



Sea-ice indicators of polar bear habitat

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Abstract. Nineteen subpopulations of polar bears (*Ursus maritimus*) are found throughout the circumpolar Arctic, and in all regions they depend on sea ice as a platform for traveling, hunting, and breeding. Therefore polar bear phenology – the cycle of biological events – is linked to the timing of sea-ice retreat in spring and advance in fall. We analyzed the dates of sea-ice retreat and advance in all 19 polar bear subpopulation regions from 1979 to 2014, using daily sea-ice concentration data from satellite passive microwave instruments. We define the dates of sea-ice retreat and advance in a region as the dates when the area of sea ice drops below a certain threshold (retreat) on its way to the summer minimum or rises above the threshold (advance) on its way to the winter maximum. The threshold is chosen to be halfway between the historical (1979–2014) mean September and mean March sea-ice areas. In all 19 regions there is a trend toward earlier sea-ice retreat and later sea-ice advance. Trends generally range from -3 to -9 days decade⁻¹ in spring and from $+3$ to $+9$ days decade⁻¹ in fall, with larger trends in the Barents Sea and central Arctic Basin. The trends are not sensitive to the threshold. We also calculated the number of days per year that the sea-ice area exceeded the threshold (termed ice-covered days) and the average sea-ice concentration from 1 June through 31 October. The number of ice-covered days is declining in all regions at the rate of -7 to -19 days decade⁻¹, with larger trends in the Barents Sea and central Arctic Basin. The June–October sea-ice concentration is declining in all regions at rates ranging from -1 to -9 percent decade⁻¹. These sea-ice metrics (or indicators of habitat change) were designed to be useful for management agencies and for comparative purposes among subpopulations. We recommend that the National Climate Assessment

include the timing of sea-ice retreat and advance in future reports.

1 Introduction

The International Union for Conservation of Nature (IUCN) Polar Bear Specialist Group (PBSG) recognizes 19 subpopulations of polar bears (*Ursus maritimus*; Obbard et al., 2010; Fig. 1 and Table 1). They are found throughout the sea-ice-covered areas of the circumpolar Arctic, especially over the continental shelf and inter-island channels. Polar bears depend on sea ice as a platform for hunting ice seals, their primary prey. Sea ice also facilitates their seasonal movements, mating, and, in some areas, maternal denning (Wiig et al., 2015). Some polar bears remain on sea ice year-round, but in more southerly areas where the ice melts completely, all bears are forced to spend up to several months on land, largely fasting until freeze-up allows them to return to the ice again (e.g., Stirling et al., 1999; Stirling and Parkinson, 2006). The global population size of polar bears is roughly estimated to be about 25 000 (Obbard et al., 2010). Genetic analysis shows that gene flow occurs among the various subpopulations, which are considered to be semi-discrete (Paetkau et al., 1999; Peacock et al., 2015; Wiig et al., 2015).

Multiple approaches have been taken to construct sea-ice metrics for studies of survival and body condition in specific polar bear subpopulations (Table 2). These have generally focused on subpopulation-specific metrics such as the number of ice-free or ice-covered days per year (Obbard et al., 2007; Regehr et al., 2010, 2015; Hamilton et al., 2014), the dates of spring sea-ice breakup and/or fall sea-ice freeze-up (Stirling and Parkinson, 2006; Regehr et al., 2007; Lunn et al.,

Table 1. Polar bear subpopulation region names, abbreviations, and areas. See Fig. 1 for a map of the regions. The area of each region includes the marine portion only, not land. The number of cells is the number of SSM/I grid cells. The percent of total area is with respect to all regions (last row). The percent of area shallower than 300 m and deeper than 300 m are given in the last two columns. The pole hole (second to last row) is the circular area around the North Pole excluded from analysis due to the satellite orbits. The Arctic Basin region (AB) surrounds the pole hole but does not include it. All regions includes all 19 subpopulation regions plus the pole hole.

Abbreviation	Subpopulation	Number of cells	Area (10^3 km^2)	% of total area	% $\leq 300 \text{ m}$	% $> 300 \text{ m}$
KB	Kane Basin	81	53	0.3	68	32
BB	Baffin Bay	1042	656	4.3	28	72
LS	Lancaster Sound	380	243	1.6	73	27
NW	Norwegian Bay	108	70	0.5	84	16
VM	Viscount Melville	157	101	0.7	64	36
NB	Northern Beaufort	1055	677	4.4	23	77
SB	Southern Beaufort	529	333	2.2	59	41
MC	M'Clintock Channel	224	140	0.9	100	0
GB	Gulf of Boothia	100	62	0.4	99	1
FB	Foxe Basin	883	528	3.4	97	3
WH	Western Hudson Bay	326	188	1.2	100	0
SH	Southern Hudson Bay	744	417	2.7	100	0
DS	Davis Strait	2416	1367	8.9	40	60
EG	East Greenland	2237	1387	9.0	27	73
BS	Barents Sea	2379	1540	10.0	63	37
KS	Kara Sea	1645	1054	6.9	87	13
LP	Laptev Sea	2169	1393	9.1	84	16
CS	Chukchi Sea	1840	1117	7.3	98	2
AB	Arctic Basin	4307	2813	18.3	15	85
	Pole hole	1799	1193	7.8	0	100
	All regions	24 421	15 332	100.0	50	50

2014; Laidre et al., 2015a; Obbard et al., 2016), or the sea-ice concentration (Rode et al., 2012; Peacock et al., 2012, 2013). Sea-ice metrics have mainly been selected based on the specific region under study or developed for single studies or data sets. There is a need to develop standardized circumpolar metrics of polar bear habitat based on the satellite record of sea ice that allow for regional comparisons of habitat change and for tracking changes into the future, e.g., as in Vongraven et al. (2012). Thus the objective of this study is to propose and produce metrics of polar bear sea-ice habitat that are also relevant to other Arctic marine mammal (AMM) species.

In this study we used daily sea-ice concentration data to calculate several sea-ice metrics for each of the 19 polar bear subpopulation regions for the period 1979–2014. The metrics are date of spring sea-ice retreat, date of fall sea-ice advance, average sea-ice concentration from 1 June to 31 October, and the number of ice-covered days per year. We calculated each metric for the total marine area of each region and for the shallow depths only ($\leq 300 \text{ m}$). Shallow depths are more biologically productive and are considered to be better polar bear habitat (Durner et al., 2009).

Several previous studies have divided the Arctic into distinct regions and calculated the sea-ice area trend in each region (e.g., Stroeve et al., 2012; Perovich and Richter-

Menge, 2009; Parkinson and Cavalieri, 2008). While this is a straightforward and useful way to document changes in sea ice, other metrics of sea-ice habitat are more relevant to marine mammals whose life history events, such as hunting and breeding, depend on the annual retreat of sea ice in the spring and advance in the fall. Many ecologically important regions of the Arctic are ice covered in winter and ice free in summer and will probably remain so for a long time into the future. Therefore the dates of sea-ice retreat in spring and advance in fall, and the interval of time between them, are key indicators of climate change for ice-dependent marine mammals (Stirling et al., 1999; Stirling and Parkinson, 2006).

2 Data

As in Laidre et al. (2015a) we used the Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data (Cavalieri et al., 1996) data set available from the National Snow and Ice Data Center (NSIDC) in Boulder, CO. This product is designed to provide a consistent time series of sea-ice concentrations (the fraction, or percentage, of ocean area covered by sea ice) spanning the coverage of several passive microwave instruments. The sea-ice concentrations are produced using the NASA Team algo-

Table 2. Recent literature where sea-ice metrics were used for analysis of polar bear habitat. Note that these studies examined habitat for a single polar bear subpopulation (or geographically close set of subpopulations). Bold text gives names of sea-ice metrics. Abbreviations: PM (passive microwave), SIC (sea-ice concentration), CIS (Canadian Ice Service).

