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Sea Ice and Migration of the Dolphin and Union Caribou Herd in the Canadian Arctic: An Uncertain Future

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ABSTRACT. Caribou (*Rangifer tarandus groenlandicus* × *pearyi*) of the Dolphin and Union herd migrate across the sea ice between Victoria Island and the adjacent Canadian Arctic mainland twice each year, southward in fall–early winter and northward in late winter–spring. As a result of warmer temperatures, sea ice between Victoria Island and the mainland now forms 8–10 days later than it did in 1982, raising questions about the impact of delayed ice formation on the ecology of the herd. We examined movements of female Dolphin and Union caribou as they relate to sea-ice crossings using four satellite collar datasets (46 caribou) obtained between 1987 and 2006. Since the late 1980s, Dolphin and Union caribou have been moving by early October to the southern coast of Victoria Island, where they stage until sea-ice formation allows migration across the sea ice to winter range on the mainland. Caribou spending the summer farther north on Victoria Island arrive later at the coast, which shortens their time spent on the staging area. During the study period, the collared caribou began crossings as soon as sea-ice formation allowed. Most caribou departed from just a few areas and tended to use the same departure areas each year. Highest mortality occurred during the fall–early winter ice crossing and in mid to late winter. Our research raises the question of how the Dolphin and Union caribou will persist in supporting harvesting if the crossing becomes riskier for them or if the seasonal migrations between Victoria Island and the mainland are interrupted.

Key words: caribou, *Rangifer*, Dolphin and Union herd, migration, sea ice, climate, satellite collar, Canada, Nunavut

RÉSUMÉ. Les caribous (*Rangifer tarandus groenlandicus* × *pearyi*) du troupeau Dolphin-et-Union migrent en passant sur la glace de mer entre l'île Victoria et la partie continentale adjacente de l'Arctique canadien deux fois par année, se dirigeant vers le sud à l'automne et au début de l'hiver, et vers le nord à la fin de l'hiver et au printemps. En raison des températures plus chaudes, la glace de mer entre l'île Victoria et la partie continentale se forme maintenant de huit à dix jours plus tard qu'en 1982, ce qui a pour effet de soulever des questions sur les incidences de la formation tardive de la glace sur l'écologie du troupeau. Nous avons examiné les mouvements des caribous femelles de Dolphin-et-Union pendant qu'elles traversaient la glace de mer à l'aide de quatre ensembles de données obtenus par colliers-satellites (46 caribous) entre 1987 et 2006. Depuis la fin des années 1980, les caribous de Dolphin-et-Union se déplacent vers le début d'octobre vers la côte sud de l'île Victoria, où ils transitent jusqu'à ce que la formation de la glace permette la migration pour passer l'hiver sur la partie continentale. Les caribous qui passent l'été plus au nord sur l'île Victoria arrivent à la côte plus tard, ce qui a pour effet de raccourcir le temps qu'ils passent en halte migratoire. Au cours de la période visée par l'étude, les caribous dotés d'un collier commençaient à traverser dès que la formation de la glace le permettait. La plupart des caribous partaient de quelques endroits et avaient tendance à partir des mêmes endroits d'une année à l'autre. Le taux de mortalité était le plus élevé pendant les traversées de l'automne et du début de l'hiver, ainsi que vers le milieu et la fin de l'hiver. Notre étude soulève la question à savoir comment les caribous de Dolphin-et-Union vont réussir à soutenir la chasse si les traversées deviennent de plus en plus risquées pour eux ou si les migrations saisonnières entre l'île Victoria et la partie continentale sont interrompues.

Mots clés : caribou, *Rangifer*, troupeau de Dolphin-et-Union, migration, glace de mer, climat, collier-satellite, Canada, Nunavut

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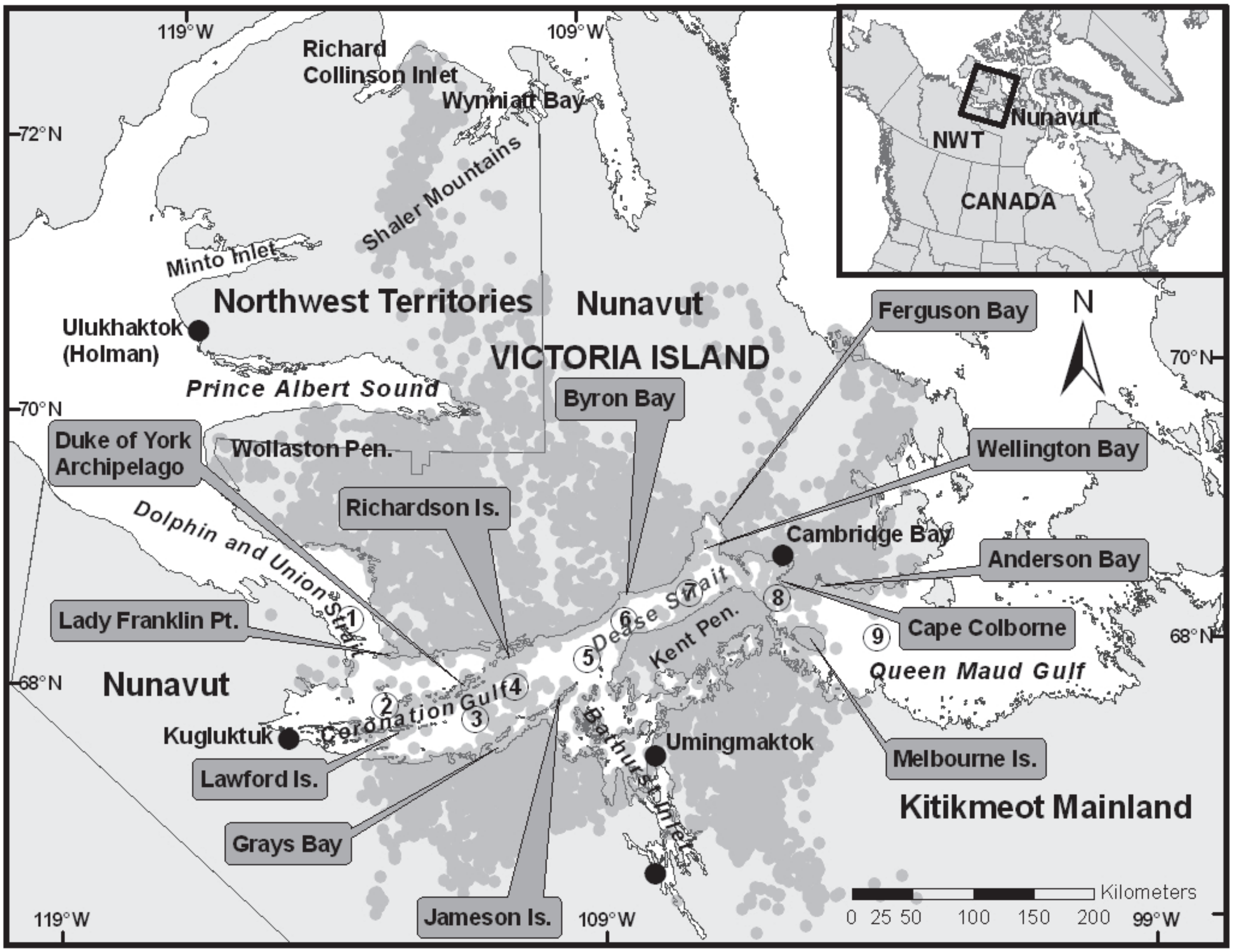

FIG. 1. Collar locations (dark grey shading in the background) of four studies of Dolphin and Union caribou, 1987 to 2006. Numbers within circles indicate locations of the nine sea-ice stations used to assess archived sea-ice data in eastern Dolphin and Union Strait, Coronation Gulf, Dease Strait, and western Queen Maud Gulf (details in Table 1).

INTRODUCTION

The seasonal movements of Dolphin and Union caribou (*Rangifer tarandus groenlandicus* × *pearyi*) on Victoria Island are notable because in the fall and early winter these caribou make directional movements to the south and stage along the southern coast while waiting for the sea ice to form. As the ice forms, the caribou migrate across the sea ice to the central Canadian Arctic mainland (Fig. 1). In late winter–spring, they return across the sea ice to Victoria Island for calving and remain there on summer and fall ranges before once again returning to their mainland winter range. The scale of the migrations across the sea ice (thousands of individuals) is unusual among caribou. The other North American caribou that seasonally cross sea ice are Peary caribou (*R. t. pearyi*); however, because of their relatively small population sizes, only tens to low hundreds of individuals typically cross at one time (Miller, 1990; Miller et al., 2005).

