Ecological Applications, 19(5), 2009, pp. 1365–1375
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Loss of Arctic sea ice causing punctuated change in sightings of killer whales (*Orcinus orca*) over the past century

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Abstract. Killer whales (*Orcinus orca*) are major predators that may reshape marine ecosystems via top-down forcing. Climate change models predict major reductions in sea ice with the subsequent expectation for readjustments of species' distribution and abundance. Here, we measure changes in killer whale distribution in the Hudson Bay region with decreasing sea ice as an example of global readjustments occurring with climate change. We summarize records of killer whales in Hudson Bay, Hudson Strait, and Foxe Basin in the eastern Canadian Arctic and relate them to an historical sea ice data set while accounting for spatial and temporal autocorrelation in the data. We find evidence for "choke points," where sea ice inhibits killer whale movement, thereby creating restrictions to their Arctic distribution. We hypothesize that a threshold exists in seasonal sea ice concentration within these choke points that results in pulses in advancements in distribution of an ice-avoiding predator. Hudson Strait appears to have been a significant sea ice choke point that opened up approximately 50 years ago allowing for an initial punctuated appearance of killer whales followed by a gradual advancing distribution within the entire Hudson Bay region. Killer whale sightings have increased exponentially and are now reported in the Hudson Bay region every summer. We predict that other choke points will soon open up with continued sea ice melt producing punctuated predator–prey trophic cascades across the Arctic.

Key words: Arctic; change point; choke point; climate change; distribution; Hudson Bay, Canada; killer whale; Orcinus orca; *predation; sea ice; subarctic.*

INTRODUCTION

Killer whales (*Orcinus orca*) have been implicated as major ecosystem modifiers creating trophic cascades as a result of ecosystem perturbations that include human commercial whaling (Estes et al. 1998, Springer et al. 2003, 2008; but see DeMaster et al. 2006, Trites et al. 2006). Killer whales typically exist at highest densities in temperate waters that offer greater primary productivity where they consume a wide variety of prey items, including fish and marine mammals (Ford 2002). In many regions, different ecotypes show exclusive specialization to certain prey items. For example, in the eastern North Pacific the "transient" ecotype preys exclusively on marine mammals, whereas the "resident" ecotype preys exclusively on fish (Ford 2002). Killer whales may move into northern waters as sea ice disappears and as top predators may initiate major ecosystem adjustments, becoming major players in the reorganization of Arctic oceans currently undergoing global warming.

The killer whale is poorly known in the Canadian Arctic; Reeves and Mitchell (1988) provides the only comprehensive review of the species in the eastern Arctic (but see Higdon 2007 for an update). Killer whales were historically present in Davis Strait and Baffin Bay and were often reported in bowhead (*Balaena mysticetus*) whaling logbooks. However the species appears to be a recent arrival to the Hudson Bay region (Fig. 1), and early authors had no evidence of killer whales there (Degerbøl and Freuchen 1935). Davis et al. (1980) suggested sporadic occurrence, and Reeves and Mitchell (1988) concluded that some killer whales possibly entered Hudson Strait and Hudson Bay on an annual basis. Inuit knowledge suggests killer whales were not present prior to the mid-1900s but are now observed on a regular basis (Gonzalez 2001).

Hudson Bay, Hudson Strait, and Foxe Basin (the Hudson Bay region) are located in the eastern Canadian Arctic. Hudson Bay is a fairly shallow (mean depth ~150 m) and large (1.23×10^6 km^2) estuarine system connected to the Labrador Sea through Hudson Strait (300–900 m depth, 65–240 km width). North of Hudson Bay, Hudson Strait also connects the Arctic Archipelago to the Labrador Sea through Fury and Hecla Strait (~160 km long, 16–24 km wide) and Foxe Basin, a broad shallow basin generally less than 100 m deep. The region exhibits Arctic oceanographic and sea ice conditions much farther south than anywhere else along the North American continent (Stewart 2000).

Manuscript received 27 November 2007; revised 20 June 2008; accepted 2 September 2008; final version received 7 October 2008. Corresponding Editor: K. Stokesbury.

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Ice cover in Hudson Bay undergoes a complete cryogenic cycle each year, with freeze-up typically occurring in late October and November and breakup usually complete by the first week of August. There is significant interannual variability (Crane 1978, Markham 1986) depending on ice thickness and weather (Drinkwater 1986). Sea ice usually persists in Hudson Strait throughout the year (Gough and Houser 2005), and killer whales may have historically been prevented from entering Hudson Bay because of this. Ice-adapted Arctic and subarctic marine mammals in the region include five species of seals (ringed, *Pusa hispida*; bearded, *Erignathus barbatus*; harbor, *Phoca vitulina*; harp, *Pagophilus groenlandica*; hooded, *Cystophora cristata*), Atlantic walrus (*Odobenus rosmarus rosmarus*), polar bears (*Ursus maritimus*), and three species of whales in addition to killer whales (narwhal, *Monodon monoceros*; beluga whale, *Delphinapterus leucas*; bowhead whale) (Stewart and Lockhart 2005).

Climate change is expected to be most pronounced at high latitudes and a pattern of decreased ice extent is apparent throughout the Northern Hemisphere (Parkinson and Cavalieri 2002, Overpeck et al. 2005). As a relatively low-latitude inland subarctic sea with Arctic characteristics, Hudson Bay is one of the areas in which the rate and degree of climatic warming is predicted to be greatest (Parkinson 2000, Gough and Wolfe 2001, Comiso 2003). Some climate change scenarios suggest an ongoing climate shift toward steady near ice-free conditions at the end of this century (Boer et al. 2000, Overpeck et al. 2005, IPCC 2007). In Hudson Bay both the extent and duration of sea ice has decreased in recent decades (Parkinson and Cavalieri 2002, Houser and Gough 2003, Gough et al. 2004, Stirling et al. 2004, Gagnon and Gough 2005). These declines been implicated in changes in fish communities (Gaston et al. 2003) and negative effects on seabirds, ringed seals, and polar bears (Stirling et al. 1999, Gaston et al. 2002, 2005, Ferguson et al. 2005, Stirling and Parkinson 2006).

Tynan and DeMaster (1997) suggested that the effects of declining sea ice are likely to be initially reflected by shifts in marine mammal range and abundance. Killer whales in the Canadian Arctic sometimes hunt along ice edges and leads (Reeves and Mitchell 1988) but typically avoid heavy ice concentrations. Declining sea ice may be allowing killer whales to penetrate farther into the Arctic environment and stay for longer periods of time. Here we report on the recent increase in killer whale sightings in the Hudson Bay region and examine how changes in sea ice concentration may have affected movements and distribution (also see Melnikov et al. 2007). The distribution of islands in the Arctic (vs. the Antarctic's one island) creates points of ice blockage (i.e., choke points; Wilson et al. 2004) that could result in punctuated adjustments of killer whale distribution in Arctic waters. In particular, we test whether Hudson Strait has been a choke point restricting access to Hudson Bay by killer whales and that recent sea ice loss has reversed this situation. We examined correlations between the frequency and distribution of sightings and sea ice concentration to determine if declining sea ice is related to killer whales being seen both more often and farther west into Hudson Bay.

