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Two caribou mortality events in Northwest Alaska: possible causes and management implications

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Abstract: During fall and winter 1994–1995 and winter 1999–2000, caribou (*Rangifer tarandus granti*) from the Western Arctic Herd experienced high, localized mortality in northwest Alaska near Cape Thompson. Substantial numbers of caribou wintered in this area during 1986–1987, 2001–2002, and 2002–2003 without suffering high mortality. During the 1994–1995 event, 2000 to 3000 caribou died out of roughly 10 000 that wintered in this area. About 4000 caribou perished out of approximately 20 000 that wintered here during 1999–2000. During both mortality events, gross characteristics and tissue analyses indicated caribou in this area were malnourished. Weather near Cape Thompson during winter 1994–1995 was colder, windier, and had more snow than other years when caribou wintered in this area; in contrast, conditions during 1999–2000 were not unusually severe. Additionally, Cape Thompson experienced 2–5 occurrences of severe conditions during winter 1994–1995 while 1999–2000 experienced only 1 such occurrence at most. Several indicators suggested severe storms killed some caribou before starvation was fatal. Cape Thompson consistently experienced higher wind, lower ambient air temperature, and shallower snow cover than other portions of winter range used by this herd. Unlike years when caribou wintered in this area without experiencing high mortality, caribou were in relatively poor body condition during the autumn that preceded each die-off. Although these mortality events were inconsequential to size of this caribou herd, they raised local residents' concerns that contaminants had poisoned caribou and possibly jeopardized human health. Muskoxen *(Ovibos moschatus)* in this area were not affected by weather or snow conditions during either caribou mortality event.

Key words: caribou, malnutrition, mortality, *Rangifer tarandus*, snow, weather, windchill.

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Introduction

Most caribou (*Rangifer tarandus granti*) of the Western Arctic Herd (WAH) have wintered in southern portions of their range since the mid-1980s. However, during winters 1986–1987, 1994–1995, 1999–2000, 2001–2002 and 2002–2003, ≥30 000 WAH caribou wintered in the northwest portion of their range. During two of these winters (1994–1995 and 1999–2000) caribou wintering along the Chukchi Sea coast between Cape Lisburne and Cape Krusenstern experienced high, localized mortality. During both events the highest mortality was near Cape Thompson, an area characterized by chronic high wind and severe winter weather (Wilimofsky, 1966).

These die-offs concerned users and managers of the WAH for several reasons. The WAH last peaked at 242 000 caribou in 1970 and then declined to 75 000 caribou by 1976. From 1976 to 1990 the WAH grew 13% annually. It has numbered >400 000 caribou since 1990 and in 2003 numbered 490 000 caribou (Dau, in prep.). The total range of this herd encompasses ~363 000 km^2 (140 000 mi^2). In 2003, density of the WAH over its total range was 1.4 caribou/km^2 (3.6 caribou/mi^2). However, the 'functional density' (estimated number of caribou present on a seasonal range from telemetry data/area of seasonal range) individual caribou experienced on a daily basis has been much higher. For example, density on summer range reached 4.1 caribou/km^2 (10.7 caribou/mi^2) in 2003, and the maximum density observed on winter range was 10.2 caribou/km^2 (26.4 caribou/mi^2) in the Nulato Hills during 1990–1991 (Dau, 2003). These winter range densities are conservative because they do not include caribou from the Teshekpuk Lake Herd, Central Arctic Herd (CAH), or Seward Peninsula reindeer (*Rangifer t. tarandus)* that also use portions of WAH winter range. The sustained high WAH population level and high seasonal densities raise the possibility of another precipitous decline in the future.

Additionally, caribou are a critical source of meat for most residents of northwest Alaska and provide a vital link to the cultural identity of indigenous users. Recreational use of the WAH by nonconsumptive users is increasing as the availability of wild and remote areas declines worldwide. Similarly, use of the WAH by recreational hunters and commercial operators has increased as hunting opportunities in other portions of Alaska have been restricted. Finally, proximity of these mortality events to potential sources of environmental contaminants, e.g., radionuclides from the Project Chariot site and heavy metals from the Red Dog Mine, caused residents of this area to question whether caribou had been poisoned and, in turn, jeopardized human health.

This paper describes these caribou mortality events and examines the roles weather, snow, and severe storms may have played in causing them. It also describes management implications of both die-offs and contrasts behavioral and population responses of a resident muskox *(Ovibos moschatus)* population to WAH caribou.

Methods

Physical and biological systems near Cape Thompson have been previously described (Wilimofsky, 1966). Vegetation is largely decumbent and sparse on exposed ridge tops (Johnson *et al.*, 1966).

After receiving reports from hunters of small numbers of dead and moribund caribou near Point Hope during winters 1994–1995 and 1999–2000, we searched the area within 15–25 km (10–15 mi) of the Chukchi Sea coast between Cape Krusenstern and Cape Lisburne during May and June 1995 and June 2000 using a Piper PA-18 airplane. Residents of Kotzebue, Kivalina, and Point Hope were hired as observers during these flights. We flew transects or contour lines depending on terrain to maximize search coverage. We searched for carcasses a total of 21.7 hr on 4 and 6–8 June 1995, and 23.2 hr during 3–5 June 2000. In both years, high wind prevented us from searching roughly 300 km^2 (115 mi^2) of the northernmost tip of the Lisburne Hills. In 1995 and 2000, search intensity was approximately 0.4–0.8 min/km^2 (1–2 min/mi^2) over elevated terrain (~1000 km^2 or ~400 mi^2) where most carcasses were located, and 0.2 min/km^2 (0.5 min/mi^2) over lowland tussuck tundra. Decumbent vegetation, sun-bleached hair and the presence of antlers on many bulls in 1995 made carcasses easily visible for up to 1 km (0.5 mi) from the airplane. We did not attempt to quantify a correction factor for carcasses missed during the surveys. Also, during aerial searches we did not attempt to distinguish males from females, or calves from adults, because too many carcasses were nondescript.

