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Recent changes in seasonal variations of climate within the range of northern caribou populations

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Abstract: The Arctic is one region where it is expected that the impacts of a globally changing climate will be readily observed. We present results that indicate that climate derivatives of potential significance to caribou changed during the past 50 years. Many temperature derivatives reflect the increasing overall temperature in the Arctic such as decreases in the number of days with low temperatures, increases in the number of days with thaw, and days with extremely warm temperatures. Other derivatives reflect changes in the precipitation regime such as days with heavy precipitation and number of days when rain fell on snow. Our results indicate that specific caribou herds from across the Arctic were subjected to different variations of these derivatives in different seasons in the recent past. Examination of temperature and precipitation at finer time-steps than annual or monthly means, shows that climatic variations in the region are neither consistent through the seasons nor across space. Decadal changes in seasonal patterns of temperature and precipitation are shown for selected herds. A process for assessing caribou-focused climate derivatives is proposed.

Key words: climate, derivatives, *Rangifer tarandus*.

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Introduction

Many studies have reported increases in Arctic temperatures during the later portion of the 20th century (McBean *et al.*, 2004). Such changes have potential impacts on both the ecosystems and the people who inhabit these regions. Many of the studies have focused on changes in mean annual temperature of the Arctic regions (Polyakov *et al.*, 2002a, b). Recently, studies have begun to examine the general warming of the Arctic by examining changes in finer detail. Some studies focus on seasonal changes (Polyakov *et al.*, 2002b), some on spatial changes (Polyakov *et al.*, 2003), and others on decadal changes in fine seasonal features (Whitfield *et al.*, 2004). While such climatological studies increase our confidence in the magnitude and distribution of the changes in temperature and precipitation taking place, they are not always directly transferable into ecological impacts.

Animals and plants adapted to the Arctic have evolved to accommodate seasonal and spatial variations in climate. For thousands of years, caribou (*Rangifer. tarandus*) herds have moved across individual ranges in the Arctic, congregating for calving in spring, rutting in fall, and distributing themselves across the range during the winter. The movements, while not necessarily driven by climate, are clearly linked in a manner that allows caribou to be successful as a species. However, changes in climate have the potential to present energetic challenges at key stages in the annual cycles of these nomadic animals. Such changes will also impact those people dependent on caribou for their lifestyle (Eamer *et al.*, 1997).

Climatologists and modelers have demonstrated considerable success in resolving climatic variations when averaged across time and space. We know with a high degree of certainty that the temperature of the earth has increased by 1.5 °C in the past 100 years (IPCC, 2001). This has been confirmed by analysis of observational data (Mann *et al.*, 1999) and the outcomes of global climate models (e.g., IPCC, 2001). At the other extreme, individual organisms live on finite portions of the earth and are subjected to day-to-day changes in weather at a scale where climatologists and global climate models do not excel.

It appears almost paradoxical that warmer temperatures would be detrimental to an Arctic species such as caribou. Two important climate-related habitat features that influence caribou are the occurrence of snow and the prevalence of insects (Gunn & Skogland, 1997). Any changes that make foraging more difficult on a consistent basis would impact caribou energetics (Russell *et al.,* 1993). Almost all climate models project more precipitation in a greenhouse future, particularly in the Arctic. The Arctic is dry, receiving an average of 4 cm of precipitation annually, mostly in the form of snow. Models suggest that doubling the levels of greenhouse gases in the atmosphere could cause a 30–50% increase in Arctic snowfall (Russell, 1993). During periods of heavy snow, caribou must expend considerable energy foraging for the lichen (Russell & Martell, 1984). Decreased forage availability under deep snow cover has been associated with high calf mortality (Adamczewski *et al.*, 1988). A deeper winter snow pack may also increase vulnerability to predation because wolves may travel on snow crusts that caribou would sink through (Brotton & Wall, 1997) or concentrate caribou in regions where wolves are abundant. The carry-over effects of poor winter conditions include low calf birth weight and subsequent calf survival (Skogland, 1984).

