ENVIRONMENTAL EFFECTS ON THE FALL MIGRATION OF EIDERS AT BARROW, ALASKA

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Received 1 May 2004, accepted 3 December 2004

SUMMARY

DAY, R.H., ROSE, J.R., PRICHARD, A.K., BLAHA, R.J. & COOPER, B.A. 2004. Environmental effects on the fall migration of eiders at Barrow, Alaska. Marine Ornithology 32: 13-24.

We studied the effects of environmental factors on the migration of Common and King Eiders (*Somateria mollissima* and *S. spectabilis*) past Barrow, Alaska, during fall migration in 1997 and 2000 with ornithological radar and visual observations. Among-day variation in movement rates was high, with birds apparently flying at any time if migratory conditions were favorable. Movement rates were significantly higher during good visibility than poor visibility, higher during tailwinds than crosswinds and headwinds, higher during strong crosswinds than weak ones and higher during weak headwinds than strong ones. Eider groundspeed velocities averaged 83.5±0.3 km/h and were significantly higher with good visibility and strong winds, higher with good visibility at night than with poor visibility at night, higher with crosswinds and tailwinds than with headwinds, higher with weak headwinds than with strong ones and higher with strong tailwinds and crosswinds than with weak ones. Eiders flew slightly south of northwest (310º). Flight directions differed significantly by time of day and visibility, but the differences are not biologically significant. Essentially all migrating eiders passing Barrow flew through a 3-km-wide zone centered on the base of Barrow Spit. Eider flocks averaged 110.4±7.1 birds and were largest during crosswinds and smallest during tailwinds. Eiders had a mean flight altitude of 12.1±0.8 m above ground or sea level (agl/asl); flight altitudes were significantly lower during headwinds than during crosswinds and tailwinds. Wind direction and strength had the greatest effect on eider migration past Barrow, in that strong tailwinds and crosswinds significantly increased movement rates, velocities (if crosswinds or tailwinds), flock sizes and flight altitudes. Monitoring of eider migration should be modified to increase the accuracy and precision of population estimates by using a stratified systematic sampling scheme based on weather conditions and by sampling at night.

Key words: Alaska; eiders; environmental effects; migration; population monitoring; radar ornithology; *Somateria* spp.

INTRODUCTION

During spring and fall migration, many Common (*Somateria mollissima*) and King (*S. spectabilis*) Eiders cross the Beaufort Sea off northern Alaska while migrating between breeding and wintering grounds (Bailey 1948, Thompson & Person 1963, Johnson 1971). At the same time, smaller numbers of Spectacled (*S. fischeri*) and Steller's (*Polysticta stelleri*) Eiders, both of which are protected by the US *Endangered Species Act,* move through the same area (USFWS 1996, 2001; also see Quakenbush *et al.* 2002). Common and King Eider populations in the Beaufort Sea also have declined—by as much as 53–56%—between 1976 and 1996 (Suydam *et al.* 2000a, 2000b). Hence, the population trends of all four species in this region are of concern.

Despite concern about the status and population trends of the four eider species, little research has been done on the most appropriate way to monitor their populations. Thompson & Person (1963), Johnson (1971), Timson (1975), Woodby & Divoky (1982) and Suydam *et al.* (1997, 2000b) used a systematic sampling technique to count birds passing the base of Barrow Spit, dividing each daily count by the number of hours sampled that day and multiplying the result by the number of hours of daylight in the day to arrive at an estimated number of birds moving each day. Daily estimates were summed to provide a total for the entire migration period. A better understanding of within-day patterns of movement and the effects of environmental conditions on migration rates could improve the accuracy and precision of such estimates.

Ornithological radar has been an important research tool for more than 50 years (Eastwood 1967) because it can overcome some of the limitations of visual observation techniques that are evident when birds travel during periods of restricted visibility (e.g. at night, in fog). Ornithological radar has been used to study nocturnally moving geese, cranes and waterfowl (Cooper *et al.* 1991, 1993; Dirksen *et al.* 1997; Tulp *et al.* 1999) and nocturnal seabirds (e.g. Day & Cooper 1995; Hamer *et al.* 1995; Cooper *et al.* 2001; Cooper & Day 2003; Day *et al.* 2003a, 2003b). Radar also can be used to collect data over large areas that cannot be sampled adequately by a single visual observer (e.g. Richardson & Johnson 1981, Johnson & Richardson 1982, Hamer *et al.* 1995), to help visual observers detect and locate birds that otherwise would be missed (e.g. Kerlinger & Gauthreaux 1984, 1985; Cooper & Ritchie 1995; Cooper *et al.* 2001; Cooper & Blaha 2002) and to map the spatial distribution and movements of birds (Day *et al.*, unpubl. data). In the present study, we used radar and visual techniques to:

- monitor the migration and behavior of eiders migrating past Barrow, Alaska in fall;
- determine whether environmental factors altered any aspect of migration; and
- use insights from the radar study to improve visually based population monitoring.

Certain environmental factors (e.g. wind) have been shown to affect rates of bird migration; the effects of other factors (e.g. time of day, visibility) on the migration of eiders are poorly known, but may be important in improving monitoring programs.

STUDY AREA

The study site was located northeast of the town of Barrow, Alaska, and near the base of Barrow Spit (Fig. 1), which separates the Chukchi Sea (to the west) from the Beaufort Sea (to the east). Barrow Spit has a maximal height of ~2.5–3 m above sea level near its base. It is fairly narrow, being ~150 m wide near the base, but it widens considerably near the tip. The Plover Islands lie east of the spit and are separated from it by Elson Lagoon.

We collected data at slightly different sampling sites in 1997 and 2000, although the zone where eiders crossed the spit was sampled in both years (Fig. 1). The 1997 site (71°21.1′N 156°33.85′W; NAD 83) was located ~1 km northeast of the base of Barrow Spit and ~5 km south of the tip of Point Barrow itself. The 2000 site (71°19.38′N 156°36.71′W; NAD 83) was located at the National Oceanic and Atmospheric Administration (NOAA) Climate Monitoring and Data Laboratory (CMDL), ~3 km south of the base of Barrow Spit. Both sites lie near an area where indigenous local Iñupiat people hunt migrating eiders today ("Duck Camp" on Fig. 1) and an ancient eider-hunting site called "Birnik" (Thompson & Person 1963), indicating the long importance of this area for eider migration.

Several studies that used visual observation techniques have discussed or examined eider migration at the base of Barrow Spit [Thompson & Person 1963 (14 July–1 September 1953); Johnson 1971 (13 July–7 September 1970); Timson 1975 (27 August–16 September 1975); Woodby & Divoky 1982 (6 May–4 June 1976), Suydam *et al.* 1997, 2000a, 2000b (13 July–27 October 1994 and 10 July–16 October 1996)]. In addition, Bailey (1948) discussed both spring and fall migration in northern Alaska in general.

