Vol. 564: 225–233, 2017
doi: 10.3354/meps11964

MARINE ECOLOGY PROGRESS SERIES
Mar Ecol Prog Ser

Published February 3

Sea ice cycle in western Hudson Bay, Canada, from a polar bear perspective

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ABSTRACT: Remote sensing has allowed insights into changing Arctic sea ice, but seasonal underestimation of ice presence may lead to misinterpretation of species behavior. We use the dependence of polar bears *Ursus maritimus* on sea ice to assess the utility of satellite-linked radio collar locations to indicate underestimation in sea ice on 2 ice data sets derived from satellites. We then define the ice-free period in western Hudson Bay, Canada, from a polar bear perspective using the correlation between the ice concentration and polar bear migration onshore and offshore. We found that the ice-free period in this region lengthened by 3 ± 0.8 wk over the period 1979–2015. Polar bears migrated onshore 2 wk earlier and offshore 1 wk later in the period 2005–2015 than in 1980–1989. Understanding the trends in polar bear migration and the onshore period is critical to understanding population status.

KEY WORDS: Remote sensing · Polar bears · Western Hudson Bay · Sea ice concentration

INTRODUCTION

Sea ice is an integral component of Arctic and subarctic marine ecosystem dynamics and is linked to biological processes influencing ecosystem productivity and the distribution and movement patterns of marine mammals (e.g. Wu et al. 2007, Bluhm & Gradinger 2008, Laidre et al. 2008, Post et al. 2013). Subarctic waters are covered by sea ice much of the year, with an annual ice-free period of 1–5 mo (Parkinson 2014). Polar bears *Ursus maritimus* depend upon sea ice as a platform for traveling, hunting, mating, and, in some areas, denning and producing cubs (DeMaster & Stirling 1981). Although polar bears hunt ringed seals *Pusa hispida* and bearded seals *Erignathus barbatus* whenever they are on ice, late spring and early summer are critical because seal pups and adults are more vulnerable to predation, and this is when polar bears acquire most of the energy stores required to survive the ice-free period (DeMaster & Stirling 1981, Ramsay & Stirling 1988, Stirling & Øritsland 1995, Thiemann et al. 2008, Pilfold et al. 2012, 2015).

Our study examines the utility of satellite-linked geographic positioning system (GPS) telemetry data to assist in studying the sea ice cycle. Technological advances have allowed the use of wildlife to obtain high-resolution oceanographic and environmental data in regions where human accessibility is challenging (Charrassin et al. 2002, Lydersen et al. 2002, Laidre et al. 2008, Simmons et al. 2009, Grist et al. 2011). Polar bears are a good candidate for sea ice studies because their distribution and life history are closely tied to sea ice characteristics (Stirling et al.

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1993, Mauritzen et al. 2001, Durner et al. 2009). Further, when offshore, polar bears prefer to walk on ice and avoid swimming for thermoregulation and energy conservation reasons (Monnett & Gleason 2006, Durner et al. 2011, Pagano et al. 2012, Pilfold et al. 2017). Therefore, polar bear ecology suggests the possibility of using the transmission characteristics and locations of bears tracked by GPS collars to indicate the presence of sea ice. Within the last decades, polar bear movements have been tracked extensively using satellite-linked radio collars throughout the circumpolar Arctic (Freitas et al. 2012, Auger-Méthé et al. 2016, Laidre et al. 2015, Sahanatien et al. 2015), resulting in an archive of telemetry data with high temporal and spatial resolution to evaluate sea ice data.

In this paper, we use satellite telemetry data from radio-collared female polar bears in western Hudson Bay, Canada, and sea ice concentration from the Canadian Ice Service Data Archive (CISDA) to assess sea ice biases of 2 sea ice concentration data sets derived from passive microwave sensors (Bootstrap-v2 and ASI-AMSRE) in Hudson Bay. We then use the sea ice concentration data to examine the trend in the ice-free period from a polar bear perspective.

MATERIALS AND METHODS

Polar bear telemetry data

We obtained polar bear location data from GPS Argos satellite-linked collars deployed in 2004–2009 on adult females accompanied by cubs-of-the-year (8 mo old) or 1-yr-old cubs (20 mo old). The University of Alberta Animal Care and Use Committee for Biosciences approved all animal handling protocols. Collars were deployed on 9–15 bears each autumn south of Churchill, Manitoba, following the methods of Stirling et al. (1989), resulting in >15 000 locations. GPS location accuracy was approximately 30 m (Patterson et al. 2010, Tomkiewicz et al. 2010). Most (96 %) of the locations were between 55° N–61° N and 85° W–95° W; we defined this region as western Hudson Bay (Fig. 1A).