METHODS

We conducted a survey of the available literature on killer whale sightings in the Hudson Bay region, including peer-reviewed studies, consulting reports, newspapers and government documents. We also contacted northern researchers, tour operators, conservation officers, Hunters and Trappers Organizations (HTO), and local residents to collect reports of killer whale sightings. Scientists and technicians with Fisheries and Oceans Canada (DFO) in Quebec, Nunavut, and Manitoba and staff at both the Ontario Ministry of Natural Resources and Makivik Corporation (managers of the Nunavik Land Claim) were also surveyed for sighting reports. Higdon (2007) provides more detail on how killer whale sightings are being collected and compiled throughout the eastern Arctic region (also the Appendix for more information). All killer whale reports were used regardless of data quality provided they could be accurately assigned to the correct region. Collected sighting reports are of varying quality, and some provide estimates of the number of whales observed, whereas others do not. In our analyses, group sizes were not used, just the number of sightings, so all records could be included.

Hay et al. (2000) discussed changes in community structure in the eastern Arctic and suggested that, at least since the 1960s, sighting effort has remained fairly constant. The assumption includes a trade-off between increased human population, greater use of nontraditional methods of travel (i.e., more efficient travel via motorized boats) that provide greater distances traveled against less actual time on the water (i.e., fewer traditional hunters and more weekend trips) and fewer individuals spending large amounts of time on the water. We therefore assumed that sighting frequency is an effective proxy for changes in abundance and/or distribution over time. Killer whale sightings were assigned to one of eight subregions. The Foxe Basin (FB), Hudson Bay, Hudson Strait, and James Bay-eastern Hudson Bay (JB-EHB) ecoregions were defined based on Stewart and Lockhart (2005). Hudson Bay and Hudson Strait were each further subdivided into three subregions (Fig. 1, Table 1) to facilitate comparisons with other studies that have examined sea ice trends in this region (see *Discussion*). We used an information-theoretic approach to test whether changes in sightings over time increased linearly or nonlinearly (i.e., exponentially) by selecting the regression model with the lowest AIC_c (Burnham and Anderson 1998).

We explore recent declines in sea ice as a potential factor in increased killer whale presence in the Hudson

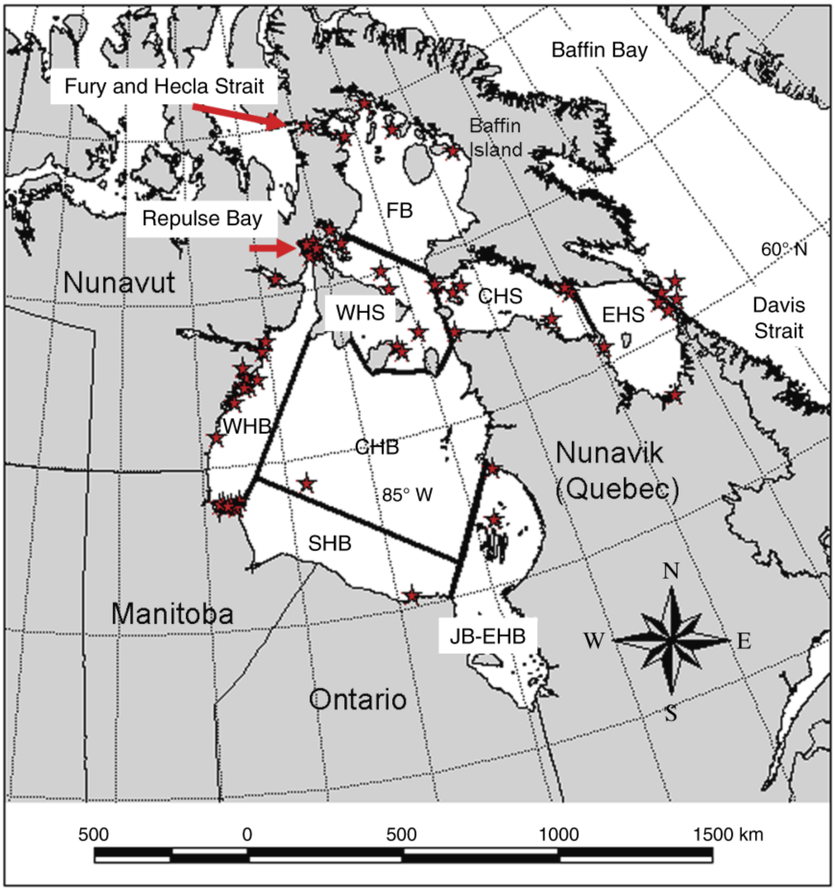

FIG. 1. Locations of killer whale (*Orcinus orca*) sightings ($n = 67$ sightings) in the Hudson Bay region in eastern Canada, with boundaries for the eight defined subregions (see Table 1 for names of subregions identified for sea ice analyses) and 5° lines of latitude and longitude. The figure excludes killer whale reports from 2006 ($n = 12$, all in WHB), which were removed from the analyses of sea ice relationships to reduce bias. Also shown are three additional records in Davis Strait east of Hudson Strait but just outside the study area.

Bay region. July sea ice concentration (%) data for 1900–2006 were extracted from the Met Office Hadley Centre for Climate Prediction and Research sea ice and sea surface temperature (SST) data set, HadISST1 (Rayner et al. 2003; data *available online*).[4] These data are a unique combination of monthly median, globally complete fields of SST and sea ice concentration on a 1° latitude × 1° longitude grid. July was used as this is the month when killer whales are first seasonally reported in Hudson Strait (see Higdon 2007). For each subregion, unweighted median July ice concentration was calculated for each year using complete 1° grid cells only.

Autocorrelation in the yearly ice coverage was calculated for all eight regions out to 26 years (i.e., 106/4) to assess whether there was a repeating pattern in ice concentration within a region. An analysis of covariance (ANCOVA) was used to examine the influence of subregion (main effect) and year (covariate) on spatial variation in median ice concentration. Trends in sea ice cover for each region were examined using least squares regressions and were expressed as the percentage of change per year over the entire 106-yr period, with a measure of fit provided by the coefficient of determination (r^2; Parkinson 2000, Comiso 2002, Moore and Laidre 2006). Change-point analyses (Siegel and Castellan 1988) were used to determine if (and when) significant changes in ice concentration occurred. Analyses were conducted for the different subregions using five-year moving averages (1902–2004) to reduce outliers. Change-point analyses required a subsampling routine because analyses of the complete data set violated the necessary assumption of independent errors (Taylor 2000).

We used Spearman correlation coefficients to examine impacts of sea ice conditions in Hudson Strait on killer whale sighting frequency. First we correlated the total number of killer whale sightings per decade with median decadal ice concentration. Second we examined how the western distributional limit (i.e., farther into

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[4] ⟨http://hadobs.metoffice.com/hadisst/data/download.html⟩

TABLE 1. Monthly/seasonal distribution of killer whale (*Orcinus orca*) sighting reports in the eight subregions defined for this study (1900–2006).