METHODS

We collected data on the movements, behavior and flight altitudes of birds during 17–25 August 1997 and 15 August–4 September 2000. We sampled for approximately seven hours daily using both radar and visual observations. For the purposes of recording on which dates birds moved, sampling days began at 07h00 and ended at 06h59 the following morning, so that an evening and the following early morning were classified as occurring on the same date.

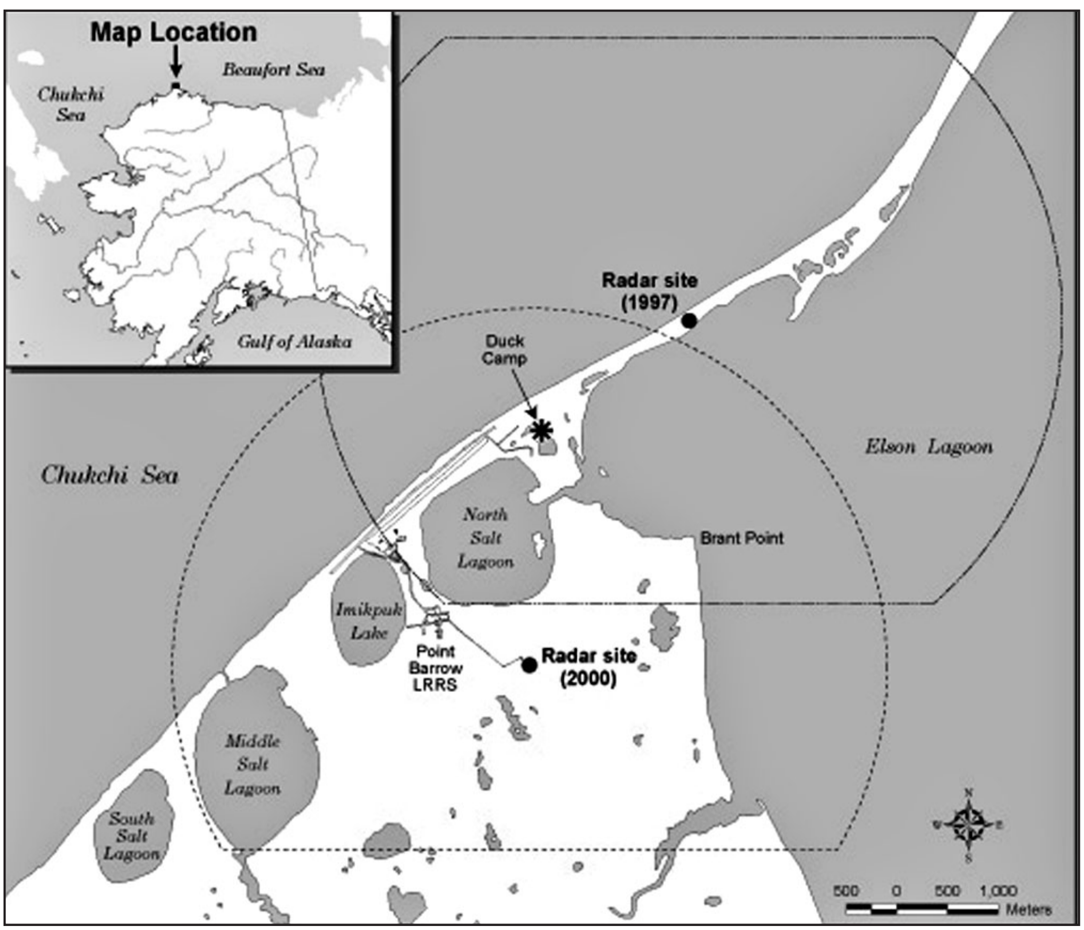

Fig. 1. Study area near Barrow, northern Alaska, in August–September 1997 and 2000. Circles enclose areas sampled by radar in 1997 and 2000.

Data collection

As much as possible, we collected radar and visual data concurrently, so we could use the radar to help the visual observer locate birds and so the visual observer could provide information to the radar operator on the identity of individual targets. Although we attempted to sample concurrently at all times, precipitation occasionally made radar sampling impossible and fog made visual sampling difficult. For both sampling methods, we collected data during 25 minutes of each half-hour session. We conducted ~170 hours of radar data collection in 393 sampling sessions (90 in 1997 and 303 in 2000) and ~130 hours of visual data collection in 316 sampling sessions (all in 2000). We also collected a few off-sampling visual data on eiders in 1997. For all radar and visual data combined, 81.5% of all sampling sessions were conducted during the daytime and 18.5% were conducted at night. For reference, on 25 August 2000, day length at Barrow consisted of 15 hours, 16 minutes of civil daylight/twilight and 8 hours, 44 minutes of darkness (data from www.sunrisesunset.com).

We recorded weather data at the beginning of each sampling session:

- wind speed [calm, 1–5 miles/h (1–8 km/h), 6–10 miles/h (9–16 km/h), etc.]
- ordinal wind direction (e.g. north, northeast, east, calm, variable)
- time of day [day, crepuscular (twilight), night]
- precipitation (e.g. none, fog, drizzle, heavy rain, snow, snow flurries)
- minimal visibility [poor (<500 m), good (≥500 m)]

Radar

We used a FCR-1411 surveillance radar (Furuno, Camas, CA, USA), a standard X-band radar transmitting at 9.410 GHz with a peak power output of 10 kW. [A similar radar is described in Cooper *et al.* (1991).]

The radar scanned a 360º arc around the radar laboratory and provided information on movement rate, behavior, groundspeed and flight path of birds. This radar has a digital color display that includes color-coded echoes (to enhance our ability to detect birds moving across the landscape), continuous on-screen plotting of echoes (to depict flight paths and ground speed) and True North display (to determine flight directions). The sampling range was 2.77 km, and the pulse length of the radar beam was 0.08 μsec.

The emphasis of the radar sampling was counting the number of flocks of flying eiders (targets) and describing aspects of their behavior. The sampling unit was a radar echo (target) on the display screen (i.e. an individual bird or a flock of birds, regardless of its size). In 1997, we used the radar in its non-shifted view setting ("Area sampled in 1997" on Fig. 1). In 2000, we shifted the screen view so that we could see farther to the north of the radar sampling site ("Area sampled in 2000" on Fig. 1) to see the base of the spit. The total area sampled by the radar was similar in both years, and we counted only birds seen crossing the eastern side of the screen unless they were seen only on the western side of the screen. Hence, despite between-year differences in sampling location and screen settings, our ability to detect eider flocks in the geographic area covered by the radar did not differ substantially.

We collected these data on each target seen on the radar display screen:

- time
- target type ["eider-like" or "non-eider-like" (see below)]
- flight velocity [groundspeed (to the nearest 8 km h^{-1})]
- flight direction (to the nearest 1º True)
- general flight behavior [straight-line (highly directional linear flight, sometimes with angular directional changes), erratic (highly irregular flight; sometimes directional overall), circling (circular flight without angular directional changes; rarely directional overall)]
- species and number of birds represented by the radar echo (when possible)

In 2000, we traced tracklines of eider flocks onto transparent acetates and digitized them using ArcGIS 9 software (ESRI, Redlands, CA, USA).