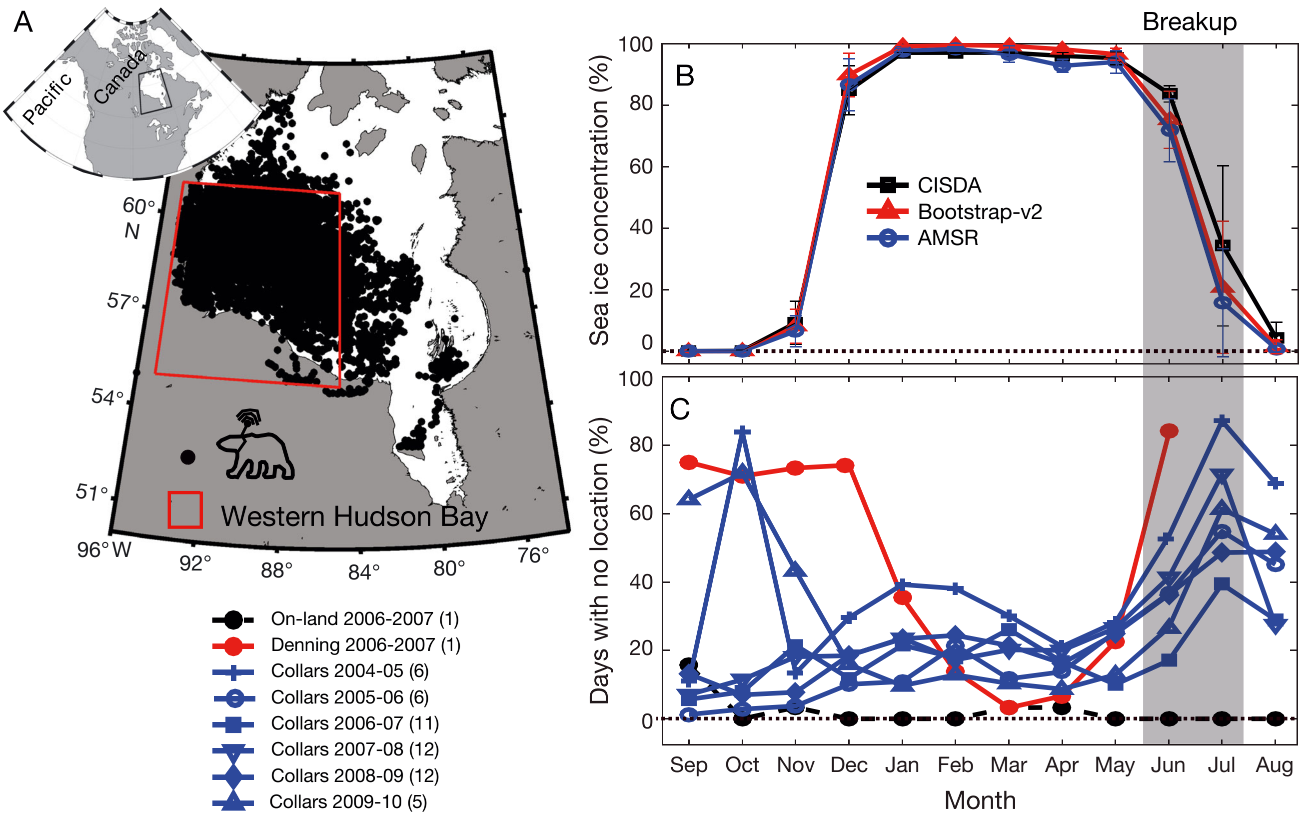

Fig. 1. (A) Geographic location of Hudson Bay, Canada. Black dots are female polar bear locations obtained from telemetry radio collars from 2004 to 2009. Most (96 %) of the locations are within the red polygon that defines western Hudson Bay. (B) Mean sea ice concentration cycle in western Hudson Bay 2004–2010. (C) Mean percentage of days per month with no locations (i.e. gaps in transmitted data). Number of collars used to calculate the means in C are indicated in the legend within brackets. Shaded area across B and C highlights the breakup period

