Migration dynamics of polar bears (*Ursus maritimus*) in western Hudson Bay

by

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ABSTRACT

Migration is a behavioral response to temporal variation in resources. While migration phenology is often predictable, phenology is expected to shift as climate change alters seasonal resource availability. We used data from satellite-linked telemetry collars on adult female polar bears (*Ursus maritimus*) in western Hudson Bay from 2004-2016 to: (1) quantify migration using multiple metrics, (2) assess environmental and biological factors that may influence migration, and (3) evaluate temporal patterns in migration. We included migration metrics (maximum distance to coast, Brownian bridge home range size, median speed (km/h), straightness index, land departure date, and land arrival date) as response variables in multivariate response variable regression models to assess the effect of environmental (ice concentration, wind speed, and wind direction) and biological (bear body condition, bear age, age of offspring, and number of offspring) factors on migration. We included year as a covariate to assess temporal effects on migration. We found that ice concentration was the only factor that consistently predicted migration patterns. Wind direction and wind speed were predictors of freeze-up migration, whereas wind direction was a key predictor of break-up migration. Migration patterns did not change temporally, suggesting lack of a climate-induced migration shift. Examining multiple migration metrics avoids oversimplification of a complex behavior and allows an in-depth investigation into what factors influence migration.

PREFACE

This thesis is an original work by Alyssa M. Bohart. Data used in this research was acquired from GPS collars deployed by Dr. Andrew E. Derocher, from the University of Alberta, and Dr. Nicholas. J. Lunn at Environment and Climate Change Canada. Dr. Derocher and Dr. Lunn provided feedback on thesis content.

Animal handling protocols that were followed received research ethics approval from the University of Alberta Animal Care and Use Committee for Biosciences, Project Name "Polar bears and Climate Change: Habitat Use and Trophic Interactions", No. AUP00000033.

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CHAPTER 1

INTRODUCTION

Migratory behavior is a response to seasonal spatial differences in resources (Dingle 2014; Dingle and Drake 2007). Predictable phenological pulses in resources provide migrant species access to food and mates (Avgar et al. 2013; Dingle and Drake 2007). Resource pulses are often followed by unsuitable conditions, causing species to migrate to other habitats and return when resources become readily available. Weather and resource fluctuations can affect migratory behavior (Hauser et al. 2017; Le Corre et al. 2017; Sabine et al. 2002) with some species more likely to migrate after harsh winters (Eggeman et al. 2016) or to travel further in resource-poor environments (Teitelbaum et al. 2015). Migratory behavior is also influenced by biological factors such as age, body condition, and reproductive state (Amstrup et al. 2001; Eggeman et al. 2016; Laidre et al. 2013; Loureiro et al. 2007; Singh and Ericsson 2014) and these factors may, therefore, also affect migration phenology.

Migration phenology is often predictable, but climate change is altering resource patterns. In particular, temporal shifts in resource availability may cause an ecological mismatch (Cushing 1990; Durant et al. 2007; Jones and Cresswell 2010), where resources become abundant earlier and migrating species miss the peak in resource availability, negatively affecting survival. Migration is energetically costly (Dingle and Drake 2007; McNamara and Houston 2008) and, because climate change is predicted to alter resource availability (Both et al. 2009; Jenni and Kéry 2003; Sharma et al. 2009; Stirling and Parkinson 2006), change competition (Ahola et al. 2007; Stirnemann et al. 2012), and alter predation risk (Barton and Schmitz 2009; Prop et al. 2015; Sharma et al. 2009), it may result in greater energy deficits.

The seasonal ice ecosystem in the Arctic influences both short- and long-distance migration in many species, including marine mammals (Hauser et al. 2017; Laidre et al. 2008).

With declining ice habitat and changing food availability in the Arctic, migration dynamics are expected to change. Changes to migration routes in response to climate change remain poorly understood in Arctic marine mammals, although variation in migration patterns occur (Barber et al. 2001; Dietz et al. 2001; George et al. 2004; Stirling et al. 1977). Temporal shifts in migration have been documented in response to the shift in ice formation due to climate change (Hauser et al. 2017), yet the issue remains unexplored for most species (Laidre et al. 2008).

Hudson Bay is one of the more southerly Arctic regions in Canada with climate change-induced temporal shifts in sea ice (Gough et al. 2004) affecting polar bears (*Ursus maritimus*; Stirling and Derocher 1993). The shift in ice cover duration has increased temporal ice fragmentation (Gagnon and Gough 2005; Sahanatien and Derocher 2012). Polar bears rely on sea ice to access their main prey, ringed seals (*Pusa hispida*) and bearded seals (*Erignathus barbatus*), although some populations of polar bears are forced ashore after the spring feeding period when sea ice melts (Amstrup et al. 2008; Laidre et al. 2008; Stirling et al. 1999). The more southerly populations, including Western Hudson Bay (WH), migrate to land as sea ice melts and migrate to sea ice when it forms (Stirling et al. 1999; Stirling and Parkinson 2006). The spring feeding period is critical for polar bears to obtain sufficient fat stores that allow them to survive on land when their primary prey is inaccessible (Lunn and Stirling 1985; Ramsay and Stirling 1988; Stirling and Derocher 1993). Although bears may forage on terrestrial foods during the on land period, only lipid-rich marine mammals provide the energy necessary for survival (Hobson et al. 2009; Ramsay and Hobson 1991; Rode et al. 2015). Polar bears are one of the Arctic species most affected by climate-induced habitat change, with bear migration phenology being linked to sea ice formation and melt, body condition, and reproduction (Derocher and Stirling 1995; Laidre et al. 2008; Stirling and Parkinson 2006). Further, southern

populations are projected to lose the greatest amount of ice habitat (Durner et al. 2009; Stern and Laidre 2016).

Aspects of polar bear migration have been examined independently, including the timing of departure and arrival on land, which has been correlated with ice concentration (Cherry et al. 2016; Cherry et al. 2013; Stirling and Derocher 1993; Stirling et al. 1999), habitat selection (Cherry et al. 2016; McCall et al. 2016), and wind (Togunov et al. 2017; 2018). There are also suggestions that movement may vary by age (Alldredge et al. 2015; Landriault et al. 2009), body condition, and reproductive status (Aars and Plumb 2010; Amstrup et al. 2001; Pilfold et al. 2017).