Eiders tend to fly in tight, undulating flocks that may exhibit lateral and/or vertical motion at small scales, even though they exhibit overall straight-line, directional flight behavior at a larger scale (see Richardson & Johnson 1981). Hence, on radar, an "eider-like" target flew with fairly specific characteristics. Their radar echoes generally were large, rapidly flying and nearly always directional. However, because of the low elevation of the radar antenna and the vertical undulations of the eider flocks, the flocks often formed inconsistently plotting echoes near the edge of the radar display screen but plotted more consistently as they approached the radar. They disappeared at times when flying low past a radar shield (e.g. at Brant Point bluffs).

Visual

The emphasis of the visual sampling was on identifying birds, counting flock sizes and estimating flight altitudes. The sampling unit was a flock of birds, regardless of size. We sampled with 10× binoculars during the day and a 5× Noctron-V night-vision scope (Varo, Electron Devices Division, Garland, TX, USA) at night. The Noctron can sample to only 100–200 m, which was far short of where most eiders crossed the spit. Consequently, sample sizes for identified radar targets were much smaller at night than during the day.

We collected these data on each bird or flock of birds seen:

- time
- identification (to lowest practical taxon)
- flock size
- lowest flight altitude [estimated to the nearest 1 m above ground or sea level (agl/asl) up to 25 m agl/asl, then in 5-m increments from 26 m to 50 m, in 10-m increments from 51 m to 100 m and in 25-m increments above 100 m; landing birds were classified as flying 1 m agl/asl]

For consistency, we attempted to record the minimal altitude as the birds crossed a north–south line running through the radar laboratory, although that was not always possible. When we could not collect data on flocks as they passed that line, we recorded the minimal altitude as far as a flock was able to be tracked visually.

Data analysis

We pooled both radar and visual data into species groups to increase sample sizes for analyses. For target identification in radar analyses, we used loons, geese, eiders, other ducks, shorebirds, and larids. In the results, we first present data on all taxa to see whether their radar targets could be misidentified as those of eiders; we then concentrate primarily on radar targets that we knew or suspected were eiders (hereafter, "eiders"). That group includes targets that we visually identified as eiders, plus unidentified radar targets that we believed were eiders, based on their eider-like flight characteristics. In a few cases, we present information on radar targets that we visually identified as eiders (hereafter, "visually identified eiders") to show how similar the "eider" data are to those for the visually confirmed data; thus, these form a subset of about one third of the "eiders" targets.

All statistical tests were 2-tailed and the level of significance (α) for all tests was 0.05. We used a Tukey HSD test for all multiple comparisons involving ANOVAs.

Radar

To determine how successful we were at correctly identifying eiders on the radar, we tabulated counts of numbers of targets of each species group in four ways, examining how different eider targets were from those of other species. First, we calculated mean flock size for all visually identified radar targets. Second, we calculated mean velocity of radar targets, regardless of relative wind direction. Third, we calculated the proportion and percentage of radar targets that exhibited straight-line, directional flight. Finally, we calculated the proportion and frequency of radar targets that we had categorized in the field as being "eider-like" in overall flight characteristics.

In subsequent data summaries and analyses, we examined the effects of four environmental factors that are known to affect migrating birds of other species. First, we partitioned the data by time of day as "daytime" (daytime and crepuscular samples) and "nighttime" (nighttime samples). Second, we partitioned the data by session visibility as "good" or "poor" visibility, as defined earlier. Third, we partitioned the data by relative wind direction by assuming that all eiders in the area would be leaving the Beaufort Sea via the base of Barrow Spit and, hence, would be flying toward the northwest. Thus, winds from the west, northwest, or north would represent headwinds; those from the east, southeast, or south would represent tailwinds; those from the northeast and southwest would represent crosswinds; and no winds would be "calm." Because sample sizes for calm conditions were very low and because mean movement rates and flight directions were similar to those seen with tailwinds, we pooled the few data for calm conditions with those for tailwinds in all analyses. Finally, we partitioned the data by wind strength as "weak" ($\leq$16 km/h) or "strong" (>16 km/h).

We tabulated counts of numbers of targets recorded during each sampling session, then converted them to estimates of movement rates (targets/h), based on the number of minutes actually sampled in that session. We used the estimated movement rates for each sampling period to calculate the mean±1 standard error (SE) movement rate of visually identified eiders and "eiders" by date, the four environmental factors (time of day, visibility, wind direction and wind strength) and each combination of wind direction and wind strength (e.g. weak headwinds vs. strong headwinds).

We examined the effects of the environmental factors on movement rates by testing the above factors in various combinations in 48 multifactor ANOVA models containing all possible combinations of the main effects (time of day, visibility, wind direction and wind strength), plus interaction terms (time of day*visibility, time of day*wind direction, visibility*wind direction and wind direction*wind strength). We included interaction terms only in those models in which both terms were also included as main effects. Before conducting statistical analyses, we added 0.167 to movement rates to avoid computing the logarithm of zero (following Mosteller & Tukey 1977), then ln-transformed the data to normalize them. The large number of zeros was a potential problem, but Monte Carlo simulations of a similar data set from near Prudhoe Bay, Alaska, indicated that the significance level of tests did not differ greatly from expected (Day & Prichard, unpubl. data).

We compared competing models with a Kullback–Liebler information–theoretic approach (Burnham & Anderson 1998) that allows model-selection uncertainty to be incorporated into parameter estimates. We calculated adjusted values [Akaike information criteria corrected for small sample sizes (AICc)] with the formula for least-squares models and used Akaike weights to estimate the relative probability that each model was the best-approximating model (i.e. that with the highest Akaike weight) in the set (Anderson *et al.* 2000). For each variable, we calculated the sum of Akaike weights (Σw_i) for all models containing that variable to estimate the probability that a given variable was in the best-approximating model. We then calculated unconditional parameter estimates and unconditional SEs (estimates and standard errors adjusted for model-selection uncertainty) for each model (Burnham & Anderson 1998, Anderson *et al.* 2000). Because we had one or more significant interactions, we used those factors in the best-approximating model to calculate a multifactor ANOVA so that we could determine the relationships of factors in the interactions.

We calculated the mean and SE flight velocity (groundspeed) of visually identified eiders and "eiders" by each of the four environmental factors and each wind direction*wind strength interaction. We then tested the effects of these factors, as described earlier.

We calculated mean, circular SD (S') and vector lengths (r) of flight directions of visually identified eiders and "eiders" by each of the four environmental factors and each wind direction/wind strength combination. Following Zar (1984: 446–450), we calculated the mean vector length (r) for each environmental factor, then used a multisample Watson–Williams test for differences in vectors. To our knowledge, no statistical test allows the use of ANOVA analyses for circular statistics, and so we were unable to test the importance of all factors together or to test interactions. Because we had to examine the data as a series of separate analyses for each set of factors, we used a Bonferroni adjustment for multiple inference by dividing 0.05 by the number of tests (in this case, four tests).