	Number of sighting reports								
Region	Jul	Aug	Sep	Oct	Dec	Summer	Fall	Unspecified	Total
Eastern Hudson Strait (EHS)		2	2						4
Central Hudson Strait (CHS)	3	1		1			1		6
Western Hudson Strait (WHS)	5	1	1			2		1	10
Foxe Basin (FB)		2			1	1		4	8
Western Hudson Bay (WHB)	6	22	2			13		4	47
Central Hudson Bay (CHB)		1							1
Southern Hudson Bay (SHB)								1	1
James Bay-eastern Hudson Bay (JB-EHB)						1		1	2
Total	14	29	5	1	1	17	1	11	79

Note: Three sighting reports at the eastern mouth of Hudson Strait, but just outside the study area, are excluded.

Hudson Bay) was correlated with median ice concentration. This was tested using Spearman correlations between median decadal sea ice concentration for each of the three Hudson Strait subregions and the maximum longitude of sightings per decade. Starting in 2006, there was a concerted effort to collect killer whale sighting reports (Higdon 2007; J. W. Higdon, *unpublished data*), and the number of records for this year may be biased upwards in comparison to previous years. We therefore excluded 2006 sightings from the Spearman correlations to have a less-biased test of sighting frequency vs. sea ice.

RESULTS

In total, we collected 79 reports of killer whale sightings (see the Appendix). These sightings were widely distributed throughout the Hudson Bay region, with another three records (from Reeves and Mitchell 1988) at the eastern end of Hudson Strait but just outside the study area (Fig. 1). In total, 38 reports were found in published sources (newspaper articles, consulting reports, government documents, and scientific papers), and 22 of these were from Reeves and Mitchell (1988). The majority of sightings ($n = 41$) were gathered through personal communications with northern residents, government employees, scientists/researchers, and ecotourism operators. A total of 45 sightings were post-1987 (i.e., the time frame not covered by Reeves and Mitchell 1988), and we also found seven pre-1987 reports that were not included by those authors. Twelve sightings (all from WHB) occurred in 2006, when the authors and other researchers made extensive efforts to collect reports. To reduce bias these sightings were removed from analyses of temporal trends. Four sightings did not provide the decade and were also excluded from sea ice analyses.

Since 1900, the number of killer whale sightings per decade has increased exponentially (Fig. 2; $r^2 = 0.75$, $F_{1,9} = 26.31$, $\text{AIC}_\text{c} = -11.40$; vs. a linear increase, $r^2 = 0.62$, $F_{1,9} = 14.47$, $\text{AIC}_\text{c} = 32.38$). Early sightings were mostly limited to Hudson Strait, with the first Hudson Bay records occurring in the 1940s and most since the 1960s. Killer whales appear to be rare in SHB and JB-EHB, with the majority of sightings occurring in WHB (Figs. 1 and 2, Table 1). The lack of offshore records (CHB, $n = 1$) is likely a function of observer effort (the one sighting was reported by a wildlife observer program for oil and gas development; Milani 1986). Killer whales are first reported in Hudson Strait in July, and reports in Hudson Bay peak in August (Table 1). Whales have also been reported as late as December (an ice entrapment in FB; Reeves and Mitchell 1988). A number of reports noted season only or provided no season (Table 1; but were still included in sea ice analysis as they could be assigned to the proper decade).

Trends in median ice concentration over time were significantly negative ($P < 0.0001$) for FB (–0.45% per year), EHS (–0.60%), CHS (–0.80% per year), and WHS (–0.24% per year) explaining 24–74% of variation (Table 2). The biggest declines in July sea ice concentration occurred in the three Hudson Strait subregions, and of these the largest decline occurred in CHS (Fig. 3). Sea ice trends in the three Hudson Bay subregions were

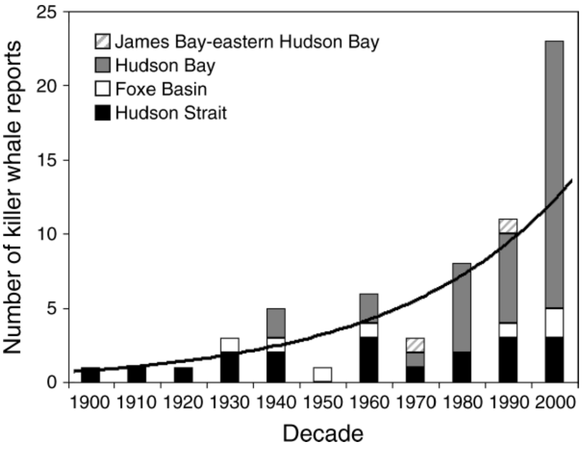

FIG. 2. Number of killer whale reports per decade, subdivided into the four ecoregions of Stewart and Lockhart (2005). Four records with no date information are excluded (one in Foxe Basin and three in Hudson Bay), and 12 sightings from 2006 also excluded to reduce bias associated with increased effort to collect sighting reports. An exponential line is fitted to the total number of sightings 1900–2004 ($r^2 = 0.75$).

TABLE 2. Trends in median July sea ice concentration over time, 1900–2004, for eight areas within the Hudson Bay region.

Region	Area†	Trend (% per yr)	r^2	P
Foxe Basin	39	−0.45	0.74	<0.0001
James Bay-eastern Hudson Bay	24	+0.04	0.02	0.197
Western Hudson Bay	39	−0.03	0.01	0.302
Southern Hudson Bay	18	−0.08	0.03	0.062
Central Hudson Bay	47	−0.06	0.03	0.077
Eastern Hudson Strait	14	−0.60	0.61	<0.0001
Central Hudson Strait	19	−0.80	0.71	<0.0001
Western Hudson Strait	19	−0.24	0.36	<0.0001

† Number of 1° latitude × 1° longitude grid cells.

negative but weak (−0.03% to −0.08% per year) with the best fit regressions accounting for only 1–3% of the total variation (all not significant; Table 2). Sea ice trends in JB-EHB were weakly positive (+0.04% per year) but not significant.

There was significant year-to-year correlation in the sea ice time series among subregions, with the highest autocorrelation coefficients for FB ($r = 0.84$–0.27) and the three Hudson Strait subregions (autocorrelation coefficients ranging from 0.74 to 0.13 for EHS, 0.87 to 0.20 for CHS and 0.56 to 0.10 for WHS). Values for Hudson Bay and James Bay were considerably lower (0.36 to −0.2 for JB-EHB; 0.34 to −0.23, 0.23 to −0.13, and 0.35 to −0.15 for WHB, SHB, and CHB, respectively). Median ice concentration varied significantly with subregion (ANCOVA, df = 7, $F_{1,7} = 73.83$, $P < 0.0001$), and the interaction between subregion and year was also significant (df = 7, $F_{1,7} = 70.40$, $P < 0.0001$). Spatial correlation between subregions was highest for adjacent regions, and most pronounced for the FB and Hudson Strait subregions (Table 3).

