Methodological Considerations for At-sea Monitoring of *Brachyramphus* Murrelets in Glacier Bay, Alaska

By

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Abstract

Brachyramphus murrelets were surveyed in Glacier Bay 9-15 July, 2007. A total of 48 transects (91.7 km) extending from mid-channel to shore, were randomly located in the motorized waters of the Bay, and concurrent surveys conducted using strip and line transect methods. Bird distribution was mapped relative to depth and distance from shore. Small water bodies were censused. In addition, flying murrelets were counted as they passed in and out of the Bay through Sitakaday Narrows.

Marbled Murrelets (*B. marmoratus*) comprised 87 percent and Kittlitz's Murrelets (*B. brevirostris*) 13 percent of the population. The lower bay and the middle bay, collectively, contained over 75% of the murrelet population, with highest densities in the lower bay. The highest numbers of Kittlitz's Murrelets were in the upper West Arm and associated fjords.

Bird distribution relative to shore showed two peaks—one at 200-400 meters offshore, and a higher peak > 3 km from shore. The density of birds in the shoreline stratum (< 200 m from shore) was less than half the density in the next 200 m interval. The highest peak, > 3 km from shore, reflected high numbers of birds encountered in the middle of the lower bay— a shallow-water zone of strong mixing and generally high productivity. Birds were clearly stratified relative to depth. Mean depth for all birds was 110 m. The highest densities were found in waters 50-100 meters deep, while stratified waters > 250 m deep were relatively little used.

Line transects returned substantially higher population densities, and lower coefficients of variation, than strip transects. Line transects returned population estimates of 31, 318 Marbled Murrelets and 4,207 Kittlitz's Murrelets on the water. Assuming approximately 13% of the population is flying at any given time, the total population of Marbled, Kittlitz's, and all *Brachyramphus* murrelets in Glacier Bay in early July was 35,389, 4,858, and 41,389

respectively. To facilitate comparisons with earlier predator surveys in Glacier Bay (1999-2003), I adjusted population estimates for survey method (strip transects) and survey date (mid June). The adjusted population estimates for Marbled and Kittlitz's Murrelets are 20,662 and 3,271 birds respectively.

Dawn to dusk flyway counts revealed 2 distinct incoming pulses of birds in early morning and early afternoon, and two peaks of outgoing birds, in mid morning and early evening. Incoming birds peaked in phase with ebbing tides (90 minutes past high), and outgoing birds peaked with strong flooding tides (mid flood). At peak flux, more than 2000 birds an hour are entering and leaving the Bay. Based on the average daily flux of birds through the narrows, and assuming two round trips per bird per day, an estimated 10,500 murrelets (nearly 1/3 of the population) in the Bay are day users, or transients.

Temporal variation in the numbers of murrelets using Glacier Bay is high, both day to day and week to week. Bird numbers appear to increase through the breeding season, peaking in late July-early August, and then decline. Analysis of replicate survey data found that July has the lowest coefficient of variation (CV) of any summer month. Surveys conducted during this time period would return the most accurate, precise counts, and have the greatest power to detect population trends.

Given the conservation concerns surrounding *Brachyramphus* murrelets, and the importance of the Glacier Bay ecosystem to both species, the Park Service may wish to establish a monitoring program that is oriented specifically to these species. A number of recommendations are made that to increase the accuracy, precision, and power of a monitoring program for *Brachyramphus* murrelets.

Introduction

The genus *Brachyramphus* includes two closely related species: the Marbled Murrelet *(B. marmoratus*), and the Kittlitz's Murrelet (*B. brevirostris*). They are members of the Alcidae family, and share the unusual trait, for seabirds, of being non-colonial breeders. The Marbled Murrelet, which ranges from central California north to the Aleutian chain, nests primarily on natural moss platforms in the canopies of old-growth trees. The Kittlitz's Murrelet, which ranges from central Southeast Alaska north to the Seward Peninsula, and west through the Aleutian islands, nests on the ground. Both species nest inland from the coast, and attend their nests mostly during dawn and dusk to avoid detection by predators. Because they are secretive, solitary nesters, population surveys must be conducted at sea. Over the past 20 years, population declines have heightened conservation concerns for both species (Burger 2002, Kuletz et al. 2003, Huff et al. 2006, Piatt et al. 2007a).

In Southeast Alaska, population trends in Marbled and Kittlitz's Murrelets have been inferred from at-sea surveys conducted in 1991 and 1999-2003 in Glacier Bay and Icy Strait (Robards et al. 2003, Lindell 2005, Piatt et al. 2007b, 2007c, Drew et al. 2007). In Glacier Bay, there have been 9 bay-wide surveys conducted (Table 1). All of the surveys utilized 200-300 m wide strip transects, and counted all bird and mammal species encountered in the strip. With one exception, all surveys were stratified into a shoreline component and an offshore component. The 1993 survey by the USFWS (Lindell 2005) utilized a large vessel, and surveyed the offshore waters only. Only one survey (Agler et al. 1998), utilized a randomized sampling design. All others were systematic or opportunistic, with varying levels of effort devoted to the shoreline. Most surveys were conducted in June and July, with one survey conducted in early August.

The original intent of these surveys was to gather baseline data on the relative abundance and spatial distribution of all marine birds and mammals in Glacier Bay. The different sampling designs, vessels, observers, and protocols employed from year to year (Figure 1, Table 1) are potentially confounding factors in population trend analysis.

An effective monitoring program for *Brachyramphus* murrelets requires prior knowledge about how the birds are distributed spatially and temporally. It also requires understanding the effects of survey methods and covariates (weather, sea state, tide stage, vessel size) on the accuracy and precision of population estimates. All of these factors should be considered in the design of an efficient and powerful monitoring program— one that can detect relatively small changes in the population for a reasonable cost. This research project was designed to provide some of this information, and make recommendations for future monitoring of these two species in Glacier Bay.

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Study Area

Glacier Bay is a deep, 100 km-long Y-shaped fjord located on the mainland in northern Southeast Alaska (Figure 2). The Bay represents an important breeding and foraging area for thousands of *Brachyramphus* murrelets, with some of the highest recorded densities in Southeast Alaska (Lindell 2005).

The Glacier Bay study area can be broken into 5 smaller areas, each with distinctive water depths, tidal influences, degrees of mixing, and associated productivity (Figure 3). These five areas within Glacier Bay are similar to those described by Robards et al. (2003), and are defined below. Water surface areas were determined using a standard dot-grid overlain on a 1:80,000 scale nautical chart (NOAA 17318). All measurements reflect area at mean low tide.

<u>Lower Bay</u>: This sub-region includes a broad shallow sill and a narrow constriction (Sitakaday Narrows) that create strong tide rips, upwelling, and concentrations of forage fish and krill that attract whales and seabirds (Robards et al. 2003). The area is defined by the Park Service's "whale waters" boundaries. The southern boundary is demarcated by a line drawn between Point Carolus and Point Gustavus. The northern boundary is demarcated by a line drawn from the north end of Lars Island to the north end of Strawberry Island. The eastern boundary is defined by the Wilderness Waters boundary enclosing the Beardslee Islands (NOAA Chart 17318). The water surface area includes 114.8 km^2, or 9.0% of Glacier Bay proper.

<u>Beardlsee Islands</u>: A complex of numerous small islands and shallow marine waters. The boundaries of this area are demarcated by the Park Service's Wilderness Waters boundaries, and include the area south of Beartrack Cove, north of Bartlett Cove, and east of a line connecting the west side of Lester, Young, and Strawberry islands, as well as a number of small unnamed

islands lying between Strawberry Island and Beartrack Cove. The water surface area includes 56.2 km^2, or 4.4% of Glacier Bay proper.

Middle Bay: This part of the Bay is marked by relatively deep, stable, and (in summer) stratified water (Robards et al. 2003). The area is bounded to the south by the whale waters boundary, and to the north by a line that demarcates the West Arm and the East Arm (defined below) of Glacier Bay. The water surface area includes 434.0 km^2, or 34.0% of Glacier Bay proper.

West Arm: The West Arm includes all of the bays and fjords north and west of a line extending from the north shore of Geike Inlet to the southern tip of Sebree Island. It includes the deepest waters of the Bay, and in the northern extent, a number of tidewater glaciers. The water surface area includes 471.1 km^2, or 36.9% of Glacier Bay proper.

East Arm: The East Arm includes Muir Inlet and associated bays, inlets, and fjords. It includes all waters north of a line drawn from the southern tip of Sebree Island, due east to a point on the mainland shore. It includes an area of upwelling at the mouth of Muir Inlet caused by a shallow submarine sill. The water surface area includes 199.7 km^2, or 15.7% of Glacier Bay proper.

Methods

Survey Design

The goal was to design a simple random survey for *Brachyramphus* murrelets that would document distribution relative to water depth and shoreline, and yield a valid bay-wide estimate of the population on the water.

Knowing something about the distribution of animals, both in time and space, is essential to designing an optimal survey (Thompson et al. 1998, Rachowicz et al. 2006). Murrelets, like most seabirds, tend to be concentrated in areas where marine upwelling, tidal rips, and fronts create zones of mixing and increased productivity for zooplankton and forage fish (Zamon 2003, Arimitsu et al. 2007). Such concentrations of food are highly ephemeral (Gaston 2004), making them difficult to predict and map. However, averaged over time, some general patterns in Glacier Bay have become evident (Robards et al. 2003, Drew et al. in prep). For example, Kittlitz's Murrelets are more commonly found in the upper bay, especially where there is floating ice from tidewater glacier's present. And Marbled Murrelets appear to be distributed with respect to distance from shore, and water depth--environmental factors that are stable, predictable, and easily mapped.

The gradient for these two environmental factors runs perpendicular to shore. If birds distribute themselves in relation to either of these gradients, the transects should be oriented parallel to the gradient (Buckland et al. 2001). This allows the varying densities along that gradient to be sampled proportional to occurrence, resulting in an unbiased estimate of the population. For this reason, all transects in this study extended from mid channel to the shore.

The complex shoreline, with many small bays, inlets, and passages in Southeast Alaska, makes it difficult to construct an unbiased sampling design. For very small (or narrow) bodies of water, it is a simple matter to census every bird present, and there is no variance. I censused any bay which averaged less than 1000 meters shore to shore. These areas were easily censused by a meandering track, run at slow speed. In some cases, a central track allowed all birds from shore to shore to be counted.

We censused 12 areas in Glacier Bay. Two of those areas, John's Hopkins Inlet and Wachusett Inlet, had only a portion of their area censused. At John's Hopkins Inlet, ice prevented access past Jaw Point, and so an area of open water south of Jaw Point was censused. At

Wachusett Inlet, only the western end was narrow enough to effectively census. The rest was sampled by transects.

Most of the marine waters in Glacier Bay are composed of large bays, inlets, straits, and fjords. Because of their large area, they must be sampled rather than censused. To generate a random sample in these waters, I drew a line down the center of every waterway within motorized waters. On these mid-channel lines, I numbered tick marks at intervals of 1.85 km (1 nm) (although any interval could be used). These represented the universe of available starting points for transects. A random number generator was used to select 50 transect start points (without replacement) from the universe of possible start points. Transect lines were drawn from these start points to land on alternating sides of the mid-channel line. A charting program (Chart Navigator, Maptech, Boston MA) was used to project the latitude and longitude of both the start and end point for each transect.

Wilderness Waters in Glacier Bay are closed to motorized access and represent approximately 13% of the marine waters of Glacier Bay. Survey results in non-wilderness waters were extrapolated to Wilderness waters. The location of transects, census areas, and non-motorized wilderness areas are shown on Figure 4. Random transect assignment should result in sub-regions of the Bay being sampled proportional to their area; however, by chance, the West Arm was more intensively sampled and the mid-Bay less intensively sampled than expected (Table 2).

A file is available from the author (and from Glacier Bay National Park), showing transect locations, latitude and longitude of start and stop points, transect length, and the approximate location of each bird counted along the transect line.

Survey Methods

Boat-based surveys-- Surveys were conducted from the *M/V Iyoukeen*. The 9 m vessel provides ample standing room for several people on the bow deck, with clear lines of sight forward. Viewing height was from approximately 2.5 m above the water. The crew consisted of 3 observers and a driver.

At the beginning of each transect, the following data were recorded: Julian date, observer name, sea state (Beaufort scale), cloud cover (%), ceiling height (m), starting latitude and longitude, and start time. All transects were run from the mid-channel towards the shore, with the transect route followed using a GPS-linked chart plotter in the cabin.

A handheld GPS was positioned on the bow, showing the vessel's position on the transect line. The vessel traveled at a relatively slow 10 km/hr. When large flocks were encountered, the vessel slowed further to ensure accurate and complete counts. All transects ended within 30 m of the shoreline.

Three observers collected data on each transect: one observer did a line transect; one did a strip transect, and one recorded distance from shore for each bird. The job assignments rotated one position with each successive transect to cancel any observer effect in comparing methods. Communication between the observers was allowed, and the observers were not visually screened, so detection rates for the two methods are not independent.

For the strip transects, an observer counted all birds detected on the water within 100 m of the transect centerline. Birds were tallied by group, with a group being defined as birds with an average separation distance of less than 3 meters. For line transects, an observer counted all birds on the centerline, and other birds farther from the centerline as time allowed (Buckland et al. 2001). When a bird/group was detected, the observer would estimate the distance, and read the angle to the bird with an indicator on the bow (Figure 5). On occasion, true distances to birds on the water were measured with a laser rangefinder (NewCon-Optik, Toronto, Canada).

For every bird detected, the third person noted the boat's distance from shore (from GPS) and the bird's distance forward of the boat. At the conclusion of each transect a laser rangefinder was used to measure distance from boat to shore (high tide line). The offset between this distance and the GPS-indicated distance was used to adjust all distance-to-shore measurements.

Because one of the assumptions of both line and strip transects is that distances are estimated accurately (Buckland et al. 2001), the crew was tested on a daily basis. During testing sessions with murrelets nearby, crew members would independently estimate and record their estimate of distance to each bird. Then, the driver would report the actual distance as measured by a laser rangefinder. When few birds were present, we conducted tests using painted brown floats similar in size and shape to murrelets. Over 424 trials (375 birds, 49 floats), among 3 primary observers, the mean estimated distance to a target was 85 m. The mean true distance was 89 meters, for a mean error of -4 meters (-4.5%).

The precision measured in these tests has application to the line transect method, where the observer is estimating line of sight distance to each bird, or bird group. It is less applicable to strip transect, in which the observer is estimating the perpendicular distance between a bird and the transect line projected some distance ahead of the vessel. There is a method for measuring that perpendicular distance (Heinemann 1981) but it requires a stable platform.

<u>Flyway Counts.</u> A 3-person crew was placed on the western shore of Young Island, at Sitakaday Narrows in lower Glacier Bay (Figure 6) to monitor *Brachyramphus* murrelets flying into and out of the Bay through the narrows. With practice, murrelets could be reliably identified based on size, color, and flight characteristics. Observers positioned a Leica Televid 77mm scope

(or similar) with eyepiece at 40-50x, so the navigation buoy 1 km east of Rush Point was centered in the field of view. Murrelets flying in or out of the Bay between the scope and the navigation marker (3.4 km distant) were counted.

Alternating 2-person crews conducted flyway surveys for 15 minutes, every half hour from sunrise to sunset, for 4 days (9-12 July), and from sunrise to 1100 hours on 13 July. At the start of each survey, the observer recorded their name, the Julian date, time of day, stage of tide, scope and power setting, cloud cover (%), ceiling height, precipitation, sea state, and visibility. A digital timer/alarm was used to mark the 15 minute survey period. A multiple tally counter was used to keep count of *Brachyramphus* murrelets going in (northbound) and going out (southbound) through the narrows. We noted birds holding fish as they flew, though this was only possible under good lighting conditions and for birds flying in the near field of view. A digital voice recorder was used to tally "other" species counted during the survey. Surveys were discontinued when visibility declined to "poor" (half or more of the distance not viewable) due to fog, rain, shimmer, or low light.