To examine spatial variations in movement (2000 data only), we digitized the flightlines of all "eider" flocks seen on radar, then plotted the data. We then could examine spatial variations in movement by the four environmental factors. Because movements were so uniform, however, we present here patterns for only one factor (time of day).

Visual

We calculated the mean and SE flock sizes and flight altitudes of visually identified eider flocks by each of the four environmental factors and each wind direction/wind strength combination. We then tested the effects of these factors with multifactor ANOVA models containing the main effects wind direction, wind strength and wind direction*wind strength interaction, as described earlier. We could not, however, include the main effects time of day and visibility because we had little or no data in some categories (night, poor visibility).

RESULTS

Target identification

We used the characteristics of visually identified targets to determine our accuracy rate at correctly identifying eider targets on radar. Compared with other species tracked, eiders had the largest mean flock size (110; range: 1–1 180), the highest groundspeed (~84 km/h) and the highest incidence of eider-like flight (100%, Table 1). Nearly all species groups exhibited high percentages of straight-line (directional) flight behavior on radar (Table 1). Geese had the second-largest mean flock size and the second-largest mean ground speed and were the only other species group that exhibited a high incidence of eider-like flight (82%). Brant (*Branta bernicla*) were the species that we most often confused with eiders because they flew in large flocks and with velocities similar to those of eiders. Loons, especially large flocks flying with a tailwind, also could cause confusion in target identification. Other ducks caused little confusion, except for large flocks flying with strong tailwinds. Shorebirds usually flew in loose flocks that occasionally broke into small individual targets that were diagnostic most of the time. Larids usually occurred in small flocks, flew slowly and tended to have a meandering flight; however, large flocks flying tightly with a strong tailwind occasionally caused confusion.

The correct identification rate (the number of correctly identified eider targets, divided by the number of correctly identified eider targets, plus the number of other targets that were incorrectly classified as eider-like: 279 / 279 + 134 = 413) was 67.6%. Hence, we misidentified 32.4% of eider-like targets.

Movement rates

Movement rates of "eiders" varied dramatically among dates in both 1997 and 2000 (Fig. 2). The overall mean movement rate was 6.8 targets/h in 1997 (range: 0.5–15.2; n = 90 sampling sessions), 4.6 targets/h in 2000 (range: 0–12.8; n = 303) and 5.1 targets/h (n = 393) across both years combined.

Mean movement rates of "eiders" were significantly affected by all four environmental factors (Tables 2 and 3). The best-approximating model for movement rates of "eiders" included the parameters visibility, wind direction, wind strength and wind direction*wind strength, all of which occurred in all models in the 90% best-model set [Appendix 1 (Note: Appendices are available at the *Marine Ornithology* Web site, www.marineornithology.org]. This model had an Akaike weight of 0.373, a considerably higher probability than any other model tested (Appendix 1). Movement rates were significantly higher during good visibility than during poor visibility, significantly higher during tailwinds than during crosswinds and headwinds, significantly higher during strong crosswinds than weak ones, significantly higher during weak headwinds than strong ones and not significantly different between

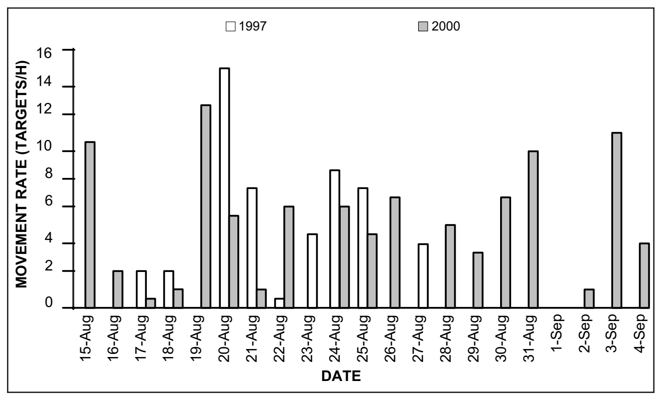

Fig. 2. Mean daily movement rates (targets/h) of radar targets that were visually identified as eiders or suspected to be eiders ("eiders") on ornithological radar near Barrow, northern Alaska, in August–September 1997 and 2000. In 1997, data were collected daily between 17 and 25 August; in 2000, data were collected daily between 15 August and 4 September.

TABLE 1
Target identification on ornithological radar near Barrow, northern Alaska, August–September 1997 and 2000, based on visual observations conducted concurrently with radar sampling. Sample size (n) refers to numbers of visually identified radar targets of each species group.

Species group	Flock size (mean±SE)	(n)	Velocity (ground speed; km/h) (Mean±SE)	(n)	Straight-line behavior (%)	(n)	Eider-like flight (%)	(n)
Loon	2.0±0.2	99	74.8±1.4	73	98.6	73	44.6	74
Goose	34.9±3.1	121	77.9±1.3	99	98.0	101	82.2	101
Eider	110.4±7.1	346	83.5±0.6	279	98.2	278	100.0	279
Other duck	30.1±8.0	43	67.1±2.7	36	86.1	36	28.6	35
Shorebird	24.5±9.8	6	74.0±8.5	5	100.0	5	20.0	5
Larid	2.6±0.5	76	52.1±1.9	72	81.9	72	9.7	72

SE = standard error.

weak and strong tailwinds. They also were significantly higher during strong crosswinds and tailwinds than during strong headwinds and higher during weak tailwinds than during crosswinds and headwinds (Tables 2 and 3; Appendix 2; results of multifactor ANOVA for best-approximating model).

Velocity

"Eiders" flew rapidly, averaging 83.5±0.3 km/h groundspeed (Table 2). Visually identified eiders also flew quite rapidly, averaging 83.5±0.6 km/h groundspeed (n = 279 targets). Groundspeeds of "eiders" ranged between 56 km/h and 137 km/h. Of the 819 "eider" flocks, 89.7% ranged between 72 km/h and 88 km/h, and 94.7% ranged between 64 km/h and 97 km/h.

Mean groundspeed velocities of "eiders" were significantly affected by three of the four environmental factors (Tables 2 and 3). The best-approximating model for velocities of "eiders" included the parameters visibility, wind direction, wind strength and wind direction*wind strength, all of which occurred in nearly all models in the 90% best-model set (Appendix 1). Although the Σw_i for time of day, which also was in the best-approximating model, also was high (Appendix 3), that model-weighted parameter estimate was not significant as a main effect (Appendix 2); further, its interactions (time of day*visibility and time of day*wind direction) also were not significant. The best-approximating model included those parameters, plus time of day and its interactions, and had an Akaike weight of 0.217. However, that model was not substantially better than several others (Appendix 1). Velocities of "eiders" were significantly higher during good visibility and strong winds, significantly higher with good visibility at night than with poor visibility at night, significantly higher with strong crosswinds and tailwinds than with weak ones and significantly higher with weak headwinds than with strong ones (Tables 2 and 3, Appendix 2; results of multiple comparisons in ANOVA on best-approximating

TABLE 2

Movement rates (targets/h) and groundspeed velocity (km/h) of radar targets that were known or believed to be eiders ("eiders") on ornithological radar near Barrow, northern Alaska, August–September 1997 and 2000, by environmental factor. Sample size (n) refers to numbers of radar sampling sessions in each category.