Increased summer temperatures are correlated with increased insect harassment on caribou resulting in decreased feeding times during the critical post-calving period (Russell *et al.*, 1993). Bad insect years can have impacts on fall body condition which in turn impacts weaning strategies, decreased probability of pregnancy (Cameron & Ver Hoef, 1994), early intra-uterine loss in lactating females (Russell *et al.*, 1998) and overwinter calf survival (Clutton-Brock & Albon, 1990).

Ecologists and climatologists may benefit from convergence of their independent but obviously related perspectives. If the ecological impacts of climate variations take place at fine time and space scales important to ecologists, then climatologists need to converge towards this reality. In the present study, we explore the potential for convergence by linking zonal trends and fine scale decadal variations in temperature and precipitation to selected herds of caribou in the Arctic.

Methods

For this analysis we selected 4 herds that are representative of different regions in the north: the Porcupine caribou herd (PCH) in western North America, the George River Herd east of Hudson Bay, the Queen Elizabeth island "group," representative of high arctic conditions and the Taimyr Herd in Russia.

The climatological information presented here was derived from 2 global Arctic databases described by Groisman *et al.* (2003) and Whitfield *et al.* (2004) from climate observation sites in all countries in the Arctic. Climate derivatives are simple forms based on the temperature and precipitation data obtained from individual climate sites. Groisman *et al.* (2003, 2004) assessed trends in daily climate derivatives: rain on snow; days of thaw, extremely warm days and cold nights, and days with "heavy" precipitation. They report trends in all these for derivatives that are consistent with warming of the Arctic climate in winter and spring. Whitfield *et al.* (2004) assessed recent patterns of decadal shifts in temperature and precipitation from observations from the circumpolar arctic. They describe spatial areas where climate variations between decades were consistent. These clusters of stations are described in detail in that paper. Here we examine the shift-pattern of those clusters that overlap the range of the 4 caribou herds being considered. In this first stage we chose to compare only a limited set of the interactions between herds and the shifts in climate, limiting our consideration to only 2 temperature shift-patterns and 3 for precipitation shift. Finally, we consider evidence that climate is affecting the distribution of the Porcupine caribou herd.

Zonal climate derivatives are estimates of the series of annual or seasonal occurrence of climatic derivatives. The results are a weighted measure of the frequency of events that can be directly calculated from daily climate observations, and provide a robust measure of changes in these types of events. While differences between these series exist with respect to magnitude and directions of shifts, Groisman *et al.* (2003, 2004) show that significant trends for a variety of measures exist that are consistent with those expected from models of climate that include increasing CO_2.. The number of days with rain on snow is used as an example of those zonal trends. Rain on snow is simply the count of the number of days with precipitation when temperatures were above zero and snow was present on the ground. These simple algorithms are based on the climatic record alone, and not confirmed by comparison with local weather conditions.

Seasonal variations were assessed using the method described by Whitfield *et al.* (2004) where temperatures for 11-day intervals (33 periods per year) and precipitation for 5-day intervals (73 periods per year) were compared between the 2 decades 1976–85 and 1986–95. Results for individual stations were clustered based on the probability of a shift in the variables with the annual time span. Whitfield *et al.* (2004) showed that these shifts in seasonal pattern are spatially homogenous in different areas within the Arctic; and different regions in the Arctic have changed in different ways.

Determining the distribution of the Porcupine caribou herd in winter during years of deep or shallow snow conditions and in spring during years of early and late snowmelt was based on satellite locations of collared cows. The locations were analyzed using kernel analysis to produce utilization density grids for the 4 classes (deep/shallow snow and early/late spring). The proportional use by caribou in polygons representing community hunting was calculated within ArcView by dividing the total use in a polygon compared to the total use of all polygons. The variance of use among years was determined using jackknife analysis. We conservatively concluded that polygons were significantly different with respect to caribou use if the 95% confidence intervals did not overlap. See McNeil *et al.,* this volume for a more detailed description of the methodology