<u>Radar Surveys.</u> Murrelets can be detected flying inland in the predawn hours with the aid of high-frequency radar (Burger 2001, Cooper et al. 2001). I used a Furuno model FR-8122, 12 KW, X-band radar with a 1.2 m (4 ft.) un-tilted antenna mounted on a radar arch above the vessel's cabin. Prior experimentation showed the settings that yielded the highest detection rates (Appendix A). Surveys were conducted from the head of Berg Bay on 7 July, and from the head of Geikie Inlet on 10 July (Figure 7), beginning 1 hour before sunrise, and ending one hour after sunrise (approximately 0300-0500 hrs).

At the beginning of each survey, I recorded GPS coordinates of the survey location, cloud cover, sea state, precipitation, wind speed and direction. During the survey, I recorded the number of murrelets detected in varying time intervals, from 3 minutes to 10 minutes, depending on the number of birds being tracked and the corresponding signal clutter (echo trails) on the screen. The screen would be refreshed (cleared) at the start and end of each time interval, and the time noted. Murrelets were distinguished from other birds by their high flight speed (22 m/s) and linear flight paths (Burger 2001, Elliot et al. 2004). Data were entered directly into a laptop computer in the ship's cabin.

Data Analysis

All data collected in the field in Glacier Bay were recorded on write-in-the-rain notebooks (except for radar data) and entered into a computer for analysis. SPSS software was used for data analyses and graphical output.

Because transects varied in length, I divided the mean number of birds on each strip transect by the mean transect area to get a valid ratio estimator (Stehman and Salzer 2000). The same method was used to calculate mean density on variable-size census areas.

Line transect data were analyzed using program Distance 5.0 (Thomas et al. 2006). Analysis was based on exact distances. Widths were truncated at 180 m, and detection functions modeled using a half-normal key, cosine series expansion, and no adjustment factors. I used simple average as the expected cluster size, and stratified by species. Estimators were modeled using a range of keys and adjustment functions, with the final model selected on the basis of minimum AIC.

A basic property of line transect sampling theory is that it is the absolute size of the sample that is important, not the fraction of the population sampled. Buckland et al (2001) recommend a minimum of 60-80 detections for reliable estimation of the detection function. This threshold was met for *Brachyramphus* murrelets in this survey. On 48 random transects, totaling

91.7 km, there were 218 detections, representing 549 individuals. Kittlitz's Murrelets were relatively rare, with 69 individual birds counted in 22 detections, so these observations were pooled with Marbled Murrelets to arrive at a representative detection function (Thomas et al. 2006).

Results

Sampling Effort

In 2007, 48 randomly placed transects in Glacier Bay were surveyed using both line and strip transect methods simultaneously. A total of 91.7 km of transects were surveyed. In addition, complete censuses were made in 12 of the small bays or inlets, representing 4.6% of Glacier Bay. The random strip transects (width 200 m) sampled 1.4 % of the Bay's marine surface area. The random line transects alone (effective width 436 m) sampled 3.1% of the Bay. And line transects plus censused water bodies sampled 7.8% of the entire Bay.

Species Composition

We detected 389 *Brachyramphus* murrelets on 200-m wide strip transects, and 549 murrelets on line transects (no width constraint). Of the 549 detections, 83.4% were Marbled Murrelets, 12.6 % were Kittlitz's Murrelets, and 4.0% were unidentified. The low percentage of unidentified birds is attributable to the slow survey speed, and the fact that flying birds, which are hardest to identify to species, were not included in this survey. Unidentified birds were not included in species-specific population estimates, but are included in the *Brachyramphus* murrelet estimate.

Spatial Distribution

Relative to subregion. Marbled Murrelets were widely distributed throughout the Bay, but the bulk of the population was in the middle and lower bay (Figure 8). In addition localized areas of high Marbled Murrelet density included the area north of the Beardslee Islands, Wachusett Inlet, Whidbey Passage, Tarr Inlet, and Fingers Bay. Kittlitz's Murrelets were most abundant off Russell Island, and in John's Hopkins Inlet, Reid Inlet, Upper Muir Inlet, and Wachussett Inlet. Kittlitz's Murrelets were not common in the southern portion of Glacier Bay and none were counted south of Berg Bay.

Relative to Shore. The shoreline stratum includes waters < 200 meters from shore and the offshore stratum includes water > 200 m from shore (Piatt et al. 2007b). Assuming 906 kilometers of shoreline, exclusive of islands, in Glacier Bay proper (W. Eichenlaub, GBNP, Pers. Comm.), there are approximately 181 km^2 in this stratum, or 14.2% of the marine waters of Glacier Bay. Because of the randomized survey design, the proportion of each stratum in the sample should equal the proportions in the Bay (exclusive of the Beardlsee Islands, which are Wilderness waters, and were not surveyed). Our sampling effort in the shoreline stratum was somewhat lower (Table 3), reflecting the fact that 12 small bays with significant area in the shoreline stratum were censused rather than sampled.

Consistent with previous studies in Southeast Alaska (Agler et al. 1998, Lindell 2005, Drew et al. in prep), there was no significant difference in the density of *Brachyramphus* murrelets < 200 m from shore compared to > 200 m from shore ($P = 0.675$, $n = 48$). A finding of no significant difference in his test, however, indicates only that this particular stratification is not meaningful for murrelets.

Murrelets show two peaks of abundance relative to shore. The first occurs 200-400 m from shore, and a second, larger peak occurs > 3 km from shore (Figure 9). The density of birds in the shoreline stratum (0-200 m) is less than half that in the next 200-400 m zone, a pattern seen consistently in other areas of Southeast Alaska (ADF&G unpubl. data). This has important implications for survey tracks that parallel the coastline 100 m offshore. There are practical limits to how accurately and precisely one can follow a fixed distance from a convoluted shoreline (Figure 10), especially if the boat driver is also responsible for counting (e.g., Bodkin et al. 2002). Because of the steep density gradient from the shoreline out to 0.5 km offshore, relatively minor differences in where the survey vessel is positioned relative to shore equate to relatively large differences in birds counted. Any departure from the line 200 m offshore adds artificial variance to the population estimate, and likely, a systematic bias.

The very high densities > 3 km from shore reflect counts in the middle of the lower bay. These waters are relatively shallow, subject to extreme tidal action, and are known to be highly productive feeding areas for both whales and seabirds (Robards et al. 2003, Harney et al. 2005). Concentrations of murrelets in these waters are functionally related to water depth more than distance to shore.

<u>Relative to Depth.</u> The mean water depth below all murrelets detected was 110 m (SE=3.5, N=563), with half of all murrelets found in waters 20-80 meters deep. Murrelet density was highest in waters of intermediate depth (50-100 m) (Figure 11). Murrelets target mid-water forage fish that are concentrated in areas where tidal currents create upwelling, fronts, and other oceanographic discontinuities (Zamon 2003, Arimitsu et al. 2007). Depths in this range (~75 m) represent environments with the highest energy and a well-mixed surface layer, particularly those areas south of Sitakaday Narrows and toward the mouth of Glacier Bay (Harney et al.

2005). In these zones, most exploitable fish biomass is in upper 25 m (Robards et al. 2003) which makes it available to murrelets.

Temporal Variation

Smaller areas within Glacier Bay have been resurveyed on a finer time scale (weekly, daily) to describe temporal variation in attendance by murrelets throughout the breeding season. Romano et al. (2004) surveyed murrelets in the upper bay every 5-9 days from 14 June to 7 August 2003. They found Kittlitz's Murrelets increase slightly through mid July, and then slowly decline (Figure 12). Marbled Murrelets increase more rapidly through June and July (Figure 12), and begin declining in early to mid August. Similar patterns were observed with respect to *Brachyramphus* murrelets in the Beardslee Islands (Duncan and Climo 1991). In Icy Strait, the density of *Brachyramphus* murrelets appears to peak in mid August (Lindell 2005).

Two factors contribute to these general patterns of temporal variation. As birds begin incubation duties sometime in late May and early June, one of every breeding adult pair will be spending 24 hours on the nest, meaning lower at-sea densities. As nests either fail, or eggs hatch, more adults gradually return to the water, increasing the at-sea densities. Fledged birds may add to counts throughout the latter half of summer.

In addition to changes related to breeding phenology, birds may be drawn to Glacier Bay from surrounding areas in late summer (K. Nelson, unpubl.data), and are presumably attracted to the Icy Strait-Glacier Bay area by rich foraging opportunities. There may also be a general westward movement in preparation for the post-nuptial molt in Gulf of Alaska waters.

Flying Birds

Whether or not flying birds are counted, and how they are counted, makes a significant difference in the returned population estimate. Some surveys conducted in Glacier Bay and elsewhere in Southeast Alaska count flying birds as they intersect the survey window, or strip, on a continuous basis. Because these birds are coming from a much larger area than the strip width itself, using the strip area to calculate the density of flying birds leads to a positive bias (Spear et al. 1992).

Using the continuous count method, Lindell's (2005) surveys at 17 locations in Southeast Alaska showed the mean proportion of birds flying was 33 %, with a range of 5-76 %. In Glacier Bay, he reported 35 % (Table 4). Agler et al. (1998) using similar protocols over extensive areas, found flying birds comprised 23 % of their population estimates (cited in Lindell 2005). Drew et al. (unpubl. data) found flying murrelets in Glacier Bay constituted 9-20 % of their sample in any given year, with a 5-year mean of 13 percent (Table 5). I assume the wide range of estimates for flying birds imply reflect differing biases due to study-specific protocols and observer skill, as well as real differences in proportion of birds flying in different areas.

To estimate the degree of bias, I computed the *Brachyramphus* density for a hypothetical transect correcting for the larger area a flying bird comes from (Appendix B). Depending on the assumptions used (speed of vessel, bird, and angle of approach) the percentage of birds in flight was estimated at 5 %, which is similar to the low range measured in the predator surveys (Table 5). Further empirical data needs to be gathered to substantiate this modeled estimate.

Abundance

Census. Census results from 12 small bays or inlets within Glacier Bay returned an average of 19.5 *Brachyramphus* murrelets per km^2 (Table 6). The highest densities were found in Wachusett Inlet (45.9/km^2) and Fingers Bay (30.7/km^2). Because these are complete censuses of known-size areas, there is no variance. Berg Bay was censused 2 times, returning counts of 86 murrelets on 9 July, and 123 murrelets on 15 July. Numbers of birds counted in censuses were added to the population estimate from the random sample.

Strip Transects. Based on the strip transect results, the estimated population of *Brachyramphus* murrelets on the water in Glacier Bay, in early July 2007, was 27,538 (Table 7). The estimated population of Kittlitz's Murrelets on the water in early July 2007, was 3,692, and the estimated population of Marbled Murrelets was 23,029 (Table 7). Coefficients of Variation were 39 and 37 percent for the two species respectively.

Line Transects. If both line and strip transects return unbiased estimates of murrelet abundance, simultaneous surveys of the same transect lines should yield similar results. In this study, line transects returned a population estimate for *Brachyramphus* murrelets that was 33 % higher than strip transects. Based on line transects, the number of *Brachyramphus* murrelets on the water was 36,627, with Marbled Murrelets numbering 31,318 and Kittlitz's Murrelets numbering 4,299 (Table 8). Coefficients of variation were 0.18 and 0.38 for the 2 species respectively. If we assume 13% of the population is flying at any given time (Table 5), the population total population of Marbled, Kittlitz's, and *Brachyramphus* murrelets in the Bay in early July was 35,389, 4,858, and 41,389 respectively.

Although it is commonly assumed that no birds are missed within the width of a strip transect, some birds are inevitably missed, especially when seas are rough. The detection function for this survey is shown in Figure 13. The maximum detection distance from the centerline was 218 m, and the effective strip width was 97 m. The CV for the population *Brachyramphus* murrelet population estimate was 17 %, which is a little more than half the CV for strip counts on the same lines. The component percentages of this variance were 12.2 % for detection probability, 73.7 % for encounter probability, and 14.1 % for cluster size. Mean cluster size was 2.44.

Adjusted Population Estimate. Comparing the current population estimate for Marbled and Kittlitz's Murrelets with estimates made in prior years is complicated by difference in survey methods. These include differences in the date of the survey, transect layout (if not random), visibility (different weather), and protocols for counting flying birds. Empirical data can be used to adjust population estimates based on the date the surveys were conducted (Figure 12), and to account for flying birds (Table 5).

To estimate the mid June population estimate from a 12 July survey, I reduced the number of Marbled Murrelets by 20.6 % and the number of Kittlitz's Murrelets by 21.6 % using the percentage change predicted by the trend lines in Figure 12. To estimate the total population, including flying birds, I increased the population estimates by 13 %, which is the mean percentage of *Brachyramphus* murrelets flying over 5 years of surveys in Glacier Bay (Table 5). With these adjustments, the mid-June 2007 population estimates for Glacier Bay, using strip transect methods, are 20,662 Marbled Murrelets, and 3,271 Kittlitz's Murrelets.

Flyway Counts

In an at-sea survey, the observer himself moves past birds that are essentially stationary on the water. Flyway counts are analogous to migration counts (Dunn and Hussell 1995), or radar surveys (Burger 2001), where the observer remains stationary and the birds fly past. The fact that *Brachyramphus* murrelets make predictable, daily, long-distance foraging flights, and can be counted in the hundreds or thousands per hour (van Vliet, unpublished data, Whitworth et al. 2000, Lindell, unpubl. data) suggest potential value as a monitoring method.

Time of Day. In this survey, murrelets were counted from shore with a spotting scope as they flew north (in) and south (out) of Glacier Bay through Sitakaday Narrows in the lower bay (Figure 6). The numbers of birds flying through this narrows each day was impressive. Between sunrise to sunset, we counted an average of 331 murrelets per 15 minute survey flying into the Bay (SE 32.8, N=108). Birds arrived in two main pulses, mid morning and mid day (Figure 14). The lulls between those two incoming pulses were balanced by two pulses of birds flying out of the Bay (Figure 14). The greatest incoming pulse of birds occurred at mid day. As the rate of incoming birds slows, the rate of outgoing birds builds. By evening, thousands of murrelets are moving out of the Bay. Over 108 surveys, the mean number of birds counted (in plus out) was 521 per survey (SE = 30.13). The coefficient of variation was low, at 0.06.

Stage of Tide. Tides appear to strongly influence the timing of these pulses. Birds moved in and out of the Bay counter to the direction of tidal flow (Figure 15). The daily peak count of incoming birds occurred 1.5 hours after high tide (x = 97 minutes, SE=6.6, N=4). As the tide ebbs, large volumes of water from Glacier Bay flow through this constriction, creating major currents and tide rips. It was not uncommon to see many murrelets, and other seabirds (including thousands of Northern Phalaropes [*Phalaropus lobatus*]) actively foraging there.

The maximum number of birds coming into the Bay occurred during moderate stages of ebbing tides (1.5-2 hours past high); and the maximum number of birds flying out of the Bay coincided with maximum flooding tidal volume (3-4 hours past low tide) (Figure 15). Because significantly more murrelets are entering the Bay than leaving it during our daylight surveys, the difference is presumably leaving Glacier Bay sometime during the evening hours, after the last survey is conducted.

Transients. Such high counts of birds flying into and out of the Bay on a daily basis suggest a significant percentage of the *Brachyramphus* murrelets in Glacier Bay are transients, presumably taking advantage of opportunities to forage by day, but moving out of the Bay at night. We expect from the high densities observed in Eastern Icy Strait (Lindell 2005, Drew et al., in prep) that the outgoing birds may be settling there. Marbled Murrelets in Port Snettisham show a similar diurnal movement pattern (ADF&G, unpubl. data).