Target type	Factor	Category	Movement rate (mean±SE)	(n)	Velocity (mean±SE)	(n)
"Eiders"	Time of day	Daytime	5.1±0.3	318	83.3±0.2	661
		Nighttime	5.4±0.8	75	84.3±0.6	158
	Visibility	Good	5.4±0.4	356	83.5±0.3	781
		Poor	2.6±0.6	37	83.2±1.3	38
	Wind direction	Crosswind	4.3±0.6	80	85.8±0.6	142
		Headwind	2.7±0.4	114	75.9±0.8	117
		Tailwind	6.9±0.5	199	84.5±0.5	560
	Wind strength	Weak	6.1±0.5	175	81.6±0.5	435
		Strong	4.3±0.4	218	85.8±0.5	384
	Total	Total	5.1±0.3	393	83.5±0.3	819

SE = standard error.

TABLE 3

Movement rates (targets/h) and groundspeed velocity (km/h) of radar targets that were known or believed to be eiders ("eiders") on ornithological radar near Barrow, northern Alaska, August–September 1997 and 2000, by wind direction and wind strength. Sample size (n) refers to numbers of radar sampling sessions in each category

Attribute/ target type	Wind direction	Wind strength: Weak (mean±SE)	(n)	Strong (mean±SE)	(n)
Movement rate					
"Eiders"	Crosswind	3.4±0.8	40	5.2±0.8	40
	Headwind	4.0±0.6	46	1.8±0.4	68
	Tailwind	8.5±0.9	89	5.5±0.6	110
Velocity					
"Eiders"	Crosswind	82.9±1.3	55	87.7±0.5	87
	Headwind	77.2±1.1	68	74.0±1.3	49
	Tailwind	82.2±0.6	312	87.4±0.5	248

SE = standard error.

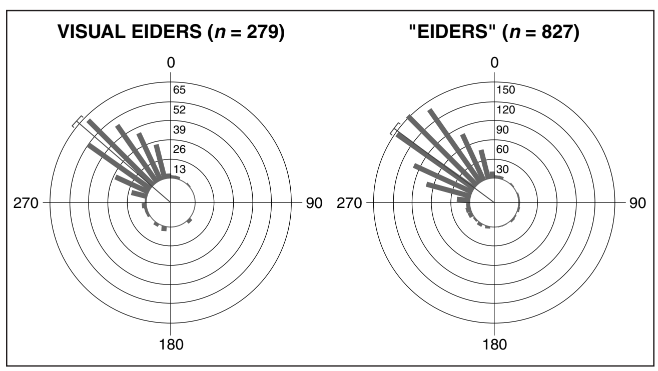

Fig. 3. Flight direction of radar targets that were visually identified as eiders ("visual eiders") and radar targets that were known or believed to be eiders ("eiders") on ornithological radar near Barrow, northern Alaska, August–September 1997 and 2000, by 10º categories. The solid line indicates the mean direction; the width of the small bar at the end of the line indicates the circular standard deviation.

model). No effect was seen of weak winds on velocity, regardless of wind direction. Velocities did not differ significantly by time of day.

Flight direction

Visually-identified eiders flew a mean direction of 310±*S*′26º (n = 279; *r* = 0.903), or slightly south of northwest (Fig. 3). Nearly all (~93%) were heading toward the northwest (i.e. 270–359º), with only ~2% heading toward the northeast (i.e., 000–089º), <1% heading toward the southeast (090–179º) and ~4% heading toward the southwest (180–269º). "Eiders" flew a mean direction of 306±*S*′29º (n = 827; *r* = 0.878), or slightly south of northwest and only a few degrees from that for visually identified eiders (Fig. 3). Nearly all (~92%) were flying toward the northwest, with only ~2% heading toward the northeast, ~2% heading toward the southeast and ~4% heading toward the southwest.

Mean flight directions of "eiders" were significantly affected by two of the four environmental factors. Mean flight directions differed significantly by time of day (F = 13.692; df = 1,825; $P < 0.001$) and visibility (F = 10.807; df = 1,825; P = 0.001) but did not differ by wind direction (F = 1.132; df = 2,824; P = 0.323) or wind strength (F = 3.331; df = 1,825; P = 0.068). We did not examine the effects of wind direction and wind strength together because of difficulties associated with comparing interaction terms in circular statistics. We believe that these differences may be statistically significant, but they are not biologically significant, especially because of the pronounced lack of spatial variability in movements (see next subsection).

Spatial patterns

"Eiders" exhibited a very circumscribed flight pattern as they passed Barrow Spit (Fig. 4). They tended to approximate the coastline as they passed Brant Point, then swung northwestward to pass over North Salt Lagoon and Duck Camp. Although we show only one set of results here, this pattern was seen with all environmental conditions (e.g. the daytime vs. nighttime comparison in Fig. 4), with only a few birds crossing into the Chukchi Sea in areas other than this 3-km-wide zone (e.g. the few targets passing over Middle Salt Lagoon).

Visual data

Eider flocks averaged 110.4±7.1 birds (n = 346 flocks), with ~66% of the flocks consisting of ≤100 birds and ~42% consisting of ≤50 birds. On the other hand, ~7.5% of the flocks consisted of >300 birds, and ~3.5% consisted of >400 birds (Fig. 5, Table 4). Because of small sample sizes, we could test only the effects of wind direction and wind strength. The best-approximating model for flock sizes of eiders included the factors wind direction and possibly wind strength, which was marginally significant (Appendices 2–4). This model had an Akaike weight of 0.637, or much better than all others (Appendix 4). Flock sizes were significantly larger during crosswinds than during headwinds and tailwinds and possibly were larger with strong winds than with weak ones (Tables 4 and 5, Appendix 2).

Eider flocks had a mean flight altitude of 12.1±0.8 m agl/asl (n = 187 flocks; Table 4). The best-approximating model for flight altitudes of eiders included the factor wind direction and had an Akaike weight of 0.511 (Appendices 2–4). Flight altitudes of eiders were significantly lower during headwinds than during crosswinds and tailwinds (Table 4 and 5, Appendix 2).