Our objective was to use multivariate response models to assess environmental and biological factors that may influence polar bear migration patterns. We used satellite-linked telemetry data to examine migration patterns of adult female polar bears in WH, Canada from 2004 to 2016. We quantified migration patterns using several metrics, including distance, home range size, speed, tortuosity, and land departure and arrival dates. To encompass the complexity of migration and assess the influence of environmental and biological factors on migration, we used multivariate response models and all migration metrics. We examined the influence of environmental (ice concentration, wind speed, and wind direction) and biological (bear age, body condition, and reproductive status) factors on migration and examined if migration patterns were changing temporally.

METHODS

Study area

Hudson Bay (Fig. 1) is a shallow inland sea with a 125 m mean depth (Jones and Anderson 1994), which experiences an annual sea ice freeze-up (October-December) and break-

up (May-August; Gagnon and Gough 2005; Joly et al. 2011; Saucier et al. 2004). Ice forms initially in the northwest in Nunavut and continues south towards Manitoba and Ontario due to the counter-clockwise gyre (Prinsenberg 1988) and colder water temperatures in northern Hudson Bay (Saucier et al. 2004). The duration of sea ice cover varies within the bay and between years (Parkinson 2014; Wang et al. 1994). For example, sea ice breakup date in 2003 was June 21, whereas breakup date in 1984 was July 12 (Regehr et al. 2007b). WH is one of the more southern populations, centered in Manitoba and includes parts of Nunavut and Ontario (Fig. 1).

Data collection

Bears with offspring were located via helicopter and remotely immobilized using tiletamine hydrochloride and zolazepam hydrochloride (Zoletil®, Virbac Laboratoires, Carros, France; Stirling et al. 1989) as part of ongoing, long-term research on the ecology of the WH population (e.g., Derocher and Stirling 1995; Lunn et al. 2016; Ramsay and Stirling 1988; Regehr et al. 2007a; Stirling et al. 1999). GPS Argos and Iridium satellite-linked telemetry collars (Telonics, Mesa, AZ) were deployed on adult female bears (≥ 5 years old) in August-September 2004-2016. Collars could not be secured on male bears as their necks are wider than their heads, precluding them from tracking. Collars were programmed with a predetermined date to release after 1-2 years following deployment (CR-2a, Telonics, Mesa, AZ) otherwise, collars were removed upon recapture. Body length (straight-line distance between the tip of the nose and the end of the last caudal vertebra (cm)), axillary girth (circumference of the chest directly behind the forelimbs at exhalation), number of cubs, and cub age were recorded at capture. Cubs ca. 10 months old were classified as cubs-of-the-year (COYs) and cubs ca. 22 months old were classified as yearlings (YRLGs). Age of non-dependent bears was determined by counting

cementum layers in an extracted vestigial premolar (Calvert and Ramsay 1998). Animal handling

procedures were reviewed and approved by the University of Alberta BioSciences Animal Policy

and Welfare Committee and the Environment Canada Western and Northern Region Animal

Care Committee and were consistent with the guidelines of the Canadian Council on Animal

Care (www./ccac.ca).

Data selection

Bears were tracked between September 2004 and May 2016, although the number of

bears tracked per year varied. Telemetry locations were collected via collars either every 30

minutes, 2 hours, or 4 hours daily (30m accuracy; Tomkiewicz et al. 2010); all were standardized

to locations every 4 hours. Collar data transmission was variable: some collars transmitted

regularly every 4 hours and others had gaps (e.g., over 2 weeks between locations). To estimate

statistically precise daily movement metrics, we removed locations if ≤4 were present in a 24-

hour moving window (max of 6 locations/day). Using the 'sp' (Pebesma and Bivand 2018) and

'rgdal' package (Bivand et al. 2018) in R version 3.4.3 (R Core Team 2016), longitude and

latitude coordinates (North American datum 1983) were projected into Universal Trans Mercator

coordinate system (NAD83 Teranet Ontario Lambert, EPSG: 5321). Biologically impossible data

(rate of movement >30 km/h) and prematurely dropped collar data were removed. Prematurely

dropped collars were identified by matching telemetry location movement to ice drift.

We filtered telemetry data to only include locations on sea ice. Time on ice was defined

for each bear by finding the land departure and arrival dates using ArcGIS version 10.6

(Environmental Systems Research Institute, Redlands, CA). Land departure dates were

determined as the first location on sea ice within November-December with no subsequent

locations on land until the following autumn (Cherry et al. 2013). Land arrival dates were

determined as the first location on land during July-September, not followed by three consecutive locations on Hudson Bay until November-December. Three consecutive locations were used due to the accuracy of collars and observation of bears remaining near the WH coast when on land.

Data were divided into four ice seasons to control for variation in ice, migration, and movement phenology: freeze-up, early winter, late winter, and break-up. Movement within the freeze-up and break-up seasons were considered migration. To determine freeze-up and break-up for each bear, we performed a piecewise regression on the ice concentration of each individual bear's telemetry locations using the R package 'segmented' (Muggeo 2008). We used the same year of ice concentration data as the year of bear data to control for annual ice concentration variation. The piecewise regression calculated break point dates to differentiate seasons using *a priori* estimates. For freeze-up, *a priori* break point date estimates were calculated by identifying when maximum ice concentration occurred for an individual bear (Fig. 2). Freeze-up was defined as the period beginning with the land departure date until the break point date. For break-up, *a priori* break point date estimates were calculated by determining when ice began breaking up consistently (e.g., identifying the first 24 h without 100% ice concentration; <5 consecutive locations – one day – with 100% ice concentration; Fig. 2). The break-up season was defined as the period from the break point date until the land arrival date. We further divided seasons into early winter and late winter using March 1st as a break point date because seal pupping begins in March (Hammill and Smith 1991; McLaren 1958), influencing bear predation behavior (Ramsay and Stirling 1982). We removed bears from freeze-up if an accurate land departure date could not be estimated due to large time gaps. Bears were removed from break-up if there were < 30 locations for statistical precision. Because of the large variation in regularity of collar data

transmission, bears were removed from early winter or late winter if there were <60 locations or if the time extent of the data did not span the time extent of the seasons, for statistical precision.