The fact that there are two distinct pulses of incoming and outgoing birds, suggests that birds may be making 2 round trips, possibly provisioning young. For estimation purposes, I assumed that every bird makes 2 incoming and 2 outgoing trips per day. With an average 1324 incoming birds per hour counted over a 16 hour day, and assuming each bird comes in and out twice a day, approximately 10,500 birds are making day-use of Glacier Bay. If so, nearly a third of the murrelets we find in Glacier Bay in July are day users, or transients. Breeding birds needing to secure high-quality forage fish to provision their young may be attracted to Capelin (*Mallotus villosus*) which thrive in the relatively cold waters of Glacier Bay (Arimitsu et al., in press)

Radar Counts

Birds were successfully detected with radar as they flew inland past the heads of Berg Bay and Geikie Inlet on two separate mornings. Unfortunately, the survey data that were entered into a computer during these surveys were not backed up, and were subsequently lost to a hard drive failure. Despite my inability to quantify the counts, some qualitative impressions can be offered. The rate of birds flying inland clearly tapered off during the second hour of the surveys, which is consistent with patterns observed elsewhere (Burger 2001). And the numbers of birds flying inland was noticeably greater in Berg Bay than in Geikie Inlet, which is likely a reflection of the more extensive and better developed forestlands in the valley west of Berg Bay (Figure 7).

Discussion

This study shows that methodological factors related to the placement of sample units, timing of sampling, and methods of counting (line versus strip, flying versus sitting birds) have a large effect on the accuracy and precision of the survey results. Understanding patterns of variation in a population is a precursor to designing an accurate, precise, and powerful monitoring plan. Knowing how different methods of counting affect accuracy and precision are equally important. This discussion focuses on some of the patterns identified in this study, and their implications in terms of future surveys of *Brachyramphus* murrelets in the Glacier Bay.

Sampling in Space

In the absence of any information on the distribution and abundance of a particular species, a simple randomized sampling design is preferred. It ensures that the habitats available to a particular species are sampled proportional to area. However, if birds are distributed in different areas, at different densities, the survey's precision may be increased by sampling these areas (or strata) at different intensities. For example, in Glacier Bay, waters that are 18-36 meters deep represent just 5.4% in terms of area, but 28% of all *Brachyramphus* murrelets are found there. In contrast, waters over 183 m deep represent over 40% in terms of area, but hold just 10% of the murrelet population (this study).

In stratified random sampling, sampling effort is assigned to strata proportional to their population size, or to their variance. In the case of seabirds, variance and population size are usually correlated (Hatch 2003), so either approach can be beneficial. One of the key decisions in any monitoring program is how to best define strata. That is done with some prior knowledge about patterns of abundance in the species being monitored. In the case of Glacier Bay, the stratification commonly used (shoreline and offshore) has excellent properties from an inventory standpoint. Its utility for population monitoring of particular taxa has not been examined until recently (see Drew et al. in prep).

In previous surveys, the shoreline stratum has received the majority of survey effort (65-90 %), which is appropriate for detecting birds that occur on the beach of very near shore. For purposes of monitoring *Brachyramphus* murrelet populations murrelets, however, Drew et al (in prep) recommend the optimal allocation of effort to this stratum be 8 % (their Appendix 8). If this stratum is to be surveyed roughly proportionally (e.g., 14.2 % by area, or 12.3 % by population), then transects oriented perpendicular to the shoreline are preferred. This not only ensures *proportional* sampling of the nearshore and offshore waters, but more importantly, it samples across the steep Murrelet density gradient from 0-500 m offshore (Figure 9), and eliminates potential bias (Buckland et al 2001). Finally, straight-line transects can be unambiguously defined and accurately replicated year after year. If other considerations dictate that transects be run parallel to the shore, the distance of individual segments from the shore should be varied on a randomized basis (e.g., Raphael et al. 2007) to avoid bias.

Murrelets exhibit a distribution pattern relative to shore (Figure 9), with low numbers in the 0-200 m band, and much higher numbers in the 200-400 meter band. Similar distributional patterns were observed off the coast of Oregon, with peak abundance of Marbled Murrelets found at 500 m (11 surveys), 1000 m (6 surveys) and 1500 m (5 surveys) from the shoreline (Strong 1999). Kissling et al. (2007) also found a strong density gradient with Kittltiz's Murrelets in Icy Bay, and recommended transects be oriented perpendicular to shore to sample along that gradient. The distribution relative to shore probably has to do with mixing zones, tidal influences, and where preferred forage fish are concentrated. Regardless of actual water depth, murrelets will be foraging primarily in the top 25 m of the water column because this is where forage fish concentrate (Robards et al. 2003).

The shallow waters in the lower Bay (55-70 m) exhibit a high degree of mixing and are relatively productive (Robards et al. 2003, Harney et al. 2005). Looking over all of Glacier Bay, the highest densities of murrelets occur in waters 50-100 meters deep, and the lowest densities occur over the deepest waters (>250 m) (Figure 11). From this, a stratified sampling design that allocates more effort to the high density strata will result in a more precise population estimate. Weighing against such a stratification is the fact that the boundaries of depth-based strata are irregular, and not immediately obvious when at sea. This makes transect layout in the various depth strata somewhat challenging.

Another stratification system that might be profitably considered, alone or in conjunction with depth strata, is to allocate effort by subregion of Glacier Bay (Figure 3). The lower bay (subregion 1) is mostly intermediate depth, and in this survey, had the bulk of the Murrelet population (Figure 8). The Middle Bay is much larger, has a mix of shallow, intermediate, and deep waters, and appears to produce murrelets proportional to its size (Figure 8). The East and West Arms both produced fewer birds than would be expected based on area alone (Figure 8), and can therefore be less intensively sampled. Data collected in other surveys, at other times of the year, might suggest different allocation schemes (Robards et al., 2003, Romano et al. 2004, Drew et al., in prep).

An important cautionary note: Kittlitz's Murrelets have a different distribution than Marbled Murrelets at sea (Day et al. 2000, Romano et al., 2004). A monitoring program designed for Kittlitz's Murrelets, specifically, should consider those spatial and temporal patterns

(Kissling et al. 2007). In Glacier Bay, more survey effort would need to be devoted to "hotspots" in the upper arms and fjords of the Bay where Kittlitz's Murrelets are locally abundant.

Although I suspect it wasn't intentionally designed so, Lindell's 1993 surveys of the Bay under-sampled the East and West Arms slightly, and over-sampled the murrelet-rich (*B. marmoratus*) waters of the lower Bay by approximately 2 times what would be prescribed based on area alone (Figure 16). This may have biased his population estimate for Glacier Bay high. However, if his transects in the lower bay were expanded over that lower bay stratum only, bias would be eliminated and precision of the Bay-wide estimate would increase.

Sampling in Time

<u>Within-day variation.</u> As is typical of seabirds, murrelet use of a small area, or "patch", is often linked to available food resources, which in turn, is often tied to favorable oceanographic conditions such as stage of tide, upwelling, and thermal or salinity discontinuities (Zamon 2003, Gaston 2004, Arimitsu et al. 2007). Other factors, such as the need to deliver a large fish to a chick at night, no doubt influence feeding and staging locations. If repeated consistently, short surveys of small areas may serve as a useful index for monitoring population trends. The stage of tide, and possibly time of day, that one chooses to survey in a given patch should stay constant to reduce within-day variation (Speckman et al. 2000). Tide and time effects will vary locally, since higher bird numbers in one place are balanced by lower bird numbers someplace else.

Surveys of short time-duration (e.g., focal area scans, flyway counts, or boat-based surveys of small areas) will be most sensitive to time and tide. Pilot data should be collected over a range of times and tides to determine relationships, if any. The optimal time for surveys is determined by minimum CV. For most at-sea survey work from vessels, within-day variation is not a concern because the surveys are long enough (day-long, or multi day) to encompass the full spectrum of hours and tide stages.

Between-day variation. We expect birds to move from patch to patch *within* Glacier Bay on a daily or hourly basis (see above), but it has been implicitly assumed that the populations of birds in Glacier Bay and Icy Strait are resident in the summer. There is evidence, however, of significant day-to-day variation in attendance at these relatively large areas. Four times over a 3 year period, the entire set of Icy Strait transects was sampled in close succession (days apart). The results of those paired surveys showed between-day differences of 25-97 percent, with a mean difference of 47 percent (Table 9).

There are two possible reasons for differences of this magnitude. If the population estimates are accurate, then Icy Strait does not have a population of birds unto itself, but rather, is simply a foraging “patch” which birds from a large geographic area may choose to attend, or not attend, on any given day. There is some independent evidence for this (van Vliet 1993, Whitworth et al. 2003). Whether the murrelet population in Glacier Bay follows this model is uncertain, but the high numbers of birds flying through Sitakaday Narrows on a daily basis (Figure 14) suggest that a substantial daily flux exists. How it varies day by day, or week by week, is unknown.

Another source of day-to-day variability comes from factors affecting ability to *detect* birds. In table 9, the survey pair with the greatest difference (97%) was surveyed at almost the same point in time, but by different crews on different vessels (USGS in small vessels, USFWS in a large vessel). This suggests that “other” factors (observer skill, platform, exact transect routes, survey protocols) biased one or both estimates.

One doesn't need to know the cause of the differences (population flux versus survey bias) to recognize the implications for trend analysis. If this day-to-day variation of 50% is the norm, for whatever reason, conducting a single survey over a 2 or 3 day period will certainly underestimate the true variance in that year. The variance will not be "lost", but will be reflected at the year to year scale instead. The only way to reduce this variance, and increase power, is to conduct more surveys per year, or, wait more years to detect a trend. If there is a conservation concern for a species being monitored, waiting more years may be unacceptable.

Within-season variation. Bird numbers in Glacier Bay are known to change over the course of a summer breeding season (Figure 12). Changes at this scale are typically in response to such things as incubation (adult birds moving inland), provisioning (both adults foraging at sea for their chick), fledging (juveniles joining adults on the water), and availability of schooling forage fish (which draws birds from elsewhere). These types of changes can be detected by making repeated surveys throughout the summer.

Optimal Time to Conduct Surveys

Murrelet Surveys in Southeast Alaska are mostly conducted in June or July (Agler et al. 1998, Lindell 2005, Kissling et al. 2007a, 2007b, Drew et al. in prep). In order to maximize power to detect trends, populations should be surveyed during the period in the summer when variability, as measured by the coefficient of variation (CV), is lowest. Within Glacier Bay, 2 studies have been conducted that examined temporal variation in *Brachyramphus* Murrelet numbers during the summer. Romano et al. (2004) conducted weekly surveys in two areas in the Upper Bay (which were combined for this analysis). Duncan and Climo (1991) conducted weekly surveys over a 3 year period in the Beardslee Islands in Glacier Bay. I summarized these data and calculated within-month coefficients of variation for all month-years of data (Table 10).

The CV's ranged from a low of 0.07 (July 1987 and 2003) to a high of 70 % (August 1991), with mean CV's for June, July, and August of 0.28. 0.11, and 0.53 respectively (Figure 17). There may be valid reasons to conduct surveys in June, including better surveying weather, historic precedent, and a desire to capture temporal variability. But if the goal is to conduct a single survey with the greatest power to detect changes in the population, July is the optimal month. This conclusion applies to Glacier Bay. Other areas may exhibit different patterns, and different optimal times for surveys (Speckman et al., 2000, ADF&G unpublished data).

Line versus Strip Transects

The assumption of line transects (no birds missed on the center line) is more easily satisfied than the assumption of a strip transect (no birds missed in the strip) (Buckland et al. 2001). For this reason, line transects can be expected to return a more accurate and less variable population estimate than strip transects, especially when weather and detection rates vary by survey or observer. The improvement in precision with line transects was substantial for *Brachyramphus* murrelets (17 % versus 32 %). While I would expected line transects to have greater precision (Becker et al. 1997), I was surprised at the degree of improvement given the good survey conditions and the fact that observer effects were cancelled by the study design. This proffers an important advantage to line transects in terms of power to detect trends.

The higher absolute numbers returned by line transects versus strip transects is also to be expected, but again, the magnitude of the difference was large, with 33 % higher densities for *Brachyramphus* murrelets from line transects. Becker et al.(1997), making similar comparisons, found line transects returned densities that were 40 percent higher than some 200m wide strip transects. Differences of this magnitude will confound efforts to compare future line transect estimates with previous strip transect estimates. One simple solution to this problem is to survey a subset of transects with both methods (as in this study) so that an adjustment factor between the two estimates can be derived. Although there may be some resistance to the added work that getting an angle and distance to each bird involves, it is not a difficult job with the proper equipment and training. My crew conducted both with equal ease and expressed no preference for one method over the other.

Counting Flying Birds

Counting flying birds is a thorny problem for at-sea surveys. The additional measurements needed to adjust densities for flying birds can be burdensome (Spear et al, 1992, and Appendix B). Few Alaska surveys quantify or correct for the positive bias associated with continuous counts of flying birds. Certainly, the bias is not always small. Lindell's population estimate for Glacier Bay was 35% flying birds. Elsewhere in the region, he found the proportion of flying birds averaged 33% (Table 6). And Agler et al. (1998), summarizing data for 3 very large areas of the state, found population estimates were boosted 23% by flying birds. I substituted approximate values into the equation in Appendix B, and found that a more reasonable percentage of flying birds is on the order of 5%. This fits reasonably well with the percentage of flying birds reported on predator surveys from 1999-2003. When birds could be identified to species, the mean percentage flying was approximately 5-10% (Drew et al., in prep, Table 5, this report).

Improving Survey Precision

The precision estimates that accompany most surveys includes an element of temporal variation at the within-day and within-week scales, since at-sea surveys typically sample over multiple days, hours, and tidal stages. The reported variance also has a strong spatial component, reflecting the different counts from transects scattered throughout the Bay. As a rule, precision is increased with increasing sample size. For this reason, sampling more, shorter transects will return a more precise estimate than sampling fewer longer transects (Drew et al. in rep). The segments should be separated sufficiently in either space, or time, to be truly independent (Hurlburt 1984, Buckland et al. 2001, Kissling et al. 2007).

Although a relatively small area was sampled in this survey, the precision for line transects was reasonable, returning a CV of 0.18 to 0.38 for Marbled Murrelets and Kittltiz's Murrelets respectively. If one wants to increase precision further, more transects can be added to the survey. I examined the effect of sample size on precision by asking how much more effort would be needed to increase the precision by approximately 1/3. The transect length required to achieve a CV of 10% would require 127 km of transect, or 38% more than in this survey (Buckland et al., 2001: eq 7.12, p 244, with b=3).

Abundance

Abundance is the currency of most population monitoring programs. For a single survey in a given year, the reported confidence interval is usually interpreted to mean the *true* population size lies within that interval. A single survey a season cannot possibly capture that temporal variability in the population, and so confidence intervals derived from single-survey estimates overestimate precision.

An issue that is commonly overlooked is the effect of murrelet nesting on population abundance estimates. Most surveys in Glacier Bay are conducted in mid-June, at the height of the incubation period for *Brachyramphus* murrelets. During incubation, half of the adult breeding birds are off the water sitting on nests. We know from other studies that breeding effort in murrelets is variable year to year (Peery et al. 2004, Bigger et al. 2006). This has implications for the timing of surveys. It also has implications when reporting the abundance of birds in the population. If 50% of the population is breeding in a given year, then 25% of the total population will be missing form the area when surveys are conducted in June. If knowing the absolute size of the population is important, then population estimates in June should be adjusted upwards for the estimated proportion of birds off the water.

Population Trend versus Population Size

Concerns over bias are largely alleviated when one focuses on estimating population trend rather than population abundance. It doesn't matter if an observer misses 10% of the birds on the water, or if flying birds are counted continuously. All that matters is that the bias be consistent from year to year. Shifting the emphasis to monitoring on smaller geographic areas allows one to replicate surveys, and will result in trend analyses that are more powerful, accurate, and efficient than attempts to enumerate entire populations (Becker et al. 1997).