Each collar has one antenna for receiving GPS locations, and one for connecting to the Argos satellite to transmit GPS locations. The GPS unit calculates one GPS location every 4 h (at 21:00, 01:00, 05:00, 09:00, 13:00 and 17:00 h GMT). The Argos unit attempts to connect to the Argos satellites daily from 17:00 to 20:59 h with one transmission every 60 s (this daily connection is called the duty cycle). Only one successful transmission is necessary to send the 6 GPS locations. When the Argos unit is unable to send the locations during its duty cycle, a gap is created in the 'transmitted data'. This gap can be filled if the collar is recovered and the data are downloaded. In this study, we use the transmitted data with gaps.

The Argos antenna was lateral to the collar and submerged when a polar bear swam, thus impeding satellite connection (Durner et al. 2011, Pagano et al. 2012). The GPS antenna, however, was located on top of the collar, where it was unlikely to be submerged, and thus swimming locations were recorded. Gaps in the transmitted GPS locations during the melting period were likely related to failed Argos transmissions as polar bears swam between ice floes, or from the ice edge to land (Durner et al. 2011, Pagano et al. 2012, Pilfold et al. 2017).

The percentage of gaps per month during the melting period (June–August) was 2–4 times larger than when polar bears were on land (September–November, with the exception of 2004 and 2009 collars), or when the sea ice cover was close to 100% (December–May) (Fig. 1B,C). The small percentage of gaps per month of a collar prematurely released on land that transmitted throughout the year suggest that gaps in the transmitted data were related to polar bear activities (Fig. 1B). The exceptional gaps in autumn 2004 and 2009 could have been caused by extreme weather conditions that could have affected the satellite connection or forced polar bears to seek refuge in temporary dens.

We selected collars with >4 mo of locations and <70% data lost per month to ensure high collar performance, which resulted in 54 useable collars (5–12 per year). We extracted one location per collar per day, resulting in 11 549 GPS locations. Most (93%) of these locations were recorded at 17:00 h with the remainder recorded at 13:00 h. Most (98%) of the GPS locations were transmitted within the first 4 h of being recorded while the remainder (2%) were transmitted between 5 and 6 h of being recorded. With this, we excluded long-distance swims (>8 h), but may have included short swim events of approximately 4 h. Records of a swimming female polar bear with a yearling suggest that polar bears can swim long distances and for several days (78 to 687 km); however, the average swimming speed is slow (median 2.0 km h^{-1} and range 0.5–3.7 km h^{-1}) (Durner et al. 2011, Pilfold et al. 2017). Swimming for 4 h at these speeds results in a distance of 2–15 km, which has little significance given the spatial resolution of the sea ice data sets (i.e. 25 × 25 km and 6.5 × 6.5 km; see next section). Therefore, we believe that our interpretation that transmitted locations are from polar bears on sea ice or land is reasonable.

Sea ice concentration data

We selected 3 sea ice concentration data sets commonly used in the Northern Hemisphere: CISDA, Bootstrap-v2, and ASI-AMSRE. Key differences between these 3 data sets are spatial resolution, temporal resolution, and sources of information used to derive sea ice concentration. CISDA is the only one of the 3 to incorporate *in situ* observations of sea ice concentrations and model forecasts. Bootstrap-v2 and ASI-AMSRE sea ice concentration data are determined using an algorithm that requires the input of brightness surface temperature measurements from passive microwave sensors at specific frequencies. Bootstrap-v2 and ASI-AMSRE data may differ because they use different satellite frequencies and a different algorithm to calculate sea ice concentration. For example, the higher satellite frequency used by ASI-ASMRE allows it to have a spatial resolution of 6.25 km whereas the CISDA and Bootstrap-v2 have a spatial resolution of 25 km. More details on each data set are provided below.

In general, passive microwave derived sea ice data are associated with an underestimation error of up to 30% during breakup and freeze-up throughout the marginal ice zone and seasonal ice regions in the Northern Hemisphere (e.g. Cavalieri et al. 1991, Comiso et al. 1997, Markus & Dokken 2002). In Hudson Bay, passive microwave sea ice concentration can underestimate sea ice concentration by up to 50% compared with CISDA (Agnew & Howell 2003). Underestimation biases of passive microwave data are associated with the presence of wet snow and melt ponds during breakup, and with areas covered by frazil ice and young ice during freeze-up (Agnew & Howell 2003).