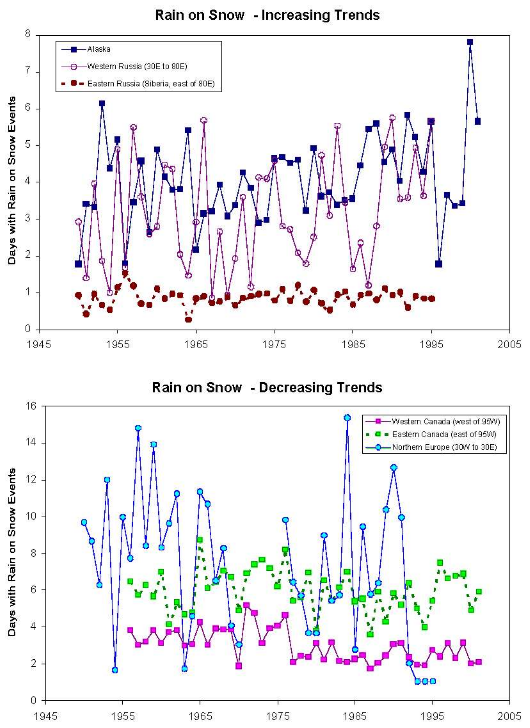

Fig. 1. Number of days with rain on snow events from 1950 to 2000. Zonal averages were calculated using the method described by Groisman *et al.* (2003, 2004). Upper panel shows zones where rain on snow events are increasing, lower panel zones with decreases.

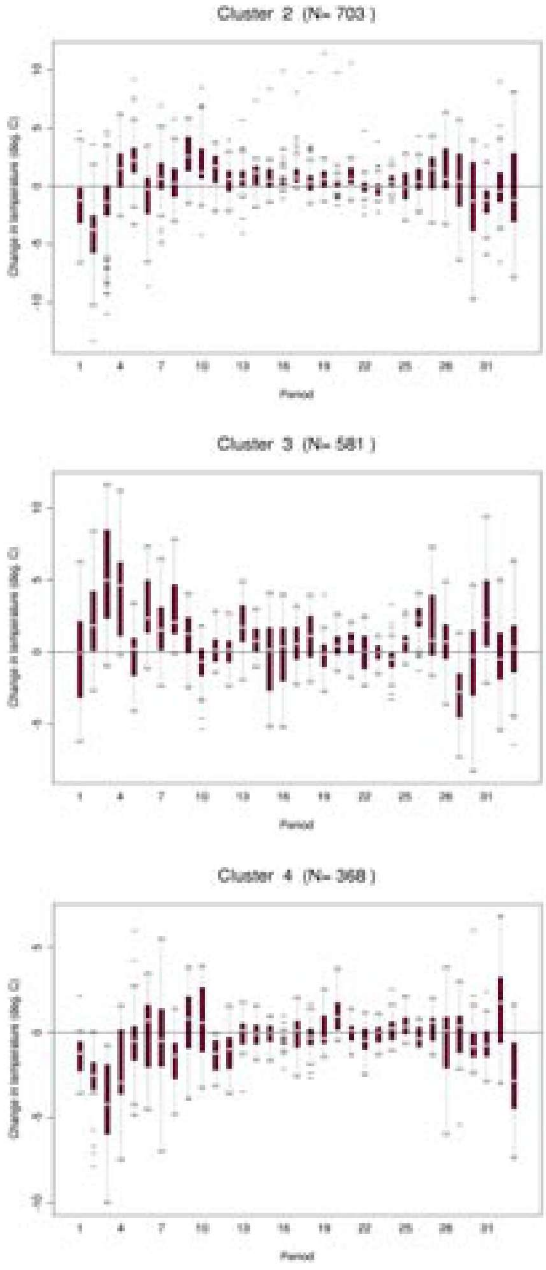

Fig. 2. Patterns of 11-day period decadal temperature shifts for clusters that correspond to the caribou herds described in the text. Numbering of temperature clusters is based on those described by Whitfield *et al.* (2004), and N indicates the number of observational stations within that cluster.