The largest of the two caribou herds on Victoria Island is the Dolphin and Union herd (Manning, 1960; Gunn and Fournier, 1996; COSEWIC, 2004). The second herd, the Minto Inlet herd, is restricted to the northwestern corner of Victoria Island; these caribou are much fewer in number, and Manning (1960) classified them as Peary caribou (*R. t. pearyi*). Dolphin and Union caribou are distinctive in appearance being most similar to but larger-bodied than Peary caribou. They have the characteristic light slate-grey antler velvet of Peary caribou (Gunn and Nishi, 1998), as opposed to the dark chocolate brown antler velvet of other barren-ground caribou (*R. t. groenlandicus*) and woodland caribou (*R. t. caribou*). Dolphin and Union caribou are genetically distinct from Peary and barren-ground caribou (Zittlau, 2004; Eger et al., 2009). Historical information compiled by Manning (1960) suggests that perhaps as many as 100 000 caribou summered on Victoria Island before the 1920s. Numbers sharply declined at the same time that trading posts opened along the coast, which led to changes in hunting practices (Manning, 1960; Freeman, 1976). Inuit elders also mention that historically in the 1920s, severe icing storms caused a significant decline of the caribou on the Island (M. Dumond, Government of Nunavut (GN), unpubl. data). Coincident with this sharp decline, migration of Dolphin and Union caribou across Dolphin and Union Strait and Coronation Gulf ceased by the 1920s, and the movement across Dease Strait between Byron Bay, Victoria Island, and Kent Peninsula stopped ca. 1930 (Freeman, 1976). From the 1920s into the 1970s, caribou were rarely seen on Victoria Island, and migrations across the sea ice were not observed.

Beginning in the late 1970s, Inuit hunters reported more caribou sightings on southern and central Victoria Island, and by the mid 1970s, a few Dolphin and Union caribou were crossing on the sea ice to the mainland (Gunn et al., 1997; Gunn and Nishi, 1998). By 1997, the estimate for the herd was 27 948 (± 3363 SE) caribou (Gunn and Nishi, 1998; Nishi and Gunn, 2004). A survey conducted in October 2007 suggested an estimate of around 21 753 (± 2343 SE) caribou within the survey area, and possibly up to 27 739 (± 2520 SE) in the herd when attempting to account for the portion of the herd outside the survey area (M. Dumond, GN, unpubl. data). Given the overlap in confidence intervals, the current trend is uncertain, but it seems likely that the herd is stable or declining (M. Dumond, GN, unpubl. data).

An assessment by COSEWIC (2004) classified the Dolphin and Union caribou as a "Special Concern" species on the basis of herd size, harvest levels, and possible threats, including deaths during sea-ice crossings. Wildlife biologists and Inuit hunters have reported caribou deaths occurring during the fall–early winter migration; when the caribou attempt to cross before the sea ice is strong enough, some animals break through the ice and die (Gunn and Nishi, 1998; B. Patterson, pers. observ. Oct. 2000; M. Dumond, GN, pers. observ. Oct. 2007). Increasing numbers of caribou have been observed on the mainland in December with a thick coat of ice on their fur (M. Dumond, GN, personal observ. and discussions with hunters), which is likely the result of falling through the ice during migration.

Evidence is accumulating that global-scale climate change is occurring rapidly in the Arctic (Barber et al., 2008). One of the predicted effects of climate change includes a shorter ice season and a correspondingly longer shipping season (ACIA, 2004). The straits between Victoria Island and the mainland are part of the Northwest Passage, and shipping there is already increasing. Shipping may affect the timing and patterns of sea-ice formation and break-up, which could interrupt caribou movements or increase the risks for caribou crossing the ice (Nunavut Planning Commission, 2004).

Thus, climate change could affect the migration, and ultimately the ecology, of this population of caribou, with implications for its conservation status and its ability to support the traditional harvest. Although the overall pattern of Dolphin and Union herd migrations is known from Inuit observations, we used telemetry to assess patterns of movement and sea-ice crossings for collared caribou along the entire southern coast of Victoria Island. We had data available from four studies done between 1987 and 2006, when movements and distribution of Dolphin and Union caribou were tracked using satellite transmitters. The earliest study (1987–89) has been reported (Gunn and Fournier, 2000), but the other three studies (1996–2006) have not been analyzed in detail. The four studies had different objectives, which determined where and when the caribou were caught and collared.

Here, we describe the duration and timing of Dolphin and Union caribou staging along the southern coast of Victoria Island in the fall and early winter, as well as the timing and pattern of sea-ice crossings during both the fall–early winter and the late winter–spring migrations. Our objectives were to describe spatial and temporal patterns in caribou movements, both within the annual cycle and from year to year. Specifically, we described (1) the timing and pattern of early winter migrations relative to trends in early winter temperatures and sea-ice formation; (2) the pattern of movements during fall and early winter staging along the coast; (3) the timing and pattern of individual movements over the sea ice relative to the timing of new ice formation; (4) the timing and pattern of individual movements over the sea ice in late winter–spring; and (5) the patterns of seasonal caribou survival.

MATERIALS AND METHODS

Climate Data

Cambridge Bay, Nunavut, is the weather station most central to the distribution of the Dolphin and Union caribou herd (Fig. 1). We used archived climate data for Cambridge Bay to determine trends in mean temperatures (mean, minimum, and maximum) as related to freeze-up for October and November (early winter) and to late winter and spring conditions during April and May from 1948 (the earliest year for which data were available) to 2008 (Environment Canada, 2008). Approximate regression lines were fitted to the data to examine trends over time. We used weather data available from Lady Franklin Point for 1958–92 to confirm that trends in fall–early winter temperatures were widespread, as well as to determine temperature differences between eastern and western portions of the study area.

Ice Conditions

To describe trends in ice formation over time, we used weekly sea-ice archive data beginning in 1982 (Environment Canada, 2010). We selected nine locations from eastern Dolphin and Union Strait to western Queen Maud Gulf (seven within Coronation Gulf and Dease Strait) roughly mid-way between Victoria Island or major islands off the southern coast and the mainland (Fig. 1). The selected

TABLE 1. Location of stations and direct sea-ice crossing distances used to quantify sea-ice formation within the range of the Dolphin and Union caribou herd. Sea-ice locations are shown in Fig. 1. Relative use classification is based on the current analysis and traditional knowledge (M. Dumond, GN, unpubl. data).

Sea-ice station	(Latitude ˚N, Longitude ˚W)	Location	Relative use by caribou	Distance (km)
1	(68.6, 113.9)	Dolphin and Union Strait	Historic	35
2	(68.1, 113.5)	West Coronation Gulf	None	59[1]
3	(68.0, 111.7)	Grays Bay	Moderate	49[2]
4	(68.2, 110.8)	Jameson Islands	Heavy	53[3]
5	(68.5, 109.0)	Bathurst Inlet	None	52
6	(68.7, 108.5)	West Kent Peninsula	Light	28
7	(69.0, 107.0)	Central Kent Peninsula	Heavy	31
8	(68.8, 105.4)	East Kent Peninsula	Heavy	21
9	(68.5, 103.4)	West Queen Maud Gulf	None	70

[1] To the Lawford Islands northeast of Kugluktuk.
[2] From Duke of York Archipelago.
[3] To Jameson Islands.

TABLE 2. Satellite collar datasets used to examine seasonal migration, distribution, and movements of adult female caribou in the Dolphin and Union herd, 1987–2006.

Dataset	Data collection period	Number of animals	Number of locations	Mean months monitored (± SE)	Duty cycle (days)	Source
VIC87–89	Mar 1987 (Apr 1988) – Dec 1989	9	1080	17 (2.4)	5 (daily: 20 May–20 Jun)	Gunn and Fournier, 2000
NWVIC96–98	Jul 1996 – Aug 1998	3	169	11 (7.3)	5 (daily: Jun and Oct – mid-Nov)	Gunn, 2005: Appendix E
SVIC99–06	Nov 1999 (Mar 2001) – Feb 2006	27	7111	31 (4.8)	7 (daily: ~5 May – 20 Jun; ~5 Oct – 20 Nov)	Government of Nunavut
NWVIC03–06	Aug 2003 – Jun 2006	10	1004	17 (2.9)	5	Government of the NWT

locations bounded the area where collared caribou crossed in fall–early winter (five of nine locations), as well as locations that the caribou used historically and areas caribou were not known to use (Table 1). Crossing distances ranged from 21 to 70 km at these sites. To determine what ice conditions existed during caribou crossings, we examined weekly ice records (and daily records if available) in relation to known timing and location of sea-ice crossing by caribou. Daily records were available only for one season (fall–early winter) in a single year (2003). Even though daily information was usually not available, the data suggest that caribou require more than 90% ice coverage to attempt a crossing. Although they may cross on recently formed new ice (< 10 cm thick), they generally wait until most of the surface is young ice (10–30 cm thick). Young ice is in the transition stage from new ice to first-year ice: it has turned grey in colour and could support a caribou or a person. Therefore, for each sea-ice location for each year since weekly record-keeping began (1982), we determined the first day when ice coverage was at least 90% and the stage of development was new ice (New Ice: code 1; < 10 cm), with at least 80% grey ice (Grey Ice: code 4; 10–15 cm) or thicker.