Flyway surveys and radar surveys are good examples of trend monitoring methods. The location of survey sites is certainly not selected at random. Sitakaday Narrows is a pinch point through which large numbers of birds funnel, making it ideal for flyway surveys. The head of Berg Bay has a good anchorage, and an extensive forested valley beyond, making it ideal for radar surveys. These methods return counts of birds per unit time, not area, and so density estimates cannot be generated. They can, however, be very useful for detecting changes in murrelet populations over time (Arcese et al. 2005, Bigger et al. 2006), as long as the proportion of the population that breeds each year is stable (Peery et al. 2004).

Other examples of trend monitoring involving at-sea work is that by Duncan and Climo (1991) in the Beardslee islands, and Romano et al (2004) in the upper bay. The densities recorded on those sites cannot be fairly extrapolated to a population estimate for all of Glacier

Bay. But if they are sampled annually over a period of years, we can reasonably assume trends in the population would be reflected in trends in these smaller areas.

Finally, some surveys straddle the middle ground. The 1991 survey in Glacier Bay surveyed the entire coastline, and so can draw very robust conclusions about birds in that stratum. But the waters > 200 m from the shore, including the bulk of the Bay waters and its murrelets, was surveyed by a handful of transects selected opportunistically, and so the estimate for the "offshore" stratum may be biased. The "zig-zag" surveys by Lindell in 1993 (Appendix C) represent an effort to blend extensive coverage with convenience. There is no "off-survey" travel time in this design, so it is efficient. However, the design under-samples the near-shore environment, so the population estimate is also potentially biased (direction unknown). Such biases are of concern only if the objective is estimating population size of murrelets. It is of little concern if the objective is to estimate population trend only.

Recommendations

What direction the Park chooses to go in terms of its monitoring program hinges on many factors, not the least of which is a clear sense of the objective. Does the Park desire better information on population trend, or population size? Does it want generalized information about many species, or better information on a few? What level of population change would they like to be able to detect, for which taxa, over what period of time? These are questions that should be addressed before deciding what a monitoring program will specifically look like.

The analysis by Drew et al.(in prep) provides a thorough analysis of the 1997-2003 "predator surveys", with a number of recommendations for how those can be modified and continued to provide cost effective monitoring for multiple species. The recommendations I offer below should not be interpreted as contradicting those by Drew et al.(in prep). They have relevance only if the Park Service wishes to initiate a monitoring program that focuses narrowly on detecting trends in *Brachyramphus* murrelets. With that as a frame, I offer the following:

1. Adopt line transects as the standard for at-sea survey work. Line transects yield population estimates that are more precise, and more accurate, across a range of viewing conditions. They are the standard for at-sea surveys of *Brachyramphus* murrelets outside Alaska, and we should follow suit. I recommend radial distances be estimated directly (as opposed to perpendicular distances, or binning), especially for surveys of few taxa.
2. Conduct surveys in July. Survey data collected throughout the summer in Glacier Bay indicates July has the lowest average coefficient of variation (CV). Surveys conducted in this month will have the highest power to detect population trends of *Brachyramphus* murrelets. It also moves surveys away from the incubation period, when variable breeding effort from year to year can confound population trends.
3. Conduct replicate surveys within a breeding season. Temporal variability in the numbers of murrelets using Glacier Bay is high, which makes the accuracy and precision of single-survey estimates correspondingly low. The way to most efficiently overcome this is to replicate surveys. I recommend 3 surveys per summer, with one in mid June (since historic surveys were conducted in June), and 2 more surveys during the first half of July.
4. Stratify by water depth. The current coastline/offshore strata is not meaningful for murrelets, and the shoreline transects are difficult to replicate precisely. Stratifying relative to depth would represent a significant improvement in both accuracy and precision, but may be difficult to implement logistically. If so, a simple random sample is preferred.

5. Stratify by sub-area within the Bay. Allocate sampling effort proportional to the observed density of Marbled and Kittlitz's Murrelets in different sub-regions of the Bay. This will significantly improve precision of the population estimates, especially for Kittlitz's Murrelets which are found mostly in fjords in the upper West and East arms of the Bay.
6. Orient transects perpendicular to shore. Murrelets are not uniformly or randomly distributed, but show a characteristic distribution relative to the shore and water depth. Transects should be oriented parallel to this gradient (perpendicular to the shore) to avoid a biased sample.
7. Count flying birds separately, and by an unbiased method. Recording flying birds by the "continuous count" method adds significant positive bias to population estimates. Other methods, though more difficult, should be adopted to eliminate this bias. The density of birds flying and birds sitting on the water should be recorded, and reported, separately. For population monitoring purposes, the simple density of birds sitting on the water is adequate.
8. For trend information, repeat the 1993 survey of Lindell (2005). The previous recommendations are aimed at providing a more accurate, precise population estimate. But for trend information, the 1993 survey by Lindell (2005) has many desirable elements. The coverage is extensive (290 km of transect), proportionately covering all motorized waters of the Bay. There is no "off survey" travel time between transects. The survey can be completed in 2 days, and therefore, is easily repeated. The transects are straight lines, and can be precisely replicated. The 1993 effort was replicated 2 times within a breeding season, and because it was done 15 years ago, it represents one of the earliest snapshots of *Brachyramphus* populations in the Park.

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Tables

Table 1. Methodological differences in surveys conducted in Glacier Bay, 1991-2003.

Survey[a]	***Survey Year***	***Survey Date***	***Sampling Design***	***% effort on shoreline***	***Transect Width (m)***	***Vessel Size (m)***	***Density birds/km²***
Piatt 1991	1991	June & July	Systematic	90	200	4-6	58.6
Lindell 2005	1993	24 June	Zig-zag	0	300	20	36.2
Lindell 2005	1993	18 August	Zig-zag	0	300	20	31.1
Agler 1998	1994	June July?	Random	13[b]	200 & 300	7.6	22.9
Piatt et al. 2007	1999	11-23 June	Systematic	65	200 & 300	8-22	18.8
Piatt et al. 2007	2000	11-23 June	Systematic	65	200 & 300	8-22	14.4
Piatt et al. 2007	2001	11-23 June	Systematic	65	200 & 300	8-22	16.5
Piatt et al. 2007	2002	11-23 June	Systematic	65	200 & 300	8-22	12.8
Piatt et al. 2007	2003	11-23 June	Systematic	65	200 & 300	8-22	12.5

[a] Date refers to when report was published.
[b] The proportion of sampling effort along shoreline for all Southeast Alaska

Table 2. Sampling effort in 2008 relative to sub-region area, based on randomized transect placement.

Subregion	**% of Water Area**	**% of Survey Effort (transect length)**
Lower Bay	9.0	9.6
Beardslee Islands	4.4	0.0
Mid Bay	34.0	18.4
East Arm	36.9	24.8
West Arm	15.7	47.2
Total	**100.0**	**100.0**

Table 3. Relative availability, sample intensity, and murrelet use in shoreline and offshore strata.

Stratum	***% of Study Area***	***% of Sample (this study)***	***% of Population (this study)***
Shoreline (< 200 m)	14.2[a]	10.3	12.3
Offshore (> 200 m)	85.8	89.7	87.7
Total	**100.0**	**100.0**	**100.0**

[a] The proportion of the study area in this stratum is calculated from 906 km of shoreline in the Bay proper (exclusive of islands), equating with a stratum area of 181.2 km^2.

Table 4. Percentage of murrelets in flight, measured on 17 areas in Southeast Alaska (Lindell 2005).

Study Area	***Area sampled (km^2)***	***birds on water/km^2***	***birds on water and flying/km^2***	***Percentage flying***
Icy Strait	71.6	20.5	33.4	38.6
Glacier Bay	87.0	22.0	33.7	34.8
Frederick Sound	79.7	3.2	5.6	41.9
Chatham Strait	50.4	2.9	3.5	19.2
Thomas Bay	2.0	34.0	140.6	75.8
Sumner Sound	110.5	13.0	19.6	33.4
Excursion Inlet	4.1	33.9	37.4	9.3
Lisianski-Portlock	24.7	8.7	14.0	37.7
Ogden- Kukkan	5.9	51.9	80.2	35.3
Olga-Peril	23.4	4.1	6.2	33.4
Freshwater-Gastineau	22.2	9.7	15.6	38.0
Taku	10.5	2.7	2.9	7.6
Stephens-Icy	25.4	26.4	30.4	13.4
Icy Strait	18.0	5.1	7.2	28.5
Gastineau-Snettisham	12.1	11.2	17.9	37.3
Snow Pass A	1.6	6.9	8.1	15.4
Snow Pass B	0.9	45.8	48.1	4.9
Total	**549.9**			**x = 33.0**[a]

[a]Mean weighted by study area size

Table 5. Percentage of Kittlitz's Murrelets and Marbled Murrelets in flight in Glacier Bay, 1999-2003. (G. Drew, USGS, unpublished data).

Percent of Birds In Flight

Year	Kimu	Mamu	Unid	all *Brachyramphus*
1999	8.7	4.6	19.7	9.4
2000	5.3	10.1	26.9	20.1
2001	6.9	7.4	23.7	12.5
2002	8.2	6.6	24.1	11.4
2003	11.9	7.0	32.6	13.0
Mean	**8.1**	**6.6**	**24.8**	**13.0**

Table 6. Census results for 14 small bays/inlets in Glacier Bay, July 2007.

Area	*Mamu*	*Mamu/km2*	*Kimu*	*Kimu/km2*	*Brach*	*Brach/km2*
Berg Bay	123	11.6	2	0.2	125	11.8
Fingers Bay	166	30.7	0	0.0	166	30.7
N. Sandy Cove	16	7.6	3	1.4	19	9.1
S. Sandy Cove	14	7.8	0	0.0	14	7.8
Shag Cove	10	4.4	0	0.0	10	4.4
Tyndall Cove	48	20.9	0	0.0	48	20.9
Tidal Inlet	214	29.7	2	0.3	216	30.0
Russell Island	62	22.1	0	0.0	63	22.5
JohnsHopkins	0	0	56	6.2	57	6.3
Reid Inlet	21	5.1	14	3.4	35	8.5
Blue Mouse	43	16.5	0	0.0	43	16.5
Wachusett	306	43.7	15	2.1	321	45.9
Totals and Grand Means[1]	**1023**	**15.1**	**92**	**1.4**[1]	**1117**	**19.5**[1]

[1] Grand means are weighted by census area size.

Table 7. Populations of murrelets on the water as measured by **strip transects** in Glacier Bay, July 2007.

Marbled Murrelets

	Water Area[1] (km^2)	*Density*	*Population*	*CV*
Small Areas (censused)	57.3	17.85	1,023	na
Large Areas (sampled)	1,218.5	18.06	22,006	0.39
Total	**1,275.8**	**18.01**	**23,029**	

Kittlitz's Murrelets

	Water Area[1] (km^2)	*Density*	*Population*	*CV*
Small Areas (censused)	57.3	1.61	92	na
Large Areas (sampled)	1,218.5	2.95	3,600	0.37
Total	**1,275.8**	**3.05**	**3,692**	

Unidentified Murrelets

	Water Area[1] (km^2)	*Density*	*Population*	*CV*
Small Areas (censused)	57.3	0.03	2	na
Large Areas (sampled)	1,218.5	0.67	816	0.35
Total	**1,275.8**	**0.64**	**818**	

All *Brachyramphus* murrelets

	Water Area[1] (km^2)	*Density*	*Population*	*CV*
Small Areas (censused)	57.3	19.49	1,117	Na
Large Areas (sampled)	1,218.5	21.70	26,421	0.32
Total	**1,275.8**	**21.60**	**27,538**	

[1] John's Hopkin's Inlet is classified as motorized, but two random transects at the head could not be reached due to ice. Instead, a 9.0 km^2 area east of Jaw Point was censused, and included in the motorized-censused category, leaving the balance of the area in the motorized-sampled category.

Table 8. Populations of murrelets on the water as measured by **line transects** in Glacier Bay, July 2007.

Marbled Murrelets

	Water Area[1] (km²)	*Density*	*Population*	*95% CI*	*CV*
Small Areas	57.3	17.89	1,025	na	
Large Areas	1,218.5	24.85	30,293	21,208-43,270	0.18
Total	**1,275.8**	**24.55**	**31,318**	**22,233 – 44,295**	

Kittlitz's Murrelets

	Water Area[1] (km²)	*Density*	*Population*	*95% CI*	*CV*
Small Areas	57.3	1.61	92	na	
Large Areas	1,218.5	3.45	4,207[a]	2,000-8,851	0.38
Total	**1,275.8**	**3.37**	**4,299**	**2,092 – 8,943**	

Unidentified Murrelets

	Water Area[1] (km²)	*Density*	*Population*	*95% CI*	*CV*
Small Areas	57.3	0.03	2	na	
Large Areas	1,218.5	0.83	1,010	367-2,775	0.54
Total	**1,275.8**	**0.79**	**1,012**	**369 – 2,777**	

All *Brachyramphus* murrelets

	Water Area[1] (km²)	*Density*	*Population*	*95% CI*	*CV*
Small Areas	57.3	19.49	1,117	na	
Large Areas	1,218.5	29.13	35,510	25,561-49,333	0.17
Total	**1,275.8**	**28.71**	**36,627**	**26,678 – 50,450**	

Table 9. Daily variation in *Brachyramphus* populations in Icy Strait, 1993, 1995, and 1998.

Year	*Survey 1*	*Survey 2*	*Percent Difference*[a]
1995	July 9th	July 11th	**25%**
1998	June 22nd	June 24th	**37%**
1998	August 17	August 19	**27%**
1999	June 14th	June 15th	**97%**
Mean			**47%**

[a] Percent difference is computed as: $\{2 \times |S_1 - S_2| / |S_1 + S_2|\} \times 100$, where S_1 is the population estimate for survey 1, and S_2 is the population estimate for survey 2.

Table 10. Coefficients of Variation (CV) by study area, year, and month in Glacier Bay. Data from Upper Bay represent Murrelet densities for Upper West Arm and Muir Inlet Entrance combined (from Romano et al. 2004). Data from Beardslee Islands are counts (from Duncan and Climo 1991).

Area	**Year**	**Month**	**N Surveys**	**Mean**	**SE**	**CV**
Upper Bay	2003	June[1]	4	24.6	2.43	**0.10**
Upper Bay	2003	July	3	27.9	1.99	**0.07**
Upper Bay	2003	August	1	27.7	--	
Beardslees	1987	June	5	248.6	90.60	**0.36**
Beardslees	1987	July	4	318.0	23.51	**0.07**
Beardslees	1987	August	3	590.0	205.73	**0.35**
Beardslees	1989	June	3	161.7	30.22	**0.19**
Beardslees	1989	July	5	558.2	107.30	**0.19**
Beardslees	1989	August	3	335.3	180.98	**0.54**
Beardslees	1991	June	3	160.0	78.14	**0.49**
Beardslees	1991	July	1	667.0	--	
Beardslees	1991	August	3	392.7	274.44	**0.70**

[1] In 2003, Upper West Arm was surveyed on July 1, and the Muir Inlet Entrance was surveyed on June 30. When these surveys were combined, I assigned the result to the June category.