Migration and movement response variables

Because bear movement is partially involuntary due to ice drift (Auger-Méthé et al. 2016; Durner et al. 2017; Mauritzen et al. 2003), we subtracted ice drift from telemetry location data to account for bear displacement due to drift. We used Polar Pathfinder Daily 25 km Ease-Grid Sea Ice Motion Vectors ice drift data from the National Snow and Ice Data Center (Tschudi et al. 2016). Inverse distance weighting was used to spatially interpolate ice drift for telemetry locations (Li and Heap 2011; Togunov et al. 2017; 2018).

We measured migration using movement variables corrected for ice drift: speed (km/h) between consecutive locations and daily straightness index. Speed was measured as the displacement (km) between consecutive telemetry locations over time (h). We calculated daily straightness index using a moving 24-hour window and straightness index = D/L, where D was the Euclidean distance between the start and end location and L was the sum of 4-hour interval step lengths between the start and end location within the 24-hour time window (Batschelet 1981). Straightness index values range between 1 (straight movement) and 0 (tortuous movement). Using a 24-hour window and straightness index to measure tortuosity is effective for finite goal-oriented movement (Benhamou 2004). Other migration variables included land departure and arrival dates per bear. To measure differences in space use, we used telemetry locations not corrected for ice drift to estimate the 95% Brownian bridge home range for each individual using the 'adehabitatHR' R package (Calenge 2015; Horne et al. 2007; Walter et al. 2015). We used the R package 'rgeos' (Bivand et al. 2019) and telemetry locations not corrected

for ice drift to calculate the maximum straight-line distance of the furthest location from the WH coastline.

Environmental and biological covariates

We investigated the effect of both environmental and biological covariates on migration behavior. Environmental covariates consisted of ice concentration, wind speed, and wind direction. Ice concentration was calculated for each bear location using collar locations not corrected for ice drift. We used sea ice data from daily Advanced Microwave Scanning Radiometry (AMSR2) visible imagery from the University of Bremen (Bremen, Germany, http://seaice.uni-bremen.de/). Ice concentration was spatially interpolated using inverse distance weighting for telemetry locations (Li and Heap 2011; Togunov et al. 2017; 2018). We determined wind speed (m/s) and wind direction for each location using surface wind direction and speed data from the National Center for Environmental Prediction (NCEP; ftp://ftp.cdc.noaa.gov/Datasets/NARR/Dailies/monolevel/). NCEP provides 3-hour interval gridded wind estimates with 0.3° resolution, therefore, we spatially and temporally interpolated wind data to match bear locations using inverse distance weighting (Li and Heap 2011). Wind was initially spatially interpolated before and after the time of bear locations using the 4 closest grid values, then linearly interpolated to align with the location fix times (Togunov et al. 2017; 2018). Wind direction ranged from -180° to 180° and was categorized into 4 groups: north (≥45° and ≤45° from wind bearings), east (>45° and ≤135°), south (>135° and ≤-135°) and west (>-135° and <-45°). Biological covariates consisted of bear age, body condition, cub age, and number of cubs. Body condition at capture was calculated using estimated body mass (kg) and body condition index (Cattet and Obbard 2005). Reproductive status was inferred from the time of collaring unless re-sighted and confirmed the following collaring season, based on a 3-year

polar bear interbirth interval (Derocher and Stirling 1995). Bears were removed if their on land locations reflected no movement from September-March, indicating denning behavior (Ramsay and Stirling 1982; Stirling and Jonkel 1972). Although bears were categorized by their reproductive status when captured in September, bears with September yearlings were likely alone during the following late winter and break-up season, as cubs typically stay with their mothers until their second year (Ramsay and Stirling 1988; Ramsay and Stirling 1986).

Statistical analysis

We analyzed migration behavior (e.g., maximum distance to coast, Brownian Bridge home range size, median speed, median straightness index, departure date, and arrival date) in two ways. We considered how each of these individual migration traits were affected by environmental and biological covariates. We additionally considered how these traits correlated with one another. To do this, we fit multivariate response variable regression models using the 'mcglm' R package (Bonat 2016) for freeze-up, early winter, late winter, and break-up. Multivariate response variable regression models allow multiple response variables to be included within one model (while holding them constant) instead of conducting several models separately, and they estimate the correlation between each response variable (Bonat 2018). Because our response variables reflected median individual values per year (or maximum), the estimated correlations can be interpreted as among-individual correlations. Our models included all migration metrics as response variables within the same model. To assess environmental and biological factors that may influence migration, we included median ice concentration, median wind speed, and median wind direction as environmental predictor covariates in our models, and bear age, cub age, and number of cubs as biological predictor covariates. Cub age and number of cubs were coded based on age and number at time of capture. Cub age was coded as "0" for

COYs and "1" for YRLGs. Bear body condition index was included as a biological covariate only within our freeze-up models due to large fluctuations and unpredictability of body condition throughout other ice seasons. We included year as a continuous predictor covariate to assess temporal patterns of migration. We tested correlations of predictor covariates using Pearson's correlation to determine collinearity (> |0.6|; Fox 2002). No covariates exhibited collinearity, therefore we included all predictor covariates in our models.

Separate models were run when including reproductive status, as sample size decreased due to bears who lost cubs during the study. We chose to perform both models excluding reproductive status and including reproductive status, to obtain more representative models using larger sample sizes and to examine the effect of reproductive status, respectively. Reproductive status included cub age and number of cubs as an interaction in our models. A combination of Gaussian or gamma-log error distributions were in the models depending on residual normality of each response variable. Diagnostics for appropriate error distributions were determined using qqplots included within the 'mcglm' R package (Bonat 2016). We used pseudo Akaike's Information Criterion (pAIC) values calculated in 'mcglm' to determine model selection (Bonat 2016). The pAIC is similar to Akaike's Information Criterion (AIC) used in model selection (Burnham et al. 2011), but contains penalty terms to account for multiple response variables in the model (Bonat 2018). One drawback to multivariate response regressions is that AICc corrected for small sample sizes is not calculated. When there were multiple top models (ΔpAIC<2), we chose the model with the least covariates as the top model. Multivariate response variable model parsimony was compared to single response variable models using pAIC (Bonat 2018).

