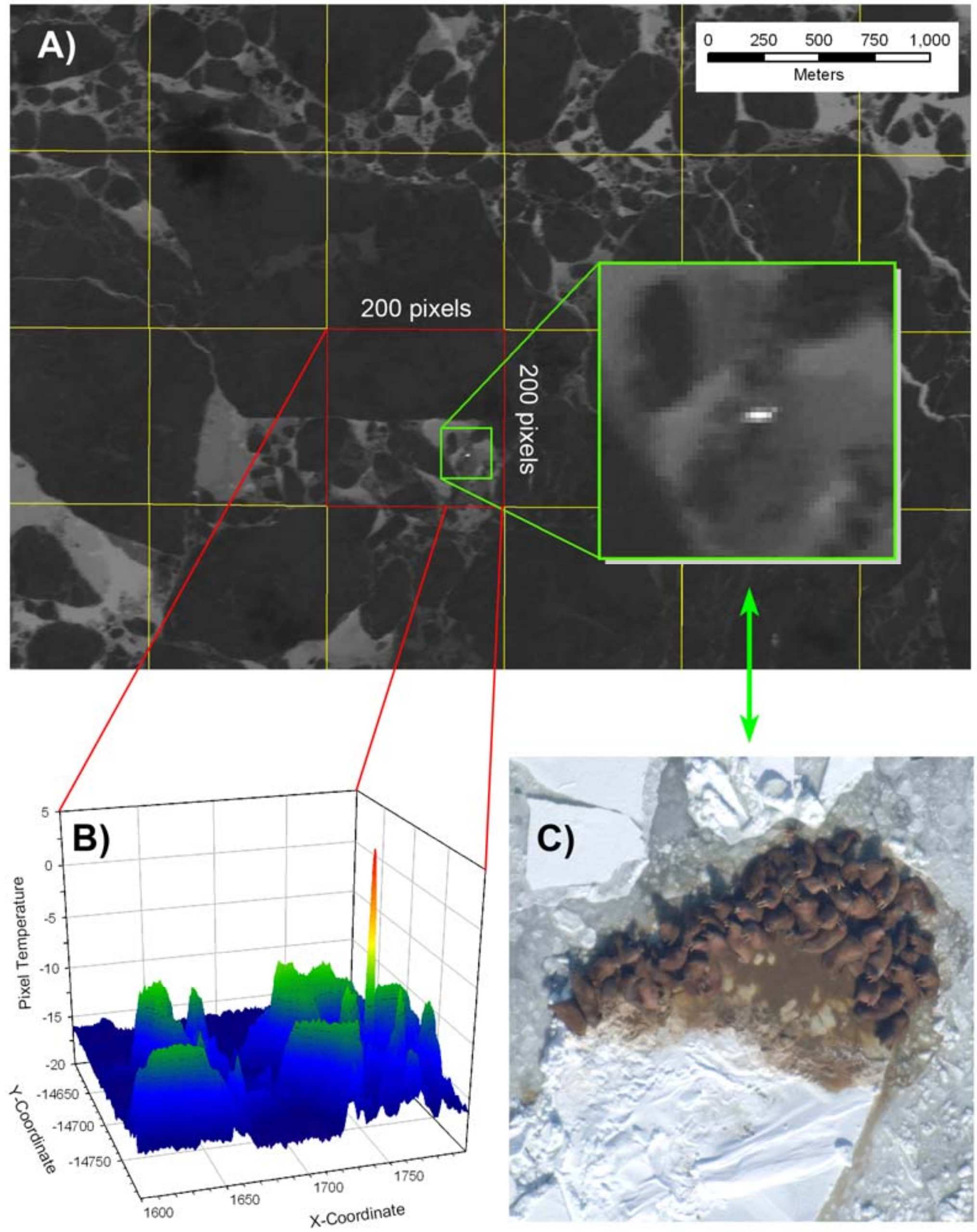


Figure 2. A) Airborne thermal image indicating tile structure and location of photographed walrus group (green square); B) 3-dimensional plot of data for selected (red) tile; C) photograph of walrus group located in selected tile (Burn et al., in prep.).

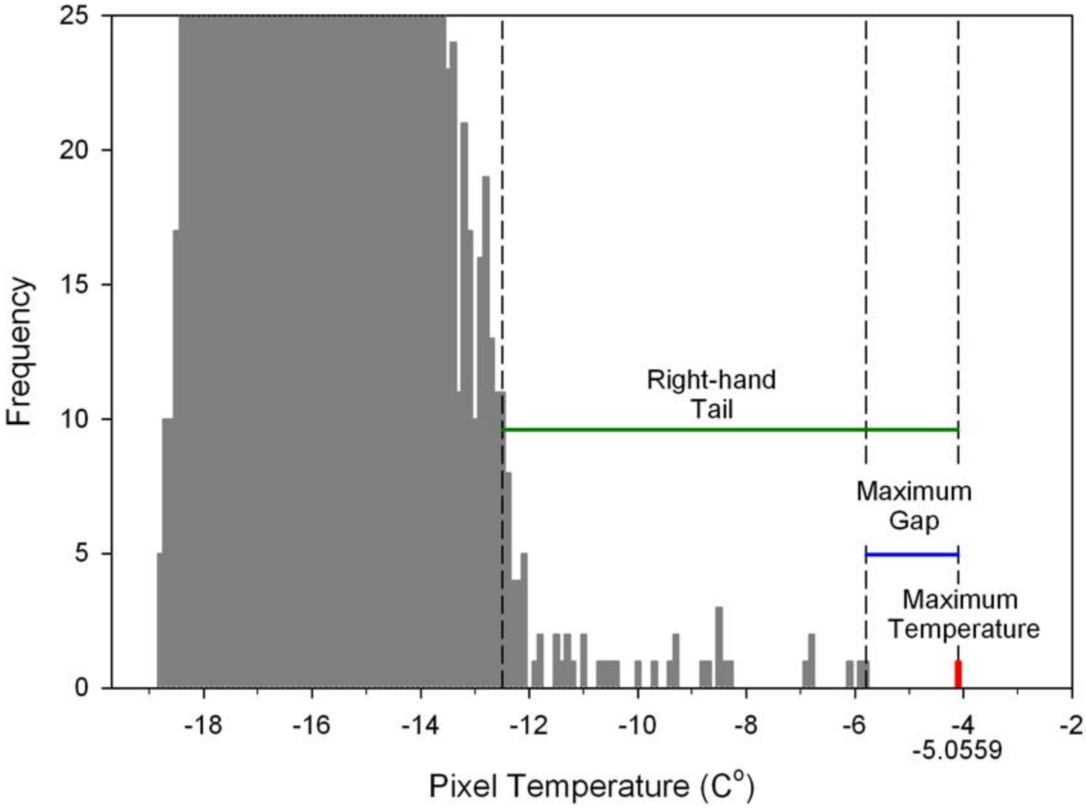


Figure 3. Temperature histogram indicating features characteristic of walrus signatures: 1) maximum temperature (red); 2) Maximum histogram gap (blue); and 3) right-hand tail (green; Burn et al., in prep.).

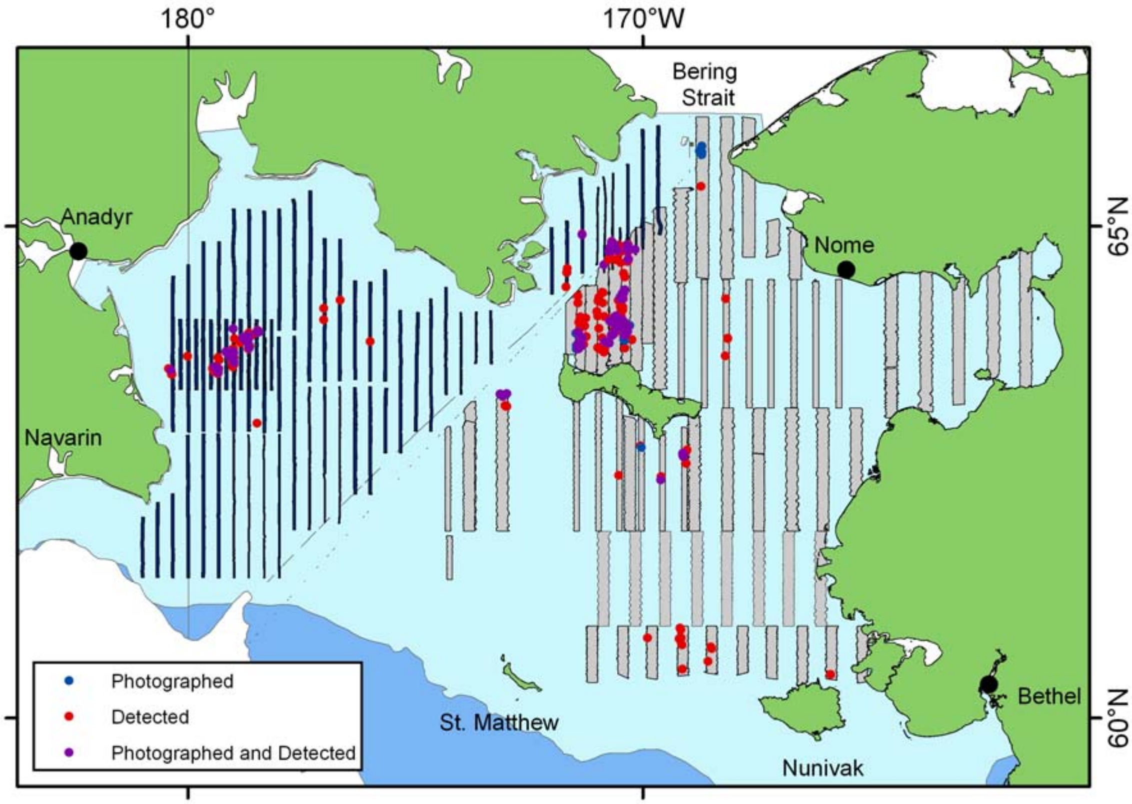


Figure 4. All surveyed transects and walrus locations on those transects (i.e., not including locations of off-transect walrus groups). Width of transect indicates strip width during survey, 1.4 to 3.3 km for Russia and 6 km or 12 km for the U.S. Dark blue indicates the maximum ice extent on 20 April (maximum study area size, 742,000 km^2); light blue indicates the minimum ice extent on 09 April (minimum study area size, 576,000 km^2). For daily account of survey effort and walrus sightings see Appendix A.