During June and early July 1995, a team consisting of a wildlife veterinarian/pathologist (J. Blake, University of Alaska Fairbanks), a veterinary toxicologist (T. O'Hara, North Slope Borough Department of Wildlife Management), two wildlife biologists (C. George, North Slope Borough Department of Wildlife Management and G. Carroll, Alaska Department of Fish and Game) and residents of Point Hope (E. Kingik & R. Koonuk) examined 101 caribou carcasses in the vicinity of Cape Thompson. Gross body characteristics were recorded during necropsies and tissue samples were collected to evaluate levels of heavy metals (arsenic, cadmium, copper, lead, zinc and iron; O'Hara *et al.*, 2003) and radionuclides (gross alpha and beta emissions as well as cesium-137, potassium-40, and strontium-90; O'Hara *et al.*, 1999). During 7–11 June 2000, 2 wildlife veterinarians (V. Woshner, North Slope Borough Department of Wildlife Management and C. Rosa, University of Alaska Fairbanks) necropsied 34 caribou carcasses in the vicinity of Cape Thompson using the same methods as in June 1995 (Woshner *et al.*, in prep.); however, radionuclide levels were not evaluated in 2000.

I purchased daily means of weather and snow parameters for Kotzebue, Barrow, Bettles, Nome, and Unalakleet from the National Oceanic and Atmospheric Administration (http://lwf.ncdc.noaa.gov). I estimated weather and snow conditions at Cape Thompson using Kotzebue weather data and monthly relationships reported by Allen & Weedfall (1966). For this paper, 'winter' is the period 1 October–15 April. I defined a severe storm as any day having a mean wind speed ≥15 mph (24 km/hr) and an average windchill ≤-60 °F (-51 °C): this corresponds to U.S. Department of Commerce (1998) criteria for issuing a 'weather warning.' I calculated windchill values using the recently revised formula provided by the National Weather Service (www.nws.noaa.gov/om/windchill):

$$\text{Windchill (°F)} = 35.74 + 0.6215\,(T_a) - 35.75\,(W_{vel}^{0.18}) + 0.4275\,(T_a)\,(W_{vel}^{0.18})$$

T_a = ambient air temperature (°F)
W_{vel} = wind velocity (mi/hr)

Snow works together with wind and ambient air temperature to affect caribou. Although 'windchill' combines the latter two variables, there is no convention for integrating the effects of snow with windchill. Therefore, I calculated a daily index of environmental severity using mean values of standing snow depth and windchill:

$$\text{Index}_{\text{daily severity}} = (-1 * \text{windchill} + 150) * (\text{daily snow depth} + 0.1)$$

Units for this index are °F-inches

I multiplied windchill by -1 and added a constant (150) to make this value >0 for all days so that windchill and cumulative snow depth would complement rather than negate each other. I added a constant (0.1) to snow depth so that the index on days having no snow would not be reduced to 0 regardless of windchill.

Besides acting synergistically with other weather parameters, the effects of snow on caribou are also cumulative over the course of a winter. For example, 30 cm of snow that falls in October and persists through April has a greater effect on caribou than 30 cm of snow that falls in late March. Therefore, I calculated a cumulative index of environmental severity using daily values for windchill and cumulative snow depth at Ogotoruk Creek:

$$\text{Index}_{\text{cumulative severity}} = (-1 * \text{windchill} + 150) * (\text{sum of daily snow depth} + 0.1)$$

Units and constants for this cumulative index of environmental severity were identical to those used for the daily index. The only difference between these indices is that snow depth was summed by day to incorporate duration of snow cover for the cumulative index of environmental severity.

I used caribou winter distribution reported by Dau (2003) to identify years and weather stations for comparing weather and snow conditions. I attempted to separately estimate the number of days mosquitoes and oestrid flies were present on WAH summer range during 1994 and 1999 using relationships developed by Dau (1986) with weather data from Kotzebue and Barrow.

Beginning in 1995, fall body condition of caribou was evaluated in September during capture operations. The body condition of each caribou handled was subjectively ranked 1 (emaciated) - 5 (very fat) based on the presence of subcutaneous fat and prominence of ribs, scapula, and spine.

To evaluate the role weather may have played in these die-offs, I tested the following null hypotheses:

1. There was no difference in weather or snow conditions at Cape Thompson between winters of high mortality (1994–1995 and 1999–2000) and winters of typical mortality (1986–1987, 2001–2002, and 2002–2003).
2. For winters 1994–1995 and 1999–2000, there was no difference in weather or snow conditions between Cape Thompson and other areas where WAH caribou wintered.

I did not combine years to evaluate spatial differences in weather conditions among caribou wintering areas during 1994–1995 and 1999–2000 (hypothesis 2) because specific wintering areas changed annually. For these comparisons, I only considered portions of range having a winter density >0.8 caribou/km^2 (2.0 caribou/mi^2) in any individual year.

I used Statistix8 analytical software (www.statistix.com) to calculate indices of environmental severity; provide descriptive statistics (median, mean, variance, skewness, and kurtosis); plot distributions of weather parameters through time; and plot frequency distributions of temperature, snow depth, and windchill. I used Kruskall-Wallis tests for multiple pairwise comparisons of median weather values among caribou wintering areas and years, and considered P-values <0.05 statistically significant.

Results

Caribou mortality

1994–1995 mortality event

Snow obscured carcasses during three aerial searches in May 1995. In June 1995 we observed 1127 caribou carcasses. The carcasses were distributed over 4400 km^2 (1700 mi^2) within approximately 15–25 km (10–15 mi) of the Chukchi Sea coast (Fig. 1). This area comprises roughly 11% of 'WAH wintering area 9' defined by Dau (2003). The highest density of carcasses was within a 1000-km^2 (625 mi^2) area near Cape Thompson. We subjectively estimated up to 3000 caribou died during this event based on the proportions of areas searched at high intensity, low intensity or not searched at all. While conducting telemetry surveys I visually estimated roughly 10 000 caribou wintered in this area during 1994–1995.