Subpopulation	Data	Years	Methods for sea-ice metric	Reference
Western Hudson Bay	Daily PM SIC	1979–2004	Calculated daily percent sea-ice cover in the region. Date of spring sea-ice breakup is the date when the ice cover fell below 50 %.	Stirling and Parkinson (2006)
Western Hudson Bay	Daily PM SIC	1984–2004	Date of spring sea-ice breakup is the date when the ice cover fell below 50 % (same as Stirling and Parkinson, 2006).	Regehr et al. (2007)
Southern Hudson Bay	Daily PM SIC	1984–2003	Date of spring sea-ice breakup is the date when the ice cover fell below 50 % (same as Stirling and Parkinson, 2006). Date of fall sea-ice freeze-up is the date when the ice cover rose above 50 %. Ice-free period is the number of days between breakup and freeze-up.	Obbard et al. (2007)
Southern Beaufort Sea	Daily PM SIC	2001–2005	Calculated the daily percent sea-ice cover for the continental shelf only (depth < 300 m). Number of ice-free days is the number of days per calendar year with ice cover < 50 %.	Regehr et al. (2010)
Northern Beaufort Sea	Daily PM SIC	1979–2006	Mean annual number of grid cells with sea-ice concentration > 50 % , calculated for continental shelf only (depth < 300 m) and excluding a buffer of one ocean grid cell along all coastlines. Second sea-ice covariate is derived from the resource selection functions of Durner et al. (2009).	Stirling et al. (2011)
Baffin Bay, Davis Strait	Mean weekly SIC (CIS)	1977–2010	Mean weekly sea-ice concentration from 15 May to 15 October.	Rode et al. (2012)
Chukchi Sea, Southern Beaufort Sea	Daily PM SIC	1985–1993, 2007–2010	Reduced-ice days per year is the number of days with sea-ice area < 6250 km ² (continental shelf of each region only, depth < 300 m). Distance to ice edge is the daily minimum distance from continental shelf to pack ice, averaged over all days in September. When pack ice is over the continental shelf the distance is set to zero.	Rode et al. (2014)
Baffin Bay	Daily PM SIC	1979–2009	Sea-ice concentration in April, May, and June for the continental shelf only (depth < 300 m). (Note that the continental shelf consists of two parts: Baffin Island in the west and Greenland in the east.)	Peacock et al. (2012)
Davis Strait	Mean weekly SIC (CIS)	1974–2007	Mean weekly sea-ice concentration from 14 May to 15 October.	Peacock et al. (2013)

Table 2. Continued.

Subpopulation	Data	Years	Methods for sea-ice metric	Reference
Canadian Arctic Archipelago	MIT general circulation model (GCM)	2006–2100	<p>Future projections of sea ice were made using the MIT GCM with 18 km grid size and monthly output, forced by “business as usual” RCP8.5 emission scenario.</p> <p>Month of spring sea-ice breakup is the first month in a given year with sea-ice concentration < 50 %.</p> <p>Month of fall sea-ice freeze-up is the first month after breakup with sea-ice concentration \geq 10 %.</p> <p>Ice-free season is the time from breakup to freeze-up. If all months of the year have sea-ice concentration < 10 % then the ice-free season is 12 months.</p>	Hamilton et al. (2014)
Western Hudson Bay	Daily PM SIC	1979–2012	<p>Calculated daily percent sea-ice cover in the region.</p> <p>Date of spring sea-ice breakup is the date when the ice cover fell below 50 % (same as Stirling and Parkinson, 2006) and stayed below 50 % for at least 3 consecutive days.</p> <p>Date of fall sea-ice freeze-up is the date when the ice cover rose above 50 % and stayed above 50 % for at least 3 consecutive days.</p> <p>Ice decay is the rate of sea-ice loss from 1 May until the date of complete disappearance of sea ice, calculated as the absolute value of the slope of the ordinary least squares regression line of ice concentration vs. time.</p>	Lunn et al. (2014)
East Greenland	Daily PM SIC	1979–2012	<p>Calculated the daily sea-ice area in the region. Defined threshold area A as halfway between mean March ice area and mean September ice area, where the means are calculated over the baseline period 1979–1988.</p> <p>Date of spring sea-ice breakup is the date when ice area fell below threshold area A.</p> <p>Date of fall sea-ice freeze-up is the date when ice area rose above threshold area A.</p>	Laidre et al. (2015a)
Chukchi Sea, Southern Beaufort Sea	Daily PM SIC	1979–2013	<p>Calculated the daily sea-ice area in each region. Defined threshold area A as halfway between mean March ice area and zero area, where the mean March area is calculated over the baseline period 1979–2013.</p> <p>Ice-covered days is the number of days each year with ice area > threshold area A.</p> <p>Calculated the mean number of ice-covered days for 1994–2013 and then projected the number of ice-covered days forward in time.</p>	Regehr et al. (2015)
Southern Beaufort Sea		2001–2010	<p>Summer habitat is the sum of monthly indices of the area of optimal polar bear habitat over the continental shelf for July through October each year (from Durner et al., 2009).</p> <p>Melt season is the time between melt onset and freeze onset (“inner melt length” from Stroeve et al., 2014).</p>	Bromaghin et al. (2015)
Southern Hudson Bay	Daily PM SIC	1980–2012	<p>Date of spring sea-ice breakup is the date when mean ice concentration falls below 5 %.</p> <p>Date of fall sea-ice freeze-up is the date when mean ice concentration rises above 5 %.</p>	Obbard et al. (2016)

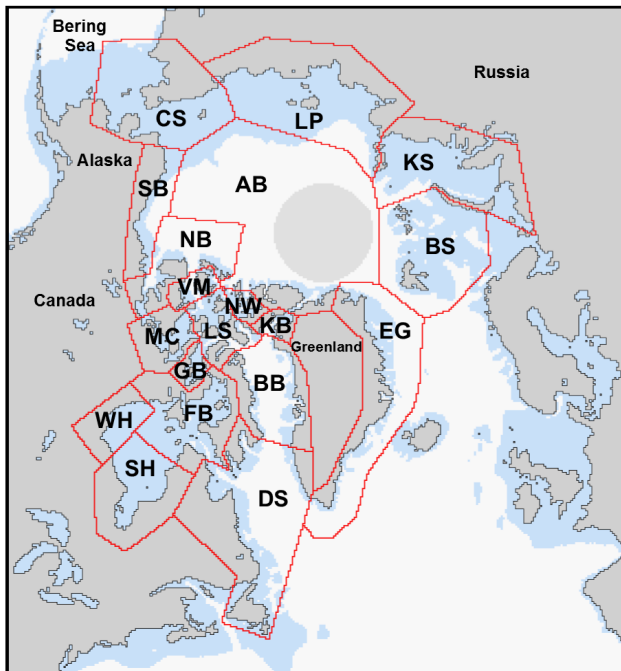


Figure 1. Map of the 19 PBSG polar bear subpopulation regions, with shallow depths (≤ 300 m) in blue. See Table 1 for subpopulation names corresponding to the abbreviations on the map.

rithm, and are provided in a polar stereographic projection (true at 70° N) with a nominal grid cell size of 25×25 km (cell size varies slightly with latitude). Temporal coverage is every other day from 26 October 1978 through 9 July 1987, then daily through 31 December 2014.