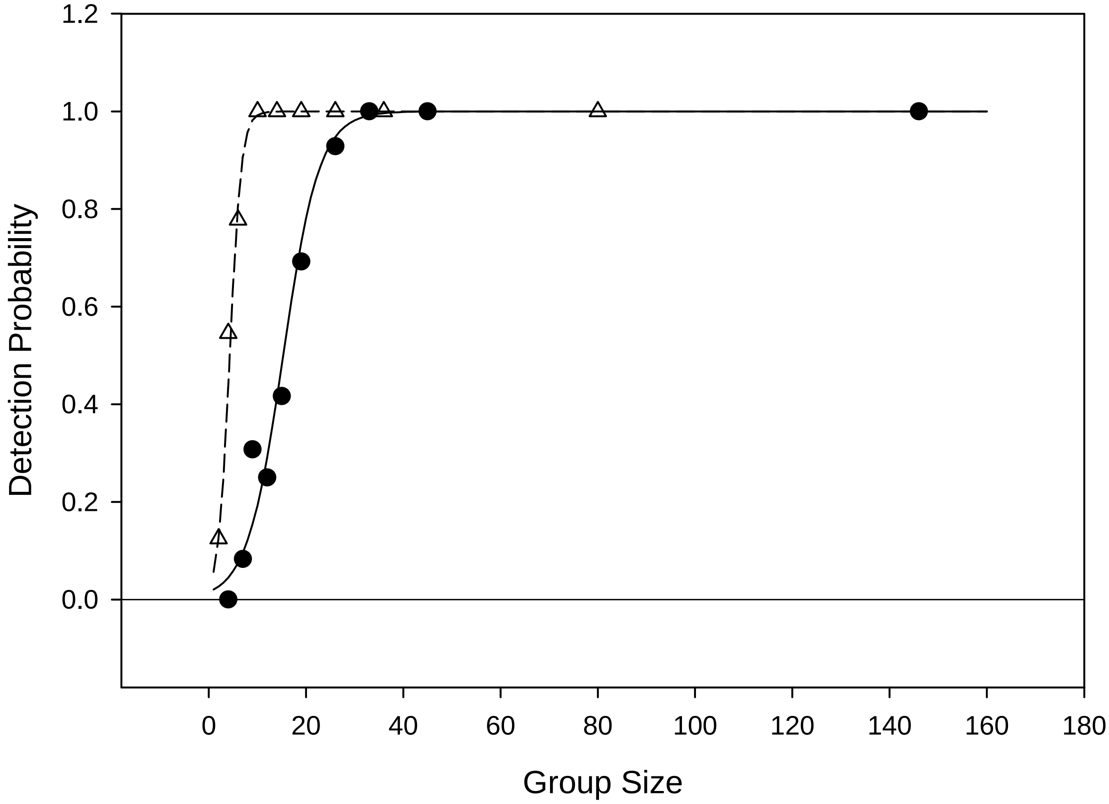


Figure 5. Estimated probabilities for detecting walrus groups in 2 m (dashed line) and 4 m (solid line) U.S. thermal imagery. Observed proportions of photographed groups detected are indicated by triangles (2 m imagery) and circles (4 m imagery). Adapted from Burn et al. (in prep.).

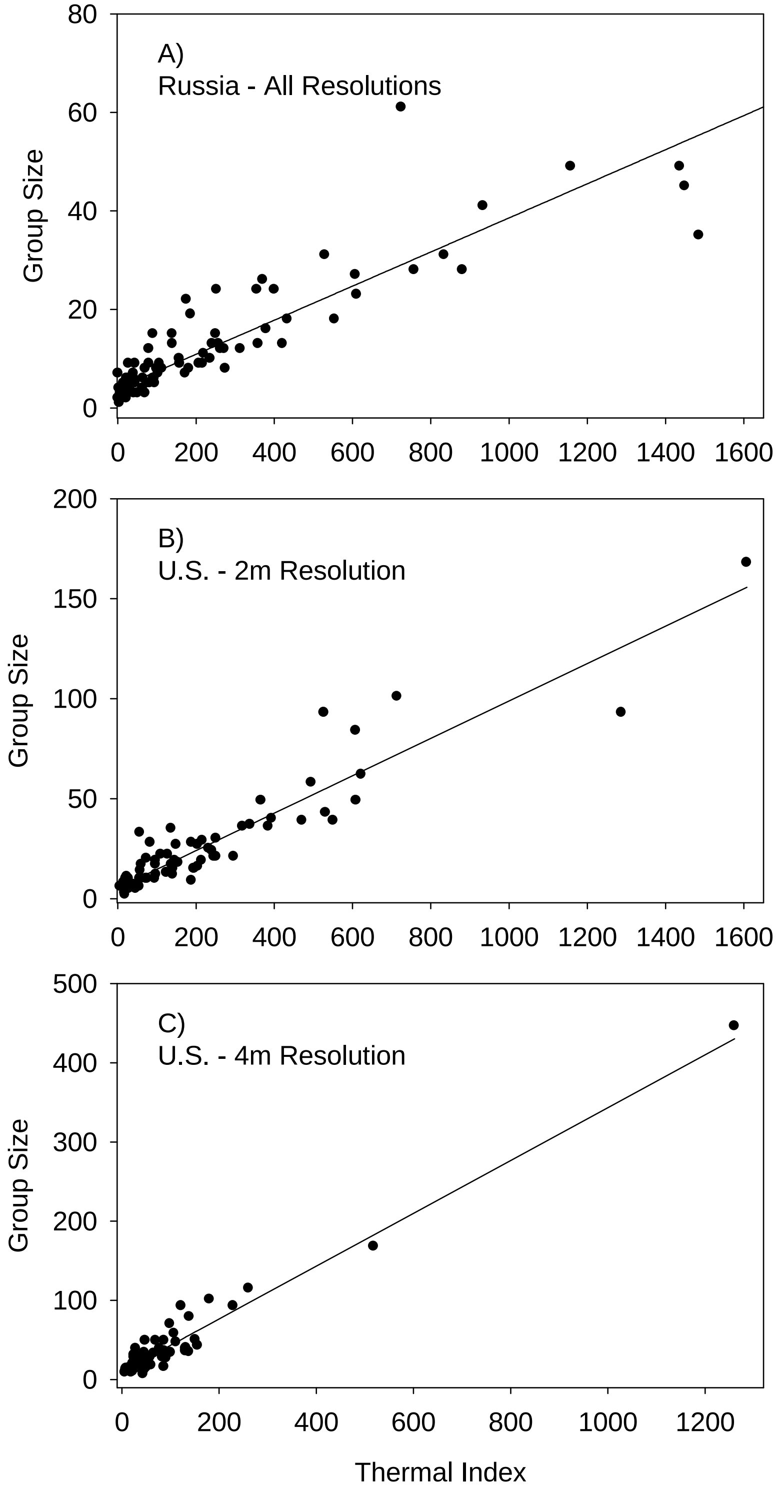


Figure 6A) Final calibration model for the Russian thermal index; B) final calibration model for the U.S. thermal index at 2 m resolution; and C) final calibration model for the U.S. thermal index at 4 m resolution (Burn et al., in prep.).