Although caribou carcasses were distributed throughout the area, most were located on ridge tops or hillsides. We did not record the posture of intact carcasses but roughly 25–50% of them were sternally recumbent and curled as if asleep or, if on their side, had their head and neck curled back over their

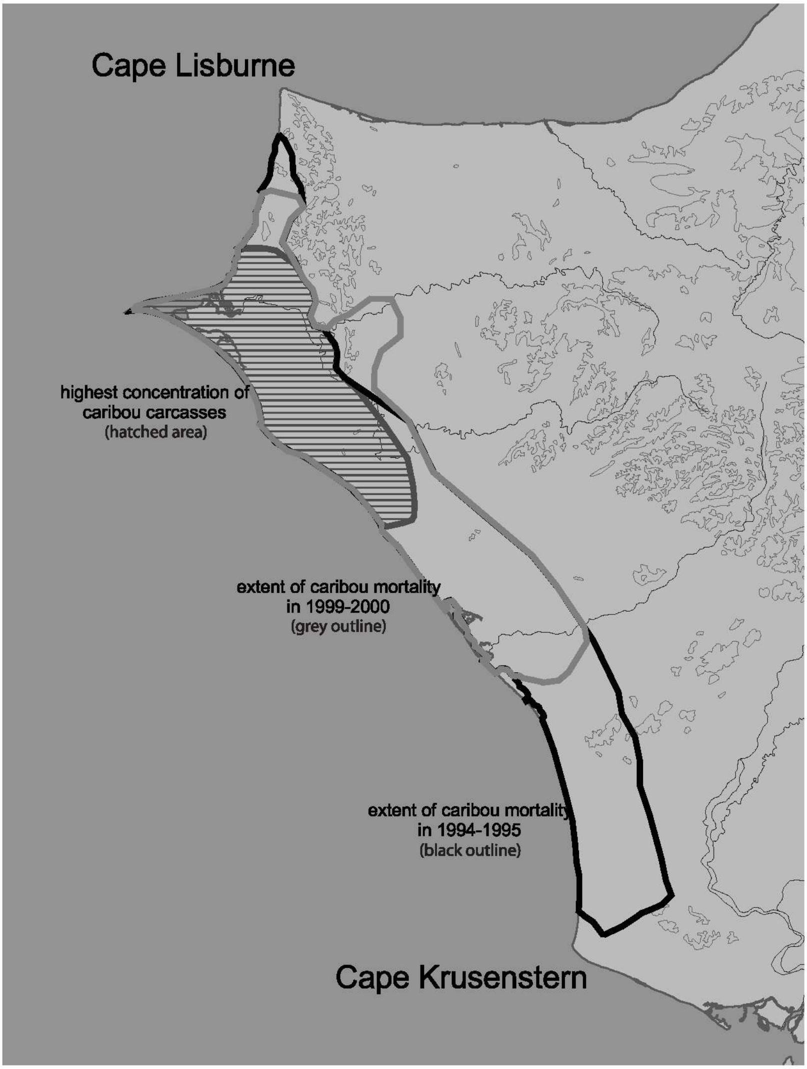

Fig. 1. Extent of caribou mortality and area of highest mortality during the 1994–1995 and 1999–2000 Western Arctic Herd mortality events in northwest Alaska.

body. Many carcasses were distributed in clusters of two to six individuals as if they had been part of a group and died within a brief time span. Many carcasses of mature bulls had 1 or both polished antlers attached to the skull. Mature WAH bulls typically begin casting their antlers during the last few days of October. The presence of hard antlers on these individuals suggests this mortality event began before mid-November 1994. Using the visual index scores developed by Neiland (1970), carcass femur marrow ranged from grade 2 (red, waxy, and filling the bone cavity) to grade 1- (deep red, mucous-like, and filling <50% of the bone cavity). The abundance of carcasses in the area overwhelmed large scavengers' capacity to consume them. Many carcasses remained virtually intact aside from loss of hair well into July, and some skeletons were still mostly articulated during summer 1996.

Necropsies of carcasses revealed extreme emaciation, serous atrophy of bone marrow, atrophy of the liver, and rocks and mineral soil in the abomasum. There were no lesions indicative of poisoning; likewise, laboratory analyses revealed no indication of poisoning by heavy metals (O'Hara *et al.*, 2003) or radionuclides (O'Hara *et al.*, 1999).

1999–2000 mortality event

As in 1995, snow obscured all carcasses during an aerial search conducted in May 2000. We observed 1878 caribou carcasses within a 3400 km^2 (1300 mi^2) area during 3–5 June 2000 (Fig. 1). This was roughly 8% of 'wintering area 9' defined by Dau (2003). During telemetry surveys I visually estimated roughly 20 000 caribou wintered in the mortality area during 1999–2000 and about 4000 caribou perished during this event. The area of highest mortality was virtually identical to that for the 1994–1995 event. Unlike 1995 however, we observed many carcasses on large ice-covered coastal lagoons in June 2000.

During late April 2000, I retrieved a radio collar from a female caribou that had died approximately 10 km (6 mi) northeast of Cape Thompson. The carcass was frozen on top of the snow and had not been scavenged by ravens (*Corvus corvax*) or foxes (*Vulpes vulpes* or *Alopex lagopus*). It appeared the cow had died two to four days before I located her. She showed no evidence of trauma and had no fluid discharge from any body orifice. The prominence of her hips, ribs and spine indicated the cow was emaciated at the time of death. Her frozen state precluded an internal examination. I broke metacarpal and metatarsal bones and her marrow was waxy and filled the bone cavity but was deep red and soft. This corresponds to a 'grade 2' visual marrow condition as reported by Neiland (1970). The deep red color of the marrow in this collared cow indicated depletion of fat reserves (Cheatum, 1949 as reported by Kirkpatrick, 1980) and was consistent with her general appearance. Nieland (1970) reported a mean marrow fat content of 42% for caribou in this grade. This suggests her fat reserves were not totally exhausted at the time of death. I speculate this cow, weakened by chronic malnutrition, died of exposure during a severe storm. Caribou fecal pellets were widely scattered over the snow surface in this general area and were <50% normal size, black, dry, and hard. Virtually all frozen urine in the area was dark brown and opaque, which could indicate caribou were catabolizing protein to stay alive.

Reports from hunters indicated a disproportionate number of calves died compared to adult caribou. Composition surveys conducted in April 2000 were consistent with these reports: we observed six 10-month-old calves:100 adult caribou within the mortality area compared to 20 calves:100 adults in other portions of winter range. During these surveys we occasionally saw caribou in the mortality area stagger as they attempted to flee the airplane. Many caribou that were lying down did not get up or show any response to the plane whatsoever.

