Marine Mammal Science

Notes

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Increasing detections of killer whales (*Orcinus orca*), in the Pacific Arctic

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Worldwide, climate change is altering habitats in both terrestrial and marine systems (Cohen *et al.* 2018). This is particularly true in the Arctic, where dramatic reductions in seasonal sea ice cover have decreased habitat for ice-reliant species (Laidre *et al.* 2015), but increased ice-free habitat for subarctic species (Moore and Huntington 2008). The reduction in seasonal sea ice, with earlier break up in the spring and later formation in the fall is the most evident climate-change driven alteration of the Arctic (Wang and Overland 2015). In the Chukchi Sea, over the past 30 yr, spring break up timing has advanced from early July to mid-June and fall freeze up is now delayed from early November into December resulting in a net increase of open water days of 5–6 wk (Laidre *et al.* 2015). Sea ice reductions in the Pacific Arctic have been linked to ecosystem shifts that include changes in abundance and distribution of benthic species (Grebmeier 2012), increases in primary production (Arrigo and van Dijken 2015), changes in beluga whale (*Delphinapterus leucas*) phenology and foraging behavior (Hauser *et al.* 2018), and increased sightings of subarctic cetaceans, including killer whales (*Orcinus orca*, Clarke *et al.* 2013*b*).

Mammal-eating killer whales are a subarctic cetacean that is a highly efficient apex predator that preys on a wide variety of marine mammal species (Matkin *et al.* 2007). Globally, killer whales strongly impact the structure of marine ecosystems by exerting top-down effects on the distribution, abundance and behavior of prey species (Williams *et al.* 2004, Barrett-Lennard *et al.* 2011). There are several lines of evidence that killer whales are increasing and becoming a major predator in the eastern Canadian Arctic

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as sea ice declines (Ferguson *et al.* 2010, Higdon *et al.* 2011, Breed *et al.* 2017). Residents of coastal communities in the Pacific Arctic have reported them hunting numerous marine mammal species including beluga whales, walrus (*Odobenus rosmarus*), and gray whales (*Esrichtius robustus*, Lowry *et al.* 1987). Prior to 2000, there were sporadic but consistent sightings of killer whales June through August and during "summer" (Fig. 1; Lowry *et al.* 1987, George and Suydam 1998, Ivashin and Votrogov 1981). Visual observations of marine mammals in the Arctic occur over relatively short time periods (days to weeks) and can be limited by fog, high winds, ice, and light availability. The use of underwater passive acoustic monitoring overcomes many of these constraints, as different species produce species-identifiable vocalizations and acoustic recording can occur year-round and in all weather and light conditions.

All killer whales produce echolocation clicks, whistles, and pulsed calls (Matkin *et al.* 2007, Riesch and Deecke 2011) but mammal-eating (hereafter "transient") killer whales produce fewer pulsed calls and whistles and use echolocation less often, likely to avoid being acoustically detected by their marine mammal prey (Matkin *et al.* 2007, Barrett-Lennard *et al.* 2011, Riesch and Deecke 2011). Further, pulsed calls and whistles of transient killer whales are lower in frequency, more narrowband, and shorter than resident killer whale signals (Deecke *et al.* 2005). Here, the occurrence of killer whale calls from passive acoustic data from a location in the southern Chukchi Sea shows that transient killer whales appear to be spending more time in the Chukchi Sea as seasonal sea ice decreases.

Passive acoustic data were collected from September 2009 through July 2016 on a hydrophone (Multi-electronique Aural-M2) deployed on an oceanographic mooring in the southern Chukchi Sea (Fig. 1). The mooring was located at 66.33°N, 168.95°W at a depth of 53 m in water 58 m deep. Acoustic data were sampled at 8,192 Hz on a duty cycle of the first 12 min/h. From 2009 to 2012, data collection occurred from 1 September through late winter or early spring the following year, with the exception of 2011 when data collection began on 1 October (Table 1). Beginning in 2013, data were collected year-round with the instruments recovered and redeployed in July of each year (Table 1). For September, October, and November of all years (except 2011), every day of every month had 24 acoustic data files with no data gaps. For data from 2013 to 2015, the only month with a different number of files per year was July, as the timing of the turn-around cruises varied by year (Table 1). Killer whale acoustic presence was determined by a three-step process. First, each acoustic data file was displayed as a spectrogram (FFT 4,096, 50% overlap, Hann window) and presence (1) or absence (0) of killer whale signals, including whistles, pulsed calls, and echolocation, was manually noted. Data files that contained only echolocation, and no other killer whale calls, were not included in the analysis because of the low-bandwidth of the recordings and because they could not be unambiguously identified as transient echolocation. Second, killer whale calls were identified both by listening to each individual call and examining spectrograms of each. The calls had the nasal-sounding characteristic of transient signals and the time-frequency characteristics of