RESULTS

Environmental and biological effects

During 2004-2016, we deployed 159 collars and 101 bears remained after isolating ice-only locations. We retained a mean of 83.3% ± 1.3 (range 19.0-99.4%) of locations for estimating daily movement metrics (Fig. 3). We removed 19 bears due to insufficient location frequency following data standardization when dividing locations into ice seasons. After removing duplicate bears (Fig. 4-7), we retained 61 bears for freeze-up, 71 bears for early winter, 52 bears for late winter, and 38 bears for break-up. We manually estimated the break point date for 50 bears because piecewise regression date estimates occurred in January-May possibly due to low sample sizes, whereas the majority of estimates occurred in late November-December. Manual estimates were based on appropriate piecewise regression estimates from other bears in the same year. The length of the freeze-up season varied per bear (range: 3 to 46 days). The date of freeze-up ranged from November 7 to December 27. The length of the break-up season ranged from 3 to 70 days. The earliest date was May 12 and the latest was August 31. Descriptive statistics can be found in Table 1, 2, and 3.

Multivariate response models excluding reproductive status contained environmental covariates, but no biological covariates in most top models. Except for the late winter season, ice concentration was the only environmental covariate that was present in all other ice season top models. The top migration model for freeze-up contained ice concentration, wind speed, wind direction, and year (Table 4). Our top early winter movement model only contained ice concentration, whereas our top late winter movement model only contained year (Table 4). The migration top model for break-up contained ice concentration and wind direction (Table 4).

Not all covariates had significant relationships with response variables in our top models. In freeze-up, we found maximum distance to coast was significantly negatively correlated with

northerly and easterly winds (Table 5). Home range size was significantly negatively correlated with ice concentration. Median speed and straightness were significantly negatively correlated with northerly winds. Departure date was significantly positively correlated with ice concentration and significantly negatively correlated with wind speed and year (Fig. 8). During early winter, home range size was significantly negatively correlated with ice concentration (Table 6) and during late winter, maximum distance to coast was significantly negatively correlated with year (Table 7). During break-up, home range size was significantly positively correlated with northerly winds (Table 8). Speed was significantly positively correlated with northerly winds and significantly negatively correlated with ice concentration. Arrival date was significantly positively correlated with northerly and southerly winds.

All top multivariate response models were compared to single response models for goodness-of-fit by comparing pAIC values. We found that the multivariate response models were more parsimonious than the single response models (Table 9).

Environmental and biological effects including reproductive status

Reproductive status models contained both biological and environmental covariates in the most parsimonious models. No single covariate was present in all top models. Our top freeze-up migration model contained wind direction and our top early winter movement model was the null model (Table 10). The top late winter movement model contained cub age and the top break-up migration model contained ice concentration and wind direction (Table 10).

Not all covariates were significantly related with all response variables in our top models. During freeze-up, maximum distance to coast, home range size, speed, and straightness were significantly negatively correlated with northerly winds (Table 11). Speed was also significantly negatively correlated with easterly winds. In late winter, maximum distance to coast, speed, and

straightness were significantly negatively correlated with cub age (Table 12). During break-up, home range size was significantly positively correlated with northerly and southerly winds (Table 13). Speed was significantly positively correlated with northerly winds and significantly negatively correlated with ice concentration. Arrival date was significantly positively correlated with southerly winds.

We tested the appropriateness of multivariate response models compared to individual single response models using our reproductive status top models. We found that multivariate response models were more parsimonious than single response models (Table 14).

Correlations between migration traits

Female bears exhibited strong positive correlations between maximum distance to coast and home range size in migration movement (freeze-up and break-up seasons; Fig. 9). Migration onto sea ice (freeze-up) showed strong negative correlations between departure date and maximum distance to coast, as well as departure date and home range size (Fig. 9a). Additionally, bears showed a strong positive correlation between speed and straightness. Bears exhibited strong positive correlations in migration onto land (break-up): maximum distance to coast and straightness, arrival date and maximum distance to coast, arrival date and home range size, arrival date and straightness, and home range size and straightness (Fig. 9b).

Movement in the early winter and late winter seasons showed strong positive correlations between maximum distance to coast and straightness, home range size and speed, and home range size and straightness (Fig. 9). Female bears exhibited strong negative correlations between maximum distance to coast and speed in the early winter season (Fig. 9c). We found that bears in the late winter season showed positive correlations between speed and straightness (Fig. 9d).

DISCUSSION

Climate change is predicted to alter resource patterns (Grémillet and Boulinier 2009; Stirling and Parkinson 2006) and migration phenology (Hauser et al. 2017; Jenni and Kéry 2003), but most studies have focused on gregarious migrants. Unlike numerous migrating species, polar bears are solitary migrants who traverse vast areas of Hudson Bay (McCall et al. 2015). Climate patterns vary spatially within the bay (Saucier et al. 2004) and bear migration is expected to vary individually, in response. We examined a suite of environmental and biological covariates, which have been poorly understood in the context of polar bear migration. Here, we documented how migration patterns respond to climate-induced temporal resource changes. We found that ice concentration and wind were linked to particular migration behaviors and reproductive status influenced non-migration movement. Different aspects of migration have been linked to both environmental and biological covariates previously. However, our study quantified migration by examining several different aspects simultaneously (e.g., distance, home range size, speed, tortuosity, and departure and arrival dates). We show that several migration aspects are significantly correlated with one another, providing insights into the complexity of migration.

Polar bears spend the majority of the year on sea ice to access prey and potential mates (Laidre et al. 2008; Stirling et al. 1999). Polar bear migration is a response to changes in ice concentration (Cherry et al. 2016). We found support for the importance of ice influencing migration in our non-reproductive status models. Ice concentration was the best and most consistent predictor of migration patterns. The length of the sea ice season in Hudson Bay has decreased and is projected to continue declining (Parkinson 2014; Stern and Laidre 2016). Because ice concentration plays an important role in migration patterns in polar bears, determining how ice concentration influences bear migration can provide base knowledge when

predicting how polar bears may adapt to a changing environment caused by climate change. Our findings further show the potential effects of ice loss on the WH population, with lower ice concentrations associated with bears that have larger home ranges in freeze-up and early winter. Furthermore, we found that bears present in low ice concentration areas had higher rates of movement during break-up. Bears may experience additional energetic stress due to increased speed in lower ice concentration habitats during break-up – a critical time when bears have the final opportunity to build-up fat stores (Galicia et al. 2019).