The change-point analyses detected significant changes in sea ice concentration for all three Hudson Strait subregions. Both CHS and WHS were subsampled every five years, but for EHS it was necessary to subsample every 10 years to meet the requirement of an independent error structure. In the EHS subregion, a significant change was detected in 1962, when sea ice concentration declined from 56% to 25% (but note the wide confidence intervals, Table 4). In CHS, two significant changes occurred, in 1937 when concentration declined from 75% to 42%, and in 1957 when concentration declined again from 42% to 16%. Both of these changes were characterized by small confidence intervals of one-year each (i.e., highly likely to have occurred that year). Three significant changes were detected for WHS: in 1912 ice concentration increased slightly, and then declined from 43% to 38% in 1942 and from 38% to 21% in 1977. All three Hudson Strait subregions showed significant declines between the late 1930s and 1970s. Results are not shown for the three Hudson Bay regions or JB-EHB as there were no significant sea ice declines. Change-point analysis was not conducted for FB because the data were in violation of the necessary assumption of independent errors (see Taylor 2000).

We found support for the influence of declining sea ice on killer whale distribution. Decadal median ice concentrations for all three Hudson Strait subregions were significantly negatively correlated (Spearman correlation coefficients) with both the number of killer whale sightings reported per decade and the maximum western longitude of sightings per decade (Table 5). The relationship between longitude and sea ice concentration was most pronounced in CHS (Fig. 4), where sea ice declines have been greatest (linear fits, $r^2 = 0.71$, $P = 0.001$ for EHS; $r^2 = 0.70$, $P = 0.001$ for CHS; $r^2 = 0.53$, $P = 0.011$ for WHS). As sea ice

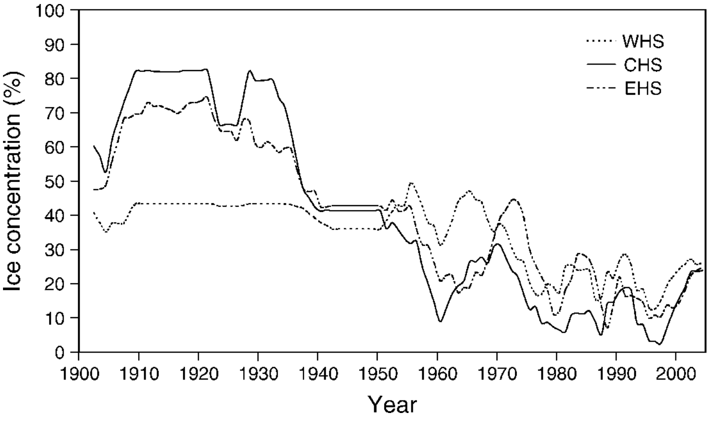

FIG. 3. Five-year moving averages of median ice concentration (calculated as unweighted mean of all complete 1° latitude × 1° longitude grids per subregion) for western (WHS), central (CHS), and eastern (EHS) Hudson Strait, 1902–2004.

TABLE 3. Spatial correlations (r) of July sea ice concentration values between subregions, 1900–2004, for the eight regions used in this study.

Region	FB	JB-EHB	WHB	SHB	CHB	EHS	CHS
Foxe Basin (FB)							
James Bay-eastern Hudson Bay (JB-EHB)	−0.043						
Western Hudson Bay (WHB)	0.117	0.137					
Southern Hudson Bay (SHB)	0.179	0.436*	0.381*				
Central Hudson Bay (CHB)	0.296*	0.563*	0.251*	0.682*			
Eastern Hudson Strait (EHS)	0.753*	−0.128	0.217*	0.266*	0.163		
Central Hudson Strait (CHS)	0.829*	−0.087	0.042	0.206*	0.225*	0.862*	
Western Hudson Strait (WHS)	0.755*	0.215*	0.165	0.417*	0.544*	0.554*	0.675*

* $P < 0.05$.

concentration declined in Hudson Strait, killer whales have been reported more often and farther west into Hudson Bay.

DISCUSSION

Previous authors have shown a progression in killer whale use of the Hudson Bay region, from no evidence (Degerbøl and Freuchen 1935), to sporadic occurrence (Davis et al. 1980), to occasional and possibly annual use (Reeves and Mitchell 1988). In this paper, we summarize the most extensive collection of sighting records of killer whales in Hudson Bay, Hudson Strait, and Foxe Basin, and show that sightings have increased exponentially, to the extent that this species now occurs in Hudson Bay on an annual basis. Killer whale use of the region has intensified considerably, especially in WHB. This increase is significantly related to a decline in sea ice in Hudson Strait, suggesting that declining ice cover has influenced killer whale distribution.

In this study, sample sizes are small, but this is not surprising given the likely low number of killer whales and the vast distances they can travel in short time periods (e.g., Lyrholm 1988, Visser 1999). For 48 records here with data (including seven 2006 WHB records that were not included in the sea ice analysis but are included in the Appendix), reported group sizes ranges from one to 20 (mean 5, median 3), suggesting the presence of multiple small groups or one large fluid association characterized by temporary immigration and emigration. Inuit local knowledge reports similar group sizes, and many hunters believe the same whales return every year (S. Ferguson, *unpublished data*). We suspect that killer whales in the Hudson Bay region remain numerically few, and this, coupled with high movement rates, limits sighting reports.

We assume that sightability of killer whales has remained largely constant over time (cf. Hay et al. 2000), although numerous changes have occurred. Travel mode may have more of an effect than noted here, as faster travel methods today (outboard motors vs. kayaks) may in fact make killer whales more difficult to see as transit time is reduced. We cannot test this assumption; however any changes in sightability due to faster travel also may be balanced by the increased coverage these faster methods allow. We assume that growing Inuit populations providing more observers are balanced by an increase in wage employment and reduced numbers of full-time hunters on the water. Even if sighting effort has remained constant, reporting and recording effort

TABLE 4. Results of change-point analyses for three Hudson Strait subregions, completed using five-year moving averages of sea ice concentration from 1902 to 2004.

Region†	Year	CI	Confidence level (%)	Ice cover change		Level‡
				From	To	
EHS	1962	1932, 1972	95	56%	25%	2
CHS	1937	1937, 1937	96	75%	42%	2
CHS	1957	1957, 1957	96	42%	16%	2
WHS	1912	1912, 1912	92	39%	43%	3
WHS	1942	1942, 1942	90	43%	38%	2
WHS	1977	1977, 1977	99	38%	21%	1

Notes: Change in ice cover is expressed within a year; e.g., in 1962, sea ice concentration declined from 56% to 25%. Confidence intervals are calculated using a bootstrapping technique provided in Efron and Tibshirani (1993) (see Taylor 2000), and measure (with 95% confidence) how well the time of the change has been pinpointed. Wider confidence intervals (e.g., for the 1962 change in EHS) indicate that the time (i.e., exact year) of the change cannot be accurately identified.