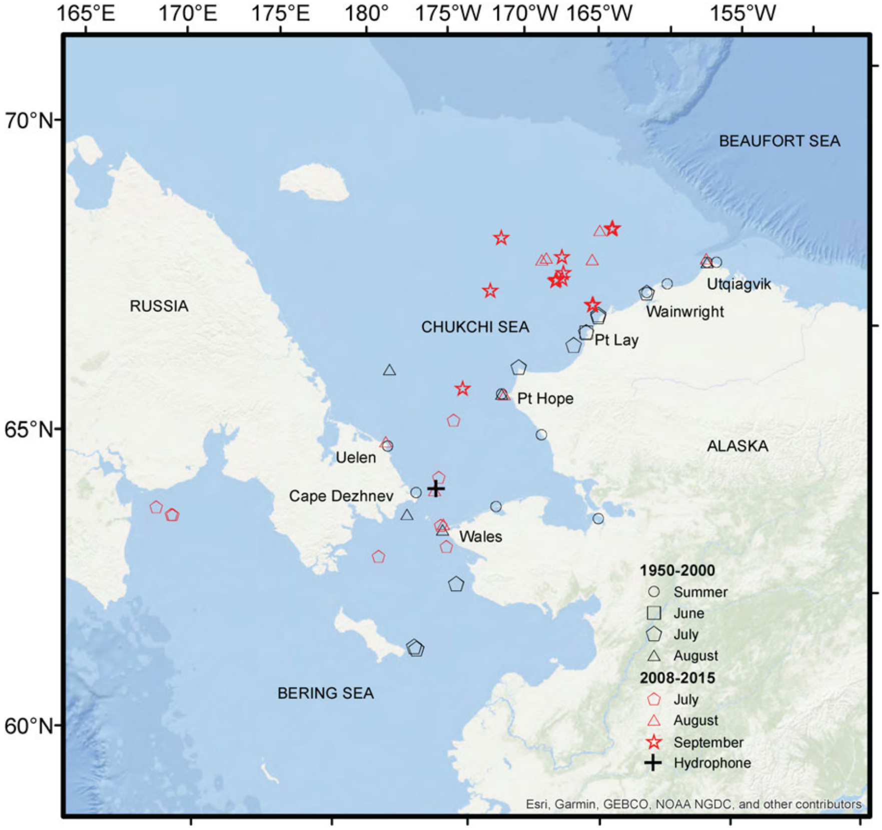

Figure 1. Sightings of killer whales by month from 1950s to 2000s (black open symbols) and 2008–2015 (red open symbols). Sightings from 1950 to 2000 were most often reported by hunters from local villages who observed the animals near shore (Lowry *et al.* 1987, George and Suydam 1998, Ivashin and Votrogov 1981). From 2008 to 2015 observations were obtained from local reports and dedicated and opportunistic shipboard and aerial surveys for marine mammals (Clarke *et al.* 2013*a*, Aerts *et al.* 2013). The location of the hydrophone that recorded the acoustic data is shown as a black +.

transient whistles (Fig. 2, Audio File S1). They are also lower in frequency and longer than calls of beluga whales, the only other odontocete that produces tonal signals and occurs regularly in the Pacific Arctic. Finally, examples of calls were confirmed in consultation with killer whale acoustics experts.[2]

To examine the fall occurrence of killer whale call detections, the total number of days with calls for September through November, annually,

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[2] Personal communication from H. Yurk, (e-mail: harald.yurk@jasco.com), November 2017. Presentation "Bigg's killer whale call 'repertoires' in the Chukchi Sea" 17th Biennial Conference on the Biology of Marine Mammals.