DISCUSSION

Target identification

The 32% error rate seen in target identification was caused primarily by geese, especially Brant, which move through the area in great numbers in August and early September (Johnson 1971). Loons, which occurred in much smaller numbers than both eiders and geese, also caused some problems in target identification during this time. Thus, if radar were to be used as the sole means of monitoring eider populations, target misidentification could

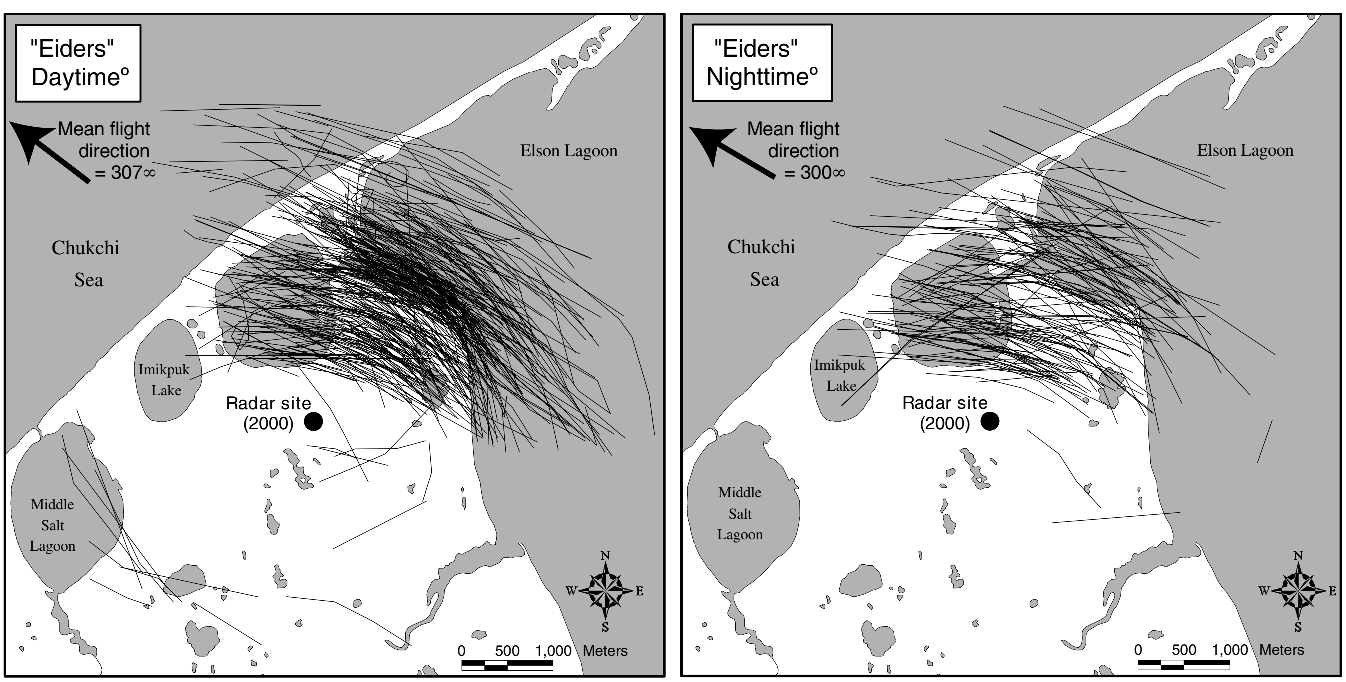

Fig. 4. Spatial movements of targets that were known or believed to be eiders ("eiders") by time of day (daytime vs. nighttime).

result in inflated passage rates when confounding species are migrating. Variations in Brant numbers, in particular, could confound ability to track eider numbers at times. However, Brant represent only a small percentage of the migrating waterfowl at Barrow (Gabrielson & Lincoln 1959, Johnson 1971, Pitelka 1974, Timson 1975). They primarily migrate inland on their way to the Chukchi Sea, mostly bypassing Barrow Spit (Gabrielson & Lincoln 1959, Johnson 1971, Pitelka 1974). Numerous radar targets seen far inland by Flock (1973) probably were Brant.

Our estimate of the misidentification rate, being based only on the period when these geese were numerous, may have been higher than the rate that would be expected for the entire fall migration period of eiders. At Barrow, Long-tailed Ducks (*Clangula hyemalis*), which may be confused with eiders on radar at times, are second in abundance to eiders; however, most migrate later than eiders do (Johnson 1971).

Movement rates

Several other authors studying eider migration at Barrow and elsewhere have found a strong effect of winds on eider migration, with movement rates being higher with tailwinds than headwinds ≥14 km/h and being generally similar between tailwinds and light ("neutral") winds (<14 km/h) from any direction (Thompson & Person 1963, Johnson 1971, Timson 1975). These authors, however, did not separate out the effects of crosswinds. In his radar studies, Flock (1972) saw a dampening effect of strong headwinds, but also found that movement rates also decreased dramatically after winds dropped to ~7 km/h. Further, hunters at Barrow expend the most effort during tailwinds, knowing that eiders, Brant and Long-tailed Ducks all show a similar effect of winds on movement rates (Timson 1975). Similar effects of tailwinds on movement rates of eiders have been found at Barrow in the spring (Woodby & Divoky 1982), and tailwinds have been found to be important predictors of increased bird migration in general (Richardson 1978). In the eastern Beaufort Sea in spring, headwinds exceeding 50 km/h depressed movement rates of King Eiders, but not Common Eiders (Byers & Dickson 2001); however, these authors did not examine the relationships statistically or over the entire migration period.

The present study found that movement rates decreased significantly during periods of poor visibility. Johnson (1971) found that movement rates of eiders at Barrow were "substantial" even during periods of heavy fog, although he presented no data to support his conclusion that movement rates were "not reduced" during such periods. Other studies of birds in general have found various effects of fog on movement rates (Richardson 1978). In the eastern Beaufort Sea in spring, Byers & Dickson (2001) found no effect of visibility <1 km on movement rates of either Common or King Eiders.

We found that movement rates did not differ between the night and the day. Within daylight hours, Johnson (1971) found that movement rates were highest between 00h00 and 06h00 and lowest between 12h00 and 18h00. Although most of his data were collected when it was not completely dark, he also saw eiders

TABLE 4
Flock size (birds/flock) and flight altitude [metres above ground or sea level (agl/asl)] of visually identified eider flocks near Barrow, northern Alaska, August–September 1997 (flock size) and 2000 (flock size and flight altitude), by environmental factor. Sample size (n) refers to numbers of flocks in each category

Factor	Category	Flock size (mean±SE)	(n)	Flight altitude (mean±SE)	(n)
Time of day	Daytime	110.7±7.1	344	12.1±0.8	187
	Nighttime	60.0±10.0	2	–±–	0
Visibility	Good	109.6±7.2	337	12.1±0.8	187
	Poor	139.1±35.4	9	–±–	0
Wind direction	Crosswind	164.3±15.1	125	9.2±0.9	49
	Headwind	57.6±5.9	64	7.3±1.2	25
	Tailwind	89.0±8.3	157	14.4±1.2	113
Wind strength	Weak	119.3±11.8	178	12.3±1.1	114
	Strong	101.0±7.5	168	11.8±1.1	73
Total	Total	110.4±7.1	346	12.1±0.8	187

SE = standard error.