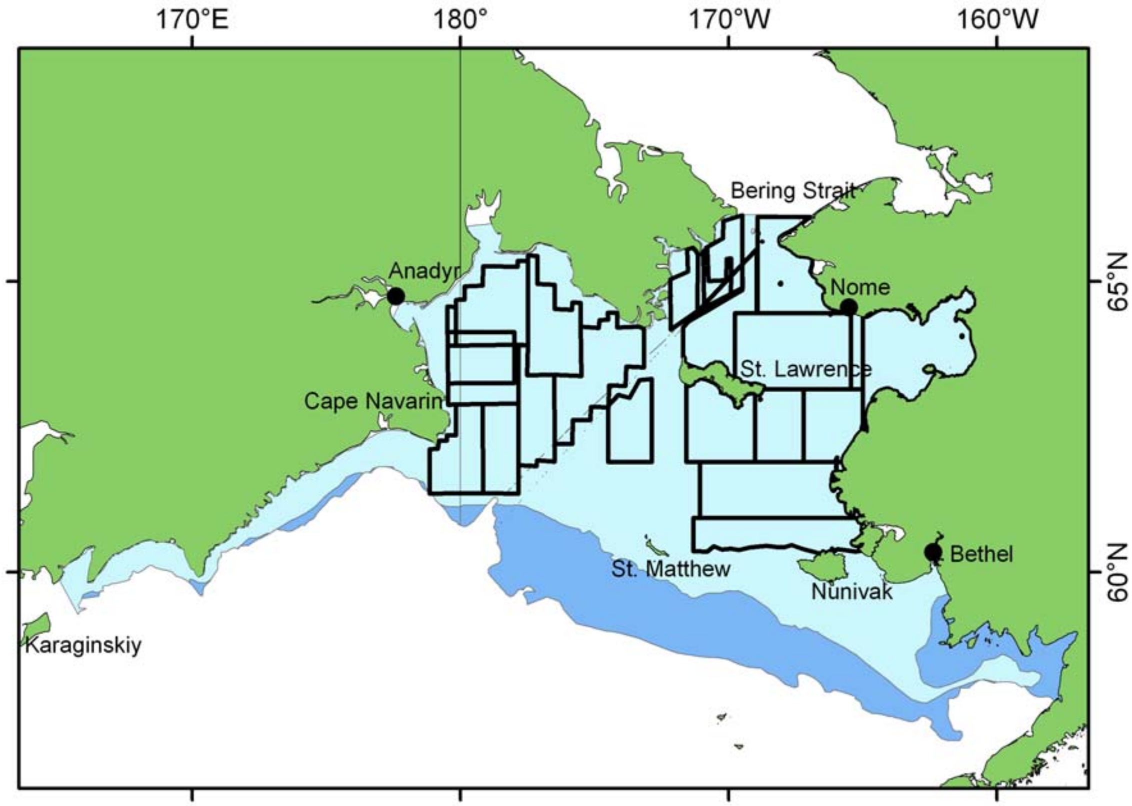


Figure 7. Final block structure and extent of surveyed area for 2006 walrus survey in both Russia and the U.S. Dark blue indicates the maximum ice extent on 20 April; light blue indicates the minimum ice extent on 09 April. For more detailed layout of block structure see Appendix A.

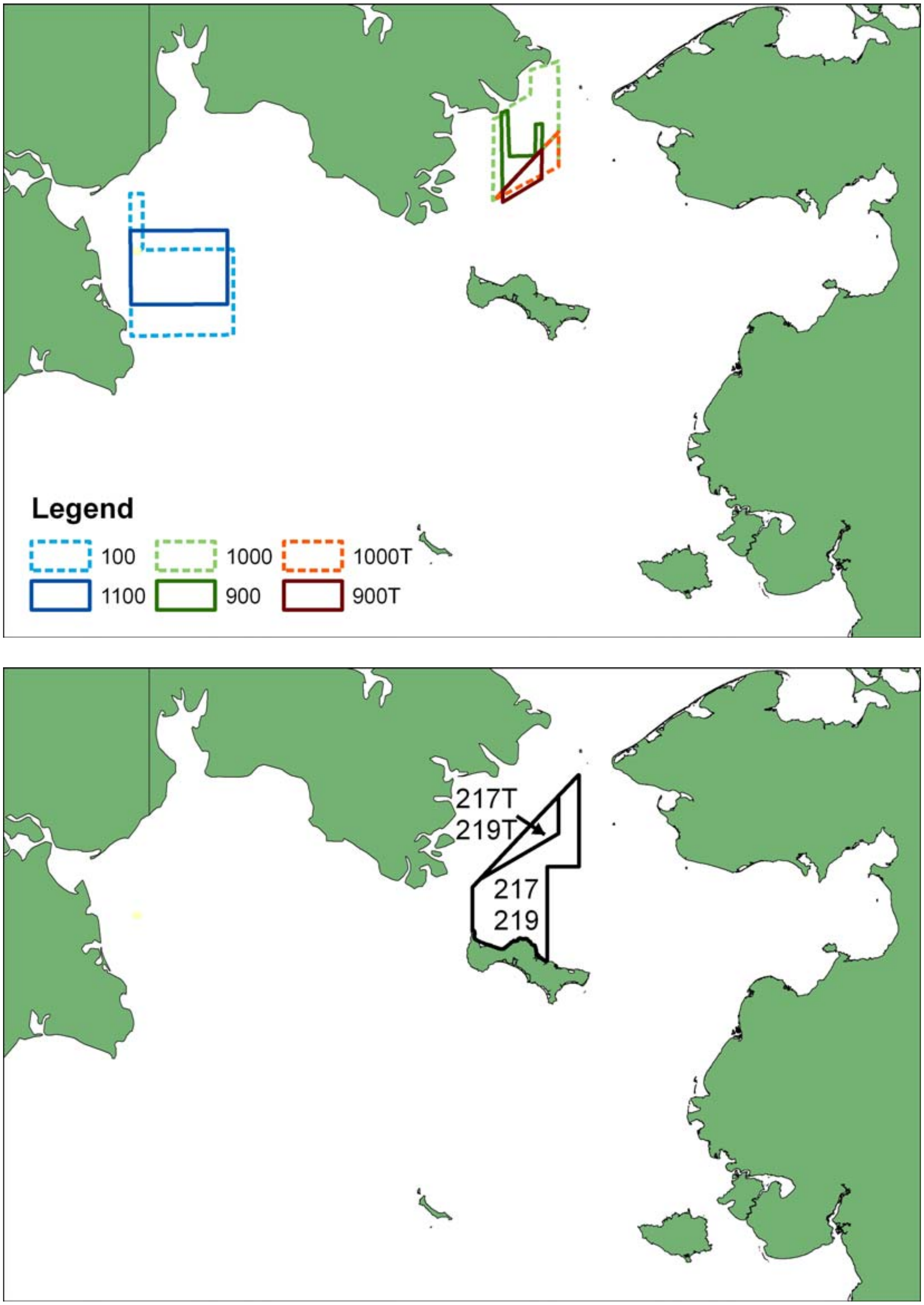


Figure 8. Replicated blocks during walrus surveys in Russia (top) and the U.S. (bottom). The triangular area designated as 1000T and 900T (Russia) and 217T and 219T (U.S.) was surveyed a total of four times.

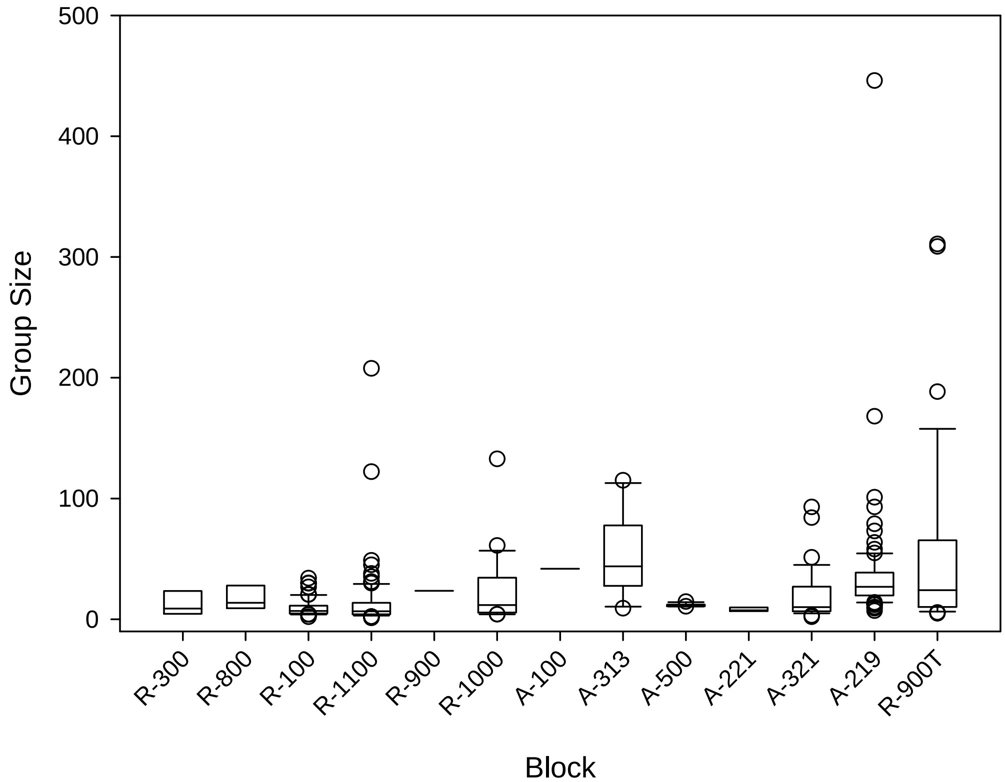


Figure 9. Estimated sizes of walrus groups detected on survey transects in the Bering Sea, April 2006. The line within the box indicates the median, and the lower and upper box boundaries indicate the 25^{th} and 75^{th} percentiles. Whiskers (error bars) above and below the box indicate the 10th and 90th percentiles, and circles indicate more extreme values.