Figures

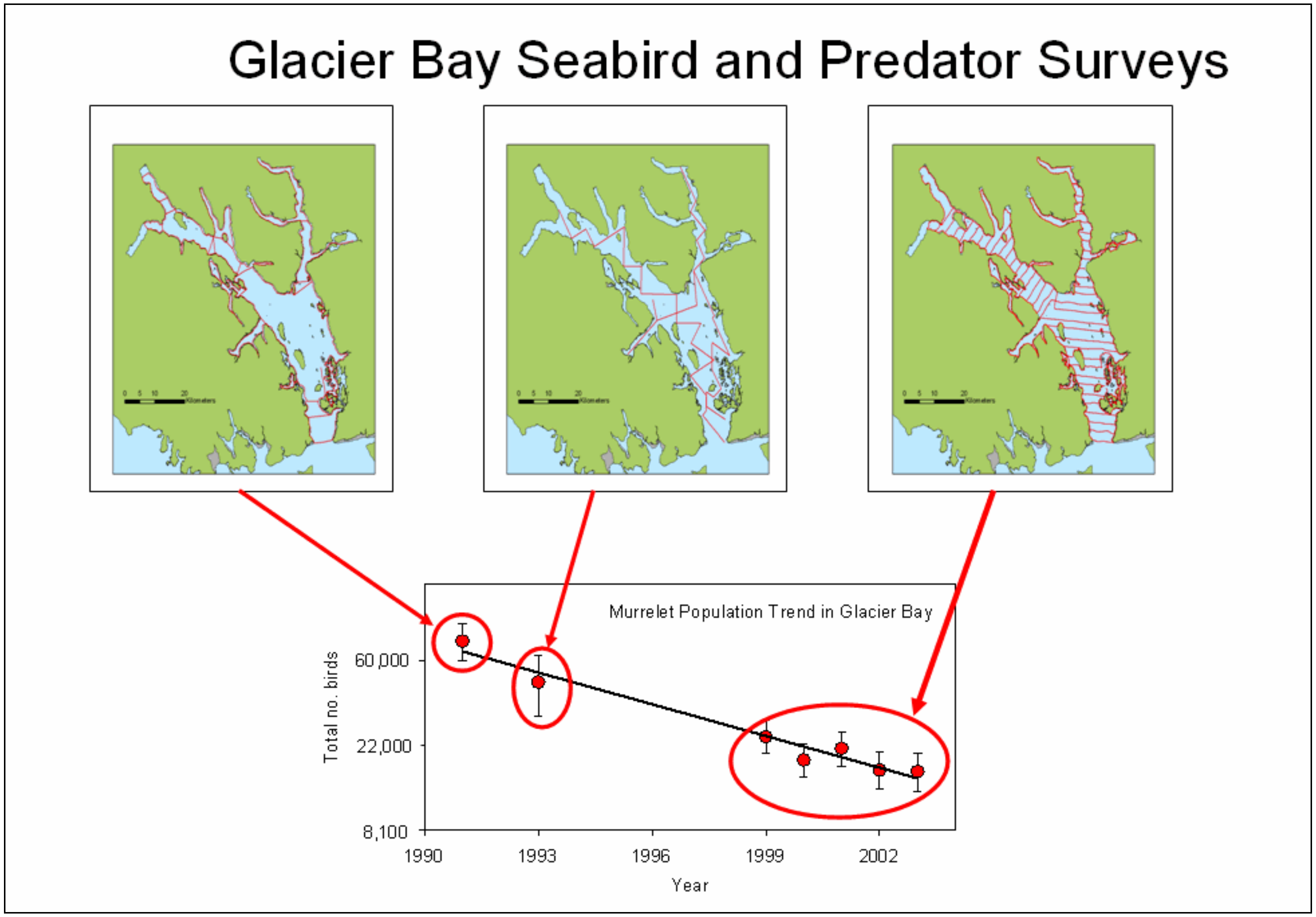


Figure 1. Population estimates and survey designs in 1991, 1993, and 1999-2003 in Glacier Bay

Figure 2. Glacier Bay study area on the mainland of northern Southeast Alaska.

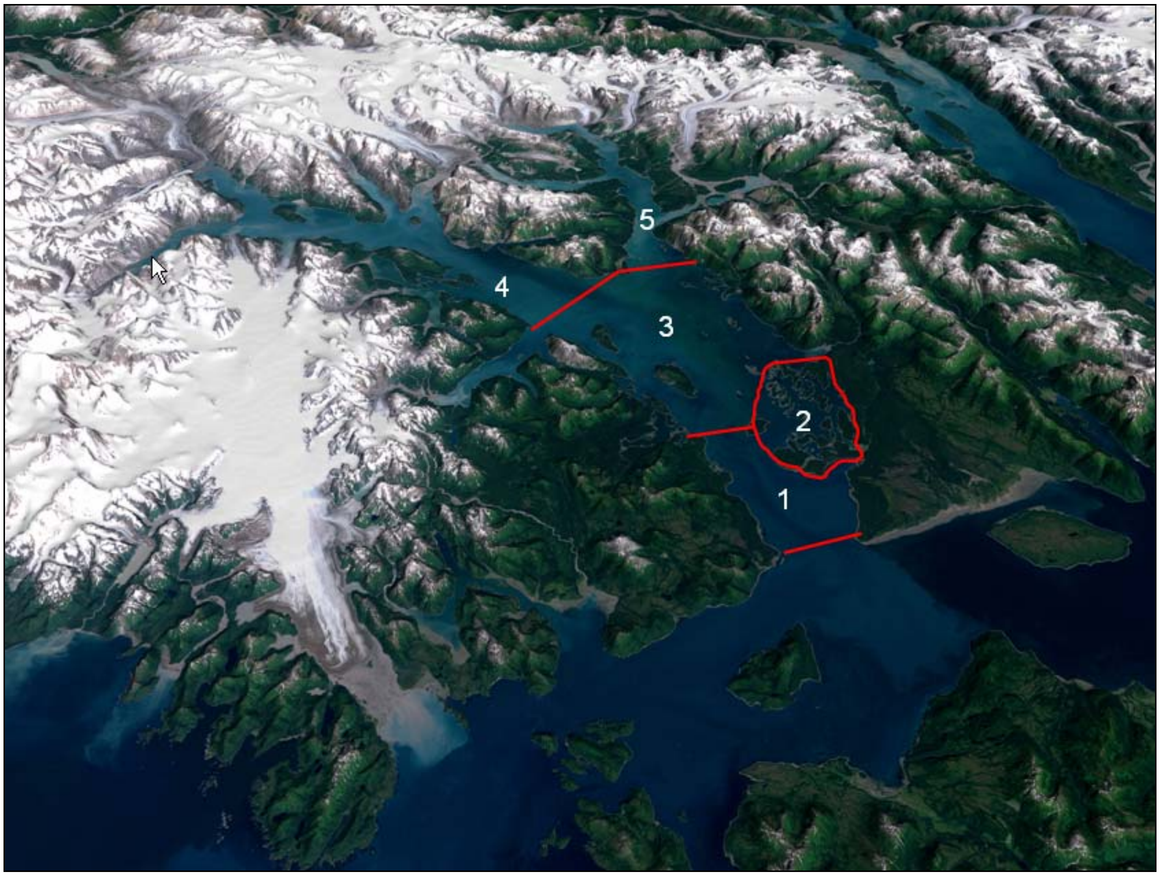


Figure 3. Glacier Bay showing approximate boundaries between 5 sub-regions: Lower Bay (1), Beardslees (2), Middle Bay (3), West Arm (4) and East Arm (5).

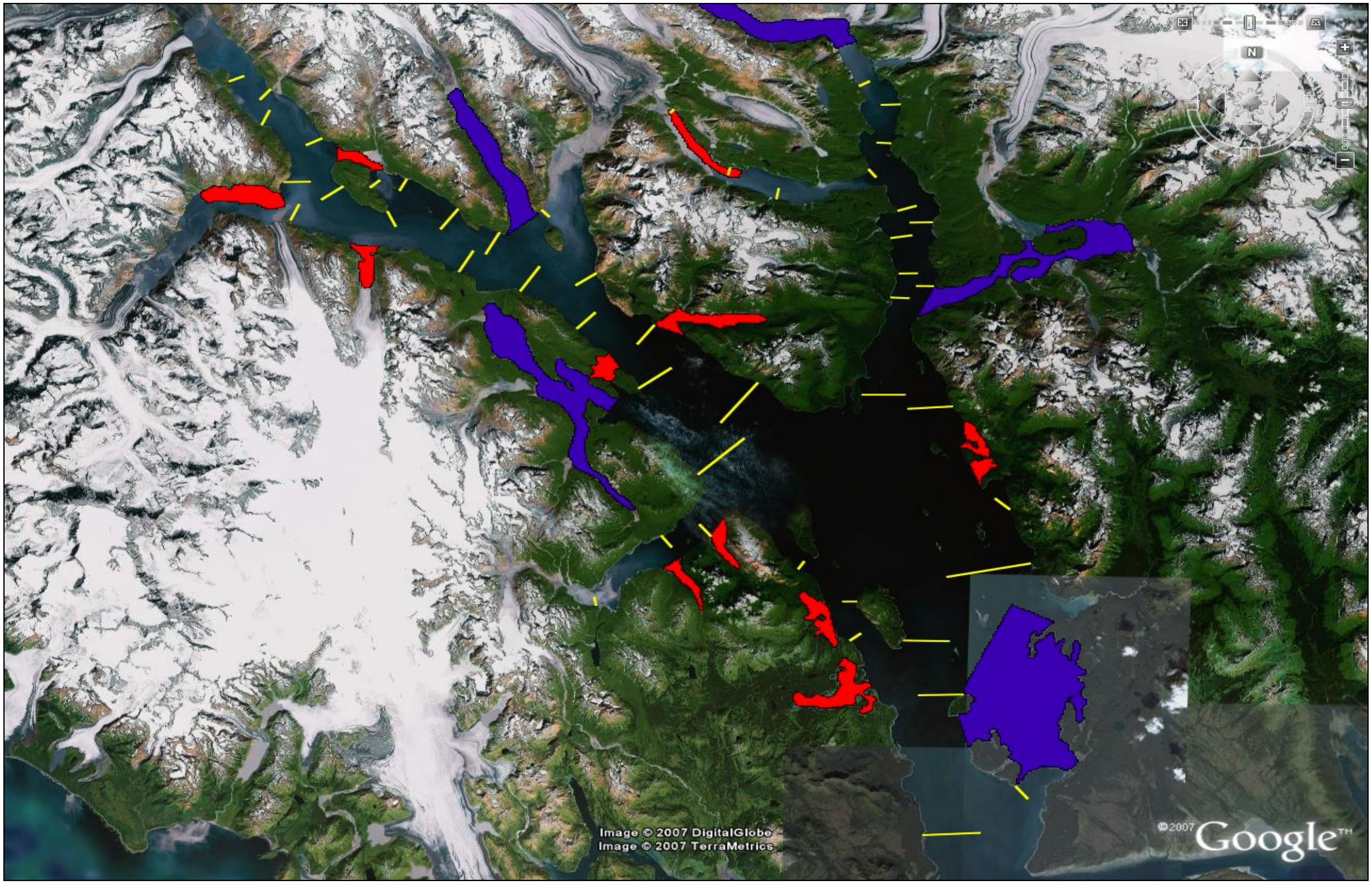


Figure 4. Sampling design for surveying *Brachyramphus* murrelets, July 2007. Blue areas are non-motorized, and were not sampled. Red Areas were censused (complete count). The remaining area was sampled by line and strip transects. Transect locations were established with random starting points along mid channel lines, and end points on nearest alternating shore.

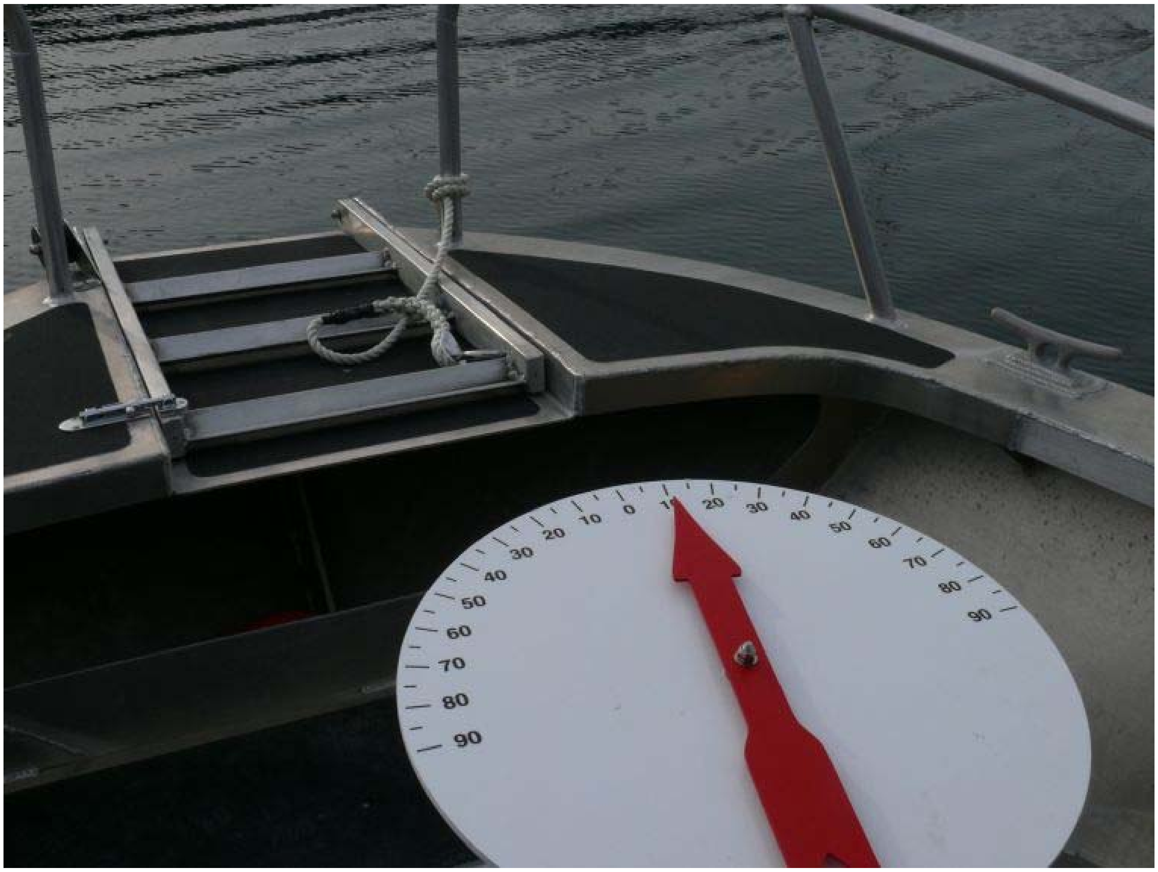


Figure 5. Angle indicator used on the line transect surveys.