Concerning the accuracy of the sea-ice concentration data, the product documentation states that it is within $\pm 5\%$ of the actual sea-ice concentration in winter and $\pm 15\%$ in summer when melt ponds are present on the sea ice and that the accuracy is best for thick ice (> 20 cm) and high ice concentration (NSIDC, 2015). This means that accuracy is less in the marginal ice zone – the band of low ice concentration between open water and consolidated pack ice. Ivanova et al. (2015) found that all passive microwave sea-ice retrieval algorithms underestimated sea-ice concentration in the presence of melt ponds and thin ice. Thus our estimates of daily sea-ice area in each region are undoubtedly biased low, but a consistent bias over time would not affect trends computed from the data.

The spatial coverage of the sea-ice concentration data excludes a small circle around the North Pole, due to the satellite orbits. This “pole hole” is entirely surrounded by the Arctic Basin region (AB in Fig. 1 and Table 1). Although the size of the pole hole became smaller in 1987 with the advent of a new satellite and instrument, we use the larger pre-1987 pole hole for consistency of calculations throughout the period 1979–2014. Our Arctic Basin region does not include the pole hole; it surrounds the pole hole.

To identify shallow depths (≤ 300 m) we used bathymetry from ETOPO1, a 1 arcmin global relief model of Earth’s surface that integrates land topography and ocean bathymetry, built from numerous global and regional data sets (Amante and Eakins, 2009). We averaged the ETOPO1 data over each SSM/I grid cell to obtain the mean ocean depth for each cell, which we then used to distinguish the continental shelf (≤ 300 m depth) from the deeper ocean. Table 1 gives the marine area of the 19 subpopulation regions, as well as the percent of the area shallower than 300 m and deeper than 300 m.

3 Methods

3.1 Preliminary data processing

Sea-ice area is defined as *sea-ice concentration* \times *grid cell area* summed over cells with sea-ice concentration greater than 15%. For each region, we calculated the daily (or every-other-day prior to 1987) sea-ice area over two sets of grid cells: (1) all cells in the region and (2) those cells in which the mean ocean depth is ≤ 300 m. We note that the 15% threshold is standard in the sea-ice literature for identifying the presence of sea ice (e.g., Parkinson, 2014) and is not based on ice concentration preferences of polar bears, which can be higher or lower depending on season (Cherry et al., 2013).

We next looked for outliers in each time series: excessively large or small values that may be the result of erroneous sea-ice retrievals due to extreme weather events or other errors. Outliers were identified by comparing each value in the time series with a five-point median-filtered version of the time series. If the difference between the actual value and the median-filtered value exceeded a certain threshold (15% of the mean March sea-ice area), then the actual value was replaced by the median value. The outlier rate was less than three values per 10 000. This procedure also led to the identification of an anomaly on 14 September 1984 that turned out to be an error in the passive microwave source data, which was subsequently re-processed by NSIDC.

We next used linear interpolation to fill in the every-other-day gaps up to 9 July 1987. We also used linear interpolation to span a data gap from 3 December 1987 to 13 January 1988. The end result was a complete time series of daily sea-ice area for each region, 1979–2014.

3.2 Dates of spring sea-ice retreat and fall sea-ice advance

The date of spring sea-ice retreat is defined here as the date when the sea-ice area drops below a certain threshold on its way to the summer minimum. The date of fall sea-ice advance is defined as the date when the sea-ice area rises above the threshold on its way to the winter maximum. These dates may or may not occur in what is normally considered to be spring or fall; they are meant to mark the transitions between winter and summer sea-ice conditions.

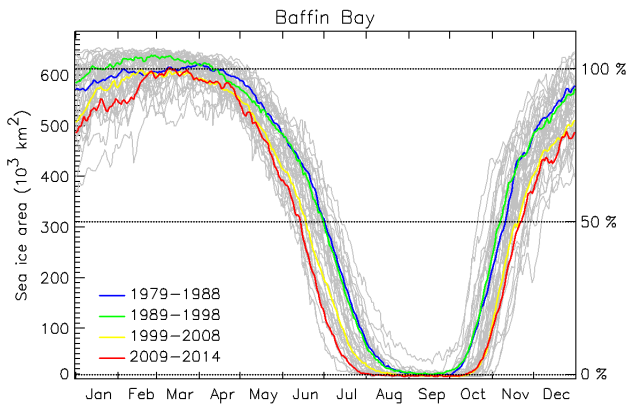


Figure 2. Daily sea-ice area in Baffin Bay (all depths), January–December, 1979–2014 (gray curves). The colored curves are decadal averages, as indicated in the legend. The upper horizontal dotted line (at $613 \times 10^3 \text{ km}^2$) is the average sea-ice area in March (1979–2014); the lower horizontal dotted line (at $9 \times 10^3 \text{ km}^2$) is the average sea-ice area in September. The middle horizontal dotted line, halfway between the upper and lower lines, is the threshold for determining the spring and fall transition dates in Baffin Bay. See Fig. S1 for similar plots for other subpopulation regions.

Arctic sea ice typically reaches its maximum area in March and its minimum area in September. Accordingly, we chose the transition threshold for each region as follows. We calculated the mean March sea-ice area over the period 1979–2014, and the mean September sea-ice area over the same period, and then chose the transition threshold to be halfway between these means. This is illustrated for the Baffin Bay region in Fig. 2 and for the other regions in Supplement Fig. S1. (Figs. 2–9 use Baffin Bay as a sample region for purposes of illustration).

Figure 3 illustrates the method for finding the dates of spring retreat and fall advance in Baffin Bay in one particular year. The daily sea-ice area (gray curve) exhibits small daily fluctuations that can be attributed to the uncertainty in the underlying sea-ice concentration data. We smooth the daily values with a low-pass Gaussian-shaped filter in which 87 % of the weight is within ± 1 week of the central value (black curve). Then, starting from the minimum sea-ice area in summer, we search forward and backward in time for the first intersections of the smoothed time series with the threshold. The backward search gives the spring date (red vertical line) and the forward search gives the fall date (blue vertical line).

Occasionally the smoothed sea-ice area time series may cross the threshold more than once in spring and/or fall. Our method always chooses the crossing date that is closest in time to the summer minimum. In practice, out of 2736 crossing dates ($36 \text{ years} \times 2 \text{ seasons} \times 19 \text{ regions} \times 2 \text{ time series per region}$), only 131 dates (4.8 %) had any potential for ambiguity. In more than 95 % of the cases there was clearly only a single crossing date.

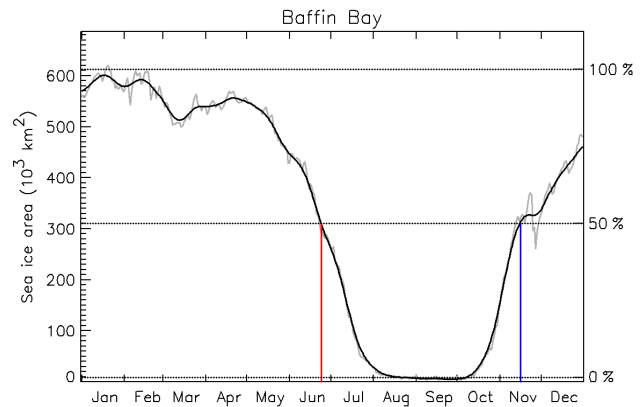


Figure 3. Determination of the spring and fall transition dates for the year 2005 in Baffin Bay. The gray curve is the daily sea-ice area; the black curve is a smoothed version. The horizontal dotted line (at $311 \times 10^3 \text{ km}^2$) is the threshold. The intersection of the threshold with the smoothed (black) curve determines the spring (red) and fall (blue) transition dates.