The effect of wind on polar bear behavior is less studied, but the importance of wind on bear movement when hunting is apparent (Togunov et al. 2017; 2018). We found further support that wind influences polar bear movement, where migration was influenced by wind speed and wind direction. Wind speed influenced the timing of migration onto sea ice, where bears exhibited earlier departures from land as wind speeds increased. Earlier departures may be facilitated by high wind speeds circulating northern ice southward towards the WH coast (Saucier et al. 2004). Wind speeds are predicted to increase in the Arctic, resulting from climate change (McInnes et al. 2011). Increased wind speeds could have negative impacts on hunting success for bears as they travel downwind in high wind speeds, impeding olfactory hunting (Togunov et al. 2017; 2018). We found that wind direction influenced both migration onto sea ice and onto land. Migration onto sea ice is suggested to be influenced partly by wind, where bears primarily travel downwind and east (Togunov et al. 2017; 2018). Bears actively forage and accumulate peak fat during break-up (Galicia et al. 2019). The influence of wind direction on break-up migration could be due to both prey searching and adjusting movement in response to ice drift when avoiding returning to land (Togunov et al. 2017; 2018).

Our findings support other evidence that suggests polar bear migration is more strongly influenced by environmental factors and not biological factors (Cherry et al. 2016). Non-migration movement in late winter was the only occurrence of a biological factor influencing movement: cub age. We found that female bears with YRLGs had greater distances from the coast than lone bears. Bears with offspring will avoid male-inhabited areas to avoid infanticide (Pilfold et al. 2014). Our findings were consistent with McCall et al. (2015), where lone bears inhabit areas closer to the coastline to access potential mates. Bears with YRLGs exhibited faster median speeds and straighter median movement than lone bears. These results differ from other findings, where bears with YRLGs travelled at slower speeds than lone bears (Amstrup et al. 2001) and tortuosity between bears of different reproductive status did not differ (Laidre et al. 2013). Our findings may differ from Amstrup et al. (2001) due to temporal differences between datasets (i.e., 1985-1997 vs. 2004-2016) or due to different ecoregions (i.e., Chukchi Sea vs. WH). Our finding that bear age was not a main factor affecting migration supports other findings where polar bear age showed no significant influence on the timing of migration (Cherry et al. 2016). Bear body condition was not significant, corroborating other studies that found polar bear body condition did not influence migration swim frequency (Pilfold et al. 2017).

Climate change is predicted to alter migration phenology, with phenological shifts already evident in several species (Hauser et al. 2017; Jenni and Kéry 2003; Lehikoinen and Jaatinen 2012). Our results suggest that migration patterns have remained broadly similar over our study period. Migration stability may be due to the temporary sea ice stability in Hudson Bay within our study period (Lunn et al. 2016). One finding suggested departure dates became earlier over our study period, although the contrary is expected. Average temperatures have increased in northern Canada over the past few decades (Ding et al. 2014), but 2013 and 2014 were

potentially anomalous years due to lower temperatures, possibly resulting in earlier departure dates within those years. Consistent with this interpretation, analyses excluding these two years provided no evidence for an effect of year on departure dates (results not shown).

The complexity of migration is often oversimplified by quantifying a single aspect (Eggeman et al. 2016; Lehikoinen and Jaatinen 2012; Visser et al. 2009). By measuring the relationship between several migration metrics and using multivariate response models to consider multiple metrics simultaneously, we encapsulated the complexity of migration. Our results show that migration metrics are not independent, but show particular patterns of correlation. As such, future migration studies should consider multiple metrics and how they may be correlated to investigate migration in depth. Future polar bear migration studies in WH and other populations should also consider correlations between migration metrics, following our findings. During freeze-up, female bears exhibited fast and straight movement, demonstrating the importance of accessing prey via sea ice (Smith 1980). The highest median speed (2.3 km/h) and median straightness (1) were measured in freeze-up. Our findings were consistent with Yee et al. (2017), where denning polar bears had higher straightness when migrating from dens to sea ice. During break-up, bears that arrived on shore earlier exhibited lower straightness. On shore arrival dates are influenced by ice concentration, as bears return to land once sea ice has melted (Cherry et al. 2013; Pilfold et al. 2017). Bears who return to land later may demonstrate straighter movement by accessing sea ice, swimming between patches of sea ice, or directly swimming to land (Pilfold et al. 2017).

Using a suite of migration metrics to examine the influence of climate change on polar bear migration, during freeze-up and break-up, we determined that only environmental factors may influence migration. Our methodology to examine multiple migration metrics and their

relationship to each other can provide a baseline of metrics used in future migration studies in other species, polar bear populations, and the WH. Contrary to other migrant species, we found that polar bear migration patterns remained relatively unchanged within the past 12 years. Continued migration monitoring can provide insight into how species respond to climate-induced resource changes.

TABLES

Table 1. Ranges of body condition and age of western Hudson Bay female polar bears used in migration pattern analyses. Telemetry location data from 2004-2016 was separated into freeze-up, early winter, late winter, and break-up seasons.

Season	Variable	Mean ± SE	Range	n
Freeze-up	Body condition index	-0.5 ± 0.1	-1.3-0.8	61
Freeze-up	Age	14.2 ± 0.6	6-25	61
Early winter	Age	14.7 ± 0.6	6-25	71
Late winter	Age	15.6 ± 0.7	7-26	52
Break-up	Age	15.7 ± 0.8	8-26	38

Table 2. Ranges of body condition, age and reproductive status of western Hudson Bay female polar bears used in reproductive status migration multivariate response models. Telemetry location data from 2004-2016 was separated into freeze-up, early winter, late winter, and break-up seasons.