Table 1. Start and end dates of recordings by year. All recordings started at 0000 UTC on the start date and recorded 24 acoustic data files of 12 min duration at the beginning of each hour. There were no missing data files from the start to the end of recording for any deployment.

Deployment year	Start date	End date	Data gaps
2009	1 September 2009	3 March 2010	
2010	1 August 2010	19 February 2011	
2011	1 October 2011	25 May 2012	1–30 September 2011
2012	1 September 2012	17 May 2013	
2013	15 July 2013	2 July 2014	1–30 June 2013, 1–14 July 2013
2014	10 July 2014	2 July 2015	3–9 July 2014
2015	5 July 2015	8 July 2016	3–4 July 2015

was divided by the total number of days available to determine the proportion of days with calls by month from 2009 to 2015. There were no data available for September 2011 (Table 1). As the resulting values were proportions, a beta regression was used to test the null hypothesis that there were no differences in the total proportion of available days

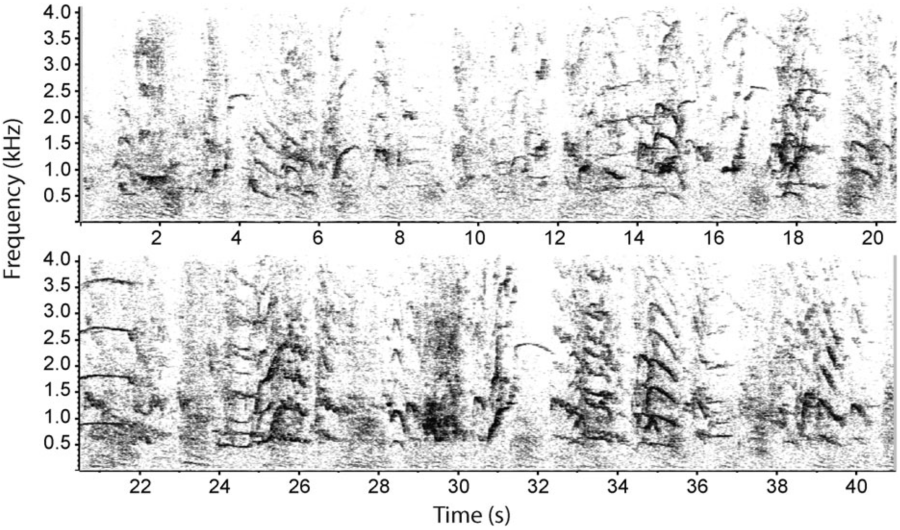

Figure 2. Spectrogram of 40 s of killer whale acoustic signals recorded on 15 September 2015 (1,024 point FFT, 87.5% overlap, Hann window). The acoustic file from which this spectrogram was produced is included as Audio File S1.

with killer whale detections by year for the months of September through November from 2009 to 2015.

Killer whale calls were detected every year from 2009 to 2015 (Fig. 3a). Signals were detected with increasing frequency in fall months (September to November) annually from 2009 to 2015, and in every month from June through November from 2013 to 2015 (Fig. 3b). Over the entire data set, the earliest detection of killer whale calls in any year occurred on 1 June 2015, and the latest on 16 November 2014. There were no detections in any other months for any years outside of June through November.

For the years for which only fall data were available (2009–2012), killer whales were recorded regularly in September and October and less commonly in November (Fig. 3a). From September through November for all years, both the number of days and the number of hours with killer whale detections increased over the 7 yr time series from 2009 to 2015 (Fig. 3a). There was a marginally significant increase in the proportion of available days with killer whale detections over time during fall months (t-stat = 3.2, df = 6, $P = 0.024$). From 1979 to 2015, sea ice extent in the Chukchi decreased in all months from June through December (Fig. 4) with the decreases from August to October on the order of 12,000–17,000 km^2 annually (Fetterer *et al.* 2017).