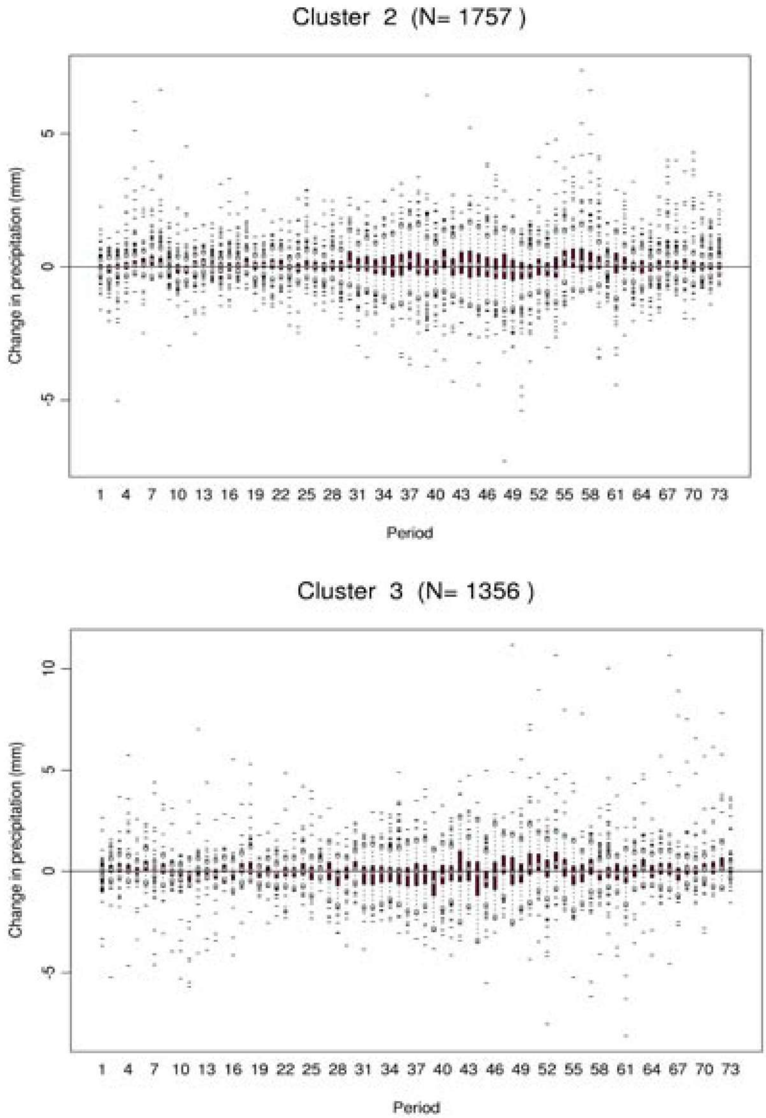

Fig. 3. Patterns of 5-day period decadal precipitation shifts for clusters that correspond to the caribou herds considered. Numbering of precipitation clusters is based on those described by Whitfield *et al.* (2004), and the N indicates the number of observational stations within that cluster.

Results

The frequency of rain on snow events in 6 zones of the circumpolar Arctic are shown in Fig. 1. Increases in the frequency of rain on snow events were observed in Alaska, Eastern and Western Russia, while decreasing trends were observed in Northern Europe, and Eastern and Western Canada over the period 1950–2000 (Fig. 1). While Groisman *et al.* (2004) report that this shift was more pronounced in the south than the north, the large differences between these broad regions shows strong regional differences, in frequency, in variability and in the direction of change. For example, in Eastern Russia, rain on snow events are infrequent with a zonal average of approximately one event per year and generally low variability, while the highest frequency of occurrence is in Northern Europe where the range (6–15) and variability is much larger.

The decadal shifts in temperature and precipitation in clusters that contain observation stations within or adjacent to the range of the 4 caribou herds are shown in Figs. 2 and 3. Fig. 2 shows the 3 temperature shift-patterns. For example, temperatures in cluster "T2," which represents the ranges of the Porcupine caribou herd and the Queen Elizabeth Island caribou herds, were warmer during much of the winter in recent decades except for late December and early January when significant cooling was observed. Significant mid winter warming was observed in cluster "T3" (representing the Taimyr Herd range), while in "T4" the George River Herd faced significant winter cooling during December and January.