CISDA sea ice concentration

The CISDA data are a combination of remotely sensed, areal and shipping reconnaissance and survey, forecaster expertise, and ground observations (Tivy et al. 2011). CISDA data are produced weekly to allow for the inclusion of data unavailable in near real time. We accessed the gridded (0.25 × 0.25°) weekly ice concentration data from 1979 to 2015 (http://ice-glaces.ec.gc.ca). The CISDA ice concentration has a small underestimation during breakup because of biases in the satellite imaging sensors with low sea ice concentration (Tivy et al. 2011). However, because CISDA integrates many different sources, CISDA sea ice data are usually treated as a good reference source for the evaluation of passive microwave sea ice data (Agnew & Howell 2003). We are not able to evaluate CISDA ice data with polar bear daily location because weekly means are not representative of daily conditions due to the dynamic properties of sea ice.

Bootstrap-v2 sea ice concentration

Bootstrap-v2 sea ice concentration was derived from measurements from Scanning Multi-channel Microwave Radiometer, Special Sensor Microwave/ Imager, and special Sensor Microwave Imager/ Sounder. Sea ice concentration was generated using Version 2 of the Bootstrap Algorithm (Comiso 2000, updated 2015) and gridded onto a 25 × 25 km stereographic grid. Temporal resolution was every other day before 1987 and daily thereafter. Data from 1979 to 2015 were obtained from the National Snow and Ice Data Center (http://nsidc.org/data/docs/daac/nsidc0079-bootstrap-seaice.gd.html). To our knowledge, there are no estimates of the errors of this data for Hudson Bay.

ASI-AMSRE sea ice concentration

The ASI-AMSRE sea ice concentration was derived from measurements obtained from the Advanced Microwave Scanning Radiometer–Earth Observing system (AMSR-E) sensor. Sea ice concentration was generated using the ASI Algorithm from AMSR-E data (Kaleschke et al. 2001, Spreen et al. 2008). The sea ice concentration data were available at daily resolution, and were gridded on to a 6.25 × 6.25 km stereographic grid. We obtained gridded data from 2002 to 2015 from the Integrated Climate Data Center (icdc.cen.uni-hamburg.de/), University of Hamburg, Hamburg, Germany. Data gaps between the end of 2011 and early 2012 were due to technical problems with the AMSR-E sensor at the end of 2011 and its subsequent replacement with the AMSR-2 sensor in 2012. Hereafter, we refer to AMSR-E and AMSR-2 as AMSR. To our knowledge, there are no estimates of the errors of this data for Hudson Bay.

Data analysis

Sea ice concentration: climatology comparison

The evaluation of Bootstrap-v2 and AMSR with CISDA was conducted for western Hudson Bay using a time scale of monthly means. We calculated monthly means of sea ice concentration from weekly charts produced by CISDA, and derived a monthly sea ice climatology (2004–2010). In the case of Bootstrap-v2 and AMSR, we calculated weekly means from daily data, and then followed the same procedure as with CISDA. We quantified differences between CISDA and the passive microwave data using residuals; negative residuals indicated underestimations, whereas positive residuals indicated overestimations compared to CISDA.

Sea ice presence: a polar bear perspective

From autumn 2004 to summer 2009, we used polar bear locations offshore as data points suggesting the presence of sea ice, and compared these against daily Bootstrap-v2 and AMSR sea ice concentration. Presence of sea ice was defined as a sea ice concentration >0%, and 'open water' as 0% ice concentration. Therefore, evaluation of Bootstrap-v2 and AMSR with telemetry data was localized and dependent on the area used by collared polar bears. We determined the percentage of polar bear locations offshore per month in apparently 'open water'. Months with a small percentage of locations in open water indicated a small underestimation error, whereas months with a larger percentage indicated a larger underestimation error. We compared the results of this analysis with the comparison with CISDA described above.

Timing of breakup and freeze-up

From a polar bear perspective, the timing of breakup and freeze-up each year was defined based on the date polar bears migrated onshore and offshore, respectively. Onshore migration was defined as the first day a location on land was not followed by a location offshore until autumn. The migration offshore was defined as the first day a location offshore was not followed by a location on land until the next summer. We estimated the median date of polar bear migration onshore and offshore by combining individual migration data each year and excluding outliers (>2 SD from the mean) (see Fig. S1 in the Supplement at www.int-res.com/articles/suppl/m564p225_supp/). For migration offshore, we used only collars from non-denning females because denning females do not return to the sea ice until the following February–March (Watts et al. 1987, Ramsay & Stirling 1988).