The acoustic detections reported here are from a single site in the southern Chukchi Sea that is located where Bering Sea waters from both the eastern and western sides of the Bering Strait converge (Fig. 1). The detection range for killer whale calls under very low ambient noise conditions is on the order of at most 10 km (Miller 2006), therefore only a very small proportion of the southern Chukchi Sea was monitored during this study. The occurrence documented here should be considered a minimum estimate of the time spent in the Chukchi Sea for three reasons. First, due to the 8 kHz sample rate of the recording, only the very low end of echolocation clicks could be detected, and were therefore not included in the analysis, and higher-frequency whistles (above 4 kHz) were not recorded. Second, mammal-eating killer whales tend to be silent when hunting, only producing calls during social interactions or after a successful kill or when pursuing large prey (Riesch and Deecke 2011, Deecke *et al.* 2005). Finally, the duty-cycled recording schedule used here (20%) may also underestimate their occurrence. Killer whale calls were sporadically detected from late July, occasionally into early October, but never later, on hydrophones deployed from 2007 to 2011 between Cape Lisburne and Utqiaġvik, Alaska, in the Pacific Arctic (Hannay *et al.* 2013). As only 5% of the available data from that study were examined for killer whale calls, it too is likely an underestimate of their acoustic occurrence to the north of the data presented here (Hannay *et al.* 2013).

In the eastern Canadian Arctic, particularly the Hudson Bay area, killer whale sightings have increased exponentially since the 1950s; this increase has been partially attributed to decreases in seasonal sea ice at "choke points" where heavy, multiyear sea ice has restricted their access in the past (Higdon and Ferguson 2009, Higdon *et al.* 2011). The proportion of bowhead whales with killer whale rake marks, which are