3.3 Summer sea-ice concentration

For each region we calculated the mean sea-ice concentration for 1 June–31 October for each year, from 1979 to 2014. While it has already been established that the sea-ice concentration in every region of the Arctic except the Bering Sea is declining in every month of the year (e.g., Perovich and Richter-Menge, 2009), the winter sea-ice cover will likely continue to provide suitable polar bear habitat for at least several more decades (especially in the Canadian high Arctic; Amstrup et al., 2008; Hamilton et al., 2014), whereas the summer sea-ice cover may not. A summer sea-ice metric, therefore, measures the change in polar bear habitat during the season when that habitat is most vulnerable to change.

3.4 Number of ice-covered days per year

We calculated the number of days per year that the sea-ice area in each subpopulation region exceeded the threshold defined in Sect. 3.2 (i.e., 50 % of the way from mean September to mean March sea-ice area). For example, in Fig. 3, the sea-ice area in Baffin Bay was greater than the 50 % threshold for 220 days in the year 2005. This sea-ice metric was used as a measure of polar bear habitat in the IUCN Red List assessment of polar bears (Wiig et al., 2015).

4 Results

4.1 Sea-ice metrics

In all 19 regions, the date of spring sea-ice retreat is trending earlier and the date of fall sea-ice advance is trending later. Along with this, the length of the summer season is increasing, the summer sea-ice concentration is decreasing, and the

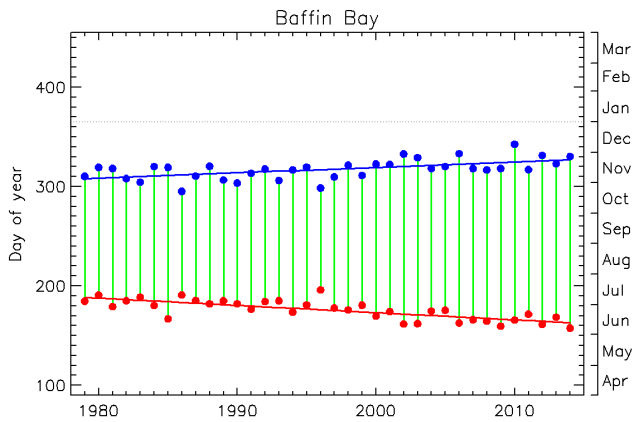


Figure 4. Dates of sea-ice retreat (red) and sea-ice advance (blue) in Baffin Bay (all depths) for 1979–2014. The red and blue lines are least-squares fits. The vertical green lines indicate the time interval between retreat and advance (i.e., length of summer season). See Table 3 for trends. See Fig. S2 for similar plots for other regions.

number of ice-covered days per year is decreasing, for the period 1979–2014 (Table 3). Nearly all the trends (88 of 95) are statistically significant. Trends in the date of spring sea-ice retreat are on the order of -3 to -9 days decade $^{-1}$ (negative being earlier), with the largest trend (-16 days decade $^{-1}$) in the Barents Sea. Trends in the date of fall sea-ice advance are on the order of $+3$ to $+9$ days decade $^{-1}$ (positive being later), with the largest trend ($+18$ days decade $^{-1}$) again in the Barents Sea. This means that over the 3.5 decades of this study, the time interval from the date of spring retreat to the date of fall advance has lengthened by 3 to 9 weeks in most regions and by 17 weeks in the Barents Sea. The summer (June–October) sea-ice concentration is declining at a rate of -1 to -9 percent decade $^{-1}$, depending on region. The number of ice-covered days is declining in all regions at the rate of -7 to -19 days decade $^{-1}$, with larger trends in the Barents Sea and central Arctic Basin. Results for the shallow (≤ 300 m) portions of each region are similar (Table 4). Note that some regions consist almost entirely of shallow depths (see Fig. 1 and Table 1).

Figure 4 illustrates results for the Baffin Bay region (see Fig. S2 for similar plots for other regions). Sea-ice retreat in spring is changing by -7.3 days decade $^{-1}$ (red) and sea-ice advance in fall is changing by $+5.4$ days decade $^{-1}$ (blue), both statistically significant. The time interval between the spring and fall transition dates is changing by $+12.7$ days decade $^{-1}$ (Fig. 5; see Fig. S3 for similar plots for other regions). The summer sea-ice concentration is changing by -4.1 percent decade $^{-1}$ (Fig. 6; see Fig. S4 for similar plots for other regions). The number of ice-covered days is changing by -12.7 days decade $^{-1}$, which is the negative of the fall-minus-spring trend: the loss of every ice-covered day occurs between the time of spring sea-ice retreat and fall sea-ice advance.

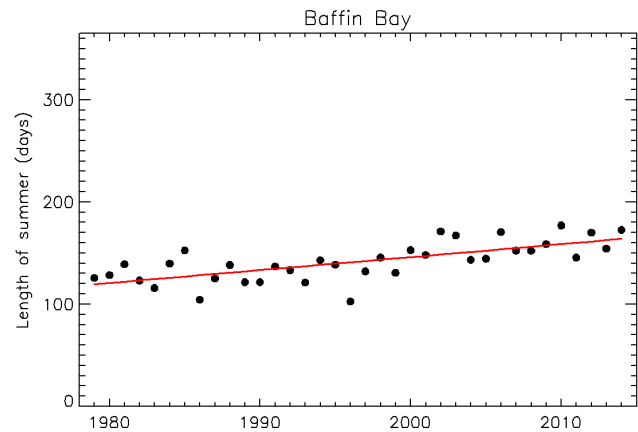


Figure 5. Length of the summer season (from spring sea-ice retreat to fall sea-ice advance) vs. year for Baffin Bay (all depths), with least-squares line in red (slope: $+12.7$ days decade $^{-1}$). See Fig. S3 for similar plots for other regions.

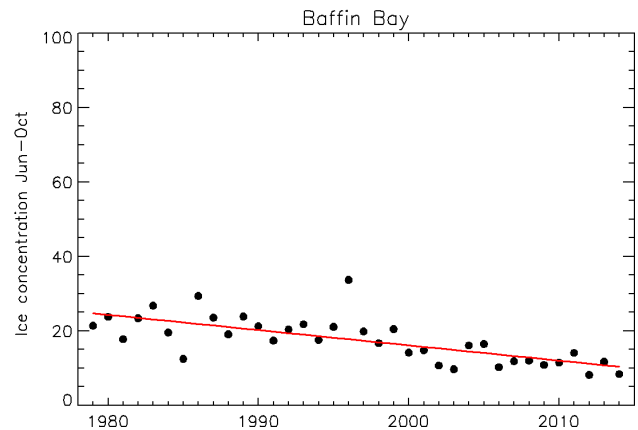


Figure 6. Summer (June through October) sea-ice concentration vs. year for Baffin Bay (all depths), with least-squares line in red (slope: -4.1 percent decade $^{-1}$). See Fig. S4 for similar plots for other regions.

We also calculated the number of ice-covered days based on a 15 % threshold of sea-ice area, as illustrated in Figs. 7 and 8 (see Fig. S5 for similar plots for other regions). The 15 and 50 % thresholds intersect the annual cycle of sea-ice area at different levels and therefore contain information about the shape of the annual cycle. In Baffin Bay, the rate of decline in the number of ice-covered days is about the same for both thresholds (Fig. 8). However, in the Chukchi Sea region (Fig. S5) the rate of decline is faster for the 15 % threshold, meaning that the rise and fall of the annual cycle of sea-ice area is steepening, leading to faster transitions between summer and winter sea-ice coverage. In the Barents Sea (Fig. S5) the opposite is occurring. Further analysis of changes in the shape of the annual cycle of sea-ice area is possible but is beyond the scope of the present study.