As in 1995, gross characteristics of carcasses necropsied during June 2000 suggested caribou were malnourished. Laboratory analyses revealed no indication of heavy metal poisoning (O'Hara *et al.*, 2003; Woshner *et al.*, in prep.).

Winter weather at Cape Thompson during years of high vs. *normal mortality*

I rejected the null hypothesis of 'no difference among the five years when caribou wintered near Cape Thompson' for each weather parameter (Kruskall-Wallis tests, all n_i = 985 days, all P<0.05). Winter 1994–1995 was colder and windier with more snow than other years when caribou were present in this area (Table 1). While pairwise comparisons of years revealed many statistically significant differences for each weather parameter (Table 2), differences in median values for these variables seem too small to be biologically significant (Table 1). The statistical significance of these differences is probably an artifact of large sample sizes (n_i = 197 days for each weather parameter annually). A possible exception to this was snow depth; in 1994–1995, median snow depth at Cape Thompson was 28.2 cm (Table 1). While this is generally not considered severe for caribou, it was two to five times deeper than any other year when caribou wintered in this area. Maximum snow depth in 1994–1995 was only somewhat greater than other years. Median snow depth was high because snow fell early, it approached maximum levels by mid- to late November and remained deep beyond mid-April. Even so, maximum and median snow depths during 1994–1995 were modest compared to levels reported in other parts of WAH range where mortality was not elevated (Table 1). Median values of individual weather parameters at Cape Thompson during 1999–2000 were not particularly severe compared to other years when caribou wintered in this area.

The index of daily winter severity graphically revealed acute weather events that were not evident in median values of individual weather variables. This approach illustrated that harsh combinations of snow and windchills occurred earlier during winter, occurred more frequently, reached more severe levels and persisted longer during 1994–1995 than any other year when caribou wintered in this area (Figs. 2 and 3). In contrast, this index indicated snow and weather conditions during 1999–2000 were similar to the three years of normal mortality near Cape Thompson except that one bout of modestly severe conditions occurred in early February 2000. The maximum index of severity reached in February 2000 barely exceeded minimum levels of severity that persisted from mid-November 1994 through April 1995. Although the temporal pattern for the index of daily severity varied among years, only 1994–1995 was substantially different from other years in terms of magnitude and shape. Therefore, I only show this index for 2001–2002 (Fig. 3) as an example of a winter that did not have unusually severe weather.

Snow depth largely determined the general shape of the cumulative index of winter severity (Figs. 2 and 3). In all but 1994–1995, acute storms evident in the daily indices of severity were largely obscured by the effect of snow accumulation. In 1994–1995, though, the magnitude of windchills was such that five or six storms occur as spikes in the general trend of this index. Although it seems conceptually reasonable to meld duration with depth when trying to assess the effects of snow on caribou, the daily index of severity that ignored snow accumulation better reflected acute periods of severe conditions. A strength of the cumulative winter severity index is that it ascribes a higher value to a late winter storm than to one of equal strength that occurs in late fall or early winter. As with the daily index of severity, the shape and magnitude of the cumulative index of severity was substantially different only during winter 1994–1995. Therefore, in the interest of space, I only show this index for 2001–2002 (Fig. 3) as an

Table 1. Winter[a] weather and snow conditions near major Western Arctic Herd wintering areas during years of high caribou use of the Cape Krusenstern–Cape Lisburne area, northwest Alaska[b].

Year	Caribou wintering area	Weather station	Median air temp. (°C)	Median wind velocity (m/sec)	Median windchill (°C)	Median snow depth (cm)	# Days wind ≥11 m/sec (25 mph)	# Days wind ≥22 m/sec (50 mph)	# Days windchill ≤40 °C	# Days windchill ≤60 °C	# Severe storms
1986–1987	Lisburne Hills/Noatak/Wulik/Kivalina[c]	Kotzebue[d]	-14.8	8.7	-27.7	14.0	67	14	43	7	1
	Nulato Hills	Unalakleet	-5.0	6.2	-14.9	2.5	17	0	4	0	0
	Kobuk/Selawik/Buckland	Kotzebue	-13.0	4.5	-21.7	38.1	16	0	14	0	0
	North Slope	Barrow	-21.2	5.1	-34.4	22.9	2	0	62	0	2
1994–1995	Lisburne Hills/Noatak/Wulik/Kivalina[c]	Kotzebue[d]	-16.6	9.5	-30.7	28.2	81	17	60	8	2
	Nulato Hills	Unalakleet	-10.6	4.2	-17.9	12.7	9	0	8	0	0
	Kobuk/Selawik/Buckland	Kotzebue	-16.0	4.9	-26.0	91.4	14	0	20	0	0
	Seward Peninsula	Nome	-10.0	3.7	-16.8	101.6	1	0	0	0	0
1999–2000	Lisburne Hills/Noatak/Wulik/Kivalina[c]	Kotzebue[d]	-17.2	6.5	-28.7	7.8	52	6	32	0	0
	Kobuk/Selawik/Buckland	Kotzebue	-16.0	3.7	-23.2	15.2	6	0	8	0	0
	Seward Peninsula	Nome	-9.4	3.4	-16.1	10.2	1	0	2	0	0
	middle Koyukuk	Bettles	-14.4	2.6	-21.7	40.6	0	0	13	0	0
2001–2002	Lisburne Hills/Noatak/Wulik/Kivalina[c]	Kotzebue[d]	-16.6	7.9	-28.7	5.3	62	16	10	5	1
	Kobuk/Selawik/Buckland	Kotzebue	-14.0	3.9	-23.0	17.8	12	0	9	0	0
	Seward Peninsula	Nome	-10.0	3.2	-16.6	15.2	2	0	2	0	0
	central Brooks Range	Bettles	-16.1	2.0	-20.8	45.7	0	0	3	0	0
2002–2003	Lisburne Hills/Noatak/Wulik/Kivalina[c]	Kotzebue[d]	-12.6	7.5	-24.8	10.6	60	9	18	3	1
	Kobuk/Selawik/Buckland	Kotzebue	-11.0	4.1	-18.4	27.9	8	0	4	0	0
	Seward Peninsula	Nome	-6.1	3.9	-11.9	7.6	1	0	0	0	0
	central Brooks Range	Bettles	-13.9	2.2	-19.0	40.6	0	0	4	0	0

[a] 'Winter' defined as 1 Oct–15 Apr.
[b] Weather and snow parameters calculated from daily mean values reported by the National Oceanic and Atmospheric Administration.
[c] Includes area of high caribou mortality in 1994–1995 and 1999–2000 (Dau, in press)
[d] Weather and snow values for this area estimated from Kotzebue weather observations (Allen & Weedfall, 1966).