Collar Datasets

We used four telemetry studies that spanned a 19-year period (Table 2). Only the adult female caribou from those four studies were considered in our current analyses. All caribou were captured using helicopter net-gunning, and each was fitted with a satellite-linked (PTT) transmitter. The duty cycle of transmitters varied from study to study (Table 2), as did the location of caribou capture and collar deployment, reflecting the different study objectives. The common theme for objectives was to describe seasonal movements and distribution.

Seasons

We divided each year into six periods or seasons on the basis of previously described caribou behaviour (adapted from Russell et al., 1993). We assigned locations for each individual to seasons by examining movement rates, directionality, and spatial locations of individuals, rather than by using predetermined calendar dates (cf. Apps et al., 2001).

Fall–early winter migration is the continual directional movement from post-calving summer and fall ranges south to mainland winter range (September through October–November). This migration generally begins abruptly, with an increase in the rate of directional movements and smaller deviations in turning angle. Fall–early winter migration may or may not be interrupted by staging; however, it generally continues after a period of staging, with a final leg that includes crossing on newly formed sea ice to the adjacent mainland.

Staging occurs in fall prior to early winter migration across the sea ice. Most animals stage along the southern coast of Victoria Island (within roughly 5 km of the coast) for varying periods of time before crossing newly formed sea ice (~early October to ~late October or early November).

Mid-winter is the season when animals are relatively sedentary and show little directional movement (~mid-November–mid-December to ~April to early May).

Late winter–spring migration involves relatively continual directional movement north in late winter or spring from winter range to calving areas (~21 April to ~9 June). For most animals, this migration included late winter–spring sea-ice crossings. If no calving was detected on the basis of slowed movements, then the late winter–spring migration period was considered to end at the end of June.

Calving covers movements within the extent of calving, defined by Russell et al. (2002) as the area occupied by maternal females from the time they give birth until calves initiate foraging about three weeks later (~ 10 June to 1 July). Parturition location and date were determined from a rapid reduction in movement rates and loss of directionality (Fancy and Whitten, 1991).

Summer is the time between the end of the calving period (~early July) and the start of the fall–early winter migration.

Movements

We treated each animal as a sampling unit each year. No two collared caribou were together during the study, therefore minimizing pseudoreplication (Hurlbert, 1984; Millspaugh et al., 1998). Because the actual path traveled by a caribou is always unknown with satellite location data, the distance the animal actually moves or travels can be approximated by the displacement between consecutive points (Miller and Barry, 2001). Therefore, we use the term "movement" as the difference between sequential satellite locations, and "daily movement" as that distance when corrected for days between locations. To standardize calculations among collar datasets, and as all datasets had a 5 to 7 day duty cycle for most of the year (Table 2), we considered only sequential locations with intervals of 7 days or less (97% of locations). The daily movement rate for each individual was calculated by dividing the Euclidean distance (which considers the curvature of the earth) between sequential locations by the number of days between locations. Over half of the locations (56%) were obtained from a daily duty cycle, primarily during May–June and during October–mid-November for some datasets (Table 2).

We tested for seasonal and individual differences in movement rates using analysis of variance (ANOVA) models, and if these differences were significant ($p \leq 0.05$), we tested for differences among seasons and individuals using Tukey's multiple comparison method.

We calculated the turning angle for each movement segment by comparing the azimuth of the segment to the azimuth of the previous segment. Thus, the turning angle for each segment could fall anywhere between 0˚ (no deflection in movement direction) to 180˚ (complete reversal of direction). This measurement provides an indication of the pattern of movement beyond simple distance displaced per day. Turning angle was examined among seasons and within datasets using ANOVA models, as above.

We used a linear regression to examine whether caribou summering farther north initiated their fall directional movements earlier than animals summering farther south, which had less distance to travel to the staging area and the point of origin for their sea-ice crossing. (Summering latitude was defined as the latitude at which the caribou initiated those fall movements.)

Staging

We determined the number of days caribou spent staging along the southern coast of Victoria Island and examined the duration of staging over time and among datasets. We examined whether there was a relationship between summering farther north and duration of staging and whether date of ice formation affected duration of staging.

Sea-Ice Crossings

We examined the collar data for both southward (fall–early winter) and northward (late winter–spring) crossings of the ocean straits. We used GIS (ArcView 3.2; Environmental Systems Research Institute, Redlands, California, USA) to determine the last collar location before crossing and the first location after crossing. The movement rates during crossings (km/day) were determined by summing all distances moved by each individual between sequential locations for a particular crossing and dividing this sum by the number of days used in crossing. Individual rates were summed by dataset and year and were compared using ANOVA models. The actual numbers of days taken to cross were examined using the SVIC99–06 dataset (daily satellite locations), and we compared the number of days taken for fall–early winter and late winter–spring crossings using a nonparametric Wilcoxon test. We also examined whether date of sea-ice formation affected date of initiation of sea-ice crossings in the fall–early winter period.

To examine fidelity to crossing locations and zones, we used GIS to record where mapped crossing segments intersected an imaginary line running ~2–4 km offshore and roughly parallel to the southern coast of Victoria Island and a similar line off the mainland (and cutting across the mouth of Bathurst Inlet). We assigned 0 km to the western end of each line, providing a km-marker for the start of each sea-ice migration. Lines were ~500–530 km in length. For all caribou with more than one year of sea-ice crossing locations, we calculated the distance between both fall–early winter and late winter–spring departure locations for consecutive years to examine fidelity. We used linear regression to examine whether location of initiation of sea-ice crossing (west to east) affected the date of crossing for both southward and northward crossings. For broad descriptions, Victoria Island was divided (roughly midway) into western (> 109˚ W longitude) and eastern (< 109˚ W longitude) sections.

Survival

Survival analysis was conducted on the SVIC99–06 dataset, which had the largest sample size, and for which the fate of collared animals was best known. We inferred a death to have occurred when the satellite data indicated that a caribou had not moved for several days (Schaefer et al., 1999). Although evidence such as disarticulated carcasses, crushed long bones, or, if only the collar was retrieved, tooth marks or blood on the collar, indicated predation in some cases (Hearn et al., 1990; Schaefer et al., 1999), the long time interval between caribou death and collar retrieval precluded definitive identification of cause of death in several cases. Therefore, we consider here only deaths owing to harvest by humans and deaths assumed to be from natural causes (i.e., occurring far from human settlements and not associated with known hunting activities).

We entered collared caribou into the survival and mortality database on the day after collaring. We estimated annual survival rate from 10 June (the assumed start of calving; Gunn and Fournier, 2000; Nishi, 2000) through 09 June the following year using the Kaplan-Meier product-limit estimator, modified by Pollock et al. (1989) to allow the staggered entry of animals.

To determine whether an elevated risk of mortality was associated with fall–early winter or late winter–spring migrations, we used z-tests (Heisey and Fuller, 1985) to compare monthly (i.e., 30 day) survival probability for caribou identified by the movement data across four biological seasons: *late winter–spring migration*, 21 April–9 June; *calving and summer*, 10 June–20 September; *fall–early winter migration*, 21 September–30 November; and *winter*, 1 December–20 April. To further illustrate seasonal (i.e., migration-related) changes in risk of mortality for caribou, we estimated the penalized likelihood estimate (PLE) of the instantaneous hazard (h(t)) using program PHMPL (Joly et al., 1998, 1999). The hazard function illustrates changes in instantaneous rate of death over time (in this case across the biological year) for the population in question. We allowed PHMPL to determine the smoothing parameter automatically. Subsequent movement data indicated that collared caribou tended to migrate in segregated eastern or western sections (see RESULTS); accordingly, we assessed whether mortality risk was similar for caribou migrating in the eastern or western sections by including a grouping indicator as a covariate in an Anderson-Gil proportional hazards model (Therneau and Grambsch, 2000; DelGiudice et al., 2002). Small sample sizes necessitated pooling data among years, and also precluded rigorous analysis of the impact of additional covariates on survival.

All values are presented as means ± 1 SE. We used SAS software (SAS, 2004) for all tests except those described in RESULTS under the heading *Survival*. Significant differences were assumed at $\alpha = 0.05$.