Table 3. Trend in date of spring sea-ice retreat (days decade⁻¹), trend in date of fall sea-ice advance (days decade⁻¹), trend in length of summer season (days decade⁻¹), trend in June–October sea-ice concentration (percent concentration decade⁻¹), trend in number of ice-covered days (days decade⁻¹), and correlation of de-trended dates of spring retreat and fall advance (dimensionless). All quantities are computed from the total marine area of each region, regardless of depth (compare Table 4), for the period 1979–2014. The trend in the length of the summer season (fall–spring trend) is equal to the fall trend minus the spring trend. Statistical significance is indicated by * (95 % level) or ** (99 % level) according to a two-sided F test (for trends) or a two-sided *t* test (for correlations).

Subpopulation	Spring trend	Fall trend	Fall–spring trend	Jun–Oct ice concentration	Ice-covered days	Correlation of dates
Kane Basin	−6.8 *	5.6 **	12.4 **	−5.4 **	−14.1 **	−0.55 **
Baffin Bay	−7.3 **	5.4 **	12.7 **	−4.1 **	−12.7 **	−0.64 **
Lancaster Sound	−5.4 *	4.7 **	10.1 **	−4.4 **	−10.6 **	−0.11
Norwegian Bay	−1.2	4.3	5.5	−1.6	−7.1 *	−0.21
Viscount Melville	−4.0	7.9	11.8 *	−4.7 **	−12.3 **	0.36 *
Northern Beaufort	−6.0 *	3.1	9.0 *	−4.3 **	−9.3 *	−0.40 *
Southern Beaufort	−9.0 **	8.8 **	17.8 **	−9.3 **	−17.5 **	−0.50 **
M’Clintock Channel	−4.1 **	5.9 **	10.0 **	−5.1 **	−11.1 **	−0.74 **
Gulf of Boothia	−8.6 **	7.6 **	16.2 **	−8.9 **	−18.6 **	−0.57 **
Foxe Basin	−5.3 **	5.7 **	11.0 **	−3.3 **	−11.4 **	−0.58 **
Western Hudson Bay	−5.1 **	3.5 **	8.7 **	−2.9 **	−8.6 **	−0.25
Southern Hudson Bay	−3.0 *	3.6 *	6.6 **	−1.8 *	−6.8 **	−0.35 *
Davis Strait	−7.4 **	9.2 **	16.6 **	−1.0 **	−17.1 **	−0.35 *
East Greenland	−5.7 **	4.8 *	10.5 **	−1.4 *	−10.4 **	−0.34 *
Barents Sea	−16.4 **	18.2 **	34.6 **	−3.8 **	−41.0 **	−0.46 **
Kara Sea	−9.2 **	7.3 **	16.5 **	−7.9 **	−16.9 **	−0.49 **
Laptev Sea	−6.9 **	7.0 **	13.9 **	−9.4 **	−13.5 **	−0.78 **
Chukchi Sea	−4.0 **	5.3 **	9.3 **	−4.0 **	−8.9 **	−0.39 *
Arctic Basin	−11.9 **	15.2 **	27.1 **	−6.0 **	−24.6 **	0.35 *

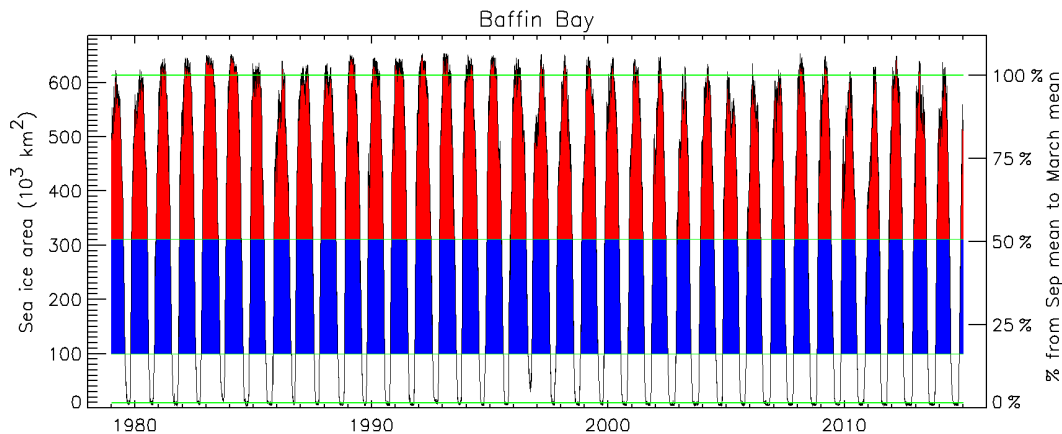


Figure 7. Sea-ice area in Baffin Bay (all depths), 1979–2014. Top green line is mean March sea-ice area; bottom green line is mean September sea-ice area. Two thresholds are shown: 15 and 50 % of the way from the mean September area to the mean March area.

4.2 Correlation of de-trended dates

Figure 4 shows that there is year-to-year variability about the trend lines in the dates of spring sea-ice retreat and fall sea-ice advance. Subtracting out the trend lines leaves residuals. We calculated the correlation of the spring residuals with the fall residuals (Table 3, last column). The correlation is negative in most regions, often significantly so. This means that an early spring sea-ice retreat (relative to the trend line) tends to be followed by a late fall sea-ice advance (relative to the

trend line), and vice versa. The de-trended spring and fall dates for Baffin Bay are shown in Fig. 9. The negative correlations are likely the result of the ice–albedo feedback, discussed in Sect. 5.4.

In regions with a strong negative correlation, this suggests a method for predicting the date of fall sea-ice advance, once the date of spring sea-ice retreat has been observed. (1) Find the slope (*S*) of the least-squares fit of the de-trended fall dates vs. the de-trended spring dates (as in Fig. 9, red line). (2) Calculate the projected date of retreat (*D_r*) and date of

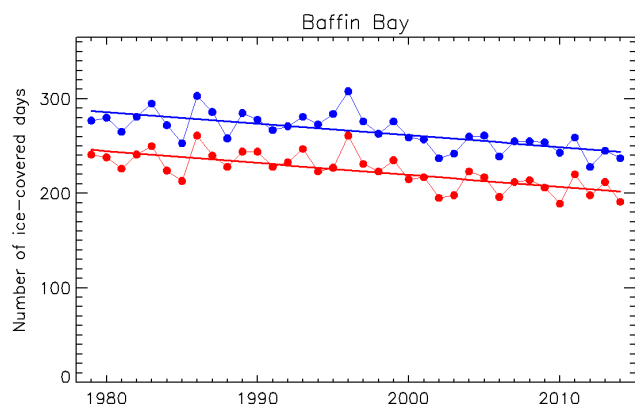


Figure 8. Number of ice-covered days in Baffin Bay (all depths), 1979–2014, based on two thresholds: 15 % (blue) and 50 % (red) (see also Fig. 7). Least-squares lines are also shown. See Fig. S5 for similar plots for other regions.

advance (D_a) for the current year by extrapolating the historical trends (Table 3). (3) In the current year, once the date of spring sea-ice retreat has been observed (D_r^{obs}), predict the date of fall sea-ice advance as $D_a + S \times (D_r^{\text{obs}} - D_r)$. This is the date projected by the trend line plus the anomaly predicted by the historical correlation of the spring and fall dates. This method should give several months of lead time for the predicted date of fall sea-ice advance, with a higher degree of skill than simply predicting a continuation of the fall linear trend, in those regions where the spring and fall dates are significantly correlated.