Table 2. Kruskall-Wallis test statistics for multiple pairwise comparisons of weather parameters estimated[a] for Cape Thompson during years when caribou wintered in this area; an italicized value indicates a statistically significant difference (all n_i = 197 days; all critical values = 80.46; all $P<0.05$).

	Mean rank	Year 1986–1987	1994–1995	1999–2000	2001–2002
Air temperature					
1986–1987	513.5				
1994–1995	435.7	77.73			
1999–2000	451.1	62.40	15.34		
2001–2002	469.9	43.53	34.21	18.87	
2002–2003	594.8	*81.35*	*159.08*	*143.75*	*124.87*
Wind velocity					
1986–1987	552.3				
1994–1995	546.2	6.08			
1999–2000	424.0	*128.22*	*122.14*		
2001–2002	459.4	*92.85*	*86.77*	35.37	
2002–2003	483.1	69.14	63.06	59.08	23.71
Windchill					
1986–1987	494.3				
1994–1995	413.7	*80.62*			
1999–2000	475.1	19.18	61.44		
2001–2002	479.3	15.00	65.62	4.18	
2002–2003	602.7	*108.42*	*189.04*	*127.60*	*123.42*
Snow depth					
1986–1987	467.9				
1994–1995	840.1	*372.20*			
1999–2000	427.3	40.58	*412.77*		
2001–2002	275.1	*192.81*	565.01	*152.23*	
2002–2003	429.4	38.46	*410.66*	2.11	*154.35*

[a] Values estimated from daily means of weather and snow depth measurements recorded in Kotzebue (Allen & Weedfall, 1966).

air temperature, and lower windchill temperature than other wintering areas except for the North Slope in 1986–1987. In each of the five years when caribou were present near Cape Thompson, wind velocity was significantly higher than in any other wintering area (Kruskall-Wallis pairwise comparisons, all $P<0.05$). The relatively deep snow at Cape Thompson in 1994–1995 (28.2 cm) was significantly less than on the Seward Peninsula (101.6 cm) or in the Kobuk–Selawik–Buckland drainages (91.4 cm) where substantial numbers of WAH caribou wintered (Kruskall-Wallis pairwise comparisons, both $P<0.05$).

In only one year (1986–1987) did a wintering area (North Slope) have more days of ≤-40 °C windchill than Cape Thompson. In four of five winters Cape Thompson was the only area that had any days with an average daily windchill ≤-60 °C. Similarly, Cape Thompson tended to experience one to two severe storms each winter based on U.S. Department of Commerce criteria. The North Slope was the only other wintering area that experienced a severe storm (one during 1986–1987). Ironically, the only year Cape Thompson did not experience at least 1 severe storm was 1999–2000. Compared to Kotzebue weather during nine years (1986–1987, 1987–1988, 1988–1989, 1991–1992, 1994–1995, 1995–1996, 1999–2000, 2001–2002, and 2002–2003) when density was >0.8 caribou/km^2 (2.0 caribou/mi^2) in the Kobuk/Selawik/Buckland drainages, winter 1999–2000 at Cape Thompson was not severe by any measure (Kruskall-Wallis multiple pairwise comparisons, all $P<0.05$).

example of typical winter conditions.

Winter weather at Cape Thompson compared to other caribou wintering areas

During each of the five years when caribou were present near Cape Thompson most of the WAH wintered in other portions of its range as well (Table 3).

For each of the five winters I rejected the null hypothesis of 'no difference among wintering areas' for each weather variable (Kruskall-Wallis tests; all n_i = 197 days except for Unalakleet where n_i = 125 days; all $P<0.05$). In all years Cape Thompson experienced higher wind, less snow, lower ambient

Caribou body condition

Many WAH caribou were in relatively poor body

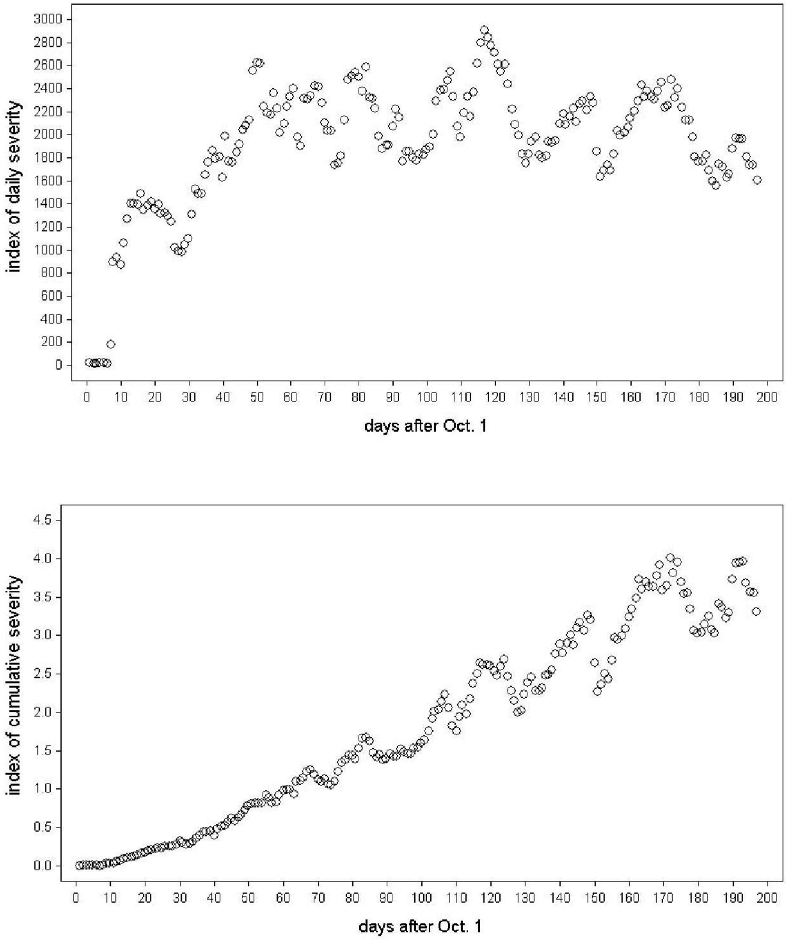

Fig. 2. Daily (top) and cumulative (bottom) indices of winter severity near Cape Thompson, Alaska, 1994–1995.