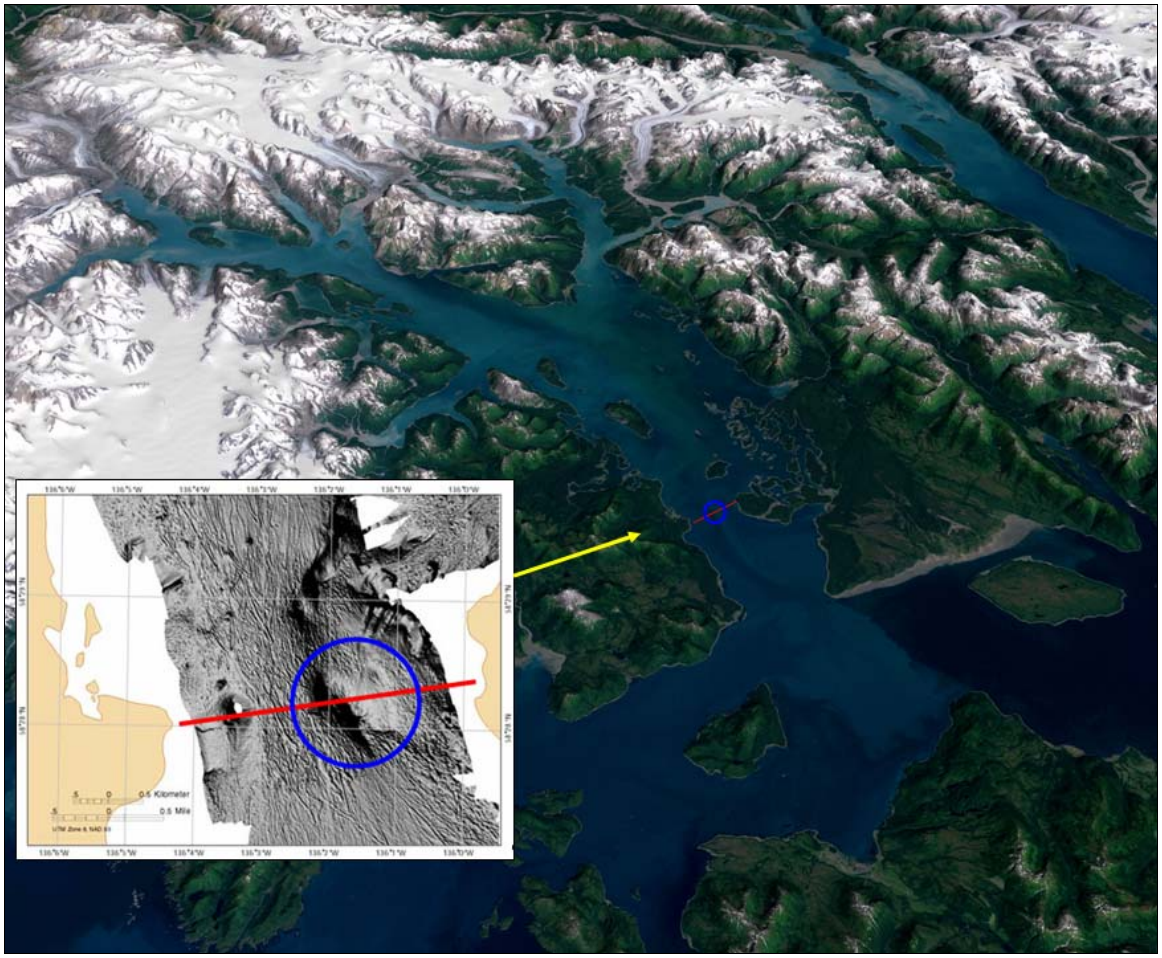


Figure 6. Flyway count location adjacent to Sitakaday Narrows. The inset image shows the bathymetry of this area, including numerous iceberg gauges in the ocean floor. The red line signifies point at which birds flying North (into the Bay) and South (out of the Bay) were counted. The blue circle marks a zone of major upwelling and heavy murrelet feeding activity, especially pronounced on ebbing tides.

Inset image from: http://soundwaves.usgs.gov/2001/07/fieldwork2.html

Figure 7. Radar survey locations in Geikie Inlet and Berg Bay. Red dot shows boat-based radar location. Forested nesting habitat for Marbled Murrelets in each area is approximated by the yellow ovals.

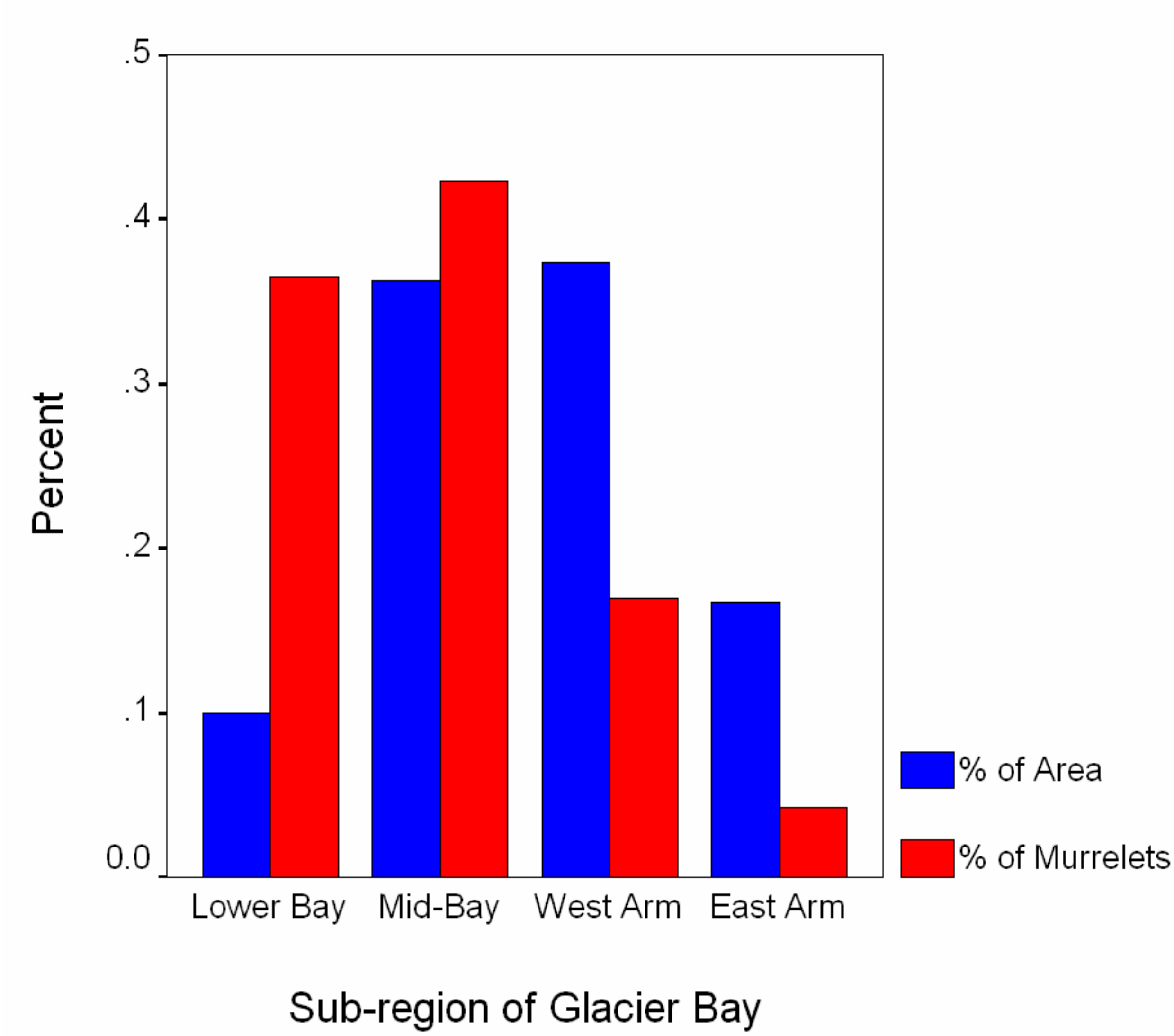


Figure 8. Relative abundance of *Brachyramphus* murrelets by sub-region in Glacier Bay, July 2007.

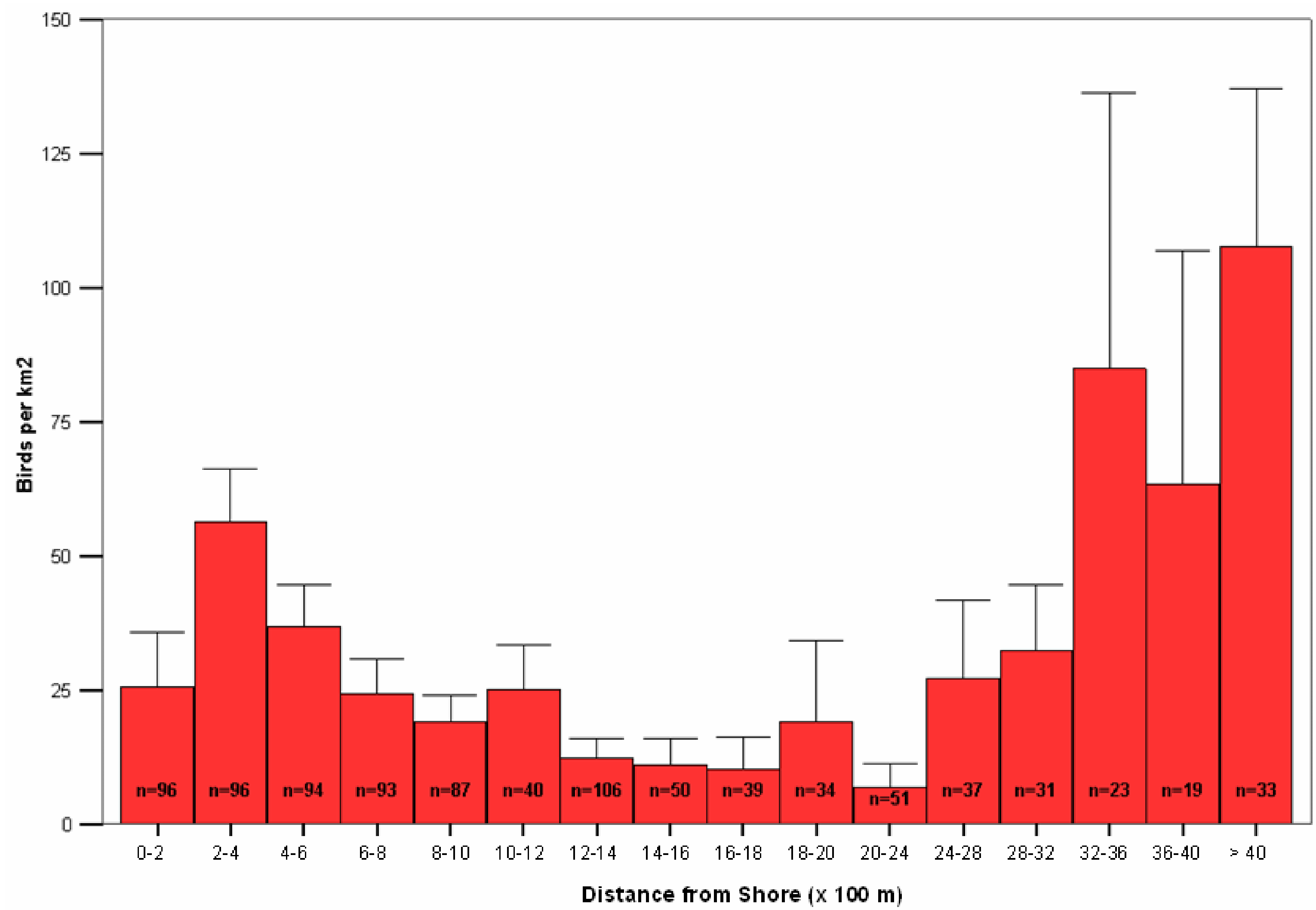


Figure 9. *Brachyramphus* murrelet distribution relative to shore. (n=100 m segments. Bars =1 SE).

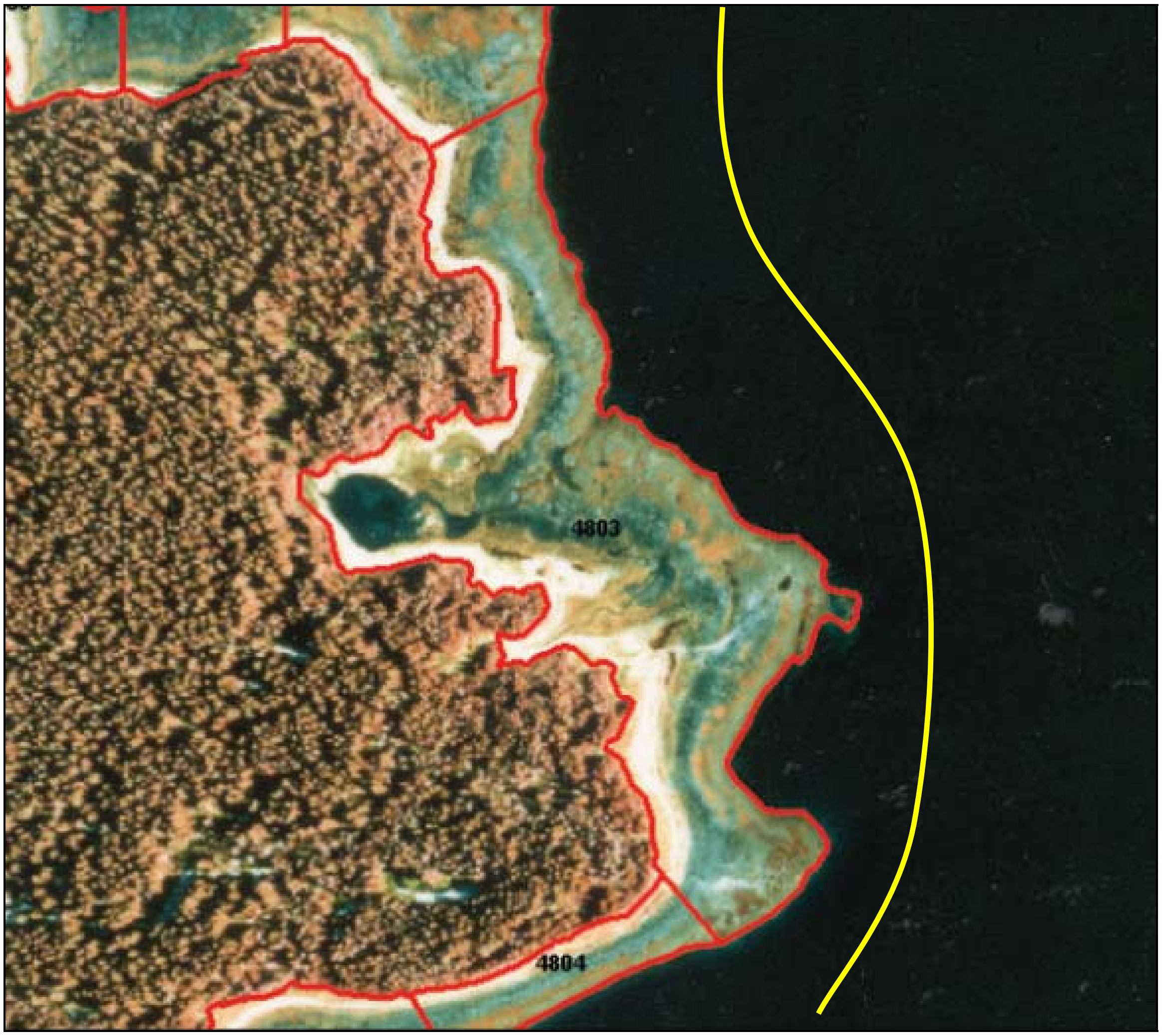


Figure 10. An example of a shoreline segment in Glacier Bay, with high- and low-tide lines in red (From Sharman et al. 2007). In a boat running “parallel to shore”, the coastline is smoothed, resulting in a track that is a varying distance to shore (in yellow), and difficult to replicate.