4.3 Spatial patterns

The spatial pattern of trends in the date of spring sea-ice retreat (Fig. 10) shows that all trends over shallow depths are statistically significant except in the Northern Beaufort, Viscount Melville, and Norwegian Bay regions. Otherwise, the continental shelves around the Arctic show significantly earlier spring retreat, generally -3 to -9 days decade $^{-1}$, with faster retreat in the northern Chukchi and East Siberian seas, Kane Basin, and especially the Barents Sea. For the date of fall sea-ice advance (Fig. 11), all regions have positive trends, but the trends are not statistically significant in some parts of the Canadian Arctic Archipelago. The rest of the continental shelf regions around the Arctic show significantly later fall advance, generally 3 to 9 days decade $^{-1}$, with larger rates in the northern Chukchi and East Siberian seas and in the Barents Sea, similar to the spring pattern. The increase in the length of the summer season (Fig. 12) shows the same pattern, with roughly double the rate (since it equals the fall rate minus the spring rate).

Note that in this analysis, the Chukchi Sea region extends south of Bering Strait into the northern Bering Sea. We know from other analyses (e.g., Laidre et al., 2015a; Parkinson, 2014) that there has been a slight increase in sea ice in the

Bering Sea. Therefore the negative trends for the Chukchi Sea reported here, while still statistically significant, are relatively small because of the inclusion of the northern Bering Sea within the Chukchi Sea region. Similarly, the trends for the Arctic Basin region are relatively large because that region includes the northern Chukchi Sea, where summer sea ice has been rapidly disappearing (e.g., Frey et al., 2015; Parkinson, 2014).

4.4 Sensitivity to threshold

The calculation of the spring and fall transition dates is based on a sea-ice area threshold that is halfway between the mean September sea-ice area and the mean March sea-ice area for each region. Different thresholds would lead to different transition dates. How sensitive are the transition dates to the actual choice of threshold? The answer can be seen in Fig. 2 (and Fig. S1). The rate of change of sea-ice area (i.e., its slope) is relatively steep at the times of threshold crossing, indicating that sea ice diminishes quickly in spring and grows back quickly in fall compared to the rate of change in winter and summer. Therefore the transition dates are relatively insensitive to the threshold, in the sense that a small change in the threshold would lead to a small change in the transition dates.

5 Discussion

5.1 Previous studies of the timing of Arctic sea-ice advance and retreat

Many studies in the last 10 years have considered changes in the timing of sea-ice advance and retreat in the context of polar bear ecology. Stirling and Parkinson (2006) used daily sea-ice concentration from satellite passive microwave data to calculate the date of sea-ice breakup (50 % concentration) in spring in Baffin Bay for each year from 1979 through 2004, finding a statistically significant trend toward earlier breakup (-6.6 ± 2.0 days decade $^{-1}$). The timing of polar bear onshore arrival in western Hudson Bay was previously shown to be significantly related to the 50 % sea-ice concentration threshold (Stirling et al., 1999). Other studies of sea-ice timing and polar bears include Regehr et al. (2007), Obbard et al. (2007), Hamilton et al. (2014), Lunn et al. (2014), Laidre et al. (2015a), and Obbard et al. (2016). These studies are summarized in Table 2, along with eight other studies where sea-ice metrics were used for analysis of polar bear habitat.

Other researchers have considered changes in the timing of sea-ice advance and retreat without specific emphasis on polar bears. Stammerjohn et al. (2012) used daily sea-ice concentration from satellite passive microwave data (1979–2007) to calculate trends in the dates of sea-ice retreat and advance at every 25×25 km grid cell. Then they identified two regions where the trends were particularly large, encom-

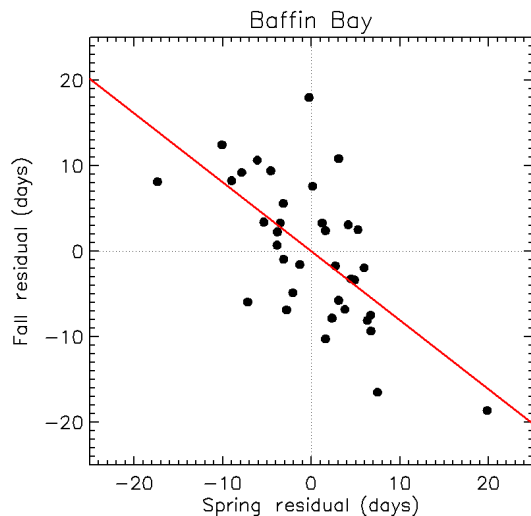


Figure 9. Date of fall sea-ice advance (de-trended) vs. date of spring sea-ice retreat (de-trended) for Baffin Bay (all depths). The de-trended dates have correlation -0.64 . This suggests that the date of fall sea-ice advance can be predicted from the date of spring sea-ice retreat with more skill than simply extrapolating the fall trend. See Table 3 for correlations in all regions. The red line is the least-squares fit.

passing parts of the East Siberian/Chukchi/Beaufort seas and the Kara/Barents seas. Dates of sea-ice retreat in these regions trended earlier by $15\text{--}18$ days decade^{-1} , and dates of sea-ice advance trended later by $10\text{--}13$ days decade^{-1} , with correlations of de-trended dates on the order of -0.8 . Their results are slightly more extreme than ours (Table 3) because their regions were specifically tailored to include the largest trends, but our results are nevertheless generally consistent with theirs.

Parkinson (2014) used daily passive microwave data (1979–2013) to calculate and map the number of days per year with sea-ice concentration $\geq 15\%$, finding that most of the Arctic seasonal ice zone (roughly all regions in Fig. 1 except the Arctic Basin) is experiencing a loss of $10\text{--}20$ days decade^{-1} , with the most rapid loss in the Barents Sea. They also found that the trends are not sensitive to the 15% threshold, with similar trends obtained using 50% . The results are consistent with ours (Table 3) that show a decrease in the number of ice-covered days.

Frey et al. (2015) used daily passive microwave data (1979–2012) to study the timing of sea-ice breakup, freeze-up, and persistence in the Beaufort, Chukchi, and Bering seas, finding trends toward earlier breakup and later freeze-up in the Beaufort and Chukchi seas, with steeper trends since 2000. They also used wind and air temperature data to determine that for the localized areas that are experiencing the most rapid shifts in sea ice, those in the Beaufort Sea are primarily wind driven, while those offshore in the Canada Basin are primarily thermally driven.

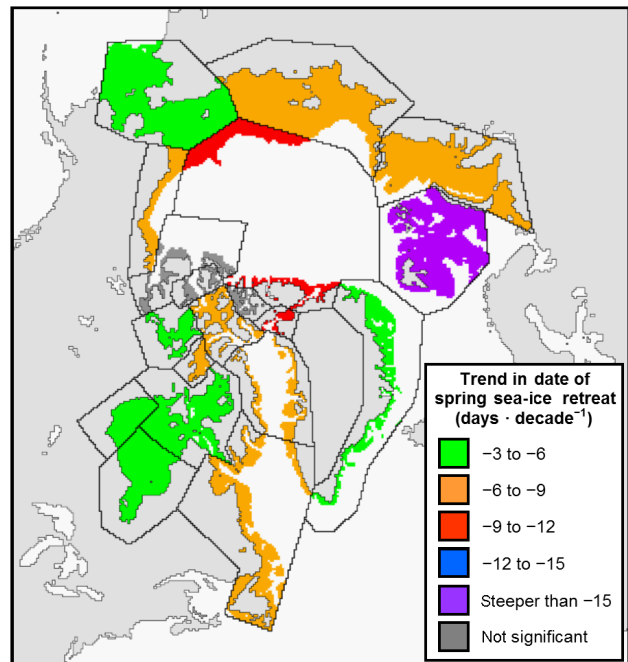


Figure 10. Trend map of the date of spring sea-ice retreat for the shallow parts of each PBSG region. Trends are also given in Table 4.