† Every fifth year subsampled for CHS and WHS regions; every 10th year subsampled for EHS region (to meet requirements of independent errors).

‡ Indicates number of passes through the data set before change is identified (i.e., level 1, first pass through the data set, and strongest change in data).

TABLE 5. Spearman correlation coefficients between decadal median ice concentration for each of the three Hudson Strait subregions and (A) the total number of killer whale sightings per decade, 1900–2005, and (B) the maximum western longitude of killer whale sightings per decade, throughout the entire Hudson Bay region.

Region	r_S	t	df	P
A) Number of sightings per decade ($n = 11$ decades)				
EHS	−0.863	−5.12	9	<0.001
CHS	−0.751	−3.41	9	<0.001
WHS	−0.742	−3.32	9	0.009
B) Maximum western longitude of sighting per decade ($n = 11$ decades)				
EHS	0.925	7.29	9	<0.001
CHS	0.875	5.41	9	<0.001
WHS	0.747	3.37	9	0.008

varies among different communities and collection efforts have been heterogeneous (see Higdon 2007).

Less-effective reporting of killer whales occurs in Ontario and Nunavik. However, local knowledge suggests that killer whale abundance in these areas is low. Cree residents along the Ontario coast report seeing killer whales "very occasionally" and that they are more common further west (C. Chenier, *personal communication*). Ontario Cree do not have a word for killer whale (Johnston 1961), suggesting that these sporadic observations are a recent phenomenon. In Nunavik, researchers have heard incidental reports of occasional killer whale sightings, but there has been no systematic data collection (B. Doidge, *personal communication*; J.-F. Gosselin, *personal communication*). This local knowledge again suggests low frequency of sightings in comparison to communities in western Hudson Bay. However, we did collect several recent reports from Nunavik communities on Hudson Strait after these analyses were completed.

None of the four Hudson Bay/James Bay subregions showed significant declines in July sea ice since 1900. Other studies have found significant trends towards earlier ice breakup and later freeze-up since the 1970s (Stirling et al. 1999, 2004, Gagnon and Gough 2005, Stirling and Parkinson 2006). Since 1900, July ice concentration has increased slightly in the JB-EHB subregion, but not significantly. Stirling et al. (2004) reported a statistically insignificant trend for the same area, and Stirling and Parkinson (2006) found a weak, nonsignificant trend toward earlier breakup in eastern Hudson Bay (1978–2004). However Gagnon and Gough (2005) found a statistically significant trend toward earlier breakup in James Bay and southern Hudson Bay. Gough et al. (2004) defined a southwestern Hudson Bay study area, similar to our SHB, with a significant increase in the length of the ice free season since 1971. Our longer time frame relative to previous studies may explain this discrepancy as our results may be less sensitive to more recent accelerated changes associated with climate warming (Walther et al. 2002). We did not define a separate subregion for eastern Hudson Bay but included it with James Bay in the JB-EHB ecoregion (Stewart and Lockhart 2005). Killer whale observations are rare there (see Fig. 1), which may be due to reduced prey populations, as the area harbors no narwhal, none or few bowheads, and significantly smaller beluga whale densities relative to WHB (Stewart and Lockhart 2005).

Repulse Bay is located in the northwest corner of WHB, adjacent to the western end of WHS. In recent years this has become a "hotspot" for killer whale reports in the Hudson Bay region (see Fig. 1). The first killer whale sighting there occurred in the 1940s (Gonzalez 2001) and they are now observed on an annual basis (Higdon 2007). Repulse Bay typically reaches open-water conditions later than other areas in

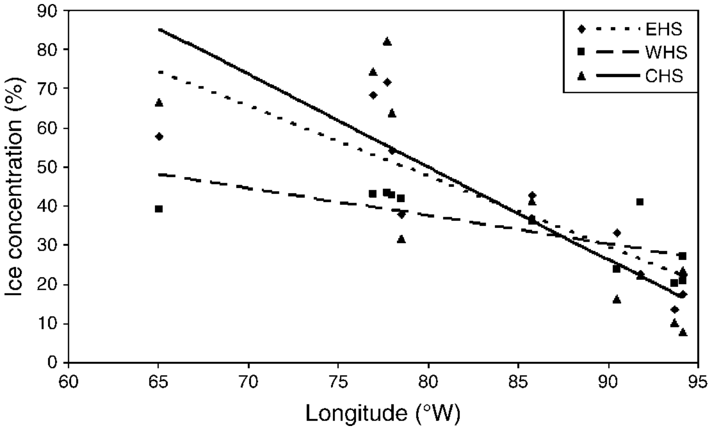

FIG. 4. Relationship between maximum western longitude of killer whale sighting per decade and median decadal sea ice concentration in the three Hudson Strait regions.

WHB or WHS because it receives ice from FB (Stewart and Lockhart 2005). Yet this area contains the most sighting reports, despite Arctic killer whales being considered pagophobic. Repulse Bay may be a focal area for killer whales because of greater overall productivity and the high diversity of potential marine mammal prey species. Northwestern Hudson Bay is an area of high productivity, centered on the Roes Welcome Sound polynya (Stirling 1997), and occupied by large numbers of marine mammals, including bowheads (both historically and again now with population recovery from past commercial harvesting) and narwhal. Local Inuit have observed killer whales predating marine mammals but not fish (S. Ferguson, *unpublished data*).

The HadISST1 sea ice data set (Rayner et al. 2003) was used here because it extends further back temporally than data used in other studies (e.g., satellite data available since the 1970s). However it has lower spatial resolution than other data sets. The primary purpose of HadISST1 is to force global-scale general circulation models (GCMs) in the simulation of recent climate and for evaluating coupled atmosphere-ocean models. For the northern hemisphere ice data, HadISST1 used the "Walsh" data set (Walsh 1978, Walsh and Johnson 1978, Walsh and Chapman 2001) for 1901–1995 as the main data source, updated using satellite-based data after 1978. The ice data for the Northern Hemisphere are directly comparable to the Walsh data (Rayner et al. 2003) and thus provide the most accurate and temporally complete record of large-scale sea ice concentrations over the last century.

We found a significant reduction in July sea ice concentration throughout Hudson Strait. The biggest declines have occurred in CHS, which we postulate to be a choke point that historically restricted killer whale access to Hudson Bay. Timing of complete ice retreat for Hudson Strait varies from late June to mid-August (Crane 1978, Houser and Gough 2003). The opening of the choke point in CHS in the late 1930s predates Canadian Ice Service (CIS) data, which started in 1968 (Wilson et al. 2004), and is the data set most often used by researchers studying recent changes in ice conditions (e.g., Houser and Gough 2003, Gough et al. 2004, Gagnon and Gough 2005, Gough and Houser 2005). Most studies are limited to a relatively narrow time period and most examine dates of spring breakup and fall freeze-up, not summer ice conditions as assessed here. Compared to WHB, we have few records for Hudson Strait, which may due to several factors. Killer whales may make relatively rapid movements through Hudson Strait to reach WHB, where summertime prey densities are higher (Richard et al. 1990, Fisheries and Oceans Canada 1998). This would reduce the likelihood of local residents observing killer whales. However differences in reporting are also a factor, and improved monitoring in additional communities will undoubtedly add more records. During the past several summers, killer whales have been seen attacking beluga in Hudson Strait, and Nunavik Inuit have reported increased sightings (J. Peters, *personal communication*).