condition during the September preceding each mortality event. During WAH capture work at Onion Portage we did not begin recording body condition of individual caribou until September 1995. Indeed, the 1994–1995 die-off prompted us to begin recording this information during capture operations; however, we did note that many caribou were in poor condition during September 1994. Additionally, Valkenburg *et al.* (1996) reported body weights of female WAH calves collected in fall 1994 (71.5 lb) were lower than fall 1992 (89.2 lb) and fall 1995 (81.1 lb). Caribou captured at Onion Portage were in poor condition in September 1999 compared to other years (Fig. 4). Although we have no specific information regarding the fall body condition of caribou that wintered near Cape Thompson, there is no reason to believe their condition was substantially different from WAH caribou in other portions of their range.

Effects of winter conditions on muskoxen

Direct observations of muskox and their tracks during winters 1994–1995 and 1999–2000 revealed no unusual behavior: muskoxen were distributed on wind swept ridge tops and exhibited little movement or activity. We located only 1 muskox carcass following the 1994–1995 caribou mortality event, and none following the 1999–2000 event. During a muskoxen census between Cape Krusenstern and Cape Lisburne during June–July 2000, adult mortality appeared normal and calf production was the highest ever observed (30 calves:100 adults).

Discussion

Skoog (1968) noted that caribou are well adapted to northern climes and stated that weather conditions, other than icing events, are unlikely to affect the dynamics of mainland populations. Skoog (1968) further indicated coastal areas are most prone to icing from freezing rain or crusting by freeze-thaw cycles. Icing conditions are most common, and their significance to caribou most pronounced, during late winter and spring when caribou are migrating and females are carrying a near-term fetus. Similarly, Davis & Valkenburg (1985) reported there was no evidence that weather had directly influenced the population dynamics of the WAH since 1960. Reports of weather conditions substantially impacting caribou populations indicate these effects are mostly manifested through high calf mortality especially during parturition (Jackson 1900, 1904, 1906; Banfield, 1954; Kelsall, 1957; all as reported by Skoog, 1968). During a panel discussion regarding the effects of severe storms on caribou at the Tenth North American Caribou Workshop (Girdwood, Alaska, May 2004), each of the four panelists (with extensive experience as big game guides,

Table 3. Distribution of Western Arctic Herd caribou during winters when caribou were present between Cape Lisburne and Cape Krusenstern, northwest Alaska (Dau, 2003).

Year	Wintering area	% of WAH present	Caribou density #/km² (#/mi²)		Approximate number of caribou present	Closest weather station
1986–1987	Lisburne Hills/Noatak/Wulik/Kivalina[a]	12	0.8	(2.0)	33 000	Kotzebue
	Nulato Hills[b]	38	2.9	(7.4)	107 000	Unalakleet
	Kobuk/Selawik/Buckland[c]	38	2.2	(5.7)	107 000	Kotzebue
	North Slope[d]	12	0.8	(2.0)	33 000	Barrow
1994–1995	Lisburne Hills/Noatak/Wulik/Kivalina[a]	8	0.8	(2.2)	36 000	Kotzebue
	Nulato Hills	55	6.7	(17.4)	250 000	Unalakleet
	Kobuk/Selawik/Buckland	26	2.4	(6.3)	119 000	Kotzebue
	Seward Peninsula[e]	6	0.8	(1.9)	30 000	Nome
1999–2000	Lisburne Hills/Noatak/Wulik/Kivalina[a]	9	1.0	(2.6)	43 000	Kotzebue
	Kobuk/Selawik/Buckland	42	4.1	(10.5)	199 000	Kotzebue
	Seward Peninsula	17	2.1	(5.4)	83 000	Nome
	middle Koyukuk[f]	12	1.7	(4.3)	56 000	Bettles
2001–2002	Lisburne Hills/Noatak/Wulik/Kivalina[a]	26	2.9	(7.6)	126 000	Kotzebue
	Kobuk/Selawik/Buckland	22	2.2	(5.7)	108 000	Kotzebue
	Seward Peninsula	30	3.7	(9.6)	148 000	Nome
	central Brooks Range[g]	9	1.3	(3.5)	43 000	Bettles
2002–2003	Lisburne Hills/Noatak/Wulik/Kivalina[a]	7	0.8	(2.2)	37 000	Kotzebue
	Kobuk/Selawik/Buckland	21	2.1	(5.5)	105 000	Kotzebue
	Seward Peninsula	42	5.1	(13.3)	205 000	Nome
	central Brooks Range	13	2.0	(5.2)	65 000	Bettles

[a] 42 841 km² (16 541 mi²); includes area of high caribou mortality in 1994–1995 and 1999–2000.
[b] 37 343 km² (14 418 mi²). [c] 49 024 km² (18 928 mi²). [d] 42 419 km² (16 378 mi²).
[e] 39 979 km² (15 436 mi²). [f] 33 901 km² (13 089 mi²). [g] 32 209 km² (12 436 mi²).

a reindeer herder, subsistence hunters, and a retired biologist) noted that icing conditions were particularly hard on caribou.

The two mortality events reported here are consistent with the literature in that they occurred on the coast of northwest Alaska, and they did not affect the overall population dynamics of the WAH. Although it did not appear freeze–thaw crusts or rain-on-snow had contributed to either event, wind-hardened snow affected caribou as icing would by precluding access to some food and increasing the energetic costs of getting to food that was present.

Wind direction and velocity, and even ambient air temperature to a more limited extent, may change substantially and abruptly as weather fronts move across the earth's surface. Using daily median values to represent weather conditions near Cape Thompson probably underestimated the severity of winter conditions on caribou because they dampened short-term periods of severe conditions that could exceed thresholds for survival (Table 1). This dampening effect is even more pronounced for characterizations of winter severity that calculate an average index over the course of an entire winter.