Steele et al. (2015) looked at the timing of sea-ice retreat in the southeastern and southwestern Beaufort Sea using daily sea-ice concentration data (1979–2012). They found no trend in the date of retreat in the southeastern Beaufort Sea but did find a trend toward earlier retreat in the southwestern Beaufort Sea. Furthermore, an increase in monthly mean easterly winds of ~ 1 m s^{-1} during spring was associated with an earlier summer sea-ice retreat of $6\text{--}15$ days, offering predictive capability of sea-ice retreat with 2 to 4 months of lead time.

Our methods in the present study are based on our previous work. Laidre et al. (2015a) calculated the timing of sea-ice advance and retreat in 12 Arctic regions (1979–2013) for the Conservation of Arctic Flora and Fauna (CAFF) Arctic Biodiversity Assessment (ABA). Laidre et al. (2015b) focused on polar bear habitat in East Greenland, including changes in the timing of sea-ice advance and retreat. Laidre et al. (2012) examined narwhal sea-ice entrapments and the timing of fall sea-ice advance in six narwhal summering areas of Baffin Bay. Heide-Jørgensen et al. (2013) considered changes in the timing of spring sea-ice retreat in the North Water Polynya. All these studies found trends toward earlier spring sea-ice retreat and later fall sea-ice advance from the 1980s to present.

Our sea-ice metrics are currently being used in the IUCN PBSG Status Table (<http://pbsg.npolar.no/en/status/status-table.html>), the primary source of scientific information for managers, nongovernmental organizations, and the public on the status of the world's polar bears. The Status Table includes trends in the dates of spring sea-ice retreat, fall

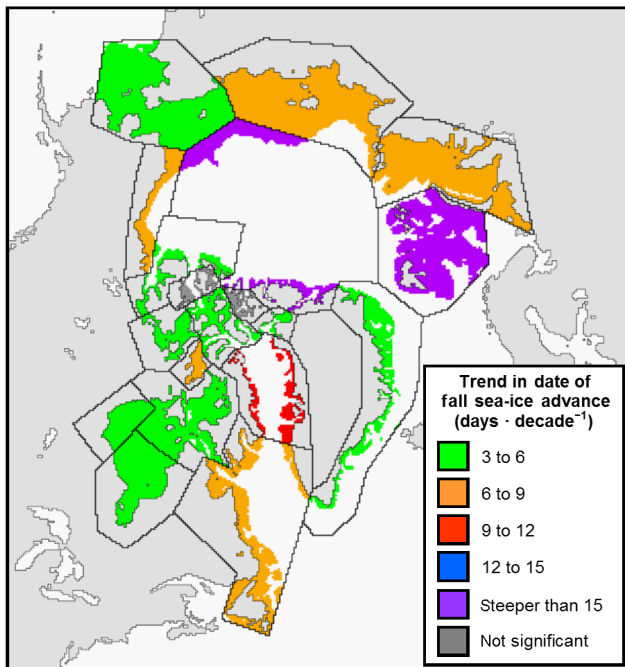


Figure 11. Trend map of the date of fall sea-ice advance for the shallow parts of each PBSG region. Trends are also given in Table 4.

sea-ice advance, and summer (June–October) sea-ice concentration for each of the 19 polar bear subpopulations, as reported here, and will be updated accordingly. The IUCN Red List assessment of polar bears (Wiig et al., 2015) used the number of ice-covered days per year as its sea-ice metric, as presented here in Sect. 3.4.

5.2 Relevance to other Arctic marine mammal species

While the metrics reported here were tailored specifically to polar bears and polar bear ecology, they can be considered relevant for a range of other AMM species. Besides the polar bear, AMMs are typically considered to be three cetacean species (the narwhal, *Monodon monoceros*; beluga, *Delphinapterus leucas*; and bowhead whale, *Balaena mysticetus*) and seven pinniped species (the ringed seal, *Pusa hispida*; bearded seal, *Erignathus barbatus*; spotted seal, *Phoca largha*; ribbon seal, *Phoca fasciata*; harp seal, *Pagophilus groenlandicus*; hooded seal, *Cystophora cristata*; and walrus, *Odobenus rosmarus*) (Laidre et al., 2008; Laidre et al., 2015a). These species all occur north of the Arctic Circle for most of the year and depend on the Arctic marine ecosystem for all aspects of life. In a few cases some may live outside the Arctic for part of the year. All depend on the timing of sea-ice advance and retreat for different aspects of their life history, and thus the metrics in this study may be relevant to understanding changes in the regions where these AMMs occur.

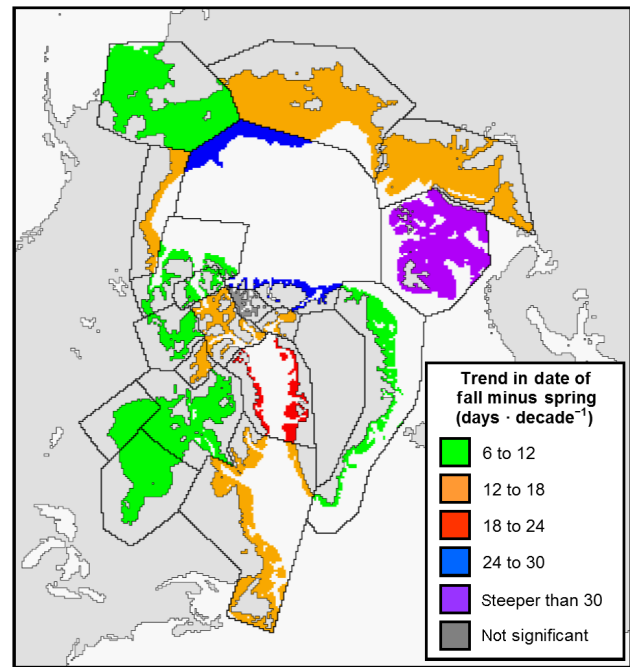


Figure 12. Trend map of the length of the summer season for the shallow parts of each PBSG region. Trends are also given in Table 4.

5.3 Variability in the timing of sea-ice advance and retreat

The dates of sea-ice advance and retreat, as shown in Figs. 4 and S2, vary about the trend lines. Some regions such as East Greenland have high year-to-year variability, while other regions such as Foxe Basin have low year-to-year variability (as measured, for example, by the standard deviation of the residuals about the trend line). The high variability is likely due to advection of sea ice through the region due to wind and currents, while the low variability indicates a lack of such advection, as noted by Laidre et al. (2012), who found that three sheltered sites on the western side of Baffin Bay had low variability in fall freeze-up dates, while sites near the North Water Polynya in northern Baffin Bay, and in the East Greenland Current, had high variability. In regions where sea-ice advance and retreat are primarily driven by thermodynamics, the year-to-year variability will be lower than in regions where wind and currents are strong.

5.4 Correlation of dates of sea-ice retreat and advance

The negative correlations between the de-trended dates of sea-ice retreat and advance (Tables 3 and 4) are likely the result of the ice–albedo feedback, noted also by Stammerjohn et al. (2012). When sea ice retreats earlier than average in spring, the ocean has more time to absorb heat from the sun. The extra heat is stored in the upper ocean through the summer, and must be released to the atmosphere in the fall before

Table 4. Same as Table 3 but for the shallow (≤ 300 m) portions of each region.