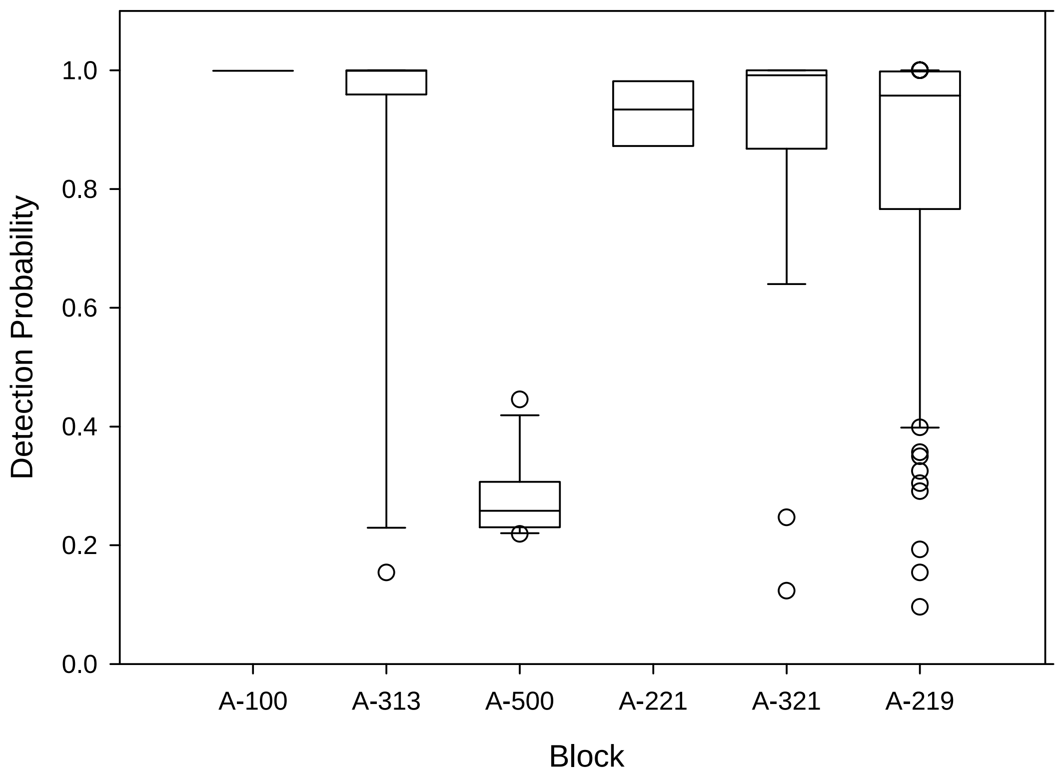
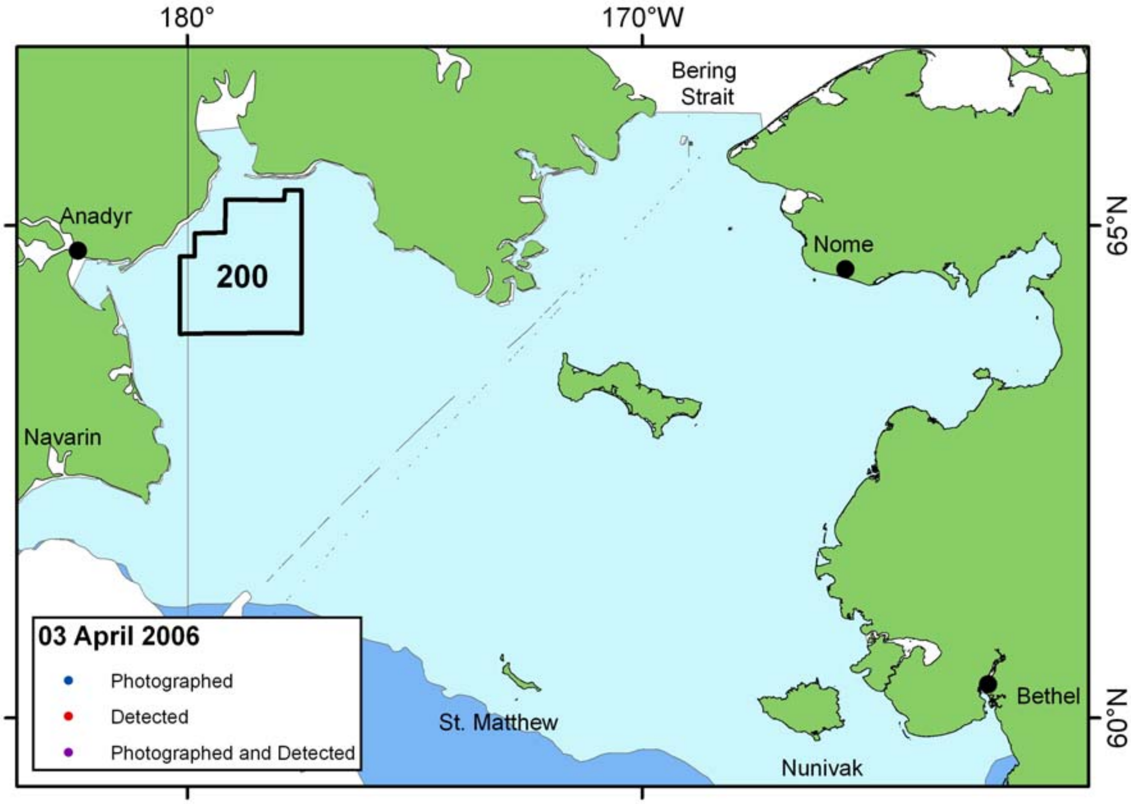
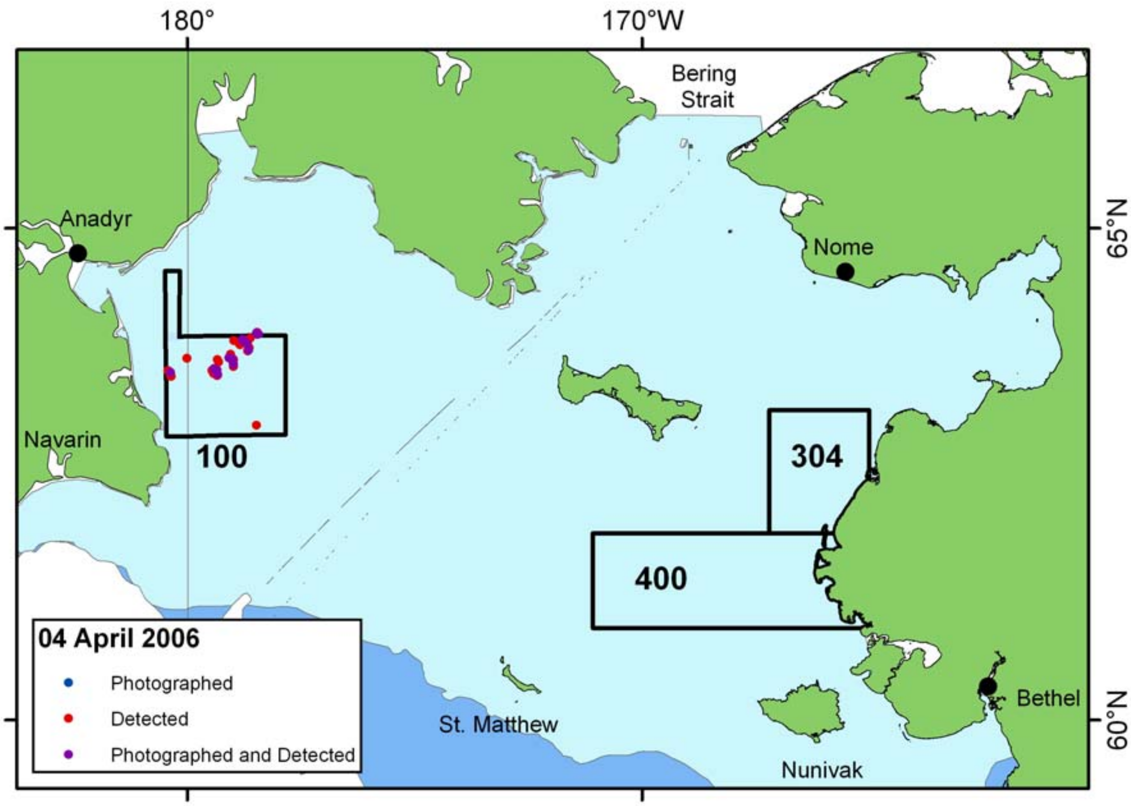