We determined freeze-up and breakup dates using daily sea ice concentration data averaged over the region defined as western Hudson Bay. The date of freeze-up was defined, based on findings from earlier studies, as the first date that the spatially averaged sea ice concentration reached and remained ≥10 % until the next summer (Stirling et al. 1999, Cherry et al. 2013). We explored 3 definitions for breakup date: the first date the sea ice concentration fell below (1) 50 %, (2) 30 %, and (3) 20 %, and did not increase until autumn (Stirling et al. 1999, Cherry et al. 2013). We calculated the Pearson product-moment correlation (r^2) between freeze-up and polar bear migration offshore, and between breakup date and polar bear migration onshore (Table 1). We used the sea ice concentration with highest correlation with the onshore migration to define our breakup date.

We define the ice-free period as the period between the date of breakup and freeze-up, and we estimated its trend from 1979 to 2015. Assuming that the relationship between ice concentration and polar bear migration held before 2004 and after 2009, our estimate of the ice-free period beyond these years can also be used as a measure of the onshore period experienced by polar bears in western Hudson Bay. We repeated the analysis using weekly mean sea ice concentration to include CISDA.

RESULTS

Evaluation of passive microwave sea ice data in Hudson Bay

From 2004 to 2010, the monthly sea ice concentration derived from Bootstrap-v2 and AMSR were similar to CISDA estimates (Fig. 1B). In every month, except June and July, the passive microwave data were within 5 % of the CISDA data (Fig. 2A). Bootstrap-v2 underestimated the sea ice concentration in June (9 %) and July (12 %). AMSR also underestimated the sea ice concentration in June (11 %) and July (19 %).

Over the same period, the percentage of locations offshore in apparently 'open water' was largest in July. Twenty percent of the locations were in open water using Bootstrap-v2 and approximately 30 % when using AMSR (Fig. 2B). The percentage was smaller (<10 %) in months when western Hudson Bay was ice-free (i.e. August–October), or with >50 % sea ice concentration (December–June). These results support that the largest underestimations of sea ice by passive microwave data occur during breakup. From the perspective of how polar bears use the sea ice, Bootstrap-v2's estimates were less biased than those of AMSR.

Polar bear migration and its relationship with freeze-up and breakup

Polar bears migrated offshore between 23 and 28 November between 2004 and 2008 onto the first sea ice formed along the coast (Fig. 3A; Fig. S2, Table S1 and Video S1 in the Supplement at www.int-res.com/articles/suppl/m564p225_supp/). There was a weak positive correlation between the median date of migration offshore and freeze-up date (Table 1). The difference between these 2 dates was small (<5 d; Table 1). The time series of freeze-up date from 1979

Table 1. Results of the Pearson correlation (r^2) between the onshore migration of polar bears and the sea ice breakup date (2006–2009). The freeze-up date is defined as the 10 % sea ice concentration. Three breakup date definitions are evaluated (first day with ≤50 %, ≤30 % and ≤20 % sea ice concentration). The best fit was based on the highest correlation. The difference (diff) between the day of breakup (freeze-up) and the migration onshore (offshore) is shown beside the corresponding correlation column

Sea ice data source	Breakup						Freeze-up	
	r^2_{50} (p_{50})	$diff_{50}$	r^2_{30} (p_{30})	$diff_{30}$	r^2_{20} (p_{20})	$diff_{20}$	r^2_{10} (p_{10})	$diff_{10}$
Bootstrap-v2	0.93 (0.07)	−18	0.90 (0.10)	−15	0.89 (0.11)	−11	0.47 (0.42)	−4
AMSR	0.93 (0.07)	−20	0.88 (0.12)	−18	0.89 (0.11)	−15	0.60 (0.28)	−2