Season	Variable	Mean ± SE	Range	n
Freeze-up	Body condition index	-0.5 ± 0.1	-1.3-0.8	52
	Age	14.3 ± 0.7	6-25	52
	1 COY	-	-	15
	2 COYs	-	-	17
	1 YRLG	-	-	16
	2 YRLGs	-	-	4
Early winter	Age	15.1 ± 0.7	7-25	49
	1 COY	-	-	15
	2 COYs	-	-	13
	1 YRLG	-	-	16
	2 YRLGs	-	-	5
Late winter	Age	16.5 ± 0.8	9-26	33
	1 COY	-	-	8
	2 COYs	-	-	7
	1 YRLG	-	-	12
	2 YRLGs	-	-	6
Break-up	Age	16.1 ± 0.9	9-26	27
	1 COY	-	-	6

2 COYs	-	-	6
1 YRLG	-	-	11
2 YRLGs	-	-	4

Table 3. Summary statistics for western Hudson Bay female polar bear migration pattern variables in the freeze-up, early winter, late winter, and break-up seasons. Data was based on telemetry locations collected from 2004-2016.

Season	Variable	Mean ± SE	Range	n
Freeze-up	Maximum distance to coast (km)	173 ± 12	31-548	61
	Brownian bridge home range (km^2)	7074 ± 893	224-51017	61
	Median speed (km/h)	1.4 ± 0.0	0.5-2.3	61
	Median straightness index	0.8 ± 0.0	0.4-1.0	61
	Departure date	Nov. 23 ± 1 day	Nov. 4-Dec. 11	61
Early winter	Maximum distance to coast (km)	368 ± 11	182-689	71
	Brownian bridge home range (km^2)	15861 ± 900	1993-39537	71
	Median speed (km/h)	0.8 ± 0.0	0.4-1.3	71
	Median straightness index	0.8 ± 0.0	0.7-0.9	71
Late winter	Maximum distance to coast (km)	291 ± 12	90-481	52
	Brownian bridge home range (km^2)	17425 ± 894	2843-28833	52
	Median speed (km/h)	0.8 ± 0.0	0.4-1.1	52
	Median straightness index	0.7 ± 0.0	0.5-0.9	52
Break-up	Maximum distance to coast (km)	158 ± 13	52-388	38
	Brownian bridge home range (km^2)	6899 ± 1109	339-38278	38
	Median speed (km/h)	0.9 ± 0.0	0.5-1.3	38
	Median straightness index	0.6 ± 0.0	0.4-0.9	38
	Arrival date	Jul. 23 ± 3 days	Jun. 30-Sept. 1	38

Table 4. Comparison (using pAIC) of top 5 female polar bear migration (freeze-up and break-up season) and movement (early winter and late winter season) non-reproductive status multivariate response models in western Hudson Bay. Data was collected from adult females in western Hudson Bay from 2004-2016. Response variables: maximum distance from coast, Brownian bridge home range area, median speed, and median straightness. Freeze-up season models included land departure dates and break-up season models included land arrival dates as additional response variables. The pAIC values are the modified AIC score that account for multiple response variables. The ΔpAIC is the difference between the top model pAIC value and the respective models and w is the weight of the pAIC score given the available data and candidate models. Covariate definitions: iceconc is the median ice concentration in the local habitat of an individual bear, windspeed is the median wind speed (m/s) in the local habitat of a bear, winddirection is the median direction of the wind in the local habitat of a bear, year is the year of the data and age is the age of the bear.

Season	Model	pAIC	ΔpAIC	w
Freeze-up	Iceconc, windspeed, winddirection, year	3058.70	0.00	0.84
	Iceconc, windspeed, winddirection	3062.44	3.74	0.13
	Iceconc, winddirection, year	3066.74	8.04	0.02
	Age, iceconc, windspeed, winddirection	3067.82	9.12	0.01
	Iceconc, windspeed, year	3069.26	10.56	0.00
Early winter	Iceconc	3035.58	0.00	0.56
	Iceconc, windspeed	3037.02	1.44	0.27
	Iceconc, year	3039.08	3.50	0.10
	Null	3041.94	6.36	0.02

	Iceconc, winddirection	3042.80	7.22	0.02
Late winter	Year	2202.10	0.00	0.46
	Iceconc, windspeed, year	2203.32	1.22	0.25
	Iceconc, year	2203.50	1.40	0.23
	Null	2207.98	5.88	0.02
	Iceconc, windspeed, winddirection, year	2208.72	6.62	0.02
Break-up	Iceconc, winddirection	1944.04	0.00	0.83
	Age, iceconc, windspeed, winddirection	1948.48	4.44	0.09
	Iceconc, windspeed, winddirection	1949.52	5.48	0.05
	Age, iceconc, windspeed, winddirection, year	1951.88	7.84	0.02
	Iceconc, windspeed, winddirection, year	1952.20	8.16	0.01

Table 5. Covariate coefficient estimates for the top migration model of female polar bears, excluding reproductive status, in the freeze-up season. Data was based on telemetry locations collected in western Hudson Bay from 2004-2016. Response variable definitions: maxdist coast is the maximum distance to western Hudson Bay coast, BBHR area is the Brownian bridge home range size, median speed is the median rate of movement, median straightness is the median straightness index, and departure date is the date bears departed land onto sea ice. All covariates were scaled to 0. Covariate definitions: iceconc is the median ice concentration in the local habitat of an individual bear, windspeed is the median wind speed (m/s) in the local habitat of an individual bear, winddir_north, winddir_south, and winddir_west are categorical variables for median wind speed in the local habitat or an individual bear, and year is the year the data was collected. *Statistically significant values (α=0.05).

Response	Error Distribution	Covariate	Estimate	S.E.	Z-value
Maxdist coast	Gamma - log	Iceconc	-0.002	0.002	-0.73
		Windspeed	-0.09	0.06	-1.57
		Winddir_north	-0.26	0.35	-0.74
		Winddir_south	-0.37	0.14	-2.58*
		Winddir_west	-1.73	0.71	-2.44*
		Year	0.004	0.02	0.25
BBHR area	Gamma - log	Iceconc	-0.01	0.003	-5.51*
		Windspeed	-0.08	0.08	-1.00
		Winddir_north	-0.60	0.70	-0.86
		Winddir_south	-0.16	0.19	-0.82