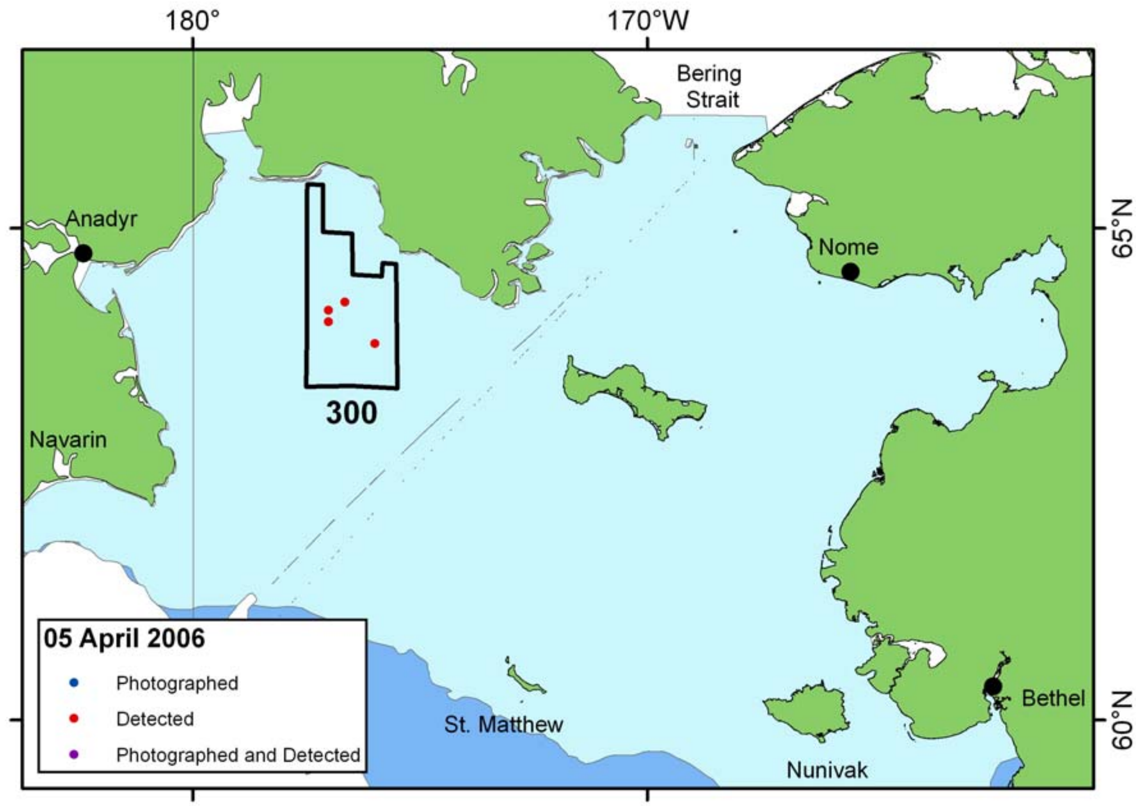
Figure 10. Estimated probabilities of thermally detecting walrus groups hauled out on U.S. survey transects in the Bering Sea, April 2006. The line within the box indicates the median, and the lower and upper box boundaries indicate the 25th and 75th percentiles. Whiskers (error bars) above and below the box indicate the 10th and 90th percentiles, and circles indicate more extreme values.



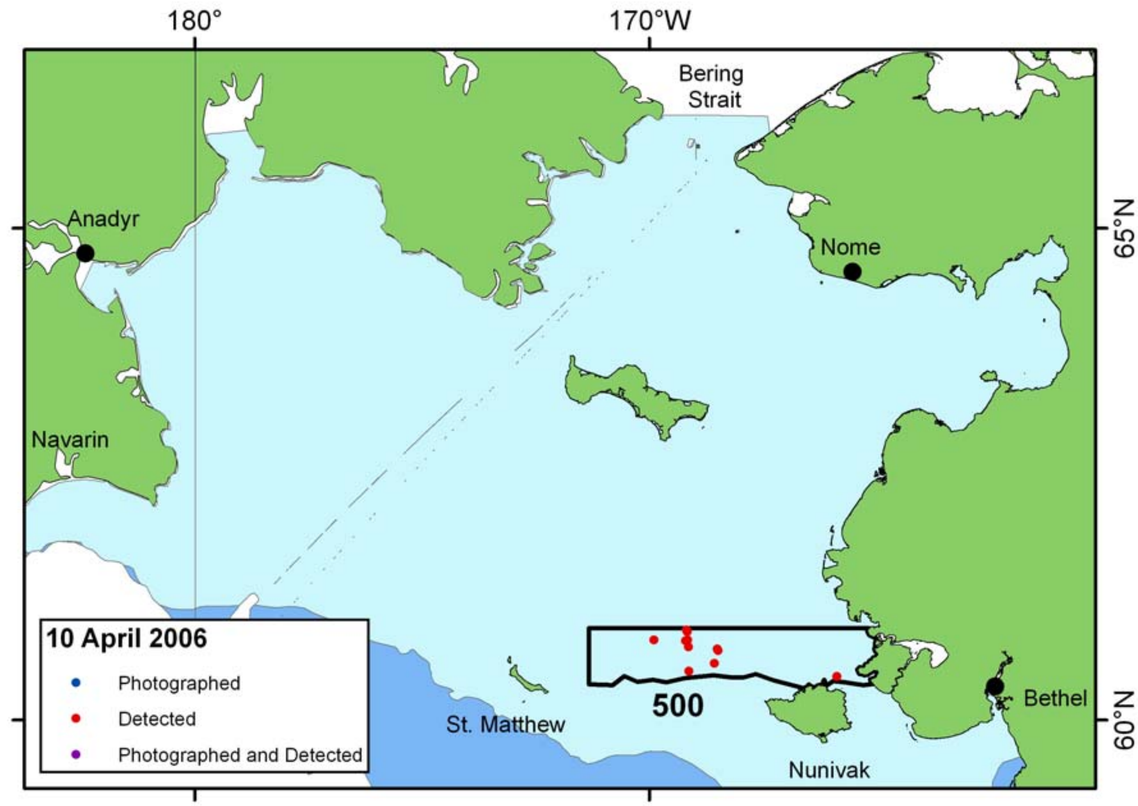
Appendix A1. Block surveyed on 03 April 2006 Alaska Standard Time.



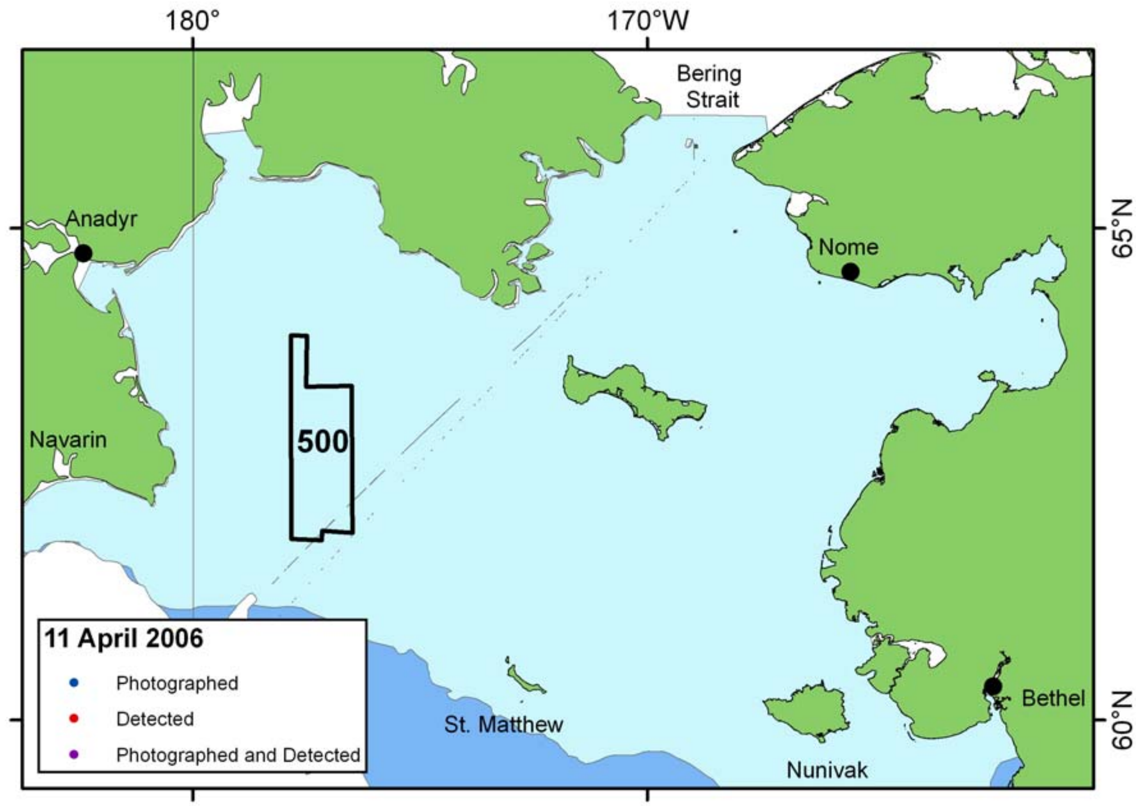
Appendix A2. Blocks surveyed on 04 April 2006 Alaska Standard Time.