Changes in precipitation may differ both in the shift-pattern and the seasonal pattern (Fig. 3). In "P2," precipitation occurred throughout the year and there has been a significant decrease during the late summer period and an increase during fall and winter. This pattern is common to the Taimyr, Eastern Queen Elizabeth Islands and eastern range of the George River herds. In "P3," precipitation was more focused in the summer months, the largest changes occurred between the decades during this period. There have been significant, albeit small, increases in

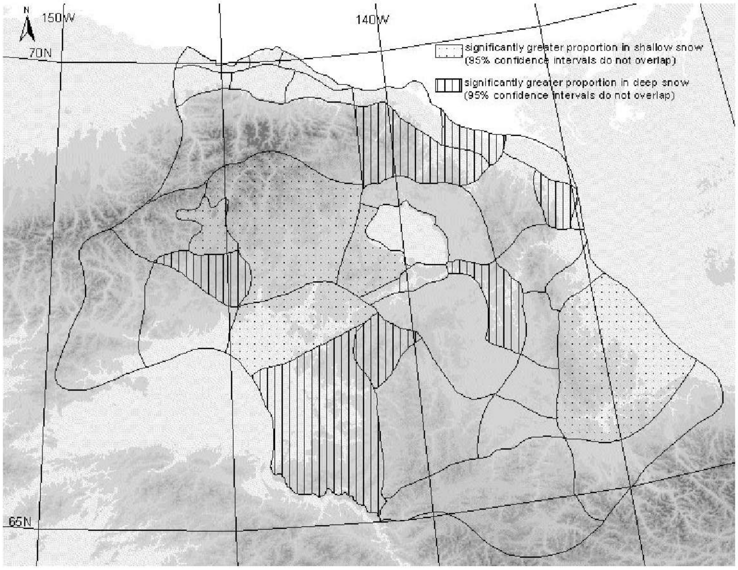

Fig. 4. Distribution of satellite tracked-female caribou in the Porcupine caribou herd during winters with heavy snowfall (stripes) and light snowfall (dots). Polygons represent hunting zones for nearby communities.

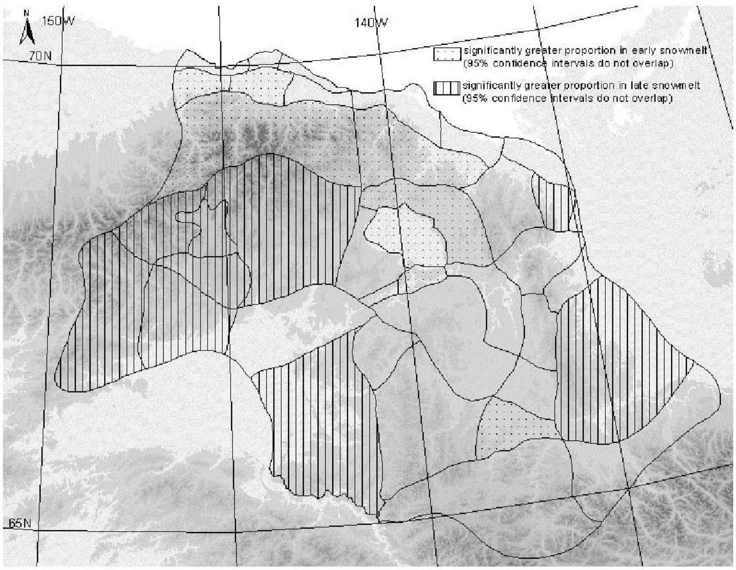

Fig. 5. Timing of spring migration for female caribou in the Porcupine Herd between winters with early snowmelt (dots) and late snowmelt (stripes). Polygons represent hunting zones for nearby communities.

precipitation during winter within the ranges of the Porcupine and western George River herds, although there is generally little winter precipitation within the range of the Porcupine caribou herd.