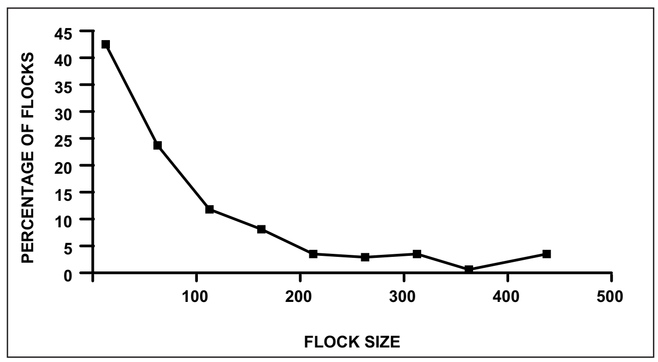

Fig. 5. Distribution of flock sizes of visually identified eiders migrating near Barrow, northern Alaska, August–September 1997 and 2000. Flock sizes > 400 are combined into the final category.

TABLE 5
Flock size (birds/flock) and flight altitude [metres above ground or sea level (agl/asl)] of visually identified eider flocks near Barrow, northern Alaska, August–September 1997 (flock size) and 2000 (flock size and flight altitude), by wind direction and wind strength. Sample size (n) refers to numbers of flocks in each category

Attribute/ wind direction	Wind strength: Weak (mean±SE)	(n)	Strong (mean±SE)	(n)
Flock size				
Crosswind	216.2±29.8	54	124.8±12.1	71
Headwind	59.0±8.2	35	55.8±8.5	29
Tailwind	84.1±11.3	89	95.4±12.3	68
Flight altitude				
Crosswind	10.1±1.1	36	6.8±1.5	13
Headwind	8.9±1.8	15	5.0±1.4	10
Tailwind	14.3±1.9	63	14.5±1.4	50

SE = standard error.

flying at dusk and dawn in late August–early September (when there are substantial periods of darkness), suggesting that these birds did not set down as it became dark and/or that conditions favorable for migration may override any diel patterns of movement. In contrast to the pattern described by Johnson, some researchers found that movement rates of eiders increased as the day progressed (Timson 1975), whereas others found no effect of time of day on movement rates of eiders (Byers & Dickson 2001). Alerstam *et al.* (1974), who were the only others to examine eider movements at night, estimated that ~20% of all Common Eiders migrating in southern Scandinavia move at night.

Velocity

Groundspeed velocities showed strong relationships to visibility, wind direction and wind strength. The effects of winds (both direction and strength) on velocity were pronounced, grouping into either faster velocities with crosswinds and/or tailwinds or slower velocities with headwinds; further, wind strength modified this pattern even further, with strong crosswinds and tailwinds having the highest velocities and strong headwinds having the lowest velocities. The significant effect of visibility on velocity at night (higher with good visibility than poor visibility) has been seen elsewhere for eiders in the Beaufort Sea (Day & Prichard, unpubl. data), suggesting that these birds naturally slow significantly in low visibility. The ~12% decrease in velocity from crosswinds to headwinds probably explains why eiders prefer to migrate with crosswinds or tailwinds.

Flight direction

Mean flight directions differed significantly with time of day and visibility but not with wind direction or wind strength; however, we believe that the statistically significant results were not biologically meaningful. The overall mean flight direction was 306º, which is similar to the overall trend in the coastline from Prudhoe Bay (central Alaska Beaufort Sea coast) to Barrow (~290º). The difference between these two directions probably was caused by the northerly movement of eiders past Brant Point before they swung west-northwesterly again (Fig. 4). In general, eiders in this region tend to follow the coastline or, sometimes, the trend of the offshore islands and approach Barrow from the southeast with a mean flight direction of ~290º (Flock 1973).

Spatial patterns

The movements of eiders that we observed matched patterns seen by previous observers at Barrow. Both Common and King Eiders are strongly coastal migrants (Johnson & Herter 1989). Clearly, the preferred migration corridor where these birds cross over into the Chukchi Sea is a zone ~3 km wide in a north–south direction that is centered on the base of Barrow Spit. This zone includes primarily Duck Camp and North Salt Lagoon but extends southward to the runway at the former Naval Arctic Research Laboratory. Birds persisted in crossing in this zone under all conditions. For example, flocks were alarmed into circling by hunters but persisted in reentering the active hunting zone, rather than changing direction to pass into the Chukchi farther north, where they could avoid the hunters (pers. obs.).

Both Thompson & Person (1963) and Johnson (1971) found three main movement paths of eiders migrating past Barrow: over the base of Barrow Spit (i.e. just north of Duck Camp), over North Salt Lagoon (i.e. over or just south of Duck Camp), or over a few miles of tundra south of there (passing south of the old Naval Arctic Research Laboratory). The third path, which we did not see, is seen primarily during October, when predominantly Common Eiders, rather than King Eiders, are migrating, snow and ice obscure the landscape and young birds cross south of the spit to perhaps 8 km inland. During periods of heavy fog and open water, these birds closely follow the coastline, suggesting that they use it for orientation. Both Flock (1972) and we saw birds following the coastline, especially at Brant Point, although our research suggested that it occurred during all visibility conditions. Flock suggested that eiders migrate westward over the ocean when that route is available to them, but that they fly over the tundra when the coastal route is not available (i.e. when the sea ice comes in) or when juveniles (which are believed to be less wary of land than adults are) are migrating during periods of limited visibility. Likewise, villagers at Gambell, on St. Lawrence Island in the Bering Sea, indicate that all species of eiders avoid crossing the spit at that community when the sea is unfrozen, crossing it only after the sea has frozen and the spit is covered with snow. Hence, we believe that there is not an interspecific difference among eiders in the tendency to avoid flying over land.

Flock size

Mean flock sizes of eiders passing Barrow in the fall apparently differ substantially among years: 105 birds in 1953 (Thompson & Person 1963), 54 in 1994 (Suydam *in litt.*), 61 in 1996 (Suydam *in litt.*) and 110 in 1997–2000 combined (the present study). We found that flock sizes were primarily small, in that ~66% of all flocks consisted of ≤100 birds but also that a surprising proportion were large, in that ~7.5% consisted of >300 birds. Similar proportions have been found by other researchers at Barrow, both for the proportion containing ≤100 birds (~73%, Thompson & Person 1963; ~70%, Johnson 1971) and the proportion containing >300 birds (<7%, Thompson & Person 1963; ~3%, Johnson 1971), suggesting that mean flock sizes may differ among years but that overall proportions of large and small flocks remain surprisingly constant.

Flock sizes of eiders were significantly larger during crosswinds than during tailwinds (medium overall) and headwinds (smallest overall) and possibly were larger with strong winds (this factor was marginally significant). The tendency for larger flock sizes with crosswinds reflects the fact that a northeasterly crosswind actually represents a slight tailwind, because the birds' flight direction in this area is slightly south of northwest. Similarly, Johnson (1971) found that flock size differed significantly by wind direction, being significantly higher during "favorable" winds than during "unfavorable" ones but not being significantly different from those during neutral winds. In contrast, Timson (1975) did not find a strong relationship between flock size and wind direction. The cause or causes for larger flock sizes during crosswinds and, to a lesser extent, tailwinds are unknown, but we speculate that these birds may exhibit "Grand Passage"-like events, so that, when migration conditions are best, the flocks are bigger because more birds leave at once. Conversely, the tendency for smaller flock sizes during headwinds suggests that few birds attempt to migrate under such energetically expensive conditions.