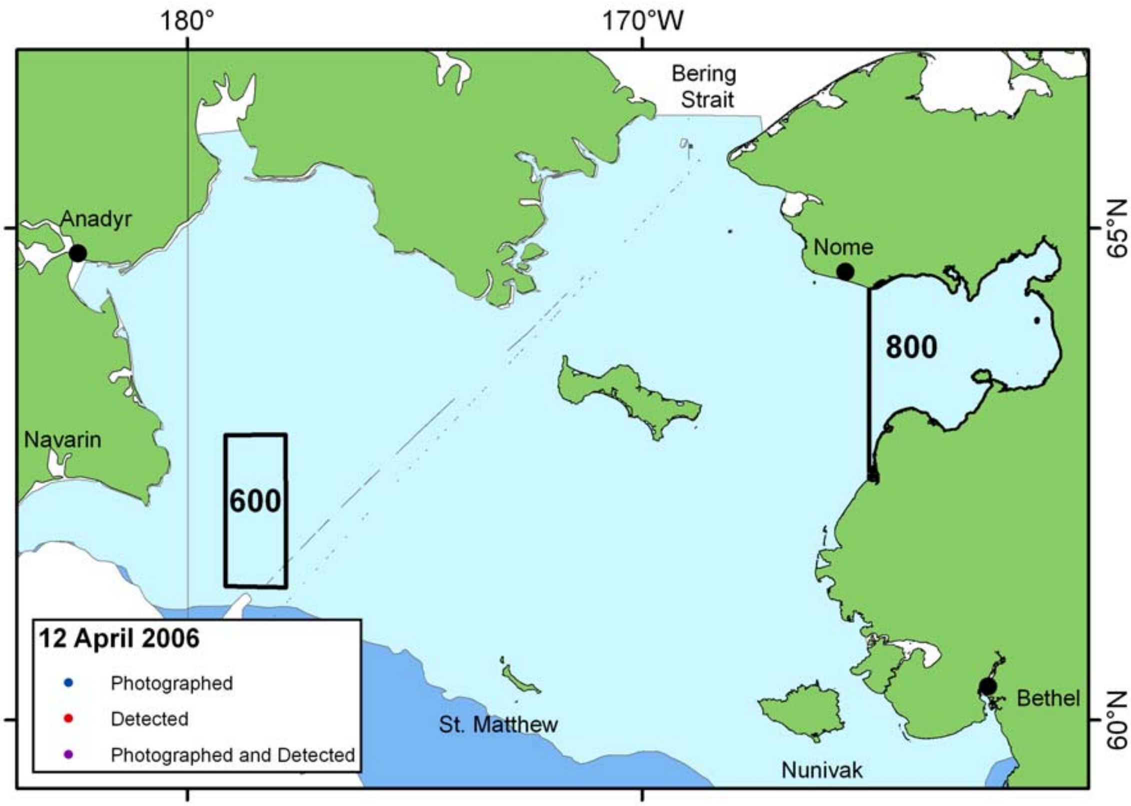
Appendix A3. Block surveyed on 05 April 2006 Alaska Standard Time.



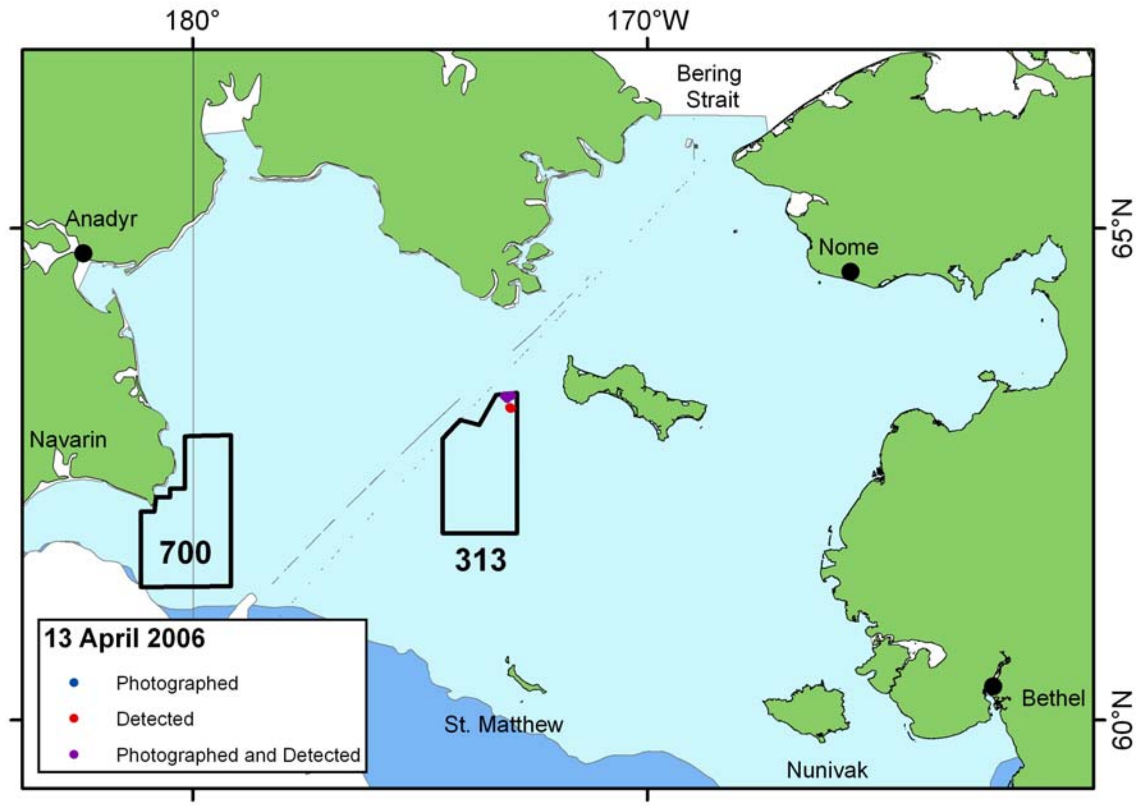
Appendix A4. Block surveyed on 10 April 2006 Alaska Standard Time.



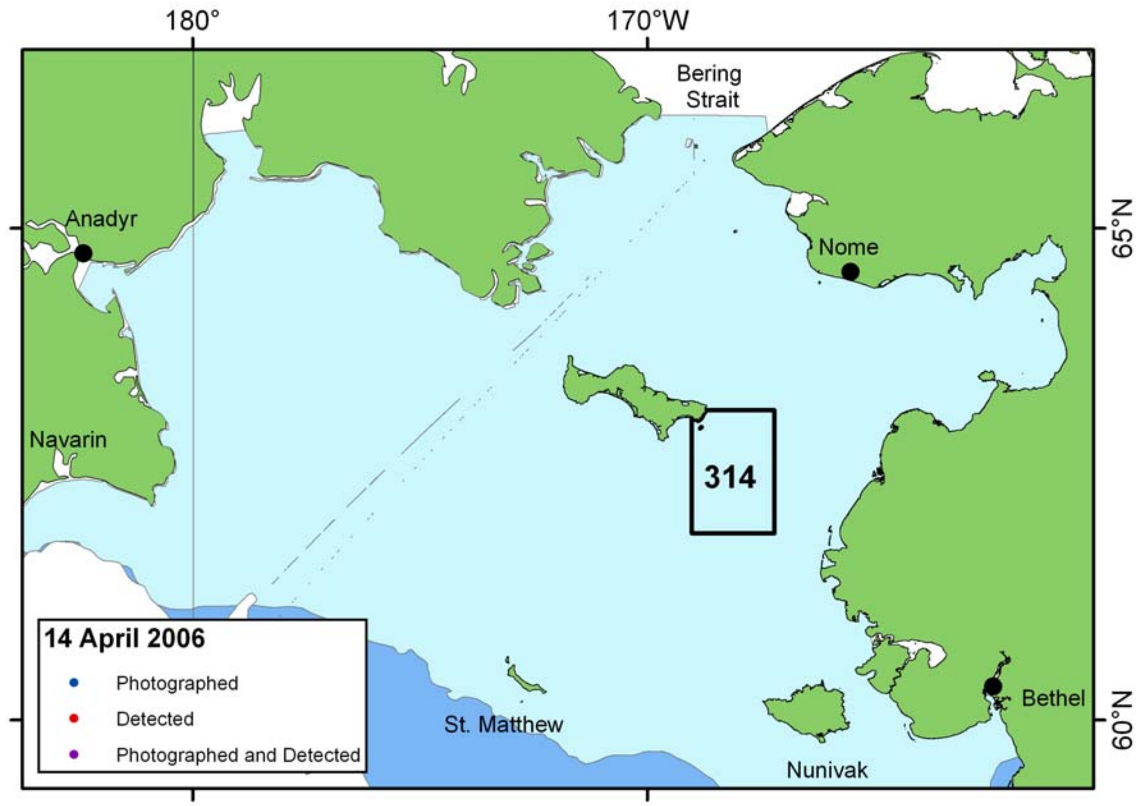
Appendix A5. Block surveyed on 11 April 2006 Alaska Standard Time.