Distribution of caribou of the Porcupine Herd appears to be sensitive to variations in climatic conditions (Figs. 4 and 5). Female caribou distribute themselves differently between heavy snowfall years and light snowfall years (Fig. 4). During heavy snowfall years the herd tended to be more scattered occupying regions with low snow accumulation such as the Richardson Mountains (a windy region with many snow free ridges) and the Ogilvie basin (lies in a snow shadow of the Ogilvie Mountains; Russell *et al.*, 1993). When snowmelt was early, the females moved north towards the calving ground sooner than when snowmelt was late (Fig. 5).

Discussion

Climate derivatives indicate that most areas in the Arctic have many fewer extremely cold days, and more extremely warm days, and that these are occurring throughout the year. Such changes are indicative of the general warming predicted for the Arctic (Polyakov *et al.*, 2002a, b, 2003). Groisman *et al.* (2003, 2004) report on zonal analysis that assesses annual series derived from observed records. They assessed the frequency of extremely warm and cold days within an annual series by counting the number of days within a year that are 2 standard deviations greater than the mean for that day [for warmer] or less that 2 standard deviations below the mean [for colder]. The "heavy" precipitation derivative is a count of the days per year when the amount of precipitation is greater than 2 standard deviations of the annual precipitation. The number of days of thaw is the total number of days when the mean temperature is above zero. All these derivatives show trends consistent with this warming pattern, such as the number of thaw days, decreases in extremely cold days and increases in extremely warm days (Groisman *et al.*, 2003). Figure 1 illustrates one climate derivative, rain on snow events, and the zonal differences in frequency, variability, and trend. Although these results and those of Groisman *et al.* (2003, 2004) are statistically robust, they are spatially very coarse and the

Table 1. *Rangifer tarandus* seasonal activity, climate and snow derivatives important during each season and the implications for *R. tarandus* based on dates for the Porcupine caribou herd.

Rangifer "stage"	Time period	Climate derivatives[a]	Snow derivatives[b]	Implications to *Rangifer*
Calving	1 Jun–30 Jun	Late spring temperatures; winter snow depth	Thawing degree days	Stall migration; delayed calving; poor post-calving forage quality; higher initial calf mortality.
Autumn	15 Sep–1 Oct	Rain on frozen ground	Basal icing	Forage unavailable; major distribution shifts.
Early winter	1 Dec–30 Jan	Heavy snow		Trade-off between energy intake *vs.* energy output; feeding times decrease; cratering times increase.
			Internal icing	Energy cost of cratering increases.
Late winter	10 Feb–30 Mar	Heavy snow		Shift to more open terrain; delay initiation of spring migration.
			Internal icing	Energy cost of cratering increases.
Spring migration	1 Apr–30 May	Rain on snow icings	Surface icing	Impacts timing of spring migration; increase energy cost of foraging; shift to wind-blown ridges; more susceptible to predation.

[a] Climate derivates are typically counts of numbers of events and have no memory.
[b] Snow derivatives are measures of persistence that contain memory.

zones extend over large areas, and for broad seasonal periods. Climatologists use "annual" or "seasonal" to represent period longer than the response time of individual animals, and do not reflect critical life stages. For example, the effect of a rain on snow event during calving may have a direct effect, while an early winter event might impact winter feeding success. In addition these derivatives are "transplanted" from southern areas where they provide insight into social, economic, and ecological impacts of a general nature. They can be used as an indicator of tendency, but not relative to direct impacts on a single species such as caribou. To assess the direct and indirect effects of such events requires analysis to be done on climate derivatives at time and space scales appropriate to the animal.