Two interactions of weather variables probably affected caribou mortality in both events. The first was the interaction between wind and snow. Chronically high wind redistributed snow into valley bottoms where most vegetation was located and packed it to almost the hardness of ice. Compaction of snow by chronically high wind is probably more important to caribou in this area than snow depth. In fact, applying any single measure of snow depth to this area is difficult because exposed ridges are almost

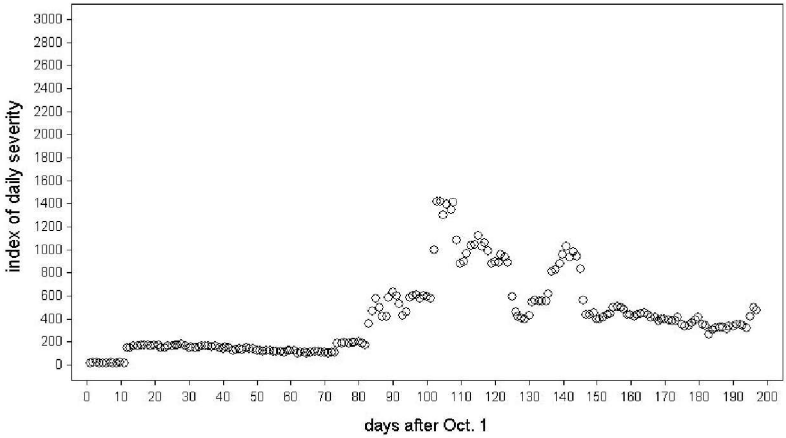

Fig. 3. Daily (top) and cumulative (bottom) indices of winter severity near Cape Thompson, Alaska, 2001–2002.

levels of wind and snow (Table 1), both the daily and cumulative indices of winter severity suggested weather variables acted synergistically to create brutal conditions on multiple occasions during this winter (Fig. 2). In contrast, winter 1999–2000 was not unusually severe by any measure. However, even average conditions near Cape Thompson are more severe than any other portion of WAH range.

The daily and cumulative indices of environmental severity (Figs. 2 and 3) were crude attempts to evaluate weather effects on caribou using a more comprehensive approach than provided by individual weather parameters. In 1994–1995, the daily index visually suggested five or six bouts of severe conditions occurred near Cape Thompson while only two severe storms were identified using U.S. Department of Commerce criteria (Table 1). I plotted each index of severity through time anticipating the cumulative index would be more revealing because it included duration of snow cover as a component of this variable. Surprisingly, neither index appeared clearly superior for evaluating winter severity. The daily index showed more day-to-day variability than the cumulative index because summing snow depth for the latter index tended to dampen the relative contribution of windchill to this value. When plotted through time, both indices at least visually revealed occurrences of severe conditions (as spikes on general trends) more clearly than temporal plots of individual weather parameters or windchill. Such indices may be useful for at least initial, qualitative assessments of winter conditions even if they are not suitable for statistical evaluation. Of course, lacking verification, it is uncertain whether either of these indices actually reflected the severity of weather on caribou.

Two possible explanations for the poor body condition observed during September 1994 and 1999 are

always blown snow-free while valley bottoms and the lee sides of hills are covered in deep, hard drifts almost regardless of how much snow has fallen. Wind-compacted snow reduces access to food and increases the energetic cost of cratering; its effects are chronic and cumulative. Unfortunately, unlike ambient air temperature and wind velocity that were measured through an automated device, no measure of snow hardness was available for these analyses. The second interaction of weather variables was wind and temperature: high wind with low ambient air temperature occasionally created very low windchills. Severely low windchills increase the energetic cost of thermoregulation and subject caribou to the acute effects of exposure.

Weather and snow conditions near Cape Thompson during winter 1994–1995 may have been severe enough to cause high caribou mortality regardless of their body condition. In addition to high median

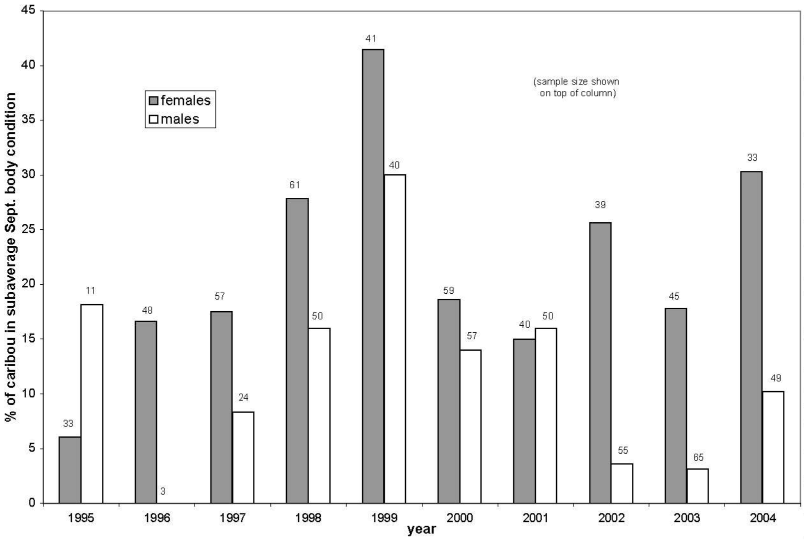

Fig. 4. Percent of Western Arctic Herd caribou in subaverage body condition in September.

1) some combination of food quality or quantity was limiting during each preceding summer (Finstad *et al.*, 2000; Finstad & Prichard, 2000) or 2) insect harassment during these summers prevented caribou from feeding and increased energy demands through avoidance behavior (Dau, 1986). Kelleyhouse (2001) reported that green-up on the WAH calving grounds (which are encompassed within summer range) began late and lagged well into summer during 1994. This likely contributed to the low fall 1994 body weights of female WAH calves reported by Valkenburg *et al.* (1996) compared to 1992 and 1995. During 1999, though, green-up was typical or perhaps even slightly early (Kelleyhouse, 2001). My attempts to model insect activity using Kotzebue and Barrow weather data only showed that these stations are not representative of WAH summer range. To my knowledge, there is no weather data for WAH summer range to evaluate levels of insect harassment. Of course, food limitation and insect harassment can act singly or in combination to influence caribou body condition during summer. Bulls and nonmaternal cows lag behind pregnant cows during the northward spring migration. Therefore, the effects of early summer range condition on body condition likely differ between maternal and nonmaternal caribou. Once mosquitoes (*Aedes* spp.), warble flies (*Hypoderma tarandi*), and bot flies (*Cephenemyia trompe*) emerge during late June, sexual segregation breaks down and most WAH caribou experience similar environmental conditions.