RESULTS

Climate Data

Between 1948 and 2008, mean fall temperatures at Cambridge Bay showed an increasing trend. Every 10 years, on average, October temperatures increased by 0.35 (± 0.20) ˚C and November temperatures by 0.39 (± 0.19) ˚C (Oct: $y = 0.035x - 79.2$; $r^2 = 0.047$, $p = 0.092$; Nov: $y = 0.039x - 100.6$; $r^2 = 0.066$, $p = 0.046$). Since 1980, the 10-year rate of increase has been greater, with October temperatures rising on average by 0.79 (± 0.47) ˚C each decade and November temperatures by 1.23 (± 0.70) ˚C (Oct: $y = 0.079x - 168.6$; $r^2 = 0.10$, $p = 0.10$; Nov: $y = 0.123x - 267.1$; $r^2 = 0.10$, $p = 0.09$). These figures suggest that from 1980 to 2008, relative warming was about 50% greater in November than in October. A fall warming trend also occurred from 1958 to 1992 at Lady Franklin Point, where mean temperatures rose by 4.5 (± 0.26) ˚C for October and 4.0 (± 0.27) ˚C for November.

Spring temperatures did not increase significantly over time from 1948 to 2008. The average 10-year increase was 0.24 (± 0.20) ˚C for April and 0.06 (± 0.17) ˚C for May (Apr: $y = 0.024x - 64.0$; $r^2 = 0.025$, $p = 0.23$; May: $y = 0.006x - 18.5$; $r^2 = 0.003$, $p = 0.70$). Since 1980, there has been a stronger warming trend in April, with mean temperatures increasing 0.96 (± 0.51) ˚C per 10 years ($y = 0.096x - 208.1$; $r^2 = 0.12$, $p = 0.07$). However, May temperatures increased by only 0.03 (± 0.52) ˚C per 10 years ($y = 0.003x - 10.6$; $r^2 = 0.0001$, $p = 0.96$).

Ice Conditions

Timing of ice formation in and near caribou sea-ice crossing sites varied, with a consistent pattern of later ice formation in the west compared to the east (Fig. 2). Generally, both new and grey ice formed in eastern Dolphin and Union Strait and western Coronation Gulf 9–10 days later than in Dease Strait and western Queen Maud Gulf. Grey ice formed on average 8 (± 0.4) days after formation of new ice.

Pooling all sampling locations, ice formation from 1982 to 2008 occurred on average 3.8 (± 1.62) days (new ice) and 3.2 (± 1.74) days (grey ice) later every 10 years (Fig. 3). Looking at change over the entire 26-year period, new ice formed on average 10 days later and grey ice 8 days later in 2008 than in 1982. Grey ice breaks up from late June to late July, and open water appears earlier in the western straits than in the eastern waters.

Movement Patterns

The seasonal distribution and movements of caribou differed among collar datasets. In the late 1980s, only one of the VIC87–89 caribou crossed the sea ice, spending two winters on islands within northern Bathurst Inlet. Winter distribution in the late 1980s extended less than 100 km

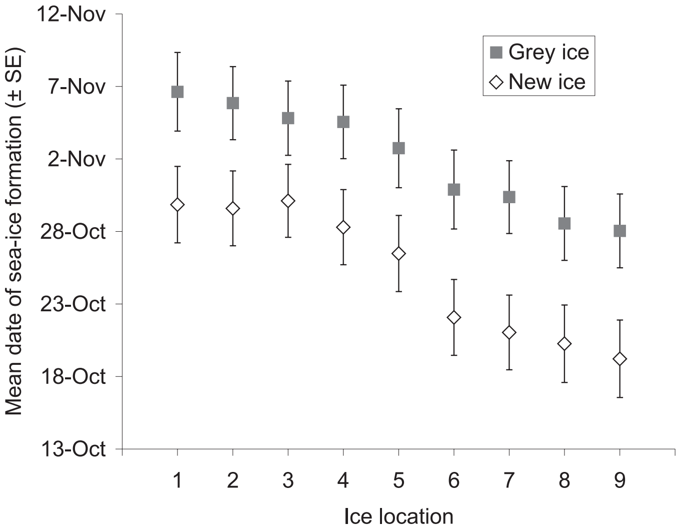

FIG. 2. Mean timing of sea-ice formation at locations (Table 1) in eastern Dolphin and Union Strait, Coronation Gulf, Dease Strait, and western Queen Maud Gulf, 1982–2008. New ice is newly formed ice less than 10 cm thick; grey ice is ice 10–15 cm thick.

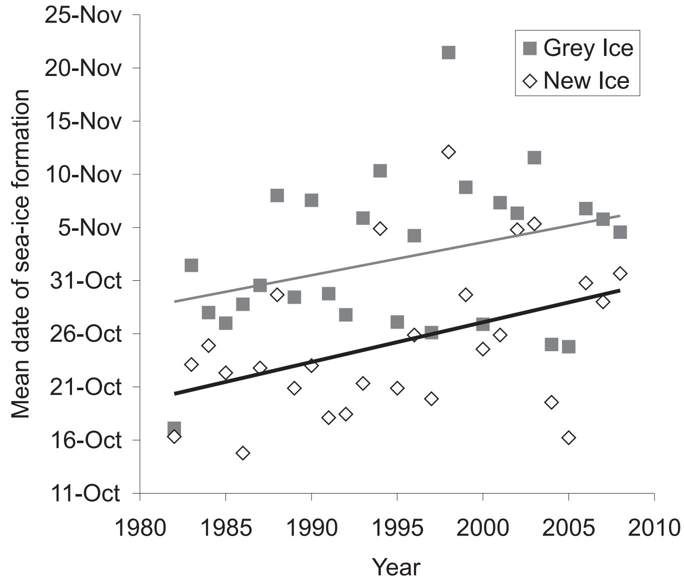

FIG. 3. Mean annual ice formation dates for all locations in eastern Dolphin and Union Strait, Coronation Gulf, Dease Strait, and western Queen Maud Gulf, 1982–2008. Regression lines for new ice ($y = 0.38x - 466$, $r^2 = 0.15$, $p = 0.026$) and grey ice ($y = 0.32x - 327$, $r^2 = 0.08$, $p = 0.078$) are also shown.

north of the southern coast of Victoria Island. After 1989, no collared caribou wintered on Victoria Island. NWVIC96–98 caribou, caught on the northwestern summer range, traveled over 350 km from their summer range to stage along the island's southern coast and winter on eastern Kent Peninsula and Melbourne Island. All SVIC99–06 caribou staged along the southern coast of Victoria Island and wintered on the mainland. Lastly, all NWVIC03–06 caribou summered in northwestern Victoria Island (up to 72.8˚ N latitude), moving a minimum of 500 km to the southern coast of Victoria Island before crossing onto the mainland for winter.

Mean daily distance moved differed seasonally (Table 3). Within individual datasets, the general seasonal pattern held, except that the VIC87–89 caribou moved shorter distances than the other groups during fall–early winter migration. Seasonal movement rates differed among individual caribou for all datasets ($F_{45,233} = 2.11$, $p = 0.0003$). Tests among datasets by season revealed significant differences only during fall–early winter migration, when daily movements by SVIC99–06 and NWVIC03–06 caribou were greater than those of VIC87–89 caribou ($F_{2,41} = 7.08$, $p = 0.002$). Seasons with low rates of movement (e.g., calving, summer, and midwinter) generally had high turning angles, indicating that movement was not directional (Table 4).

Timing and Pattern of Fall–Early Winter Migrations

The start of fall–early winter migration varied among individuals. Median dates for the VIC87–89, SVIC99–06, and NWVIC03–06 caribou were 4 September, 12 September, and 27 September, respectively (n = 13, 52, 18). Combining all data, the date of the start of fall–early winter migration was not dependent on how far north caribou were (as represented by latitude; $y = 2.00x + 118.3$, $r^2 = 0.005$, $p = 0.51$). However, within the NWVIC03–06 dataset ($y = -24.6x + 2027.2$, $r^2 = 0.67$, $p < 0.0001$) and the western sections (> 109˚ W longitude) of the SVIC99-06 dataset ($y = -23.8x + 1893.8$, $r^2 = 0.21$, $p = 0.009$), caribou located farther north (> 70.5˚ N latitude) began fall–early winter migration earlier. This was not true within the eastern section (< 109˚ W longitude) of the SVIC99-06 dataset ($y = 2.66x + 79.9$, $r^2 = 0.006$, $p = 0.74$). For SVIC99-06 animals, there was a weak correlation between mean date of new ice formation ($y = 1.14x - 94.4$, $r^2 = 0.07$, $p = 0.044$) and grey ice formation ($y = 1.24x - 132.1$, $r^2 = 0.10$, $p = 0.017$) and the initiation of fall–early winter migration.

Fall–Early Winter Staging

Combining years within datasets, median dates for the start of staging were 14 October (VIC87–89, n = 2), 3 October (NWVIC96–98, n = 3), 8 October (SVIC99–06, n = 52), and 1 November (NWVIC03–06, n = 18). Between the two datasets with the largest samples and overlapping temporal coverage, caribou collared in northern Victoria Island in 2003 initiated staging on average 24 days later than caribou collared in southern Victoria Island in 1999 and 2001. During 2003, when the datasets overlapped and sample size was greatest, there was a 20-day difference in initiation of staging.