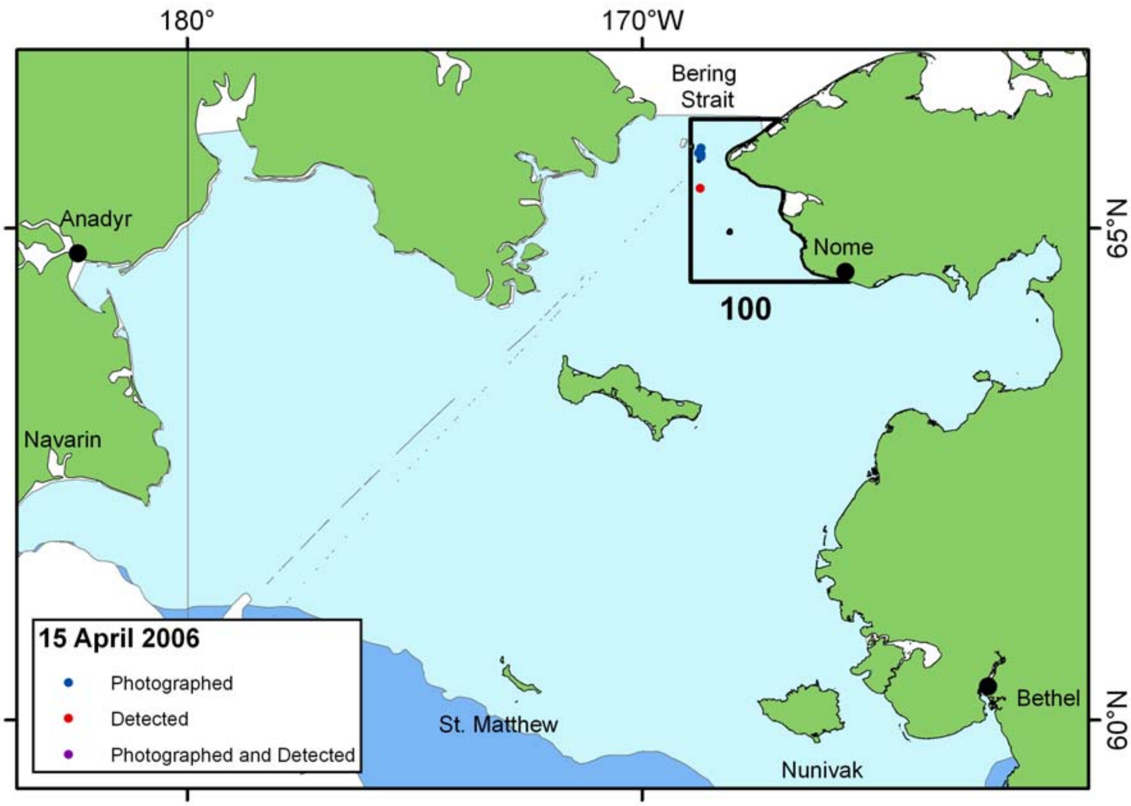
Appendix A6. Blocks surveyed on 12 April 2006 Alaska Standard Time.



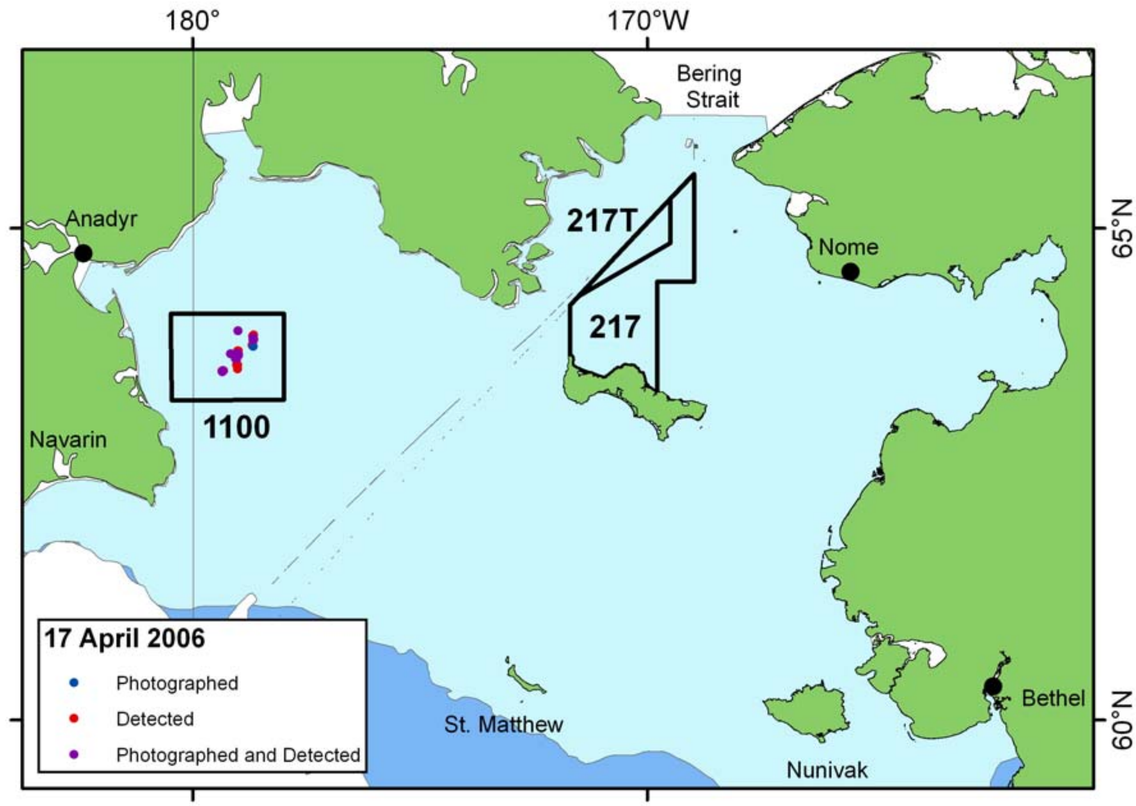
Appendix A7. Blocks surveyed on 13 April 2006 Alaska Standard Time.



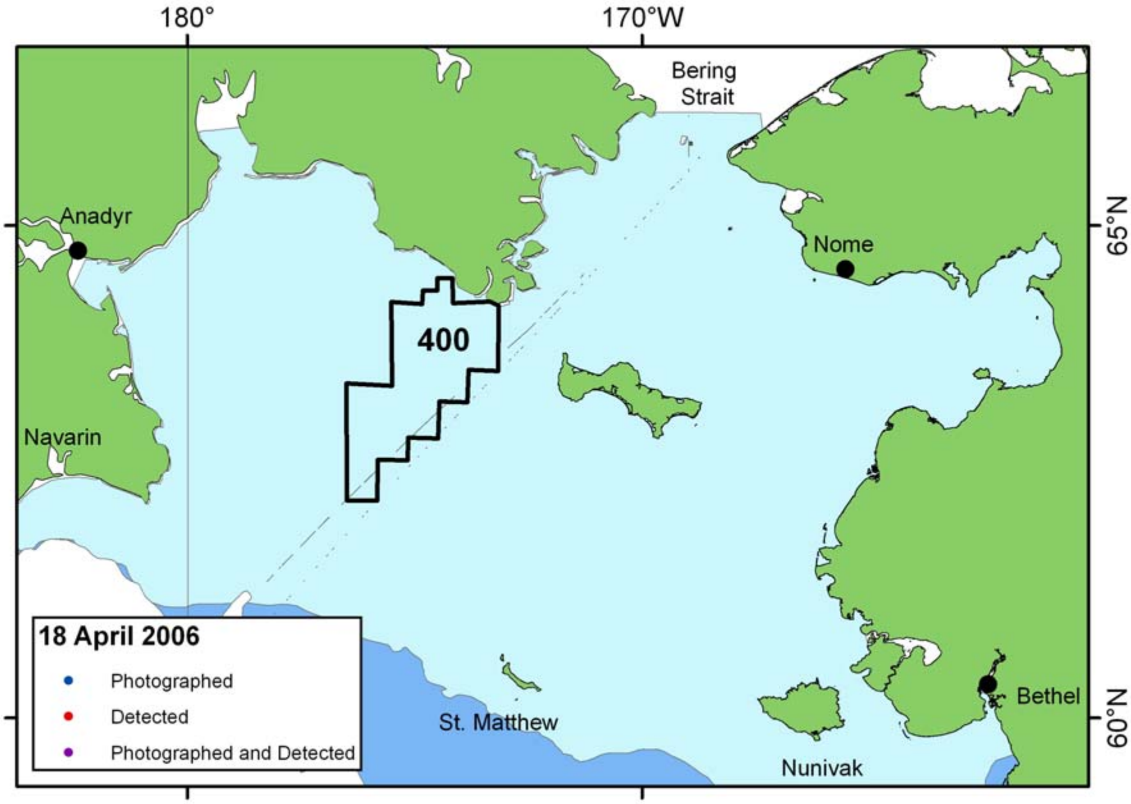
Appendix A8. Block surveyed on 14 April 2006 Alaska Standard Time.



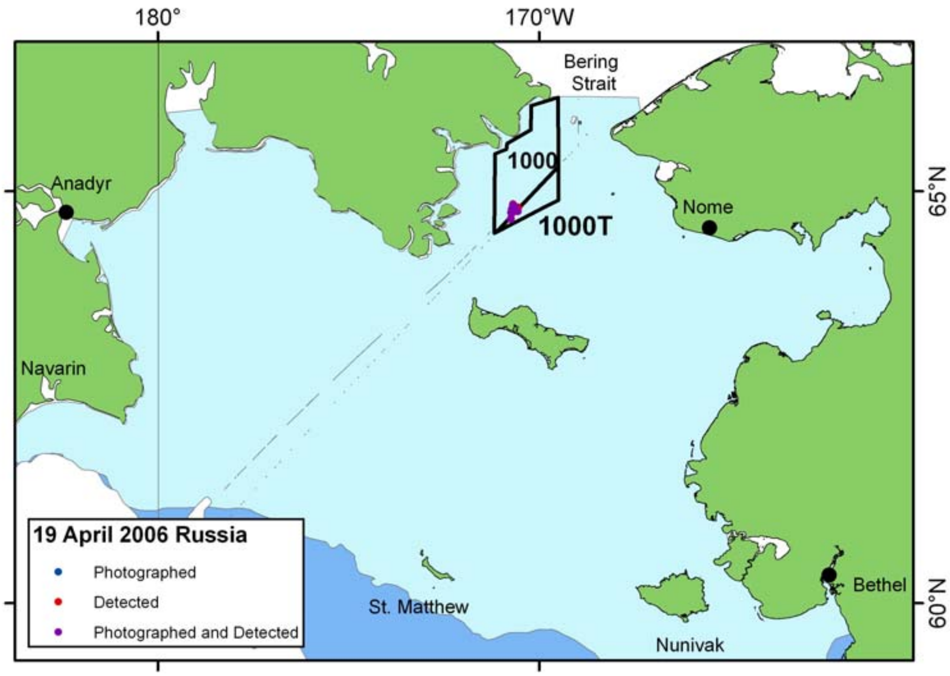
Appendix A9. Block surveyed on 15 April 2006 Alaska Standard Time.