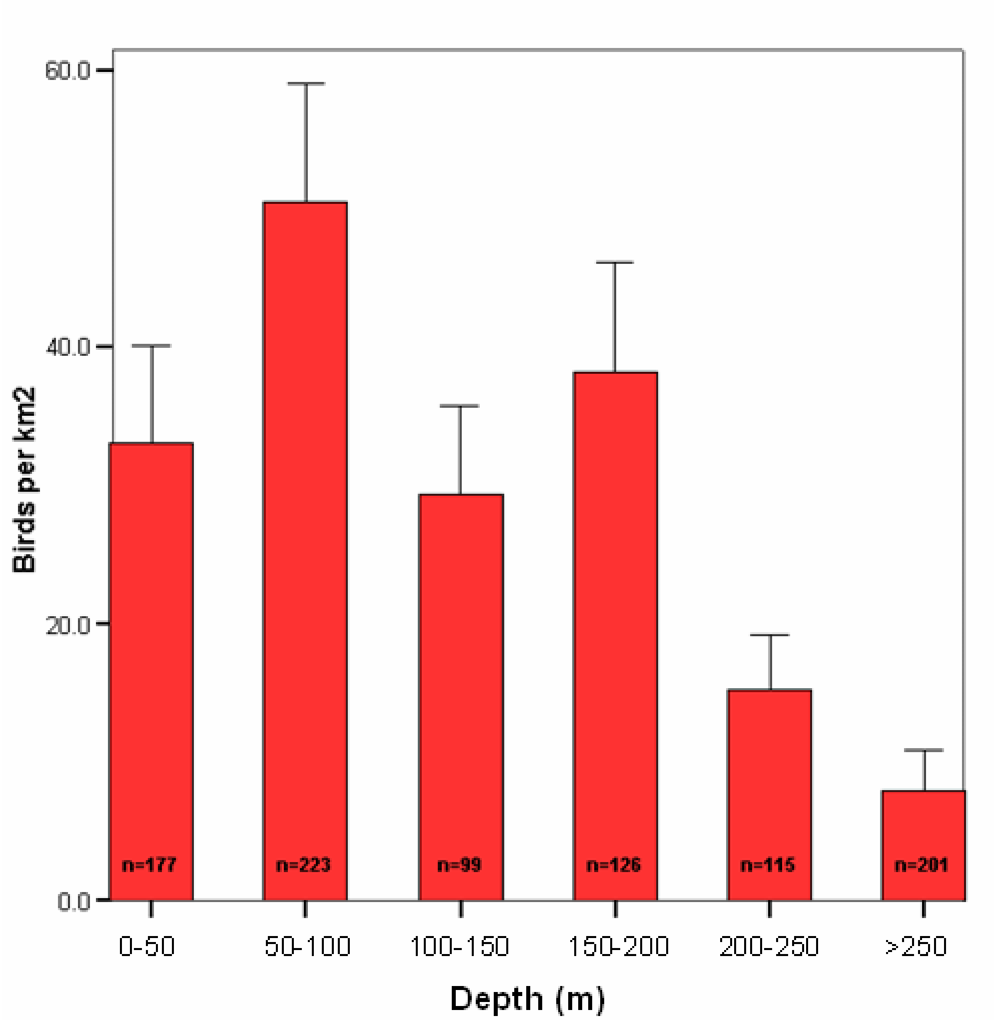


Figure 11. Density of *Brachyramphus* murrelets in Glacier Bay by water depth, July 2007. Whiskers are 1 SE, N = number of 100 m segments

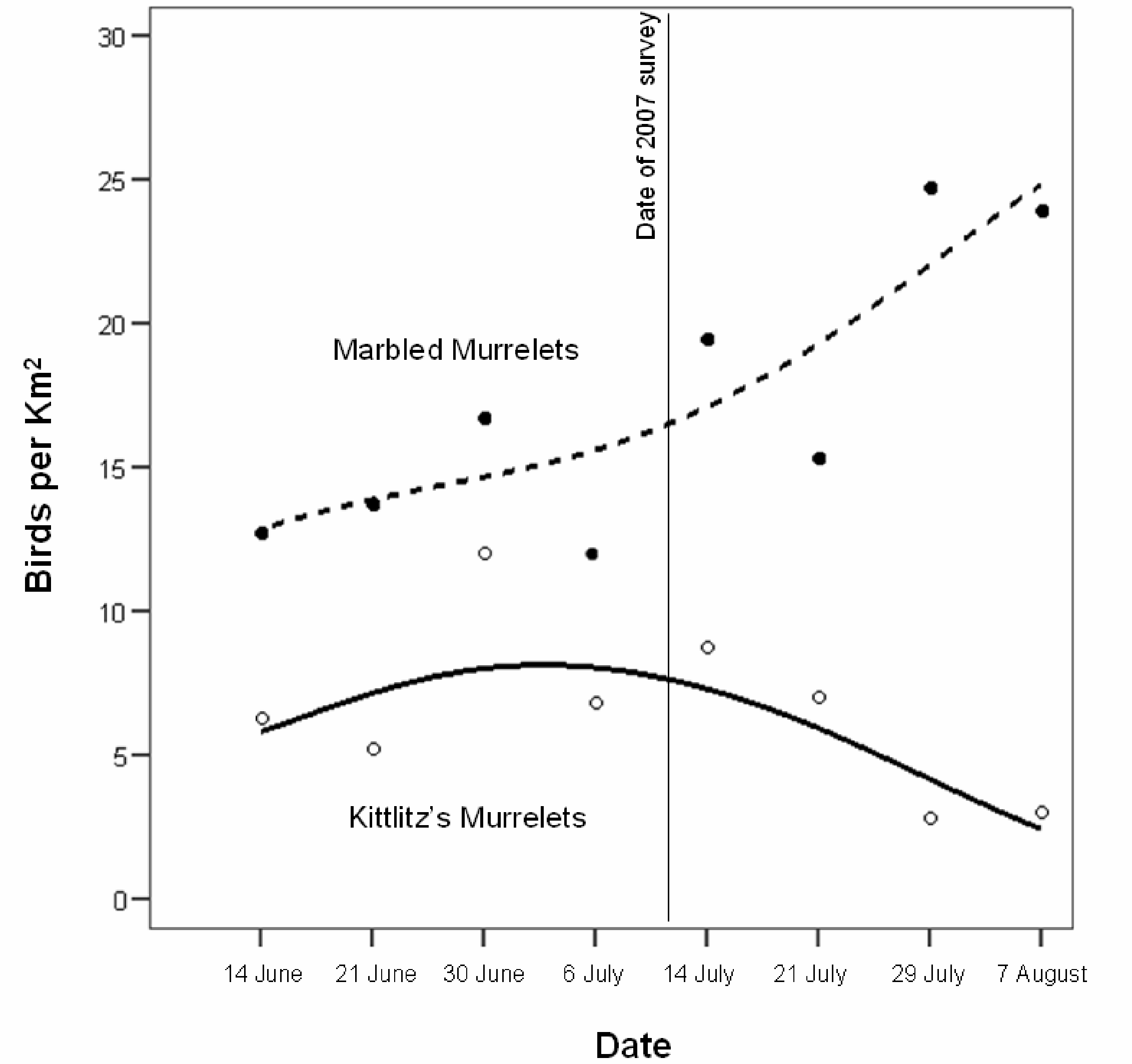


Figure 12. Change in murrelet density in Glacier Bay from 14 June through 7 August, 2003. Weekly survey data collected by Romano et al (2004) in the Upper West Arm and Muir Inlet Entrance of Glacier Bay (combined). Lines are drawn using a normal smoother function in SPSS (bandwidth multiplier = 3). Median date of surveys in 2007 is shown for reference.

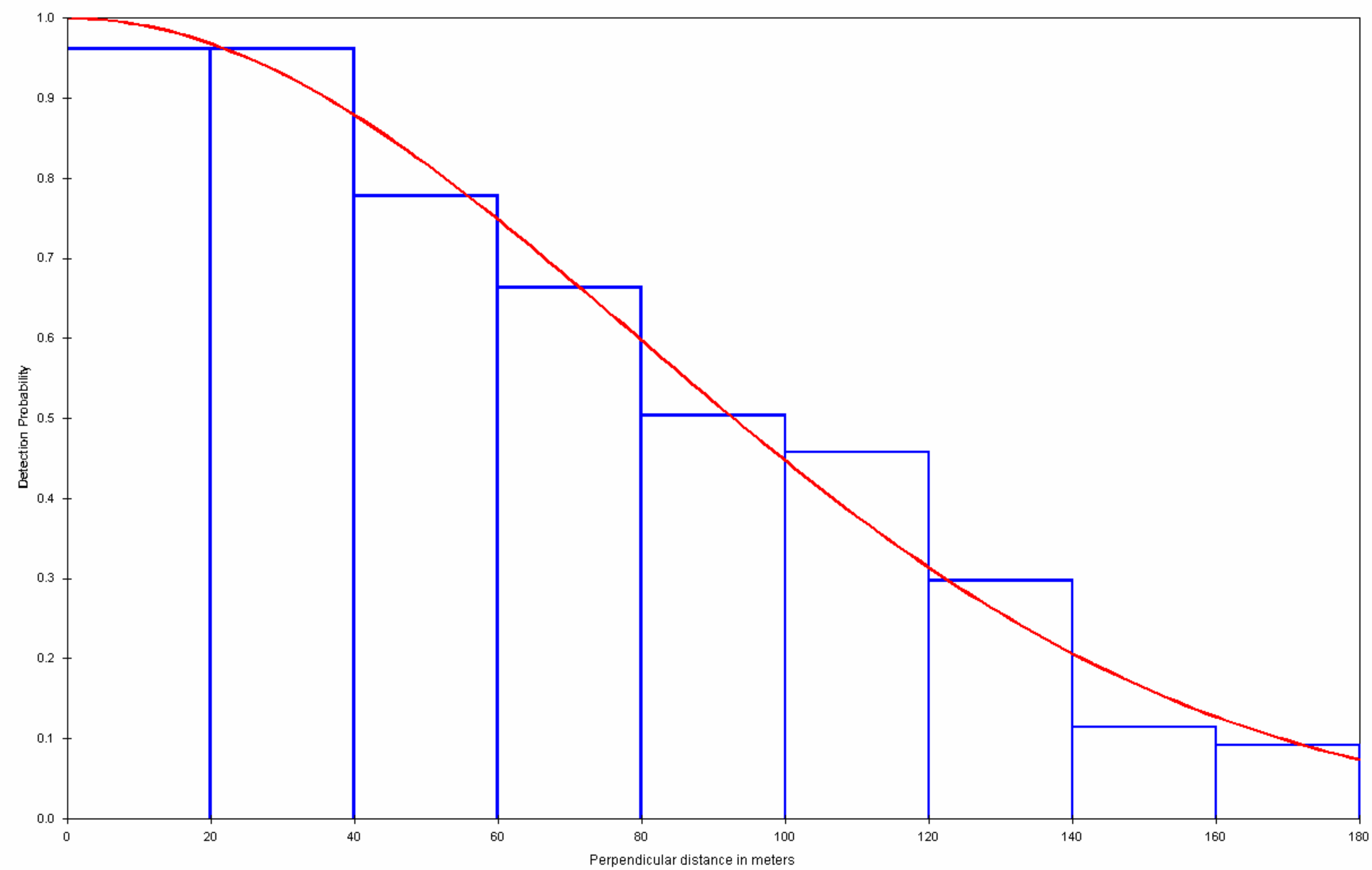


Figure 13. Detection probability for *Brachyramphus* murrelets on line transects in Glacier Bay, July 2007.

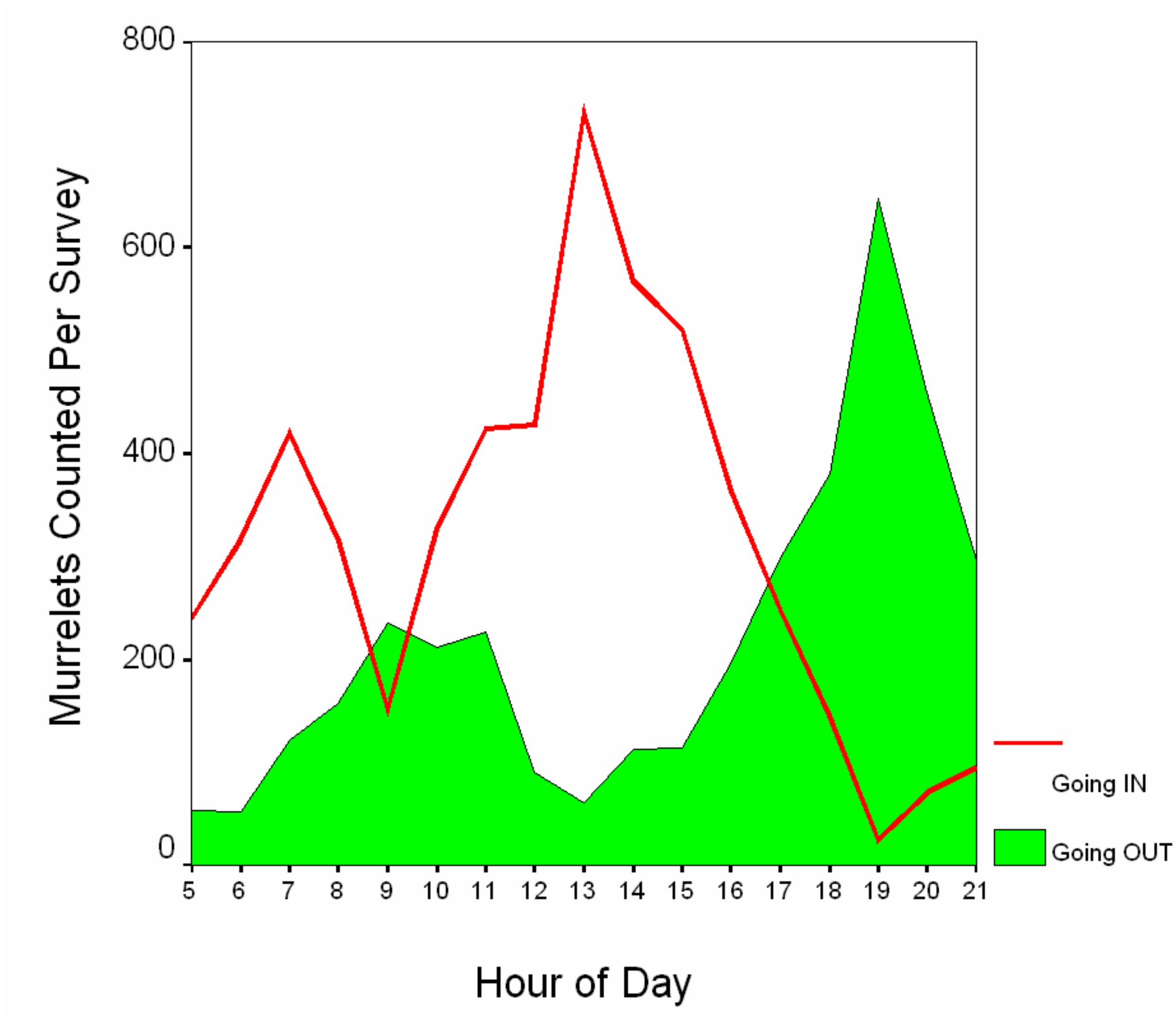
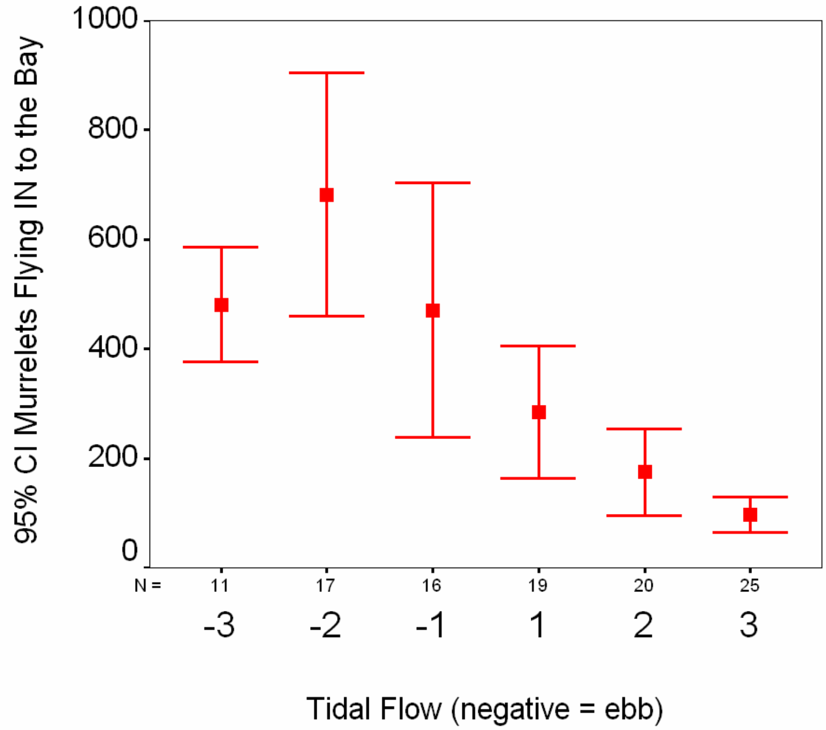


Figure 14. Temporal pattern of *Brachyramphus* murrelets flying in and out of Glacier Bay. Counts are averaged over all survey days, July 2007.