Subpopulation	Spring trend		Fall trend		Fall–spring trend		Jun–Oct ice concentration		Ice-covered days		Correlation of dates	
Kane Basin	−9.7	**	5.5	**	15.2	**	−6.9	**	−15.1	**	−0.36	*
Baffin Bay	−8.4	**	9.7	**	18.1	**	−3.3	**	−19.8	**	−0.54	**
Lancaster Sound	−7.6	**	4.6	**	12.2	**	−4.3	**	−11.2	**	−0.35	*
Norwegian Bay	−1.3		4.2		5.5		−1.6		−7.0	**	−0.21	
Viscount Melville	−4.3		6.9		11.2	*	−4.3	**	−11.7	**	0.31	
Northern Beaufort	−5.6		3.5	**	9.1	*	−3.6	*	−8.5	*	−0.62	**
Southern Beaufort	−7.3	**	8.6	**	15.9	**	−7.9	**	−15.5	**	−0.53	**
M’Clintock Channel	−4.1	**	5.8	**	10.0	**	−5.2	**	−11.0	**	−0.74	**
Gulf of Boothia	−8.6	**	7.6	**	16.2	**	−9.0	**	−18.8	**	−0.57	**
Foxe Basin	−5.2	**	5.6	**	10.9	**	−3.2	**	−11.3	**	−0.57	**
Western Hudson Bay	−5.1	**	3.5	**	8.7	**	−2.9	**	−8.6	**	−0.25	
Southern Hudson Bay	−3.0	*	3.6	*	6.6	**	−1.8	*	−6.8	**	−0.35	
Davis Strait	−6.9	**	8.0	**	14.9	**	−1.9	**	−14.7	**	−0.26	
East Greenland	−4.5	**	4.6	**	9.0	**	−3.0	*	−9.4	**	−0.30	
Barents Sea	−17.0	**	21.0	**	37.9	**	−4.2	**	−44.6	**	−0.46	**
Kara Sea	−8.8	**	7.0	**	15.8	**	−7.3	**	−16.2	**	−0.47	**
Laptev Sea	−6.8	**	6.5	**	13.3	**	−9.1	**	−13.2	**	−0.77	**
Chukchi Sea	−4.1	**	5.4	**	9.5	**	−4.1	**	−9.1	**	−0.39	*
Arctic Basin	−9.4	**	16.8	**	26.1	**	−9.0	**	−29.3	**	−0.18	

sea ice can begin to form, thus delaying fall freeze-up. Conversely, a late spring sea-ice retreat prevents the ocean from absorbing as much heat, allowing sea ice to form earlier in the fall (e.g., Perovich et al., 2007). The negative correlations are not perfect because other factors contribute to the timing of sea-ice retreat and advance, such as short-term weather events and long-term climate patterns. This is also discussed in more detail by Blanchard et al. (2011), who attributed the “re-emergence of memory” in the fall to the several-month persistence of sea surface temperatures (SSTs) over the summer, enhanced by the ice–albedo feedback. We calculated the correlation of the date of fall sea-ice advance in year n with the date of spring sea-ice retreat in year $n + 1$, but the correlation was not significant in any region, suggesting that SST anomalies do not persist through the winter.

5.5 Sea-ice area vs. extent

Some sea-ice studies use sea-ice extent, rather than sea-ice area, to characterize sea-ice coverage. Sea-ice extent is the total area of all grid cells with sea-ice concentration greater than 15 %, i.e., not weighted by the sea-ice concentration. If the sea-ice concentration in a grid cell exceeds 15 %, the entire area of the grid cell counts toward the sea-ice extent. This is useful in some contexts, but we believe that sea-ice area is a better measure of how much usable sea ice is actually present for polar bears. Also, sea-ice extent is a highly nonlinear function of sea-ice concentration, which leads to more abrupt jumps in its time series than sea-ice area.

5.6 Melt onset and freeze-up

Some investigators have approached the idea of seasonal transitions in the Arctic by examining the dates of melt onset in the spring and freeze-up in the fall, based on the presence of liquid water in the surface layer of the ice or snow (Winebrenner et al., 1994, 1996; Smith, 1998; Belchansky et al., 2004; Markus et al., 2009; Stroeve et al., 2014). In these studies, melt onset and freeze-up are closely tied to the surface air temperature, but they are not indicators of sea-ice coverage or condition. For example, at the SHEBA station in the Beaufort Sea in 1997–1998 (Perovich et al., 1999), melt onset occurred on 29 May when rain fell, but the sea ice did not actually break up until the end of July when a storm passed through. Similarly in fall, melt ponds on the surface of the ice began to freeze in mid-August but the sea ice did not actually consolidate into winter-like pack ice until early October (Stern and Moritz, 2002). Melt onset and freeze-up dates are useful as climate metrics, but for ice-dependent marine mammals, transition dates between seasons are best measured by the sea-ice coverage itself, rather than proxies tied to air temperature.

5.7 National Climate Assessment (NCA)

The NCA summarizes the impacts of climate change across the United States, now and into the future, with the goal of better informing public and private decision-making at all levels. The third NCA report was released in May 2014 (Melillo et al., 2014). It documents the decline of Arctic sea-ice extent, thickness, and volume, but not changes in the timing of sea-ice advance and retreat. One of the motivations of

the present study was to develop a sea-ice climate metric (or indicator) with relevance to marine mammals that could be used in future NCA reports. The timing of sea-ice advance and retreat satisfies all the qualifications for climate indicators put forward by the NCA (NCA, 2011).

6 Conclusions

It is well established that the area of Arctic sea ice is declining in all months of the year, based on satellite passive microwave data from 1979 to the present (Fetterer et al., 2016; IPCC, 2013). In this study we looked instead at the timing of sea-ice retreat in spring and advance in fall, because the duration of the sea-ice season (or equivalently the ice-free season) is important for polar bears. We found that there has been a consistent and large loss of habitat for polar bears across the Arctic. In 17 of the 19 subpopulation regions there are significant trends toward earlier spring sea-ice retreat, mostly ranging from -3 to -9 days decade $^{-1}$. In 16 of the regions there are significant trends toward later fall sea-ice advance, mostly ranging from $+3$ to $+9$ days decade $^{-1}$. Over the 3.5 decades of this study, the time interval from the date of spring retreat to the date of fall advance has lengthened by 3 to 9 weeks in most regions.

General circulation models (GCMs) predict ice-free Arctic summers by mid-century or sooner (IPCC, 2013; Overland and Wang, 2013). Spring sea-ice retreat will continue to arrive earlier and fall sea-ice advance will continue to arrive later, with no reversal in sight. Barnhart et al. (2015) used daily sea-ice output from a 30-member GCM ensemble, driven by the business-as-usual emissions scenario (RCP 8.5), to map the annual duration of open water in the Arctic through 2100. They found that by 2050 the entire Arctic coastline and most of the Arctic Ocean will experience an additional 1 to 2 months of open water per year, relative to present conditions, which is consistent with extrapolation of the trends in Table 3.

What are the implications of these physical changes for the global population of polar bears? Their dependence on sea-ice means that climate warming poses the single most important threat to their persistence (Stirling and Derocher, 2012; USFWS, 2013). Changes in sea ice have been shown to impact polar bear abundance, productivity, body condition, and distribution (Stirling et al., 1999; Durner et al., 2009; Regehr et al., 2010; Rode et al., 2012, 2014; Bromaghin et al., 2015; Obbard et al., 2016). Furthermore, population and habitat models predict substantial declines in the distribution and abundance of polar bears in the future (Durner et al., 2009; Amstrup et al., 2008; Castro de la Guardia et al., 2013; Hamilton et al., 2014). This study offers standardized metrics with which to compare polar bear habitat change across the 19 subpopulations and provides a starting point for including sea-ice habitat change in circumpolar polar bear management and conservation plans.

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