Hudson Strait may not be the only important sea ice choke point in the region. Another possibility is Fury and Hecla Strait, connecting FB with the Gulf of Boothia and the central Arctic. Bowhead whales travel north through Fury and Hecla Strait as sea ice breaks up in FB (Dueck et al. 2006), possibly to lower the risk of killer whale predation. We reported significantly fewer sightings in FB than in WHB, despite northern FB being an important early summer nursery area for bowhead whales (Cosens and Blouw 2003). However, after these analyses were completed we initiated a project to document Inuit traditional knowledge (*Inuit Qaujimajatuqangit*) of killer whales in Nunavut, and have conducted 23 interviews in the two FB communities (S. H. Ferguson and J. W. Higdon, *unpublished data*). Observations in FB are more frequent than reported here, and recently killer whales have been observed in most years, generally in August. Local Inuit hunters have also reported sightings of killer whales moving north through Fury and Hecla Strait.

Locations of satellite-tagged bowhead whales suggest that they adjust their distribution based on ice conditions and prefer areas with heavy ice cover (L. Dueck, *personal communication*). The loss of this predator-avoidance habitat may result in changing bowhead distribution and/or increased predation pressure. Killer whale attacks on bowhead whales have been reported throughout the study area (Hay et al. 2000, Higdon 2007; J. W. Higdon, *unpublished data*). With further sea ice declines in FB bowhead whales, particularly calves, may become more vulnerable to killer whale predation. Recent studies have suggested that killer whales are not important predators of large whales (Mizroch and Rice 2006, Mehta et al. 2007). However predation on large whales may occur more often than many suppose but is simply not often observed by scientists (also see Doak et al. 2006, Springer et al. 2008). Local hunters in FB spend their lives observing marine mammals and they have seen killer whale attacks and found dead bowheads. Inuit observers report that attacks on bowhead occur regularly in FB.

Regardless of the potential biases involved in using sighting reports, there is reasonably good evidence that killer whales were historically not present in Hudson Bay. A long history of European presence started in 1610, with over 600 voyages into Hudson Bay by the early 1900s (Cooke and Holland 1978), and a large volume of literature is available. However we know of no mention of killer whale sightings previous to the 20th century. All of the "typical" marine mammals in the Hudson Bay region were known prior to the 19th century (e.g., Pinkerton and Doyle 1805). Degerbøl and Freuchen (1935) traveled extensively in the area from 1921 to 1924, conducting surveys and having many discussions with local Inuit. They knew of no evidence of killer whales in Hudson Bay, and were told by Inuit that the whales were turned around in Hudson Strait by the presence of walrus, which they avoid (also see Higdon 2007). Degerbøl and Freuchen (1935) felt that sea ice represented a more likely barrier to movement. We agree with this and suggest that declining sea ice conditions are the most reasonable explanation for recent killer whale colonization of the Hudson Bay region.

Unlike terrestrial ecosystems that show greater productivity at low latitudes, marine ecosystems are most productive at temperate latitudes (Smetacek and Nicol 2005). Here, the ubiquitous top predator is the killer whale. As global warming shifts the temperate waters to higher latitudes, we can expect greater importance of killer whales as a top-down ecosystem force. Although controversial (Trites et al. 2006), killer whales have been linked to declines in marine mammal prey populations (Estes et al. 1998, Springer et al. 2003). Our results suggest that killer whales will extend their influence in a nonlinear trend as warming waters open up sea ice regions of the Arctic according to large-scale landscape patterns such as straits that act as choke points. Another potential choke point is Viscount-Melville Sound, typically blocked by multi-year ice, which has opened and closed to bowhead whale movements in the past (Dyke et al. 1996).

The distribution pattern we have outlined is characterized by slow temporal change and a restricted spatial pattern. July sea ice concentration throughout Hudson Strait had declined to 50% or less by the late 1930s, soon before the first Hudson Bay records are available. However killer whales did not begin to appear on a regular (perhaps yearly) basis until the 1980s. We suggest that one or several groups of killer whales began to make initial sporadic forays into western Hudson Bay, and their presence increased as (1) declines in midsummer ice conditions continued with earlier break-up and later freeze-up (Stirling et al. 1999, 2004, Gagnon and Gough 2005, Stirling and Parkinson 2006) and (2) with greater opportunities for predation of the high marine mammal prey diversity. We postulate that reduced sightings in other regions, compared to WHB, are related to reduced marine mammal prey diversity and density for south and east Hudson Bay and reduced reporting for Hudson Strait and FB.

These analyses have shown a significant negative correlation between sea ice and killer whale sighting frequency (also see Melnikov et al. 2007). This suggests that Arctic killer whales, which are considered to be pagophobic, are increasing their distribution as more open water becomes available. Several other factors may be responsible for the increase in sightings, including improved reporting, population growth, and changes in prey distribution. We consider the increase in sighting frequency to not be a by-product of improved reporting for reasons noted above. Population recovery after commercial whaling ended in 1972 is a possibility, as both Norwegian and Canadian whalers took killer whales in the Canadian Arctic (Higdon 2007). Killer whales may also be shifting their distribution in response to changing prey populations. There is widespread opinion among residents of Foxe Basin that killer whale increases are linked to an increasing bowhead population (J. W. Higdon, *unpublished data*). Nonetheless, declining sea ice has been a major factor in the changing distribution of killer whales in the Hudson Bay region.

Assuming that future predictions from climate–sea ice models prove correct, we predict more killer whale sightings in the Hudson Bay region and a range expansion farther into the Canadian Arctic Archipelago arriving both from the east and the west. The marine mammal community in the Hudson Bay region is ice-adapted with polar bear–seal as predator–prey being the dominant trophic relationship. The increase in killer whales may be the first sign of an ecological shift where, as sea ice declines further, polar bears are replaced as the dominant marine mammal predator. Predation on other cetaceans such as belugas and narwhal may increase significantly in the future if killer whales become the dominant marine predator in the Hudson Bay ecosystem. A prediction of an ice-free Hudson Bay would signal a marked change to the marine-mammal community as well as the subsistence culture of local Inuit.

Acknowledgments

This research was funded by ArcticNet, Fisheries and Oceans Canada, Natural Sciences and Engineering Research Council, Nunavut Implementation Fund, and the Nunavut Wildlife Research Trust Fund. Sea ice data were provided by the Met Office Hadley Centre. We thank the large number of people who have provided reports of killer whale sightings, and B. Doidge, C. Chenier, J.-F. Gosselin, and J. Peters for discussion on killer whales in Nunavik and Ontario. Helpful comments were provided by E. Chmelnitsky and H. Cleator, and two anonymous reviewers provided excellent advice and suggestions for improvement.