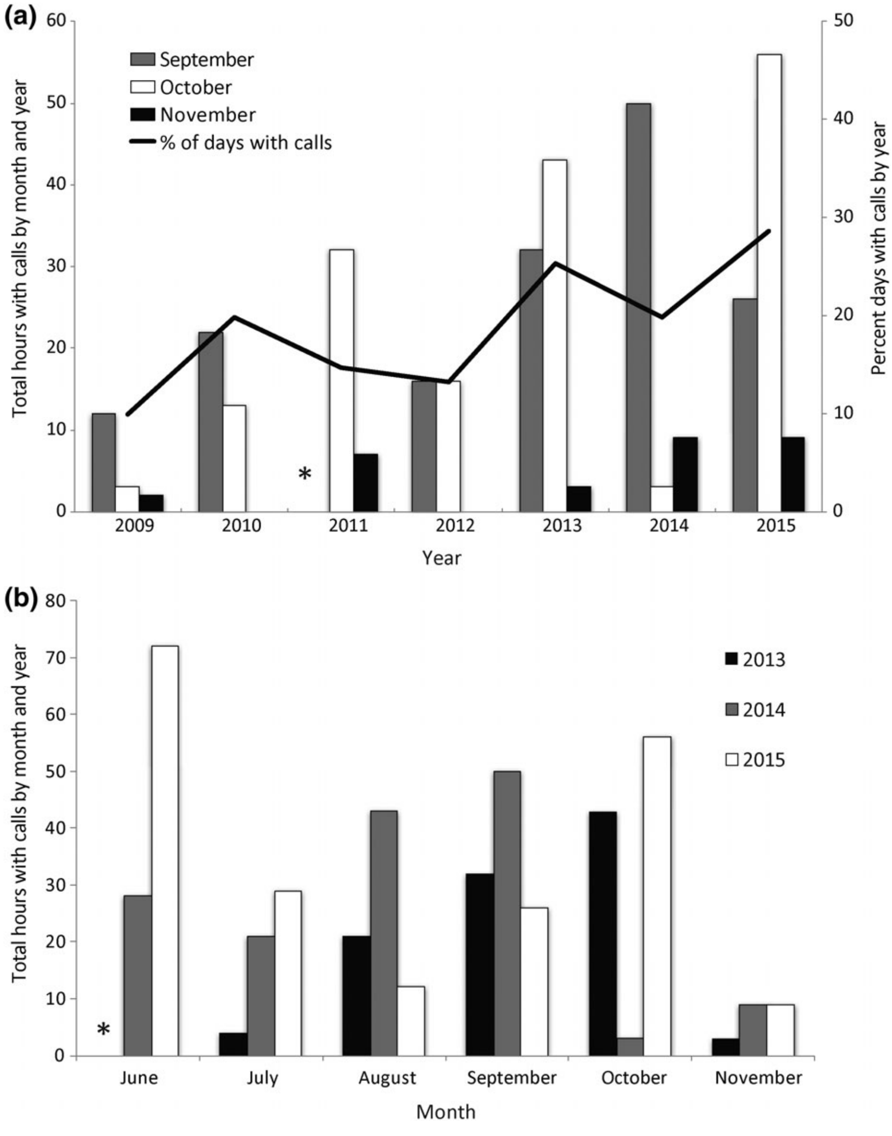

Figure 3. Acoustic detections of killer whales in the southern Chukchi Sea. (a) September–November 2009–2015. Hours with detections by month are shown as bars (left *y*-axis) and percentage of available days with calls is shown as a black line (right *y*-axis); (b) June–November 2013–2015. *Indicates that data were not available for September 2011 or June 2013.

scars caused by an unsuccessful predation event, increased from 1986 to 2012 with an estimate of 10% of adults seen between 2007 and 2012 exhibiting interaction with killer whales (Reinhart *et al.* 2013). Both narwhals (*Monodon monoceros*) and beluga whales in Hudson Bay changed their behavior and distribution in the presence of killer whales, with