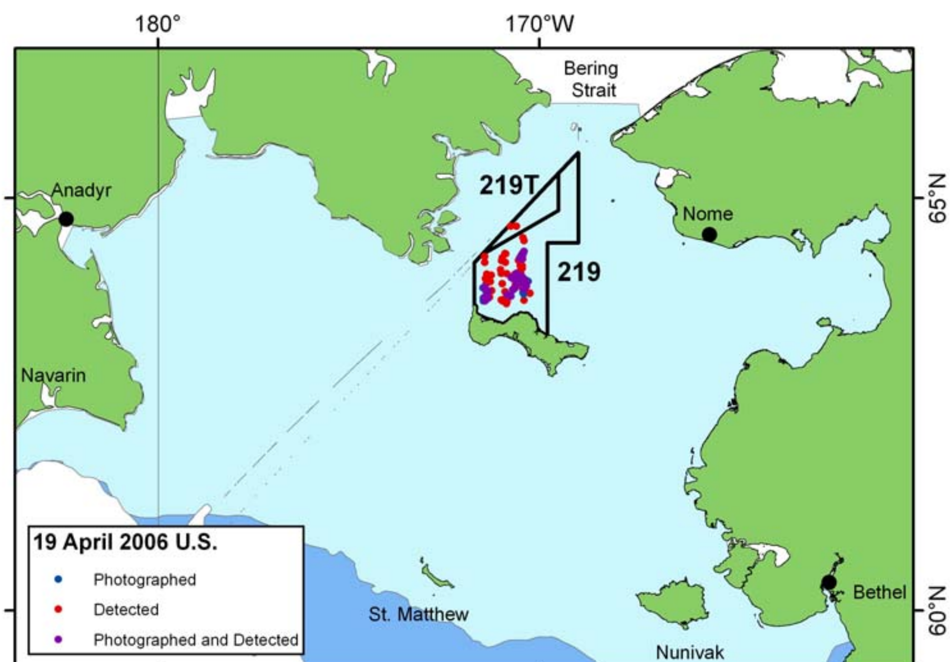


Appendix A10. Blocks surveyed on 17 April 2006 Alaska Standard Time.

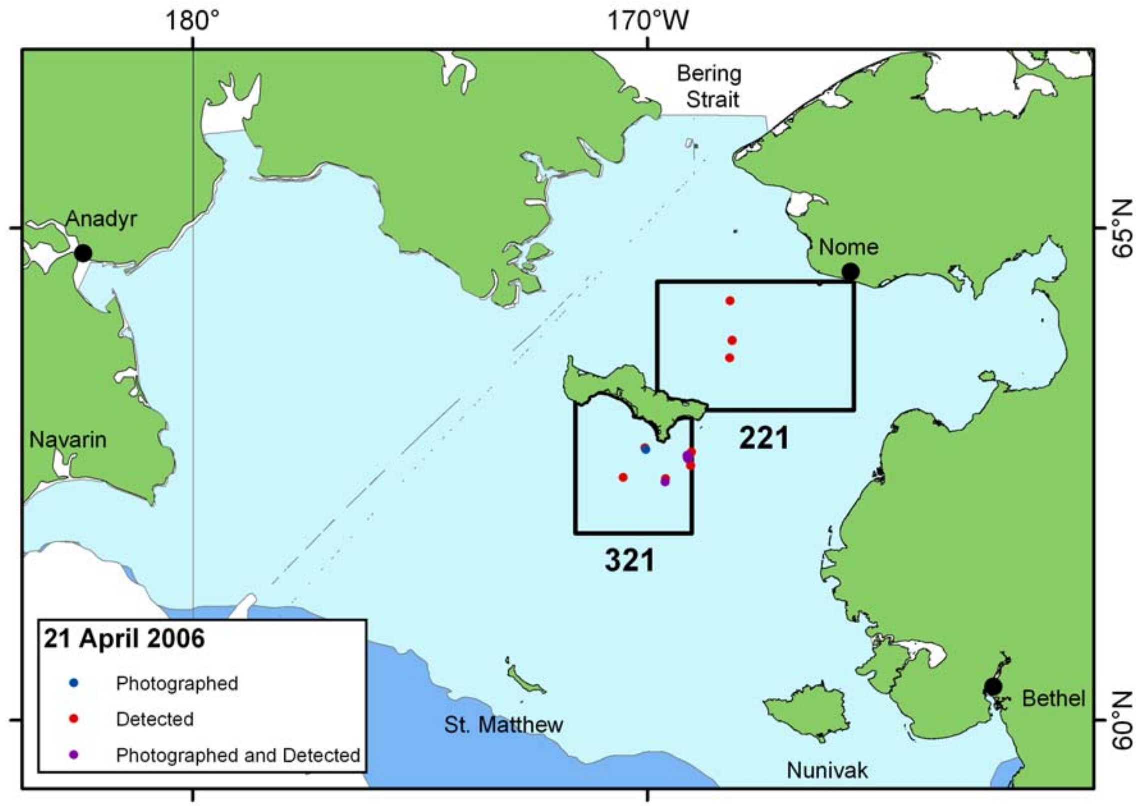


Appendix A11. Block surveyed on 18 April 2006 Alaska Standard Time.

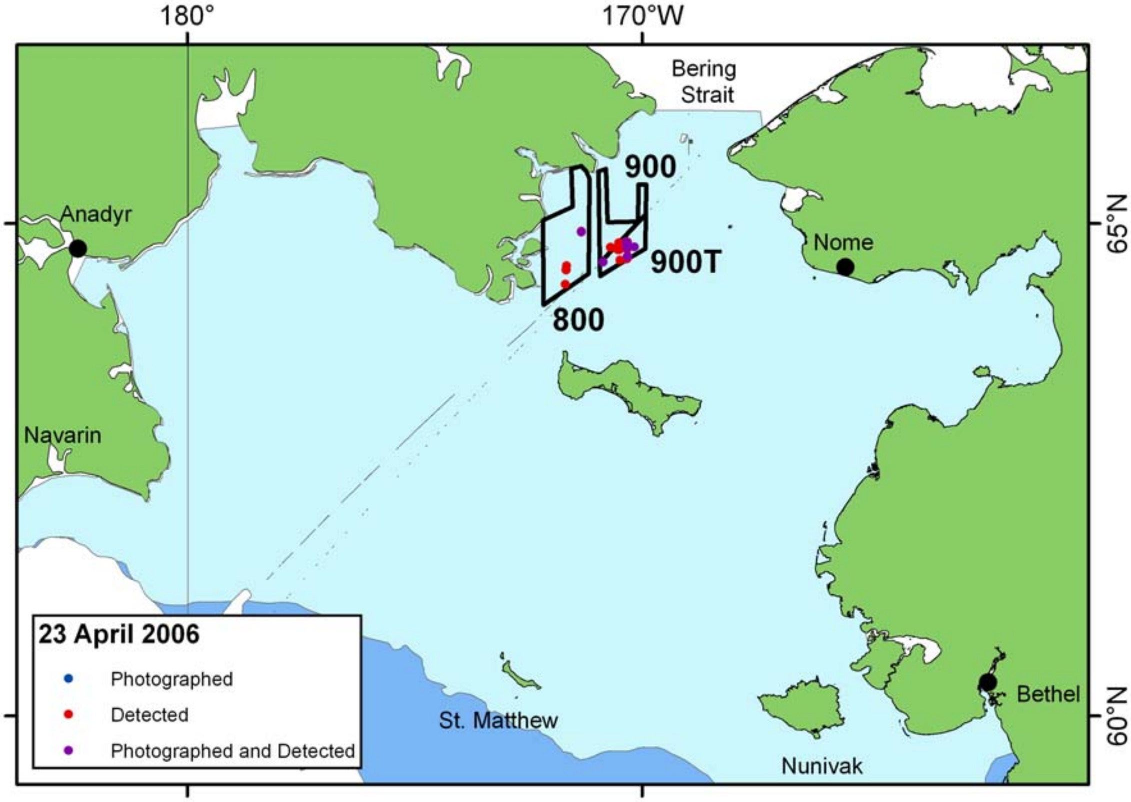




Appendix A12. Blocks surveyed on 19 April 2006 Alaska Standard Time.



Appendix A13. Blocks surveyed on 21 April 2006 Alaska Standard Time.



Appendix A14. Blocks surveyed on 23 April 2006 Alaska Standard Time.