Flight altitude

The lower flight altitudes that we observed during headwinds suggests that these birds move lower into the boundary layer of air, where winds are not so strong, to reduce the energetic costs of migration. King Eiders migrate low over the water—so low, in fact, that flocks may split to go around a small boat (Bailey 1948). Thompson & Person (1963) estimated the mean flight altitude of eiders crossing the base of Barrow spit to be 30–35 yards (~30 m) agl; however, during fog and rain, eiders crossing the spit flew lower than they did during good weather. Migrating eiders in Scandinavia are estimated to fly <30 m over the water (Alerstam *et al.* 1973).

Implications for monitoring eider populations

Wind direction and strength appear to have the greatest effect on most aspects of eider migration past Barrow: tailwinds and/or crosswinds significantly increased movement rates, flight velocities, flock sizes and flight altitudes. In contrast, wind direction had little effect on flight directions and the spatial distribution of birds passing Barrow. Movement rates also were significantly higher with strong crosswinds than with weak ones and higher with weak headwinds than with strong ones. Velocities were significantly higher with strong crosswinds and tailwinds than with strong headwinds and were significantly higher with weak headwinds than with strong ones. Hence, more and larger flocks are passing Barrow during periods of crosswinds and/or tailwinds, and they are flying faster and higher over the ground.

These results suggest that some proportion of the interannual variation in fall population estimates of eiders at Barrow may be caused by two factors:

- interannual differences in proportions of “favorable” and “unfavorable” weather conditions being sampled
- interannual differences in proportions of the population flying at night (when they cannot be sampled visually)

These factors suggest that sampling during eider migration can be modified to increase the accuracy and precision of yearly estimates of eider numbers. First, any sampling effort designed to monitor

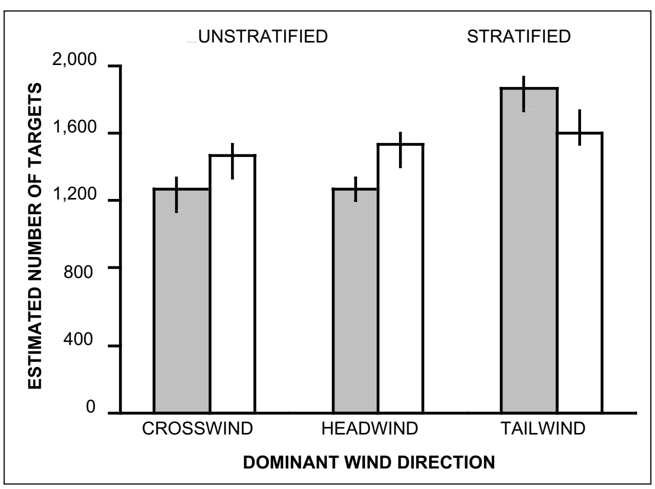

Fig. 6. Estimated numbers of radar targets of eiders migrating near Barrow, northern Alaska, August–September 1997 and 2000, by estimation method and dominant wind direction. Estimation is based on bootstrap techniques and involves 2000 iterations that sampled subsets of the same data, simulating 200 sessions of the dominant wind direction of interest and 100 sessions of each of the other two directions, and that assumed a total of 300 potential sampling sessions each of crosswind, headwind and tailwind. Vertical bars denote standard deviations (SDs).

population size, including visual sampling, should be modified from a systematic sampling scheme to a stratified sampling scheme. By stratifying the sampling periods to “good” and “poor” migration conditions based on environmental conditions, a smaller confidence interval can be achieved and interannual comparisons will be more robust. In addition, in a population that is not changing, population estimates will not vary as much because of different proportions of wind directions sampled among years. This point can be seen in Fig. 6, where we used Monte Carlo simulation to examine the effects of over-sampling or under-sampling different wind conditions during annual surveys. We assumed that wind directions for the entire fall were equally distributed among headwinds, tailwinds and crosswinds, then generated unstratified and stratified (by wind direction) estimates if sampling periods over-sampled (50% of all observations) headwinds, crosswinds, or tailwinds in a particular year. With unstratified estimates, if the proportions of wind directions sampled are not representative of the proportions of wind directions occurring during the entire fall in a particular year, actual population size will be either underestimated or overestimated (if the population actually is not changing). In contrast, with stratified estimates, fairly consistent estimates of the actual population size will be obtained, regardless of wind direction.

A second suggestion for improvement to the existing sampling scheme reflects the fact that significant numbers of eiders move at night, suggesting that adding an after-dark component would increase the accuracy of eider population estimates. Although Alerstam *et al.* (1974) suggested that ~20% of the entire Common Eider migration off southwestern Sweden in spring occurred at night, we were unable to make such estimates here. However, we believe that the nocturnal movement of eiders was substantial at Barrow in the fall, given the facts that movement rates did not differ significantly between day and night (although this lack of a significant difference may have been caused by low statistical power and small sample sizes at night, rather than a lack of a real difference) and that nocturnal hours composed a sizable proportion of the 24-hour period. Clearly, radar sampling would be even more valuable later in the rapidly shortening days of the fall, when substantial numbers of eiders (especially Common Eiders) are migrating. We believe that modifying the sampling effort in these ways should increase the accuracy and precision of the population estimation and, hence, should improve the determination of population trends.

The use of radar to collect data during periods of limited visibility, however, still would be problematic for population monitoring of eiders for two main reasons. First, as discussed above, its use would require a correction factor to compensate for target misidentification caused by problematic species (Brant, some Long-tailed Ducks) at some times of the year. Second, unless better technology becomes available to see these birds at night, one would have to assume that flock size during periods of limited visibility was similar to that visually determined during the daytime.

ACKNOWLEDGEMENTS

The 1997 study was funded by Northern Alaska Ecological Services, US Fish and Wildlife Service (USFWS), Fairbanks. Field support was provided by the Department of Wildlife Management, North Slope Borough (NSB), Barrow, AK. The 2000 study was funded by the USFWS, the US Air Force (USAF) and the US

Department of Energy–Sandia Laboratories (DOE). Field support was provided by the NSB. We thank P. Martin and T. Swem of the USFWS, G. Augustine of the USAF, B. Zak of the DOE and R. Suydam of the NSB. We especially thank R. Suydam and D. Ramey of the NSB and D. Endres of the NOAA Climate Monitoring and Data Laboratory (CMDL) for assistance, and thank R. Suydam for unpublished data on eider migration. L. Quakenbush, M. Johnson, M. Korte, P. Martin, A. Stickney, T. Zimmer and D. Schrosk helped collect data. At ABR, A.L. Zusi–Cobb provided the map figures, and J. Plissner made the flight-direction figure. This paper was improved by the reviews of A.E. Burger, A.J. Gaston and D.L. Dickson.

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