Our results show that daily climate derivatives are changing in the Arctic and that these changes have potential for impacting caribou. Different areas of the Arctic are exhibiting different recent variations in temperature and precipitation, some areas with warmer winters, some with cooler, and some with a combination. Similarly, different areas of the Arctic have different precipitation regimes and different patterns of recent change. At the scale of our 4 caribou herds, shifts in seasonal patterns in temperature and precipitation are unique to each herd. The Porcupine and Eastern Queen Elizabeth Island herds were exposed in recent periods to warmer temperatures in early winter, with cooler temperatures in January, and warmer temperatures in the April, May, June and July (Fig. 2, T2). The Taimyr Herd was subjected to cooler temperatures in November and warmer temperatures in December through June (Fig. 2, T3). The George River Herd was cooler throughout the entire period from December through May (Fig. 2, T4). These temperature shifts have varying magnitudes with some changes in some individual periods being greater than 5 °C (e.g., late January for the Taimyr Herd, Fig. 2, T3).

Precipitation shift-patterns are much more complicated, and less easily described. The landscapes used by the Taimyr Herd, the Eastern Queen Elizabeth Island Herd, and the eastern portion of the George River Herd have increased precipitation during much of the year although predominantly during winter, with increased variability (Fig. 3). The Porcupine and western portion of the George River herds have greater amounts of precipitation in July through September. The differences between these 2 alone could have impacts on caribou because higher precipitation in autumn has potential for icings that persist through the winter, while increased precipitation through the winter may reflect deeper accumulations of snow. These results are persistent across a decade, so although they cannot be used to infer the direct impact on an annual basis they suggest that the members of these herds could be subject to persistent changes.

Caribou appear sensitive to climatic features, as reflected in their distribution and timing of movement. The results presented here illustrate that the Porcupine Herd responds to deep snow by distributing itself differently under conditions of deep snow versus shallow snow and also by distributing differently if the spring snow melt begins early or late. Because the range of the Porcupine caribou herd generally has low winter precipitation, it might be more sensitive to variations in snow accumulation than herds where larger winter snow accumulations are common.

Although there appear to be links between the behavior of caribou and climatic conditions, we should reconsider how to assess climatic variations from the perspective of caribou herds. Climate derivatives suggest that conditions potentially unfavorable to caribou are becoming more common, such as rain on snow events, extreme warm temperatures during winter and the amount of winter snowfall. Griffith *et al.* (2002) indicated that the recent decline in the Porcupine caribou herd might be related to the documented increase in freeze-thaw events during spring migration. We expect that the linkages would be clearer if we could develop climate derivatives associated with a "caribou domain," keying in on life stages that have sensitivity to specific weather/climate events while maintaining the robust statistical attributes of zonal derivatives. We are pursuing such derivatives linking specific time periods, defined by caribou life stages, and coupled with specific new derivatives that relate to features impacting on caribou during those periods. We are exploring 2 types of climate derivatives. One type is similar to existing climate derivatives in that they are simply counts of events or occurrences. The second type is a "snow derivative" that accounts for short-term persistence. This allows us to deal with a variety of conditions that are critical for the formation of ice within the snowpack, such as diurnal temperature fluctuations, a series of warm days, and rainfall on cold snow. Internal icings are formed when either rain on snow takes place or warm temperatures and water move from the surface into the snowpack before freezing at a layer. Basal icings are formed when rain freezes on frozen ground, snow on frozen ground melts and refreezes, or rain on thin snow forms a high water content frozen later at the ground surface. Surface icings are formed by surface melting without percolation into the snow pack, by snow metamorphosis that may be wind-driven or as the product of solar radiation. Table 1 contains a summary of the seasonal activity of caribou using time periods for the Porcupine caribou herd (Russell *et al.*, 1993), and the climate and snow derivatives that will be assessed based on key implications for *Rangifer* during each period.

Conclusions

The preliminary results presented here indicate that there have been recent changes in climate derivatives that are of general significance in the Arctic, and that different herds of caribou have been subjected to different seasonal changes in precipitation and temperature. The Porcupine Herd shows sensitivity to snow accumulations and melting and this sensitivity may have implications to caribou availability for harvest by communities within the range of the herd. New climate and snow derivatives that may be more relevant to stages of the caribou seasonal cycle are proposed. Finally, a process to shift the study of climate and snow derivatives to a scale relevant to individual herds is needed.

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