		Winddir_west	-0.56	0.66	-0.86
		Year	0.02	0.02	0.80
Median speed	Gaussian	Iceconc	-0.001	0.001	-0.73
		Windspeed	0.02	0.03	0.71
		Winddir_north	-0.18	0.21	-0.85
		Winddir_south	-0.28	0.08	-3.39*
		Winddir_west	-0.28	0.22	-1.28
		Year	-0.003	0.01	-0.27
Median straightness	Gamma - log	Iceconc	-0.001	0.0005	-1.51
		Windspeed	0.01	0.01	0.65
		Winddir_north	0.13	0.07	1.87
		Winddir_south	-0.06	0.03	-2.13*
		Winddir_west	-0.06	0.07	-0.78
		Year	0.01	0.004	1.66
Departure date	Gaussian	Iceconc	0.06	0.02	2.47*
		Windspeed	-1.69	0.55	-3.05*
		Winddir_north	1.05	3.62	0.29
		Winddir_south	-1.29	1.38	-0.93
		Winddir_west	4.02	3.69	1.09
		Year	-0.66	0.19	-3.58*

Table 6. Covariate coefficient estimates for the top migration model of female polar bears, excluding reproductive status, in the early winter season. Data was based on telemetry locations collected in western Hudson Bay from 2004-2016. Response variable definitions: maxdist coast is the maximum distance to western Hudson Bay coast, BBHR area is the Brownian bridge home range size, median speed is the median rate of movement, and median straightness is the median straightness index. All covariates were scaled to 0. Iceconc is the median ice concentration in the local habitat of an individual bear. *Statistically significant values (α=0.05).

Response	Error Distribution	Covariate	Estimate	S.E.	Z-value
Maxdist coast	Gamma - log	Iceconc	-0.03	0.05	-0.58
BBHR area	Gamma - log	Iceconc	-0.30	0.09	-3.51*
Median speed	Gamma - log	Iceconc	-0.03	0.05	-0.56
Median straightness	Gamma - log	Iceconc	-0.01	0.02	-0.82

Table 7. Covariate coefficient estimates for the top migration model of female polar bears, excluding reproductive status, in the late winter season. Data was based on telemetry locations collected in western Hudson Bay from 2004-2016. Response variable definitions: maxdist coast is the maximum distance to western Hudson Bay coast, BBHR area is the Brownian bridge home range size, median speed is the median rate of movement, and median straightness is the median straightness index. Year was scaled to 0. Year is the year the data was collected. *Statistically significant values (α=0.05).

Response	Error Distribution	Covariate	Estimate	S.E.	Z-value
Maxdist coast	Gamma - log	Year	-0.02	0.01	-2.02*
BBHR area	Gamma - log	Year	0.02	0.02	1.38
Median speed	Gaussian	Year	0.003	0.01	0.54
Median straightness	Gaussian	Year	0.004	0.003	1.32

Table 8. Covariate coefficient estimates for the top migration model of female polar bears, excluding reproductive status, in the break-up season. Data was based on telemetry locations collected in western Hudson Bay from 2004-2016. Response variable definitions: maxdist coast is the maximum distance to western Hudson Bay coast, BBHR area is the Brownian bridge home range size, median speed is the median rate of movement, median straightness is the median straightness index, and arrival date is the date bears arrived on land from the sea ice. All covariates were scaled to 0. Covariate definitions: iceconc is the median ice concentration in the local habitat of an individual bear and winddir_north, winddir_south, and winddir_west are categorical variables for median wind speed in the local habitat or an individual bear. *Statistically significant values (α=0.05).

Response	Error Distribution	Covariate	Estimate	S.E.	Z-value
Maxdist coast	Gaussian	Iceconc	0.001	0.001	0.93
		Winddir_north	-0.42	0.27	-1.53
		Winddir_south	-0.34	0.24	-1.42
		Winddir_west	-0.30	0.16	-1.88
BBHR area	Gamma - log	Iceconc	-0.001	0.002	-0.28
		Winddir_north	0.53	0.42	1.27
		Winddir_south	0.84	0.35	2.42*
		Winddir_west	-0.10	0.31	-0.32
Median speed	Gamma - log	Iceconc	-0.001	0.0004	-3.28*
		Winddir_north	0.11	0.08	1.37
		Winddir_south	0.17	0.07	2.41*

		Winddir_west	0.05	0.05	1.01
Median straightness	Gaussian	Iceconc	0.0002	0.0004	0.35
		Winddir_north	0.09	0.08	1.15
		Winddir_south	0.04	0.08	0.56
		Winddir_west	-0.04	0.05	-0.68
Arrival date	Gamma - log	Iceconc	-0.04	0.04	-0.89
		Winddir_north	21.88	8.38	2.61*
		Winddir_south	16.77	7.53	2.23*
		Winddir_west	-4.88	5.20	-0.94

Table 9. Model parsimony comparison between multivariate response models and single response models examining factors that influence migration patterns in female polar bears, excluding reproductive status. Data was based on telemetry locations collected in western Hudson Bay from 2004-2016. All multivariate response models had lower pAIC values than single response models.

Season	Model	pAIC	ΔpAIC
Freeze-up	Multivariate response	3058.70	48.36
	Single response	3107.06	
Early winter	Multivariate response	3035.58	44.74
	Single response	3080.32	
Late winter	Multivariate response	2202.10	52.24
	Single response	2254.34	
Break-up	Multivariate response	1944.04	40.00
	Single response	1984.04	

Table 10. Comparison (using pAIC) of top 5 female polar bear migration (freeze-up and break-up season) and movement (early winter and late winter season) reproductive status multivariate response models in western Hudson Bay. Data was collected from adult females in western Hudson Bay from 2004-2016. Response variables: maximum distance from coast, Brownian bridge home range area, median speed, and median straightness. Freeze-up season models included land departure dates and break-up season models included land arrival dates as additional response variables. The pAIC values are the modified AIC score that account for multiple response variables. The ΔpAIC is the difference between the top model pAIC value and the respective models and w is the weight of the pAIC score given the available data and candidate models. Covariate definitions: iceconc is the median ice concentration in the local habitat of an individual bear, winddirection is the median direction of the wind in the local habitat of a bear, year is the year of the data, windspeed is the median wind speed (m/s) in the local habitat of a bear, cubnum is the number of cubs, cubage is the age of the cub(s), and age is the age of the bear.