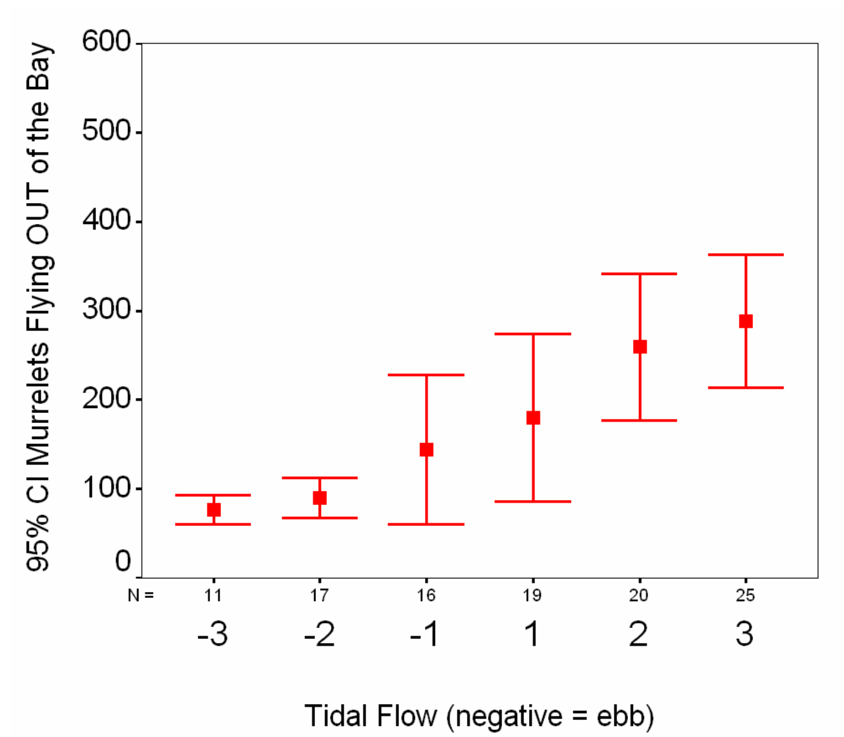


Figure 15. Relationship between flyway counts and tidal flow in Glacier Bay, July, 2007. Error bars show 95% confidence intervals

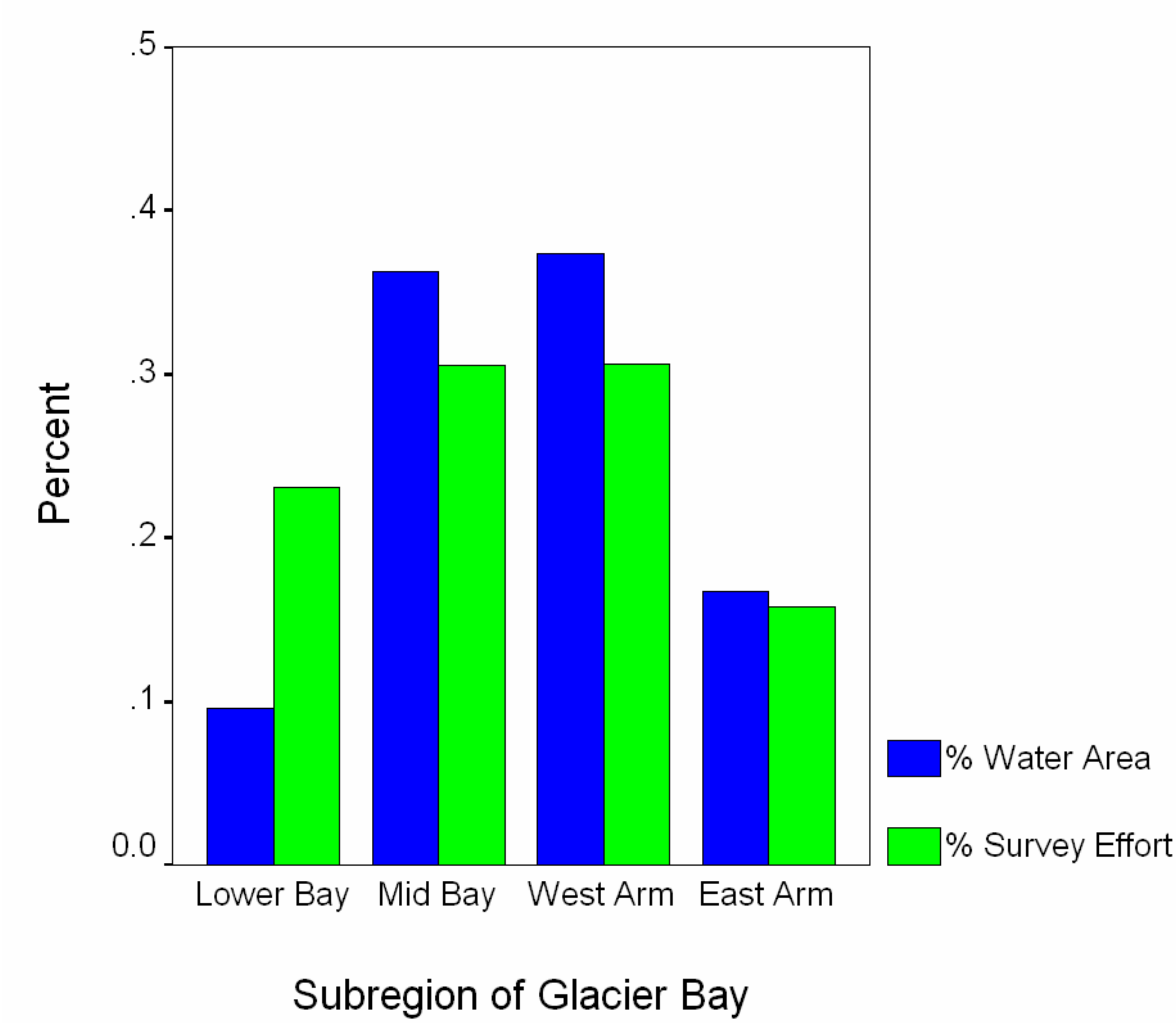


Figure 16. Allocation of survey effort by subregion in Glacier Bay surveys, 1993.

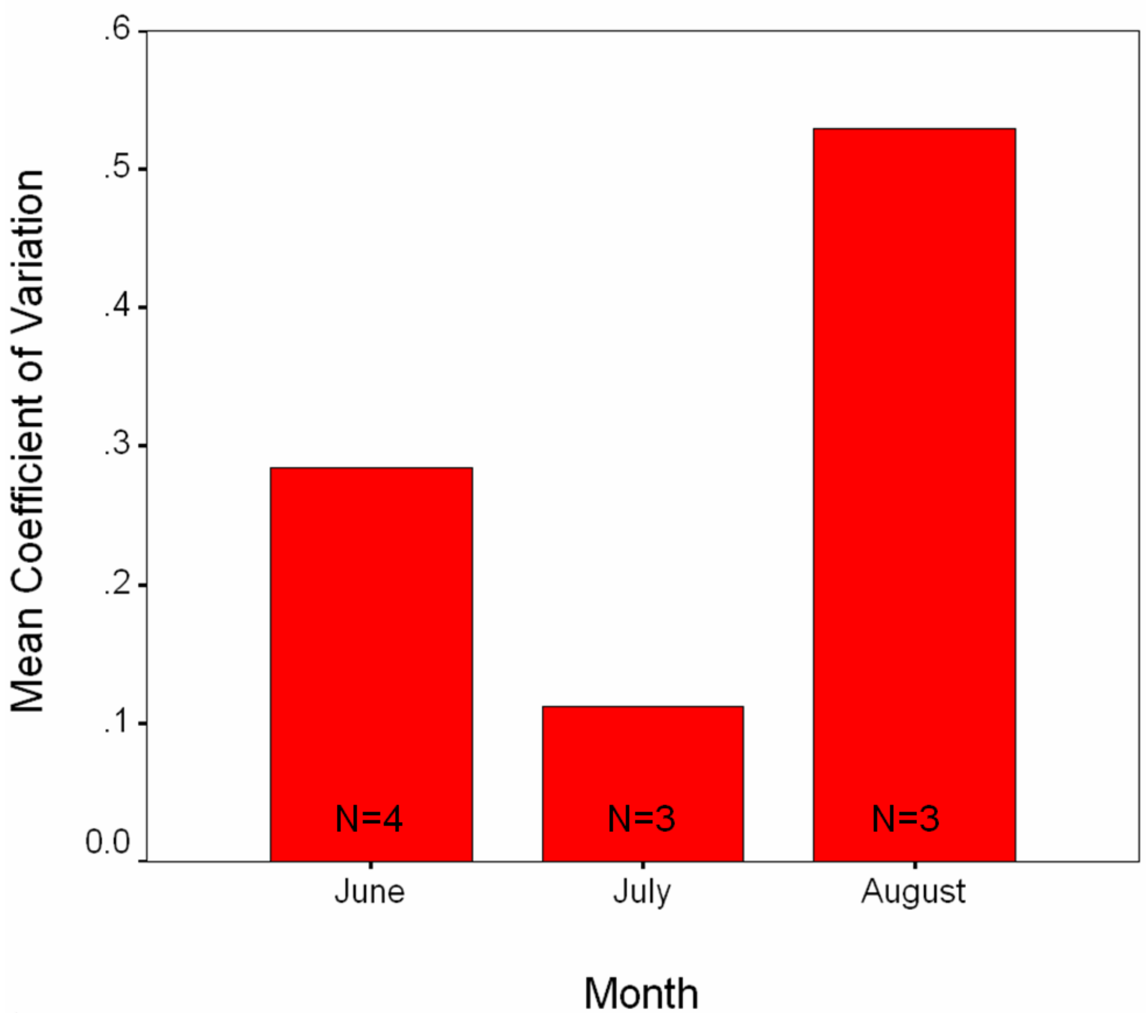


Figure 17. Coefficient of Variation (CV) by month in Glacier Bay. Data are from the Upper Bay in 2003 (Romano et al. 2004) and in the Beardslee Islands in 1987, 1989, and 1991 (Duncan and Climo 1991). CV's by study area, month and year are given in Table 10. N is the then number of area-years of data for each monthly mean.

Appendices

Appendix A. Radar settings for optimal detectability of *Brachyramphus* murrelets. These are for a Furuno FR-8122 12 KW radar with 1.2 m rotating antenna or equivalent. Important: For these settings to over-ride default automatic settings, the receiver must be set for *manual* tuning[1].

Button Controls	***Menu***	***Sub Menu***	***Setting***
Range Mode Off Center Trails Gain Control Knob (push for man) A/C Sea Control Knob (push) Rain Control Knob (push)	 Manual (push/hold to clear) Manual Manual Manual		0.75 - 1.5 km RM (Head Up) Move cursor 15 sec 100% 0% 50-80%
	Brill/Color	Range Rings Brill Echo Color Display Color Background Color	Low Blue Night Black/Red
	Display	Shape (get…) North marker Heading	Square Off Off True
	Menu:Echo	Auto Gain (disabled) Auto Sea (disabled) Auto Rain (disabled) Pulse Length Echo Stretch Echo Average Noise Rejector Interference Rejector Auto Anti-Clutter Display-Dynamic Display-Curve Antenna Speed 2nd Echo Rejector	Calm Calm Calm Short 1 Off Off Off Off Narrow 3 48 off
	Target Trails	Gradation Color Mode Level Length Time Copy Restart Narrow Own Ship	Multiple Blue Relative 1 Normal 15 s On On On (if many targets) Off
	Mark	VRM Unit Cursor Position Electronic Bearing Locator (EBL)	Km Range and Bearing Relative
	Tuning	Manual	max sensitivity[1]

[1] To enable manual tuning, press MENU, use the track ball to select TUNING, press enter, select MANUAL, press enter, select MAUNAL TUNING, press enter, roll trackball up or down to point where TUNE MAN bar (displayed top tight on screen) swings to maximum. Press ENTER. Press MENU to close menu. These settings can be saved as a "custom" setup (see manual, pp 1-36 to 1-38).

Appendix B. Estimating the area sampled when counting flying *Brachyramphus* murrelets.

Assumptions:

1) The length and width of the strip transect is known.
2) The speed of the survey vessel is known.
3) All birds crossing the transect within some "moving window" forward of the ship are detected.
4) Birds intersect the transect at a known angle, and do not change course to avoid the ship
5) Birds are flying at a known (or assumed) speed

Given those assumptions, the flyway "area" sampled by an at-sea transect can be calculated as:

$A = L \times (W + W_f)$

Where,

A = area
L = transect length
W = transect strip width, and
W_f = added width beyond strip that contributes flying birds to the count.

The added width for flyers (W_f) varies with how far a bird can come from and still intersect the moving window. That, in turn depends on the relative speed of approach towards the transect line, and how long it has to reach the line. These are functions of the flight angle towards the transect line, the length of the survey window, how far in front of the ship the murrelets pass, and the speed of the flying bird relative to boat speed.

That relationship is described by the following equation:

$$W_f = \text{sine}(\theta) * (M - D_f) * S_m/S_s$$

Where,

θ = Angle at which flying murrelets intersect the transect line.
M = Length of survey window (m)
D_f = Distance of flying murrelets in *front* of the ship (m)
S_m = Speed of murrelets (m/s)
S_s = Speed of survey ship (m/s)

An example:

A strip transect 2 kilometers long (L) and 300 m wide (W) is surveyed by a vessel traveling at a speed (S_s) of 3 meters per second (5.8 knots). On this 11 minute transect, an observer scanning a 500 x 300 m "moving window" ahead of the boat counts 2 flying murrelets. The mean angle of approach (θ) by the birds is 45 degrees, and the mean crossing distance in front of the vessel (D_f) is 150 m. The murrelets fly at an estimated speed (S_m) of 22.6 m/s (50 mph) (Elliot et al. 2004).

Substituting,

$W_f = \text{sine}(\theta) * (M - D_f) * S_m/S_s$
$W_f = 0.707 * (500-150) * 22.6/3$
$W_f = 1{,}856$ m

$$\text{Area} = L \times (W + W_f)$$
$$A = 2000 \times (300 + 1{,}856)$$
$$A = 4.31 \text{ km}^2$$

Thus, the density of *flying birds* on that transect would be 2/4.31, or 0.46 birds/km^2. In comparison, if we assumed all the flying birds came from within the 300 x 2000 m area of the strip transect (0.6 km^2), the density of flying birds would be 3.33 birds/km, or 7 times higher than true.

Because flying birds are counted with less frequency than sitting birds in at-sea surveys, the positive bias contributed by simply tallying flying birds is buffered somewhat by the larger number of sitting birds. This exercise demonstrates that had Lindell (2005) accounted for the larger area his flying birds came from, the percentage of birds in the air at any point in time in Glacier Bay would much lower. This example suggests the true number of flying birds might be 7 times lower than the 35 % he reported, or, about 5%. Until better empirical data are available, I will assume the proportion of birds in the air at any given moment in Glacier Bay is 5%.

Appendix C. Location of transects surveyed in Glacier Bay during June and August, 1993 (Lindell 2005).