SVIC99–06 caribou (n = 27) staged for longer than NWVIC03–06 caribou (n = 10) prior to crossing the sea ice: means were 26.8 (± 2.30) and 6.5 (± 2.33) days, respectively ($t = 6.20$, df = 59, $p < 0.0001$) (Fig. 4). Mean duration of staging did not differ among years for the SVIC99–06 dataset ($F_{5,40} = 1.37$, $p = 0.26$), and no trend was detectable. Considering only data since 1999, no relationship was found between length of staging and the date of either new

TABLE 3. Mean seasonal daily rate of movement by collared Dolphin and Union caribou, 1987–2006. SVIC99–06, NWVIC03–06, and VIC87–89 are subsets of the overall data: seasons with means having the same superscript letters are not significantly different from other seasons within the same dataset (Tukey's multiple comparison, $p > 0.05$).[1]

Season of the year	All data		VIC87–89		SVIC99–06		NWVIC03–06	
	Daily distance (km)	± SE	Daily distance (km)	± SE	Daily distance (km)	± SE	Daily distance (km)	± SE
Staging	9.1 [a]	0.85	–		9.6 [a]	1.14	8.2 [ab]	1.59
Late winter–spring migration	8.7 [a]	0.57	9.9 [a]	1.66	7.5 [a]	0.39	10.1 [a]	1.62
Fall–early winter migration	8.5 [a]	0.54	4.9 [b]	0.98	8.9 [a]	0.76	10.1 [a]	0.59
Calving	4.1 [b]	0.33	3.7 [b]	0.40	3.9 [b]	0.49	4.6 [bc]	0.99
Summer	2.5 [b]	0.17	2.0 [b]	0.28	2.6 [b]	0.27	3.0 [c]	0.29
Mid-winter	2.3 [b]	0.21	2.0 [b]	0.29	2.6 [b]	0.34	1.7 [c]	0.14

[1] All data: $F_{5,233} = 59.1$, $p < 0.0001$; VIC87–89: $F_{4,43} = 18.5$, $p < 0.0001$; SVIC99–06: $F_{5,125} = 32.4$, $p < 0.0001$; NWVIC03–06: $F_{5,50} = 12.6$, $p < 0.0001$.

TABLE 4. Mean seasonal turning angles (degrees of deflection) recorded for collared adult female Dolphin and Union caribou, 1987–2006. SVIC99–06, NWVIC03–06, and VIC87–89 are subsets of the overall data: seasons with means having the same superscript letters are not significantly different from other seasons within the same dataset (Tukey's multiple comparison, $p > 0.05$).[1]

Season of the year	All data		VIC87–89		SVIC99–06		NWVIC03–06	
	Turning angle (˚)	± SE	Turning angle (˚)	± SE	Turning angle (˚)	± SE	Turning angle (˚)	± SE
Staging	82.7 [ab]	3.5	-		77.5 [bc]	3.3	95.0 [a]	8.9
Late winter–spring migration	55.3 [c]	2.4	51.6 [b]	4.2	61.9 [cd]	3.4	44.2 [bc]	3.3
Fall–early winter migration	53.5 [c]	3.1	49.6 [b]	7.8	61.5 [d]	4.3	36.9 [c]	2.0
Calving	70.6 [b]	4.4	85.8 [a]	8.0	70.8 [bcd]	5.3	51.2 [bc]	12.0
Summer	81.3 [b]	3.4	87.3 [a]	4.8	85.8 [ab]	4.2	61.0 [b]	5.9
Mid-winter	93.5 [a]	2.3	87.6 [a]	5.4	95.0 [a]	3.3	95.2 [a]	2.4

[1] All data: $F_{5,234} = 27.8$, $p < 0.0001$; VIC87–89: $F_{4,43} = 11.0$, $p < 0.0001$; SVIC99–06: $F_{5,126} = 12.0$, $p < 0.0001$; NWVIC03–06: $F_{5,50} = 18.7$, $p < 0.0001$.

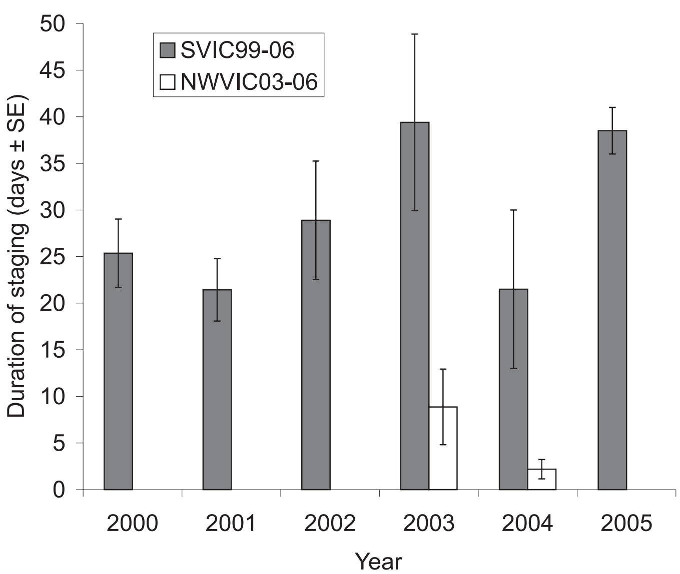

FIG. 4. Mean duration of staging by Dolphin and Union caribou along the southern coast of Victoria Island prior to crossing the sea ice to the mainland, 2000–05.

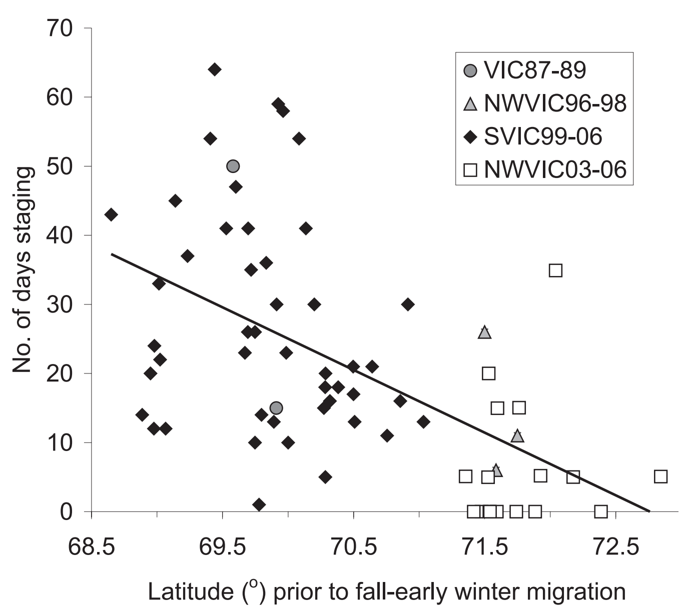

FIG. 5. Duration of staging in relation to latitude (˚ N) at the initiation of fall–early winter migration, Dolphin and Union caribou herd, 1987–2006. Regression line ($y = –9.07x + 660.2$, $r^2 = 0.31$, $p < 0.0001$).

($y = 0.35x – 84.9$; $r^2 = 0.019$, $p = 0.28$) or grey ice formation ($y = 0.19x – 35.8$; $r^2 = 0.006$, $p = 0.54$). The staging period ranged from 0 to 64 days, and date of ice formation changed by 4–5 days over the period.