Literature Cited

Boer, G. J., G. M. Flato, and D. Ramsden. 2000. A transient climate change simulation with greenhouse gas and aerosol forcing: projected climate change in the 21st century. Climate Dynamics 16:427–450.

Burnham, K. P., and D. R. Anderson. 1998. Model selection and inference: a practical information-theoretic approach. Springer-Verlag, New York, New York, USA.

Comiso, J. C. 2002. A rapidly declining perennial sea ice cover in the Arctic. Geophysical Research Letters 29:1956. [doi: 10.1029/2002GL015650]

Comiso, J. C. 2003. Warming trends in the Arctic from clear sky satellite observations. Journal of Climate 16:3498–3510.

Cooke, A., and C. Holland. 1978. The exploration of northern Canada 500 to 1920: a chronology. Arctic History Press, Toronto, Ontario, Canada.

Cosens, S. E., and A. Blouw. 2003. Size and age class segregation of bowhead whales summering in northern Foxe Basin: a photogrammetric analysis. Marine Mammal Science 19:284–296.

Crane, R. G. 1978. Seasonal variations of sea ice extent in the Davis Strait–Labrador Sea area and relationships with synoptic-scale atmospheric circulation. Arctic 31:434–447.

Davis, R. A., K. J. Finley, and W. J. Richardson. 1980. The present status and future management of arctic marine mammals in Canada. Science Advisory Board of the Northwest Territories. Yellowknife, Northwest Territories, Canada.

Degerbøl, M., and P. Freuchen. 1935. Mammals. Volume II, No. 4–5, Report of the fifth Thule expedition 1921–24. Gyldendalske Boghandel, Nordisk Forlag, Copenhagen, Denmark.

DeMaster, D. P., A. W. Trites, P. Clapham, S. Mizroch, P. Wade, R. J. Small, and J. Ver Hoef. 2006. The sequential megafaunal collapse hypothesis: testing with existing data. Progress in Oceanography 68:329–342.

Doak, D. F., T. M. Williams, and J. A. Estes. 2006. Great whales as prey: using demography and bioenergetics to infer interactions in marine mammal communities. Pages 231–244 *in* J. A. Estes, D. P. DeMaster, D. F. Doak, T. M. Williams, and R. L. Brownell, Jr., editors. Whales, whaling, and ocean ecosystems. University of California Press, Berkeley, California, USA.

Drinkwater, K. F. 1986. Physical oceanography of Hudson Strait and Ungava Bay. Pages 237–264 *in* I. P. Martini, editor. Canadian inland seas. Elsevier, Amsterdam, The Netherlands.

Dueck, L. P., M. P. Heide-Jørgensen, M. V. Jensen, and L. D. Postma. 2006. Update on investigations of bowhead whale (Balaena mysticetus) movements in the eastern Arctic, 2003–2005, based on satellite-linked telemetry. Canadian Science Advisory Secretariat Research Document 2006/050. Fisheries and Oceans Canada, Ottawa, Ontario, Canada.

Dyke, A. S., J. Hooper, and J. M. Savelle. 1996. A history of sea ice in the Canadian Arctic Archipelago based on postglacial remains of the bowhead whale (*Balaena mysticetes*). Arctic 49:235–255.

Efron, B., and R. Tibshirani. 1993. An introduction to the bootstrap. Chapman and Hall, New York, New York, USA.

Estes, J. A., M. T. Tinker, T. M. Williams, and D. F. Doak. 1998. Killer whale predation on sea otters linking oceanic and nearshore ecosystems. Science 282:473–476.

Ferguson, S. H., I. Stirling, and P. McLoughlin. 2005. Climate change and ringed seal (*Phoca hispida*) recruitment in western Hudson Bay. Marine Mammal Science 21:121–135.

Fisheries and Oceans Canada. 1998. Hudson Bay narwhal. Stock status report E5-44. DFO Science, Fisheries and Oceans Canada. ⟨http://www.dfo-mpo.gc.ca/csas/Csas/status/1998/E5-44e.pdf⟩

Ford, J. K. B. 2002. Killer Whale, *Orcinus orca*. Pages 669–676 *in* W. F. Perrin, B. Wursig, and J. G. M. Thewissen, editors. Encyclopedia of marine mammals. Academic Press, San Diego, California, USA.

Gagnon, A. S., and W. A. Gough. 2005. Trends in the dates of ice freeze-up and breakup over Hudson Bay, Canada. Arctic 58:370–382.

Gaston, A. J., H. G. Gilchrist, and J. M. Hipfner. 2005. Climate change, ice conditions and reproduction in an Arctic nesting marine bird: Brunnich's Guillemot (*Uria lomvia* L.). Journal of Animal Ecology 74:832–841.

Gaston, A. J., J. M. Hipfner, and D. Campbell. 2002. Heat and mosquitoes cause breeding failure and mortality in an Arctic nesting seabird. Ibis 144:185–191.

Gaston, A. J., K. Woo, and J. M. Hipfner. 2003. Trends in forage fish populations in northern Hudson Bay since 1981, as determined from the diet of nestling Thick-billed Murres *Uria lomvia*. Arctic 56:227–233.

Gonzalez, N. 2001. Inuit traditional ecological knowledge of the Hudson Bay narwhal (*Tuugaalik*) population. Department of Fisheries and Oceans, Iqaluit, Nunavut, Canada.

Gough, W. A., A. R. Cornwall, and L. J. S. Tsuji. 2004. Trends in seasonal sea ice duration in southwestern Hudson Bay. Arctic 57:299–305.

Gough, W. A., and C. Houser. 2005. Climate memory and long-range forecasting of sea ice conditions in Hudson Strait. Polar Geography 29:17–26.

Gough, W. A., and E. Wolfe. 2001. Climate change scenarios for Hudson Bay, Canada, from general circulation models. Arctic 54:142–148.

Hay, K., D. Aglukark, D. Igutsaq, J. Ikkidluak, and M. Mike. 2000. Final report of the Inuit traditional bowhead knowledge study. Nunavut Wildlife Management Board, Iqaluit, Nunavut, Canada.

Higdon, J. W. 2007. Status of knowledge on killer whales (*Orcinus orca*) in the Canadian Arctic. Fisheries and Oceans Canada Canadian Science Advisory Secretariat Research Document 2007/048. Fisheries and Oceans Canada, Ottawa, Ontario, Canada.

Houser, C., and W. A. Gough. 2003. Variations in sea ice in the Hudson Strait: 1971–1999. Polar Geography 27:1–14.

IPCC. 2007. Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, editors. Cambridge University Press, Cambridge, UK.

Johnston, D. H. 1961. Marine mammal survey Hudson Bay 1961. Ontario Department of Lands and Forests, Ottawa, Ontario, Canada.