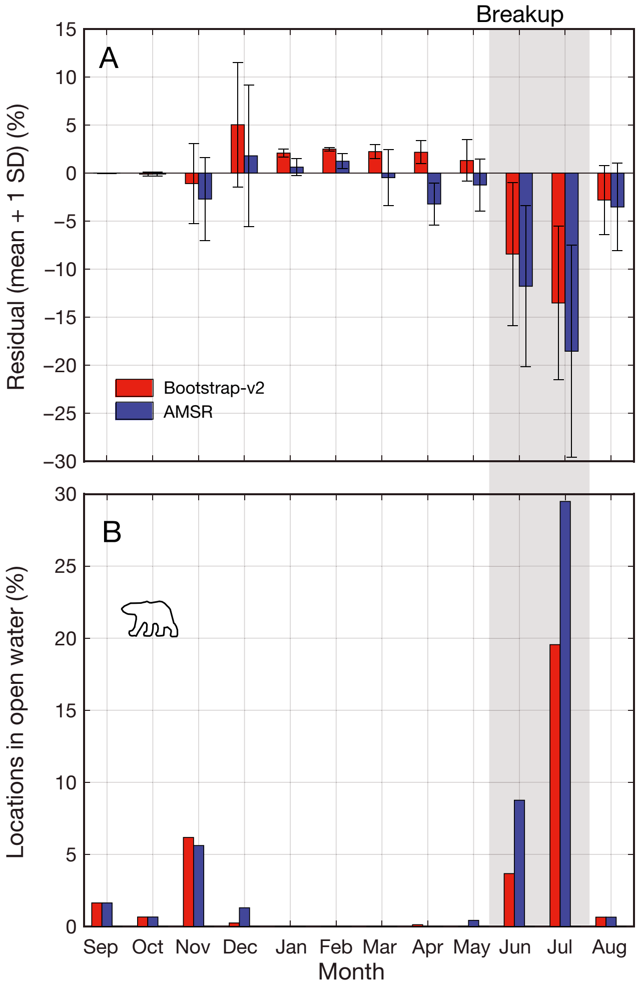

Fig. 2. Evaluation of sea ice data products (Bootstrap-v2 and AMSR) with CISDA and polar bear telemetry data. (A) Comparing passive microwave data to CISDA using residuals per month (%; 2004–2010). Negative residual indicates underestimation biases relative to CISDA. (B) Percentage of polar bear locations in 'apparently open water' per month (2004–2009). High percentage indicates an underestimation of sea ice by the ice data product. Examples of locations in apparently open water can be seen in Figs. S3 & S4 in the Supplement at www.int-res.com/articles/suppl/m564p225_supp/. Shaded area across the panels highlights the month of breakup when we find the largest underestimations of sea ice concentration

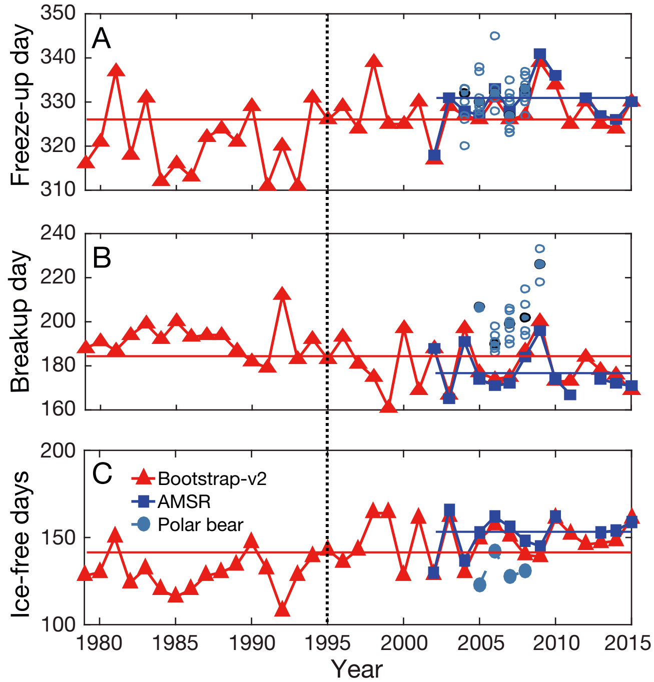

Fig. 3. Sea ice and polar bear migration in western Hudson Bay: (A) freeze-up date and the migration offshore, (B) breakup date and the migration onshore (correlations in Table 1), and (C) length of the ice-free period and the onshore period. Median date of polar bear migration (filled blue circle) and individual polar bear migration (open blue circles). Solid line of the same color as sea ice data is the mean over the entire period of available data. Black dot-dashed line across panels marks a point of change in ice regime where the means of the before and after periods are significantly different in the 3 panels. Details in Table S1 in the Supplement

to 2015 using Bootstrap-v2 shows a positive trend ($p = 0.01$) of 0.29 d yr^{-1}, with a marked shift in the 1990s (Fig. 3A). From 1979 to 1989, the mean freeze-up date (±SD) was 16 November (± 5 d), while in 2005–2015 it was delayed by 8 d to 24 November (±8 d) (*t*-test, $p = 0.01$).