There was a negative relationship between latitude at the initiation of fall–early winter migration and the length of staging (Fig. 5). For all data combined, on average every

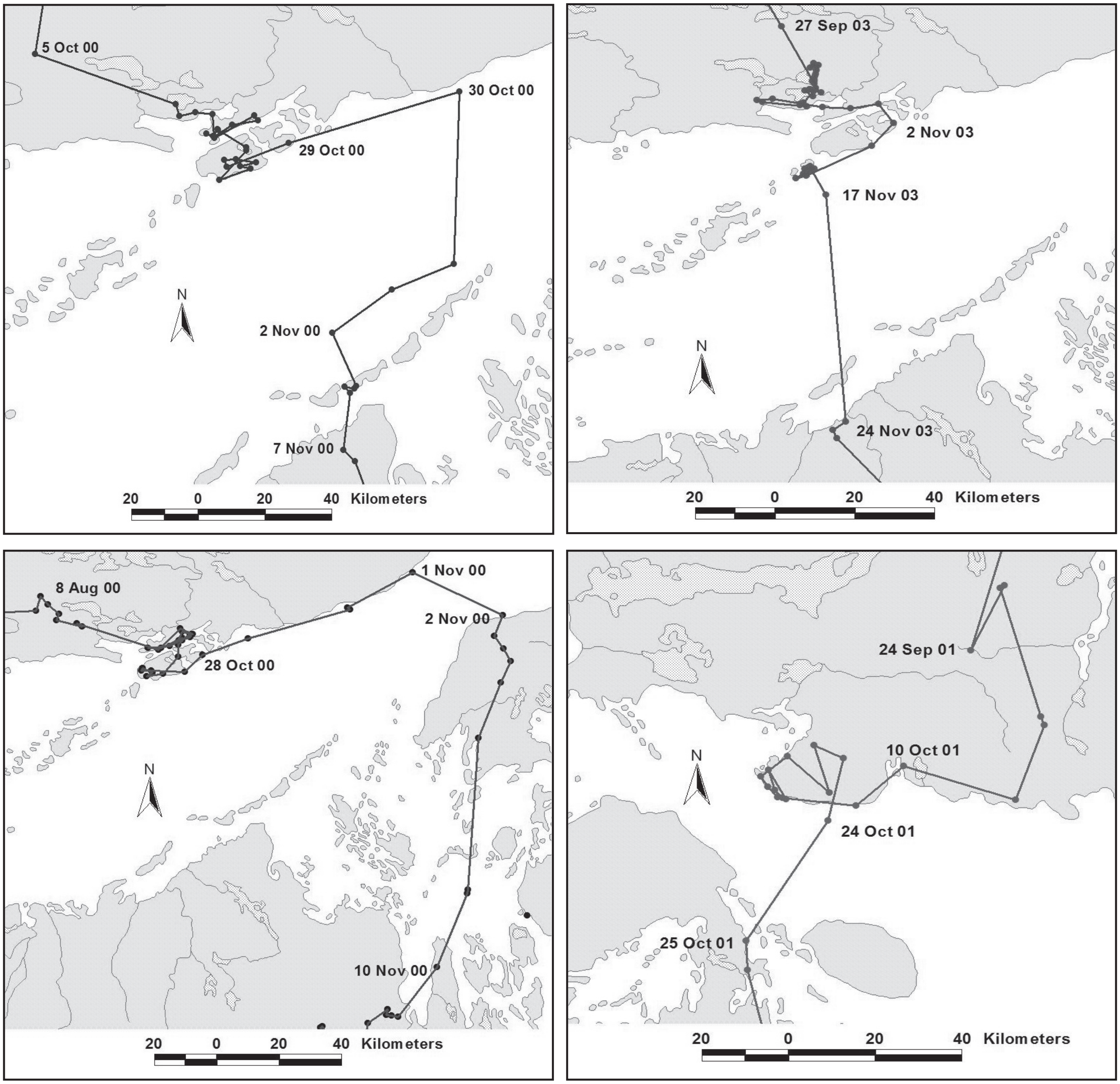

FIG. 6. Example of movements, showing shorter multidirectional movements and relatively long directional movements, during fall–early winter staging and sea-ice crossing by adult female caribou, Dolphin and Union herd, in 2000–03. Locations are primarily early winter daily collar fixes from early October to mid-November. Note that scales differ in the four examples.

one-degree increase in latitude resulted in a staging reduction of about nine days.

Turning angle during staging was high (Table 4), suggesting a high degree of multidirectional movements. Examination of the individual data suggested that in general, once caribou reached the coast they tended to localize their movements during staging, often concentrating in one of several areas (e.g., near the Richardson Islands). Many caribou would cross at these concentration areas once sufficient ice had formed, but some animals, perhaps in response to slow ice formation adjacent to their staging area, would move rapidly along the coast immediately before crossing (Fig. 6).

Sea-Ice Crossings

We recorded 87 southward crossings by 34 caribou during fall–early winter, as well as 78 northward crossings by 29 caribou during late winter–spring (Fig. 7). Annual variation in the point of departure did not depend on the number of years of data for each caribou for either southward

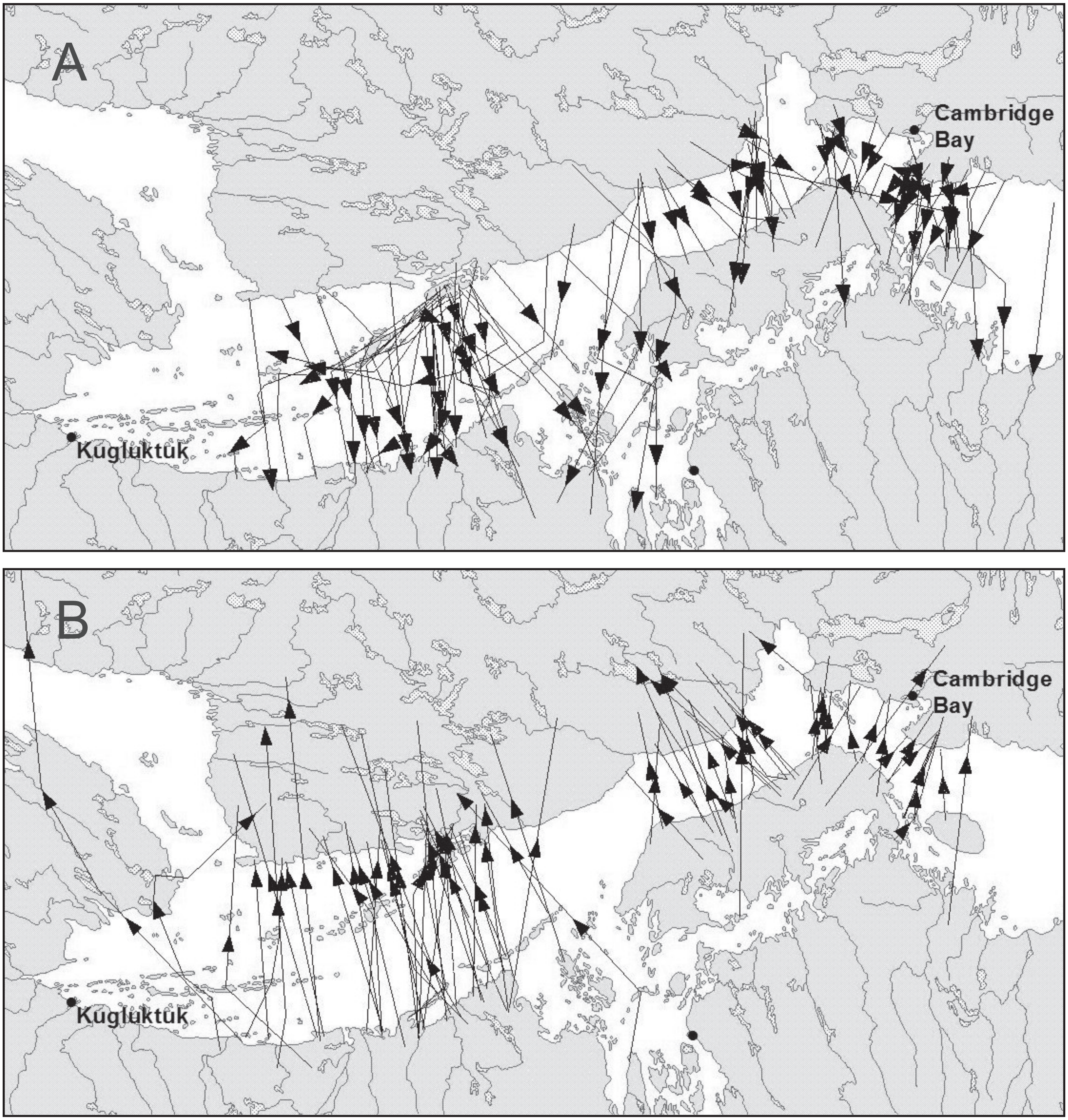

FIG. 7. Crossing locations of the Dolphin and Union caribou in (A) fall–early winter and (B) late winter–spring, 1987–2006. Arrows indicate direction of travel.

(r^2 = 0.04, p = 0.92, n = 25) or northward crossings (r^2 = 0.01, p = 0.30, n = 16). Mean distance between southward (48.1 ± 7.8 km) and northward (40.0 ± 7.2 km) ice crossings for consecutive years did not differ (t = 0.76, p = 0.45), and 45% of yearly southward crossings and 53% of northward crossings occurred within an arbitrary 20 km of the previous year's crossing (Fig. 8). Some caribou departed from the same general area for as many as five to six years, and all but three caribou were faithful to crossing to and from the western or eastern section of Victoria Island. The three exceptions were animals that normally crossed to and from the western section but each crossed once from the eastern section (n = 13, 8, and 7 crossings).