Lyrholm, T. 1988. Photoidentification of individual killer whales, *Orcinus orca*, off the coast of Norway 1983–1986. Rit Fiskideildar 11:89–94.

Markham, W. E. 1986. The ice cover. Pages 101–116 *in* I. P. Martini, editor. Canadian inland seas. Elsevier Oceanography Series 44. Elsevier, Amsterdam, The Netherlands.

Mehta, A. V., et al. 2007. Baleen whales are not important as prey for killer whales *Orcinus orca* in high-latitude regions. Marine Ecology Progress Series 348:297–307.

Melnikov, V. V., I. A. Zagrebin, G. M. Zelensky, and L. I. Ainana. 2007. Killer whales (*Orcinus orca*) in waters adjacent to the Chukotka Peninsula, Russia. Journal of Cetacean Research and Management 9:53–63.

Milani, D. 1986. Wildlife observation program, Hudson Bay 1985. Canterra Energy Ltd, Calgary, Alberta, Canada.

Mizroch, S. A., and D. W. Rice. 2006. Have North Pacific killer whales switched prey species in response to depletion of the great whale populations? Marine Ecology Progress Series 310:235–246.

Moore, S. E., and K. L. Laidre. 2006. Trends in sea ice cover within habitats used by bowhead whales in the western Arctic. Ecological Applications 16:932–944.

Overpeck, J. T., et al. 2005. Arctic system on trajectory to new, seasonally ice-free state. EOS Transactions of the American Geophysical Union 86:309–316.

Parkinson, C. L. 2000. Variability of Arctic sea ice: the view from space, an 18-year record. Arctic 53:341–358.

Parkinson, C. L., and D. J. Cavalieri. 2002. A 21 year record of Arctic sea ice extents and their regional, seasonal and monthly variability and trends. Annals of Glaciology 34: 441–446.

Pinkerton, J., and D. Doyle. 1805. Pinkerton's Geography. Printed for Samuel F. Bradford, Philadelphia, Pennsylvania, USA.

Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan. 2003. Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. Journal of Geophysical Research 108(D14):4407.

Reeves, R. R., and E. Mitchell. 1988. Distribution and seasonality of killer whales in the eastern Canadian Arctic. Rit Fiskideildar 11:136–160.

Richard, P. R., J. R. Orr, and D. G. Barber. 1990. The distribution and abundance of belugas, *Delphinapterus leucas*, in eastern Canadian waters: a review and update. Pages 23–28 *in* T. G. Smith, D. J. St Aubin, and J. R. Geraci, editors. Advances in research on the beluga whale *Delphinapterus leucas*. Canadian Bulletin of Fisheries and Aquatic Science 224.

Siegel, S., and N. J. Castellan, Jr. 1988. Nonparametric statistics for the behavioral sciences. Second edition. McGraw-Hill, London, UK.

Smetacek, V., and S. Nicol. 2005. Polar ocean ecosystems in a changing world. Nature 437:362–368.

Springer, A. M., J. A. Estes, G. B. Van Vliet, T. M. Williams, D. F. Doak, E. M. Danner, K. A. Forney, and B. Pfister. 2003. Sequential megafaunal collapse in the North Pacific Ocean: an ongoing legacy of industrial whaling? Proceedings of the National Academy of Sciences (USA) 100:12223–12228.

Springer, A. M., J. A. Estes, G. B. Van Vliet, T. M. Williams, D. F. Doak, E. M. Danner, and B. Pfister. 2008. Mammal-eating killer whales, industrial whaling, and the sequential megafaunal collapse in the North Pacific Ocean: a reply to critics of Springer et al. 2003. Marine Mammal Science 24: 414–442.

Stewart, D. B. 2000. What makes Hudson Bay special? Unpublished report prepared by Arctic Biological Consultants, Winnipeg, Manitoba for Fisheries and Oceans Canada, Winnipeg, Manitoba, Canada.

Stewart, D. B., and W. L. Lockhart. 2005. An overview of the Hudson Bay marine ecosystem. Canadian Technical Report, Fisheries and Aquatic Sciences No. 2586. Central and Arctic Region, Fisheries and Oceans Canada, Winnipeg, Manitoba, Canada.

Stirling, I. 1997. The importance of polynyas, ice edges, and leads to marine mammals and birds. Journal of Marine Systems 10:9–21.

Stirling, I., N. J. Lunn, and J. Iacozza. 1999. Long-term trends in the population ecology of polar bears in western Hudson Bay in relation to climatic change. Arctic 52:294–306.

Stirling, I., N. J. Lunn, J. Iacozza, C. Elliot, and M. Obbard. 2004. Polar bear distribution and abundance on the southwestern Hudson Bay coast during the open water season, in relation to population trends and annual ice patterns. Arctic 57:15–26.

Stirling, I., and C. L. Parkinson. 2006. Possible effects of climate warming on selected populations of polar bears (*Ursus maritimus*) in the Canadian Arctic. Arctic 59:261–275.

Taylor, W. 2000. Change-point analyzer 2.0 shareware program. Taylor Enterprises, Libertyville, Illinois, USA.

Trites, A. W., V. B. Deecke, E. J. Gregr, J. K. B. Ford, and P. F. Olesiuk. 2006. Killer whales, whaling, and sequential megafaunal collapse in the North Pacific: a comparative analysis of the dynamics of marine mammals in Alaska and British Columbia following commercial whaling. Marine Mammal Science 23:751–765.

Tynan, C. T., and D. P. DeMaster. 1997. Observations and predictions of Arctic climatic change: potential effects on marine mammals. Arctic 50:308–322.

Visser, I. N. 1999. Propeller scars and known migration of two killer whales (*Orcinus orca*) in New Zealand waters. New Zealand Journal of Marine and Freshwater Research 33:635–642.

Walsh, J. E. 1978. A data set on Northern Hemisphere sea ice extent, 1953–76. Pages 49–51 *in* Glaciological data report GD-2, Arctic sea ice, part 1. World Data Center for Glaciology, Boulder, Colorado, USA.

Walsh, J. E., and W. L. Chapman. 2001. Twentieth-century sea ice variations from observational data. Annals of Glaciology 33:444–448.

Walsh, J. E., and C. M. Johnson. 1978. Analysis of Arctic sea ice fluctuations 1953– 1977. Journal of Physical Oceanography 9:580–591.

Walther, G.-R., E. Post, P. Convey, A. Menzel, C. Parmesan, T. J. C. Beebee, J.-M. Fromentin, O. Hoegh-Guldberg, and F. Bairlein. 2002. Ecological responses to recent climate change. Nature 416:389–395.

Wilson, K. J., J. Falkingham, H. Melling, and R. De Abreu. 2004. Shipping in the Canadian Arctic: other possible climate change scenarios. Geoscience and Remote Sensing Symposium IGARSS '04. Proceedings 2004 IEEE International 3: 1853–1856.

APPENDIX

Database of reported killer whale sightings in the Hudson Bay region (*Ecological Archives* A019-056-A1).