Weather and snow conditions made it virtually impossible to appreciate the magnitude of these mortality events as they were occurring. This is surprising given the number of caribou that died in an area hunted regularly by several communities and traversed multiple times daily by small, commercial airline flights. During each event only a few hunters reported seeing dead or moribund caribou to agency staff, and those who did never saw more than several carcasses per outing. Undoubtedly, drifting snow quickly covered carcasses until summer. Even after public reports alerted ADF&G to the possibility of the 1994–1995 event, it required substantial effort to confirm high mortality had occurred and several additional flights to determine its extent and magnitude. Caribou mortality events in remote portions of Alaska may occur more frequently than commonly thought.

The presence of fat in the bone marrow of some carcasses, the initiation of male mortality by mid-November (before the chronic effects of winter could accumulate) and the clustered distribution of many carcasses suggest exposure during severe storms killed some caribou before the chronic effects of malnutrition were fatal. Mild winters during recent years may partly account for the continued large size of the WAH. If so, several consecutive years of severe winters over the entire range of the WAH following a span of relatively mild weather could have devastating impacts on the size of the WAH especially if they follow poor summers.

Fall migratory movements for WAH caribou usually cease by mid- to late November regardless of where caribou are located on their range. Even so, why did caribou in poor body condition during fall initially settle in an area with relatively little food and harsh conditions rather than move to a better area before perishing? Part of the answer may lie with the 70–80% of caribou in this area that survived these die-offs. Caribou that died may have been unwilling to abandon the relative safety from predators and access to existing feeding craters provided by other caribou for the chance of finding better feeding conditions elsewhere. Rather than abandon a harsh, sparsely vegetated area, caribou wintering near Cape Thompson adopted a 'muskox' survival strategy by gravitating toward Cape Thompson where ridges were snow free. The problem with this strategy was that the ridges held little vegetation and the weather was unforgiving. Unlike muskoxen and the caribou that survived, caribou that died obviously lacked adequate fat to carry them through a period of low food intake. Although caribou have very warm winter fur it is probably not as warm as muskox fur based on the relationship between fur thickness and insulation value (Schmidt-Nielson, 1975); additionally, caribou body structure is probably not as conducive to heat retention as muskox. My observations during both die-offs suggest caribou in this area were more active than muskoxen as they searched for food.

Even though these mortality events were insignificant to the size or trend of the WAH population, they still had management implications. The North Slope Borough Department of Wildlife Management (NSB), ADF&G, University of Alaska and, in 2000, NANA/Teckcominco (which operates the Red Dog Mine) spent substantial time and money assessing the scope, magnitude, and causes of these mortality events which impinged on other work.

The most serious implications of these die-offs were social and focused on environmental contamination and trust rather than caribou mortality per se. During summer many caribou carcasses were visible to residents of Point Hope and Kivalina. Many people interpreted the high concentration of carcasses near Cape Thompson as evidence they had died of radiation poisoning from a controlled experiment in which soil was intentionally contaminated during Project Chariot (O'Neill, 1994). Some people were concerned that heavy metals from the Red Dog Mine had contaminated the Wulik River and poisoned caribou.

Although all evidence strongly suggested the caribou had starved (O'Hara *et al.*, 1999, 2003) and substantial effort was made to convey these findings to residents of the region, many people were convinced that contaminants had contributed to or caused these caribou die-offs and suspected results to the contrary were either inaccurate or misleading. Their concern was that the caribou they depend on for sustenance were unfit to eat. Residents of Point Hope and Kivalina have long held that the Atomic Energy Commission and other organizations associated with Project Chariot during the late 1950s and early 1960s were not forthright regarding potential effects of radiation on resources and people (see also O'Neill, 1994). This perceived deceit is now part of the regions' oral history. Additionally, the transition from traditional subsistence activities to the complex resource management system in place today did not engender local confidence in agency staff. Obviously, the good-faith response by agencies to investigate these mortality events was not enough to overcome the legacy of distrust local residents have harbored for decades regarding government agencies.

Conclusions

1. Environmental conditions at Cape Thompson were consistently harsher than other WAH wintering areas.
2. Winter 1994–1995 was unusually severe near Cape Thompson compared to other years when caribou wintered in this area. In contrast, winter 1999–2000 was not severe by any indication.
3. Many WAH caribou began winters 1994–1995 (see also Valkenburg *et al.*, 1996) and 1999–2000 in poor body condition. This probably predisposed them to high mortality under severe conditions. The 1999–2000 event suggested conditions were sufficiently harsh near Cape Thompson to kill caribou in poor condition even during a typical year.
4. During each event, snow densely compacted by chronically high wind and low windchills may have acted synergistically to kill caribou during severe storms before malnutrition was fatal.
5. Muskoxen behavior and mortality within the caribou mortality area appeared unaffected by winter conditions during 1994–1995 and 1999–2000.
6. Residents of the area were not convinced that caribou had starved during either mortality event despite gross characteristics of carcasses and laboratory analyses of tissues. Solid science was not enough to overcome long-held concerns regarding the veracity of management agencies.
7. Establishing remote weather stations on WAH summer and winter range would greatly facilitate understanding the effects of weather on the population dynamics of this herd. Besides improving our understanding of basic caribou biology and facilitating management, a more complete picture of weather conditions throughout the range of this herd could alleviate public concerns regarding environmental contaminants or other issues perceived to be important.
8. The effects of weather on caribou populations are difficult to quantitatively assess. Lags among seasons, and perhaps even years, between when weather occurs and when its effects are manifested on caribou confound results. Additionally, the effects of weather on caribou are cumulative and synergistic. Acute weather-snow conditions that may kill moribund caribou are not reflected in annual or perhaps even daily measurements of conditions. Indices of environmental severity, both on a daily and long-term basis, that integrate the effects of snow depth, duration of snow cover, snow

hardness, wind and temperature, would facilitate understanding the effects of weather on caribou.

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