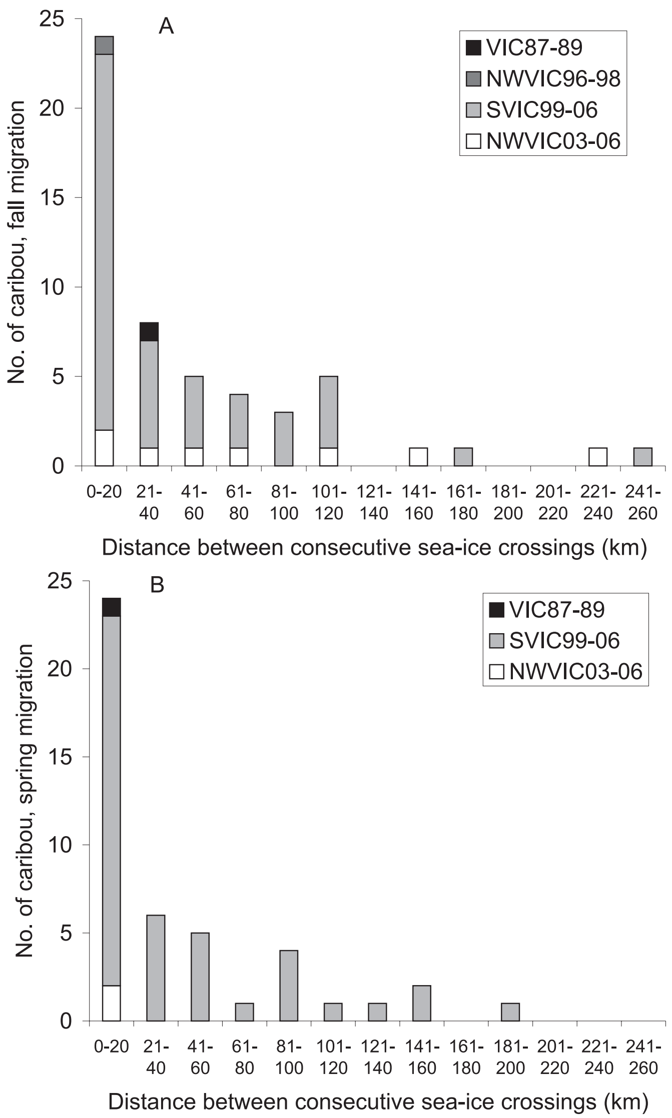

FIG. 8. Distribution of distances between (A) fall–early winter and (B) late winter–spring ice crossings by Dolphin and Union caribou in consecutive years, 1987–2006.

The overall median date of initiating fall–early winter sea-ice crossing was 1 November, and there was no obvious trend toward an earlier or later date between 1999 and 2006 for either the SVIC99–06 or NWVIC03–06 caribou. For years between 1999 and 2004 with eight or more individual crossings, the mean date of formation of new sea ice tended to be correlated with the mean date of initiation of southward ice crossing ($r^2 = 0.58$, $p = 0.08$, n = 6), so that later ice formation resulted in later crossings. For those five years with eight or more crossings, fall–early winter crossings on the sea ice occurred over 20–32 days (mean = 23 ± 2.0 days). Median date of initiation of late winter–spring sea-ice crossing was 24 May. For years between 2000 and 2004 with eight or more crossings, the northward sea-ice crossings occurred over 31–67 days (mean = 48 ± 7.5 days), a period more than twice as long as the southward sea-ice crossings in fall–early winter.

Date of initiation of crossing in fall–early winter was weakly affected by location along a west-east gradient ($r^2 = 0.11$, $p = 0.002$): caribou in the east crossed on average slightly earlier than animals in the west (11 days difference at extreme ends). During late winter–spring, the relationship was reversed and more striking. Date of crossing was significantly affected by the west-east location of initiation of the northward sea-ice crossings ($r^2 = 0.31$, $p < 0.0001$). Averaging all data, collared caribou west of Bathurst Inlet crossed on average on 11 May, and caribou east of the inlet, on 31 May.

Using only SVIC99–06 locations with daily fix locations, the mean number of days required to cross in fall–early winter (4.0 ± 0.53 days, n = 56) was over twice the time used in late winter–spring (1.7 ± 0.17 days, n = 38; $Z = 3.6$, $p = 0.0004$). Five of the fall–early winter crossings, which involved stopping on islands en route, took 10–19 days. None of the late winter–spring crossings took more than five days, and most of those requiring more than two days included stops on islands. On roughly 20% of late winter–spring migrations, caribou moved north close to the mainland coast in late winter and spent up to several weeks making local movements closer to the coast before crossing northward on the sea ice. This behaviour was observed annually only among SVIC99–06 caribou.

Mean daily movement rates during southward crossings were higher for the SVIC99–06 caribou (22.9 ± 1.7 km/day) than for the NWVIC03–06 caribou (12.0 ± 0.9 km/day; $Z = 3.3$, $p = 0.001$). Mean late winter–spring crossing daily movement rates were also higher for the SVIC99–06 caribou (29.1 ± 2.2 km/day) than for NWVIC03–06 caribou (16.8 ± 1.8 km/day; $Z = 2.4$, $p = 0.02$). Daily movement rates across the sea ice were as high as 59.8 km/day during southward sea-ice crossings and 86.9 km/day during northward sea-ice crossings.

As demonstrated by caribou collared after 1989, winter range extended on both sides of Bathurst Inlet up to 100 km from the coast, and farther south, west of the Inlet but never more than 100 km from sea ice east of the Inlet (Fig. 1). With the exception of four SVIC99–06 animals that switched sides of Bathurst Inlet for wintering after crossing on five occasions (5.7% of 87 crossings), all caribou wintered near or south of their sea-ice crossing termini on the mainland. The five switches all involved early winter movements from east to west across the middle of Bathurst Inlet.

Survival

Excluding a caribou that was shot for collar recovery, 19 collared caribou died during the study, resulting in an annual survival rate of 0.76 ± 0.049 (Table 5). Eighteen of those animals died of natural causes, and one was shot by a hunter. Hunters may have avoided harvesting collared caribou, and if so, the harvest rate may have been underestimated and the overall survival rate overestimated. Of non-hunting deaths, 50% (9 of 18 animals) occurred during a seven-week period between 20 October and 8 December,

TABLE 5. Seasonal survival rates for 27 adult female Dolphin-Union caribou monitored from October 1999 to June 2004: Seasons were calving/summer, 10 June–20 September; fall–early winter migration, 21 September–30 November; mid-winter, 1 December–20 April; and late winter–spring migration, 21 April–9 June.[1]

Season of the year	Interval length (days)	Number of deaths	Interval survival rate	± SE	Standardized 30-day survival probability	± SE
Calving/summer	103	1	0.982	0.0175	0.9952	0.0177
Fall–early winter migration	71	10	0.879	0.0377	0.9385	0.0403
Mid-winter	141	5	0.924	0.0328	0.9833	0.0349
Late winter–spring migration	50	3	0.953	0.0266	0.9715	0.0271
Annual	365	19	0.760	0.0494		

[1] Seasons were of different lengths; therefore, standardized 30-day survival probabilities are also presented for comparative purposes.

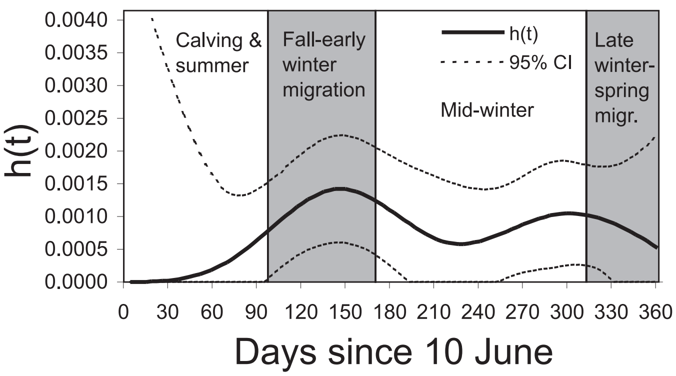

FIG. 9. Seasonal changes in the penalized likelihood estimate (PLE) of the hazard, h(t) (± confidence interval [CI]), for 27 adult female Dolphin-Union caribou monitored from October 1999 to June 2004. The PLE depicts changes in instantaneous rate of death over time.

and all were related to fall–early winter sea-ice crossing. Mid to late winter was also a period of high non-hunting mortality (39%, or 7 of 18 animals), and six of these deaths occurred during a 10-week period from 9 February to 21 April. Elevated risk of mortality during these two periods is evident from changes in the instantaneous hazard over time (Fig. 9). There was no detectable difference in mortality risk for caribou migrating in the western vs. the eastern section (Likelihood ratio test = -1.37, 1 df, $p = 0.24$).