Polar bears migrated onshore between 9 and 20 July between 2005 and 2009 (Fig. 3B, Table S1 and Video S1 in the Supplement). Migration onshore was usually over a broad area along the southwestern coast of western Hudson Bay (Fig. S3 in the Supplement). The most suited definition of breakup was the 50% ice concentration (Table 1). There was a high positive correlation ($r^2 > 0.9$, $p = 0.07$) between migration onshore and breakup from 2006 to 2009, with polar bears migrating onshore approximately 20 d after breakup (Table 1). We excluded 2005 from the correlation, because only 2 collars were available during the migration onshore. In 2005, an unusually early melting of the ice near shore may have forced most bears to swim long distances to reach the shore, resulting in temporarily lost signals (see the Supplement and Video S1).

The time series of breakup date from 1979 to 2015 shows a negative trend ($p < 0.01$) of 0.5 d yr^{-1}, with a marked shift in the 1990s (Fig. 3B). From 1979 to 1989, mean breakup date was 11 ± 4 July, while in 2005–2015 it advanced 14 d to 28 ± 9 June (*t*-test, $p < 0.01$). During the most recent decades there was also higher inter-annual variability in the breakup date.

The inter-annual variability increased from 5 ± 4 d between 1979 and 1989 to 19 ± 11 d between 1996 and 2015 (*t*-test, $p < 0.01$). The later decades included a short period (2005–2009) with a trend towards a later breakup, to which polar bears responded by arriving onshore later (Fig. 3B).

Ice-free period and onshore period of polar bears

The period on land derived from polar bear telemetry data was generally 20 d shorter than the ice-free period defined using the ice concentration data (Fig. 3C). This difference was due to the 20 day offset between breakup date and the migration onshore. Bootstrap-v2 data showed that the ice-free period lengthened at a rate of 8 d per decade (linear regression, $p < 0.01$) since 1979, increasing by approximately 21 d from 1979 to 2015 (Fig. 3C, Tables S1 & S2 in the Supplement).

While CISDA and Bootstrap-v2 had similar estimates for freeze-up (Fig. 4A), in general, Bootstrap-v2 estimated breakup approximately 10 d earlier than CISDA (Fig. 4B). Hence, the timing of breakup and the ice-free period using CISDA were closer to the onshore migration of polar bears and the onshore period, respectively (Fig. 4C). Using CISDA, the ice-free period increased from 116 ± 6 d before 1990 to 142 ± 10 d after 2004 (Fig. 4, Table S2 in the Supplement). Using Bootstrap-v2, the ice-free period increased from 128 ± 9 to 149 ± 7 d. For converting the ice-free period (as defined with sea ice data) to an estimate of the polar bear onshore period, we recommend subtracting 10 d from the ice-free period estimated using CISDA, and 20 d from the ice-free period estimated using Bootstrap-v2. With either data set, this yields an onshore period that has increased from approximately 107 d in the 1980s to 130 d in the most recent decade.