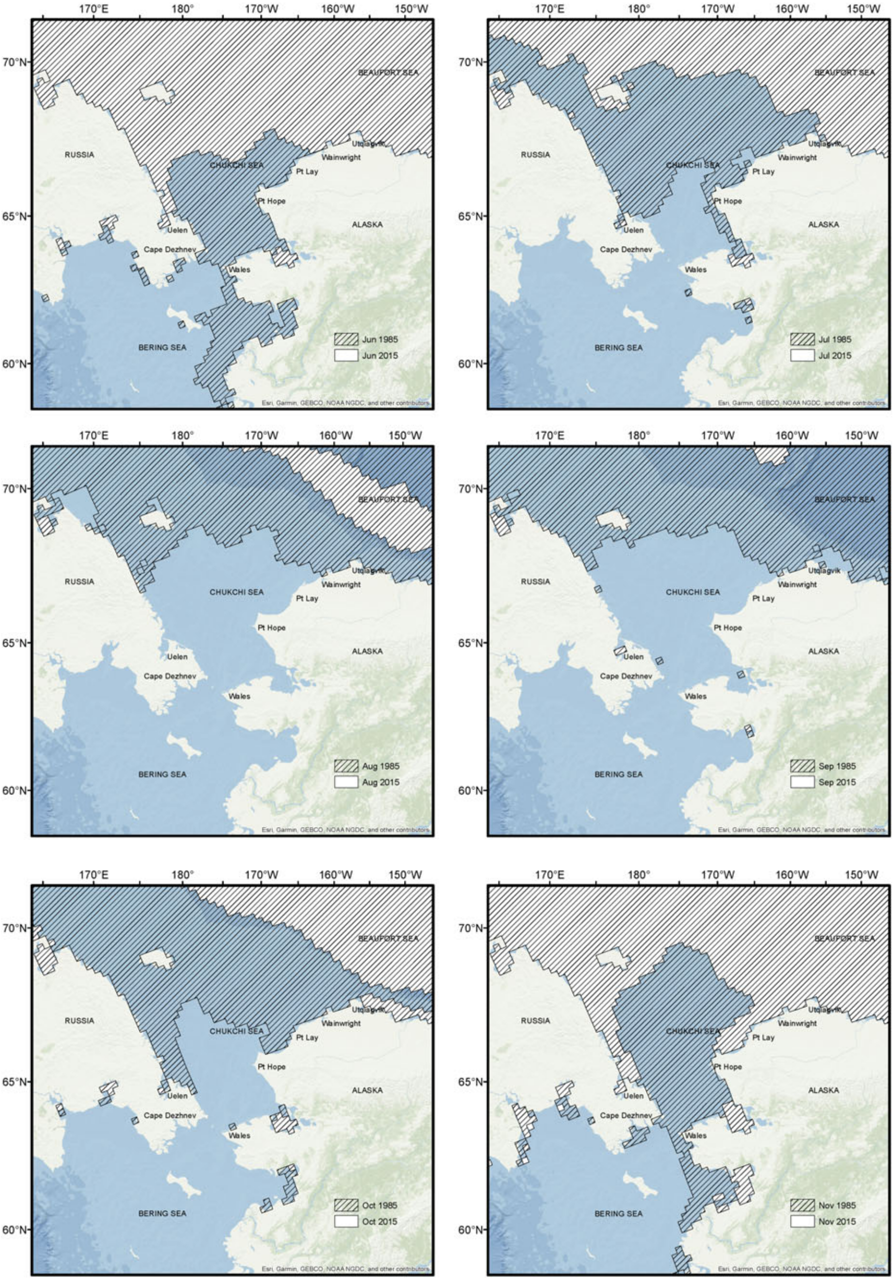

Figure 4. Monthly comparisons of sea ice extent in the Pacific Arctic between 1985 and 2015 for June through November. Sea ice extent in 1985 is shown as black hatched lines while 2015 extent is shown as white. The southern Chukchi Sea north of the Bering Strait used to be ice-covered in June and November. The sea ice extent in these months now more closely resembles ice extent from August and September from 1985. The Chukchi Sea is now largely ice-free from July through October. Credit: Sea Ice Index, National Snow and Ice Data Center (Fetterer *et al.* 2017).

narwhal behavior disrupted for over a week after predatory interactions with killer whales (Breed *et al.* 2017, Westdal *et al.* 2017). These lines of evidence from the Canadian Arctic suggest that sea ice declines are driving killer whale expansion and causing ecological shifts in predator–prey trophic relations (Higdon and Ferguson 2009).

As in the eastern Canadian Arctic, there have been increases in killer whale rake marks on bowhead whale flukes in the Pacific Arctic (George *et al.* 2017). Only 4% of bowhead whales landed between 1976 and 1992 by Inupiat hunters were documented to have killer whale scars on their flukes. More recently, this percentage has increased significantly from 1990–2001 to 2002–2012, nearly doubling for large whales to 8% (2002–2012) (George *et al.* 2017). Pre-2000 reports of killer whales in the Pacific Arctic were near shore, and were documented from June through August by residents of coastal communities, while more recent visual data suggest the species is occurring further north, offshore, and into September (Fig. 1). While this is certainly partly explained by increased survey effort offshore (enabled by reduced sea ice), the increase in habitat due to reduction in sea ice from June through November (Fig. 4) is also a likely contributor. Killer whales may be following gray whales north into the Arctic in the spring which would explain the high numbers of acoustic detections in June that roughly matches the arrival of mother-calf gray whale pairs into the Arctic (Moore and Ljungblad 1984). The call detection data presented here show that killer whales presently occur in the Chukchi Sea as late as mid-November, which corresponds both to the current onset of winter sea ice advance (Fig. 4), as well as the southbound migrations of Arctic marine mammals towards the Bering Sea (Citta *et al.* 2018).

In the Chukchi Sea, the open-water season now extends from mid-June to late-November, an expansion of ~42 d over the past 30 yr (Laidre *et al.* 2015, Wang and Overland 2015), such that sea ice in the region is becoming annual rather than perennial. Increases in acoustic detections, and likely seasonal residency of mammal-eating killer whales, coincide with these recent extreme decreases in seasonal sea ice cover. While killer whales have been documented in the Pacific Arctic region over decades by local observers (George and Suydam 1998), as in the eastern Canadian Arctic, longer access to sea-ice-free habitat suggests that their presence will continue to expand. If this does occur, killer whales will increasingly overlap spatially and temporally with both Arctic endemic and subarctic species (Moore and Huntington 2008, Laidre *et al.* 2015), and potentially play a top-down role in shaping the rapidly changing ecosystem of the Pacific Arctic (Post *et al.* 2013).

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SUPPORTING INFORMATION

The following supporting information is available for this article online at http://onlinelibrary.wiley.com/doi/10.1111/mms.12551/suppinfo.

Audio File S1. Audio file (KW15Sep2015.wav) of killer whale calls shown in Figure 2. Data were recorded in the southern Chukchi Sea on 15 September 2015.