DISCUSSION

Since the 1970s, caribou of the Dolphin and Union herd have resumed their traditional crossing on the sea ice between Victoria Island and the adjacent mainland coast. By early October, caribou migrate from inland Victoria Island to the southern coast, where they wait until sea-ice freeze-up, then cross so that they can reach the Arctic mainland coast and move onto their winter range. Caribou spending the summer farther north on Victoria Island arrive later at the coast, which shortens their time spent on the staging area. Sea-ice freezing now occurs on average 8–10 days later than in 1982. The average overall fall–early winter crossing date for Dolphin and Union caribou was 1 November, but varied over 25 days annually between 1999 and 2006. Despite the relatively short duration of monitoring, crossing dates suggest that the caribou did not linger any longer than was necessary after adequate ice formation before crossing the sea ice.

The four telemetry studies summarized here had different sample sizes, as well as different objectives that dictated where and when the collaring was conducted. In the late 1980s, only one of the nine collared cows (VIC87–89) staged along the southern coast and crossed the sea ice as far as the islands within northern Bathurst Inlet; the other eight animals did not stage or cross. All subsequently collared animals crossed sea ice to winter range on the mainland. We found that caribou collared on northwestern Victoria Island during the summer (NWVIC96–98 and NWVIC03–06) started fall–early winter migration earlier and staged later, with a shorter duration of staging. Those data indicate that at least sometimes caribou from northwestern Victoria Island also travel to and stage on the southern coast before moving across the sea ice to the mainland. The SVIC99–06 dataset had the strongest annual sample sizes, and all individuals showed staging and sea-ice crossing behaviour. The satellite telemetry data are consistent with Inuit hunter reports, 1994–97 VHF collar monitoring, and the 1997 and 2007 aerial survey results, all of which showed concentrated staging by both sexes along the southern coast of Victoria Island during fall and early winter (Nishi, 2000; Nishi and Gunn, 2004; M. Dumond, GN, unpubl. data).

Although the warming trend caused the straits to freeze later, we did not have enough data from the 1980s or 1990s relative to 1999–2006 to detect a trend in the caribou's response to the later ice formation. The data do support our contention that the caribou are staging while waiting to cross the sea ice, and that dates of freeze-up and crossing generally coincided. We are unaware of any data indicating that a substantial number of caribou ever intentionally swim to complete this migration. Rather, they appear to move back and forth along the lead-edges of the sea ice waiting for the ice to form.

The eastern straits freeze earlier than the western straits (in agreement with temperature differences between Cambridge Bay and Lady Franklin Point), and caribou cross slightly earlier in the east. Although migration-related deaths of collared caribou were detected equally in both western and eastern sections, the western crossing may be more hazardous, possibly because of the longer distance (up to 55 km). In addition, the currents between the islands would affect ice formation and possibly cause the occurrence of weak ice that could not support caribou. Observations during the October 1997 and 2007 aerial surveys recorded caribou traveling out onto the forming ice and returning or breaking through the ice (Nishi and Gunn, 2004; M. Dumond, GN, unpubl. data). Although some caribou can extract themselves, others (and possibly especially larger bulls) cannot get themselves out, and thus die. This is the basis for concerns about later ice formation—that the caribou are at greater risk of injury or death. This peril has also been observed for barren-ground caribou crossing freshwater lakes on ice too thin to support them (Miller and Gunn, 1986).

Caribou in fall–early winter took twice as long to cross the sea ice as during late winter–spring. Another difference between fall–early winter and late winter–spring migration was in staging. Although this behaviour was evident only in SVIC99–03 caribou, during about 20% of northward migrations caribou moved north closer to the mainland coast in late winter–spring and spent up to several weeks in the area, making only localized movements, before crossing. We also noted that four caribou on five occasions in 2000, 2002, and 2003 crossed to Victoria Island in spring (mainly during early May) for 9–16 days, then returned to the mainland for 3–11 days, before re-crossing to Victoria Island. We did not record such reversals or excursions during the fall–early winter migrations.

Most of the attention to the trend toward reduced ice thickness and extent in the Arctic has been focused on perennial ice rather than annual ice such as that which forms between Victoria Island and the mainland. The trend toward reduced perennial ice extent (for example, the rate of loss is 8.6 ± 2.9% per decade for September 1979 to 2006) is the result of a complicated interplay between warming temperature trends and the episodic shifts in temperature from the Arctic Oscillation (Overland and Wang, 2005; Serreze et al., 2007). Despite complexity and uncertainties, the warming trends are predicted to lead to further reductions in perennial ice (Overland and Wang, 2005; Serreze et al., 2007; Barber et al., 2008). An increase in shipping is expected through the Northwest Passage as the sea-ice season is reduced and the ice thins. However, any effects on caribou crossing of a longer shipping season and more frequent ship passages will depend on the timing of the passages. The draft West Kitikmeot Regional Land Use Plan voices residents' concern about the effects of shipping on wildlife and supports shipping only during the normal open water season, from 1 July to 15 October, or to 30 October if the shipping does not break ice (Nunavut Planning Commission, 2004).

Icebreaking related to shipping can potentially affect the movements of caribou and other wildlife. In late October 2007, barge ships kept a channel out of Cambridge Bay open by breaking the ice every 12 hours. Although this channel did not directly affect travel across to the mainland, caribou were unable to cross a frozen bay while staging along the coast, highlighting how even the width of a barge trail of open water can stop caribou (M. Dumond, GN, unpubl. data). Ice archive data indicate that on 22 October 2007, only thin new ice was present in the Cambridge Bay area. One week later, substantial amounts of new and grey ice were found in the eastern two-thirds of the straits. Overall the impact of the icebreaking in late October 2007 was to delay caribou movements by only a few days. The potential impacts of all-year or greatly extended seasonal increases in shipping, an increase in the volume of ship traffic, or a wider channel being broken, along with milder temperatures, remain unknown.

Additional questions remain about whether later freeze-up will extend the duration of staging along the southern coast of Victoria Island and delay sea-ice crossings, and whether inadequate sea-ice conditions at the appropriate time will decrease survival rates and lead to increased isolation of this herd. The implications of caribou being concentrated for a longer duration along the coast or being prevented from migrating to the mainland are largely unknown. Failure to winter or reduced time spent wintering on the mainland would likely create issues of forage availability on southern Victoria Island. Increased staging may increase the parasite load and rate of infection, which could affect herd health (Hughes et al., 2009). Local knowledge suggests a possible increase in diseased animals in the Dolphin and Union caribou herd (Dumond et al., 2007). Finally, a longer time concentrated on the southern coast could increase vulnerability to predation and human harvest.

Late winter–spring and fall–early winter sea-ice crossings were concentrated at a few locations, possibly because the crossing distance to the mainland (Cape Colbourne) or to a chain of islands (Richardson Islands) is shorter from these points. We did not find a concentration of caribou crossing at Lady Franklin Point, western Victoria Island, where Taylor (1965 in Brink, 2005) found thousands of caribou bones at a Thule site. Although our failure to find caribou at Lady Franklin Point could indicate a change in migration route, that site could also represent a good fall–early winter hunting site, or an area where male (rather than female) caribou concentrate, and not necessarily a concentration site associated with origins for sea-ice migrations. The history of caribou hunting precedes the Thule culture, as Palaeoeskimo people reached Victoria Island ca. 4500 years BP (Savelle and Dyke, 2002) and many of the hundreds of Palaeoeskimo sites are associated with caribou hunting. Predominant among them are communal caribou hunting sites on southern Victoria Island. Lines of rocks guided caribou to shooting pits on southern Victoria Island and Wollaston Peninsula (Savelle and Dyke, 2002; Brink, 2005; A. Gunn, GNWT, field notes). Brink (2005) described stone hunting structures for caribou (cairns, shooting pits, and stone fences and funnels) near Wellington Bay, where some caribou crossed in fall–early winter and then again in late winter–spring. Thus, Victoria Island caribou have been crossing the sea ice for hundreds or possibly even thousands of years. However, the numbers of animals annually making sea-ice crossings have changed, and most likely, the locations of the origins and termini of the crossing sites have also shifted over time.

The trend toward later freeze-up of the sea ice poses short- and long-term risks for the Dolphin and Union caribou. The near-future risk is increased deaths during crossings as the caribou try to cross to their wintering areas while the sea ice is still forming and too weak to bear their weight. To mitigate this risk, both the caribou and the Inuit who hunt them will have to adapt further to warming temperatures. Exact numbers of Dolphin and Union caribou harvested for subsistence by communities are not known, but the annual harvest rate is believed to be in the order of 10% (M. Dumond, GN, unpubl. data). To prevent population decline, increased mortality during sea-ice crossings may need to be compensated for by reduced harvesting. Although COSEWIC assessed Dolphin and Union caribou as a "Special Concern" species in 2004, the federal government has not yet listed the caribou under the Species at Risk Act. Listing the Dolphin and Union herd would require a management plan that would include an assessment of the risks and suitable management actions. Longer-term risks are likely if, over decades, the ice forms poorly or fails to form in some years.

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