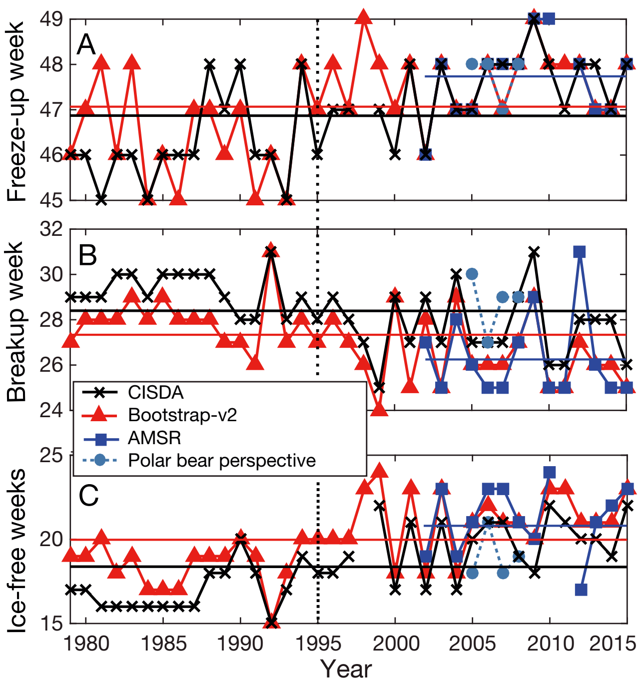

Fig. 4. Same as Fig. 3, but using weekly averages for the sea ice concentration to estimate the breakup and freeze-up, and the week of the year for migration of polar bears onshore and offshore. Details in Table S2 in the Supplement

DISCUSSION

Our evaluation of the passive microwave sea ice data with polar bear satellite-linked GPS telemetry data supports that passive microwave data underestimate sea ice during breakup in western Hudson Bay. However, we found smaller underestimation biases in the Bootstrap-v2 sea ice data (approximately 20%) than in the higher resolution AMSR sea ice data (approximately 30%). Using CISDA, we confirmed that Bootstrap-v2 and AMSR data underestimate sea ice concentration in western Hudson Bay with biases of 12% and 19%, respectively. Evaluation of the NASA Team algorithm, another passive microwave-derived sea ice concentration data source, identified underestimation biases of 43% during breakup and 33% during freeze-up (Agnew & Howell 2003). Given the contrasting bias estimates of the different algorithms, we suggest that Bootstrap-v2 may be a more appropriate sea ice concentration data set to use in Hudson Bay.

Estimating the accuracy of sea ice data is important for accurately measuring the ice-free period. Earlier studies determined that the migration of polar bears onshore occurred 25–30 d after the 50% ice concentration date in western Hudson Bay using CISDA (Stirling et al. 1999) or the NASA Team algorithm (Cherry et al. 2013). Here, using a different ice data source, we found that the migration onshore lagged the 50% sea ice concentration by approximately 20 d. Thus, the relationship between polar bear migration and ice concentration is specific to the chosen ice data, and should be considered before defining the ice-free period.

Refining how the duration of the polar bear onshore period has changed is important for understanding the effects of climate change on polar bears (reviewed in Stirling & Derocher 2012). The longer the ice-free period, the more vulnerable polar bears are to starvation (Derocher & Stirling 1995, Molnár et al. 2010, 2014). The decline in abundance of polar bears, from 1185 (range: 993–1411) to 806 (range: 653–984), in western Hudson Bay between 1987 and 2011 was attributed to the increasing onshore period (Lunn et al. 2016). We estimated that the period polar bears are onshore increased from approximately 107 to 130 d from 1979 to 2015. Molnár et al. (2010, 2014) suggested that an onshore period of 120, 180, and 210 d would result in 3–6%, 9–21%, and 29–48% of the adult male population at risk of starvation, respectively. We found that in western Hudson Bay, the lengthening of the ice-free period has continued since 1995. Given the relationship between the onshore period and the ice-free period, we suggest that future lengthening of the ice-free period in this region will only increase nutritional stress on this population.

Acknowledgements. We gratefully acknowledge the financial and logistic support from Aquarium du Québec, ArcticNet, ArcTrain, Canadian Association of Zoos and Aquariums, Canadian Wildlife Federation, Canadian Circumpolar Institute's Boreal Alberta Research, EnviroNorth, Environment and Climate Change Canada, the Isdell Family Foundation, Natural Sciences and Engineering Research Council of Canada (to A.E.D.: 261231-2013, 305472-2013; to P.G.M.: RGPIN 237438-09, RGPW 04357, RGPCC 433898), Northern Scientific Training Program of Aboriginal Affairs and Northern Development Canada, Parks Canada Agency, Pittsburgh Zoo and PPG Aquarium, Polar Bears International, Quark Expeditions, Wildlife Media, Inc., and World Wildlife Fund (Canada and International). L.C.G. thanks Xianmin Hu, Jean-Baptiste Tary, and Tomáš Barton for the various tools developed to aid with data analysis.

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Editorial responsibility: Peter Corkeron, Woods Hole, Massachusetts, USA

Submitted: July 27, 2016; Accepted: October 28, 2016
Proofs received from author(s): January 13, 2017