Season	Model	pAIC	ΔpAIC	w
Freeze-up	Iceconc, winddirection, year	2327.20	0.00	0.29
	Iceconc, windspeed, winddirection, year	2327.24	0.04	0.28
	Winddirection	2327.88	0.68	0.21
	Iceconc, winddirection	2328.60	1.40	0.14
	Iceconc, windspeed, winddirection	2330.12	2.92	0.07
Early winter	Null	2090.22	0.00	0.42
	Cubnum	2091.54	1.32	0.22
	Iceconc, windspeed	2092.36	2.14	0.14

	Iceconc	2093.32	3.10	0.09
	Year	2093.70	3.48	0.07
Late winter	Cubage	1325.22	0.00	0.63
	Cubage, iceconc	1326.64	1.42	0.31
	Null	1331.40	6.18	0.03
	Windspeed	1332.94	7.72	0.01
	Iceconc	1333.64	8.42	0.01
Break-up	Iceconc, winddirection	1335.70	0.00	0.80
	Winddirection	1338.64	2.94	0.18
	Cubnum	1345.54	9.84	0.01
	Cubage*cubnum, age, iceconc, windspeed, winddirection	1345.92	10.22	0.00
	Iceconc, windspeed, winddirection	1347.38	11.68	0.00

Table 11. Covariate coefficient estimates for the top migration model of female polar bears, including reproductive status, in the freeze-up season. Data was based on telemetry locations collected in western Hudson Bay from 2004-2016. Response variable definitions: maxdist coast is the maximum distance to western Hudson Bay coast, BBHR area is the Brownian bridge home range size, median speed is the median rate of movement, median straightness is the median straightness index, and departure date is the date bears departed land onto sea ice. Covariate definitions: winddir_north, winddir_south, and winddir_west are categorical variables for median wind speed in the local habitat or an individual bear. *Statistically significant values ($\alpha=0.05$).

Response	Error Distribution	Covariate	Estimate	S.E.	Z-value
Maxdist coast	Gamma - log	Winddir_north	-0.07	0.31	-0.23
		Winddir_south	-0.43	0.17	-2.51*
		Winddir_west	-1.80	1.02	-1.77
BBHR area	Gamma - log	Winddir_north	-0.59	0.60	-0.99
		Winddir_south	-0.55	0.27	-2.06*
		Winddir_west	-2.28	1.94	-1.18
Median speed	Gaussian	Winddir_north	-0.25	0.20	-1.28
		Winddir_south	-0.35	0.09	-3.68*
		Winddir_west	-0.59	0.28	-2.14*
Median straightness	Gamma - log	Winddir_north	0.10	0.06	1.61
		Winddir_south	-0.11	0.03	-3.22*
		Winddir_west	-0.14	0.10	-1.47

Departure	Gaussian	Winddir_north	5.18	3.81	1.36
date		Winddir_south	0.64	1.82	0.35
		Winddir_west	6.18	5.31	1.17

Table 12. Covariate coefficient estimates for the top migration model of female polar bears, including reproductive status, in the late winter season. Data was based on telemetry locations collected in western Hudson Bay from 2004-2016. Response variable definitions: maxdist coast is the maximum distance to western Hudson Bay coast, BBHR area is the Brownian bridge home range size, median speed is the median rate of movement, and median straightness is the median straightness index. Cubage is the age of the cub(s). *Statistically significant values ($\alpha=0.05$).

Response	Error Distribution	Covariate	Estimate	S.E.	Z-value
Maxdist coast	Gamma - log	Cubage	-0.28	0.10	-2.91*
BBHR area	Gaussian	Cubage	-4681.16	2562.55	-1.83
Median speed	Gaussian	Cubage	-0.09	0.05	-2.02*
Median straightness	Gamma - log	Cubage	-0.10	0.04	2.61*

Table 13. Covariate coefficient estimates for the top migration model of female polar bears, including reproductive status, in the break-up season. Data was based on telemetry locations collected in western Hudson Bay from 2004-2016. Response variable definitions: maxdist coast is the maximum distance to western Hudson Bay coast, BBHR area is the Brownian bridge home range size, median speed is the median rate of movement, median straightness is the median straightness index, and arrival date is the date bears arrived on land from the sea ice. Covariate definitions: iceconc is the median ice concentration in the local habitat of an individual bear, winddir_north, winddir_south, and winddir_west are categorical variables for median wind speed in the local habitat or an individual bear. *Statistically significant values (α=0.05).

Response	Error Distribution	Covariate	Estimate	S.E.	Z-value
Maxdist coast	Gamma - log	Iceconc	0.002	0.001	1.23
		Winddir_north	-0.59	0.36	-1.63
		Winddir_south	-0.22	0.26	-0.85
		Winddir_west	-0.14	0.16	-0.88
BBHR area	Gamma - log	Iceconc	-0.002	0.003	-0.76
		Winddir_north	1.15	0.51	2.26*
		Winddir_south	1.14	0.40	2.85*
		Winddir_west	-0.09	0.36	-0.26
Median speed	Gamma - log	Iceconc	-0.001	0.0005	-2.12*
		Winddir_north	-0.13	0.12	-1.02
		Winddir_south	0.23	0.09	2.61*
		Winddir_west	0.04	0.06	0.62

Median straightness	Gaussian	Iceconc	0.0003	0.0003	0.85
		Winddir_north	0.03	0.08	0.39
		Winddir_south	0.005	0.06	0.07
		Winddir_west	-0.01	0.04	-0.15
Arrival date	Gamma - log	Iceconc	-0.0002	0.0002	-1.02
		Winddir_north	0.13	0.05	2.56*
		Winddir_south	0.05	0.04	1.12
		Winddir_west	-0.01	0.03	-0.38

Table 14. Model parsimony comparison between multivariate response models and single response reproductive status models examining factors that influence migration patterns in female polar bears, including reproductive status. Data was based on telemetry locations collected in western Hudson Bay from 2004-2016. Early winter models were not included because the null model was the top model. All multivariate response models had lower pAIC values than single response models.

Season	Model	pAIC	ΔpAIC
Freeze-up	Multivariate response	2327.20	47.98
	Single response	2375.18	
Late winter	Multivariate response	1325.22	41.94
	Single response	1367.16	
Break-up	Multivariate response	1335.70	43.52
	Single response	1379.22	

FIGURES

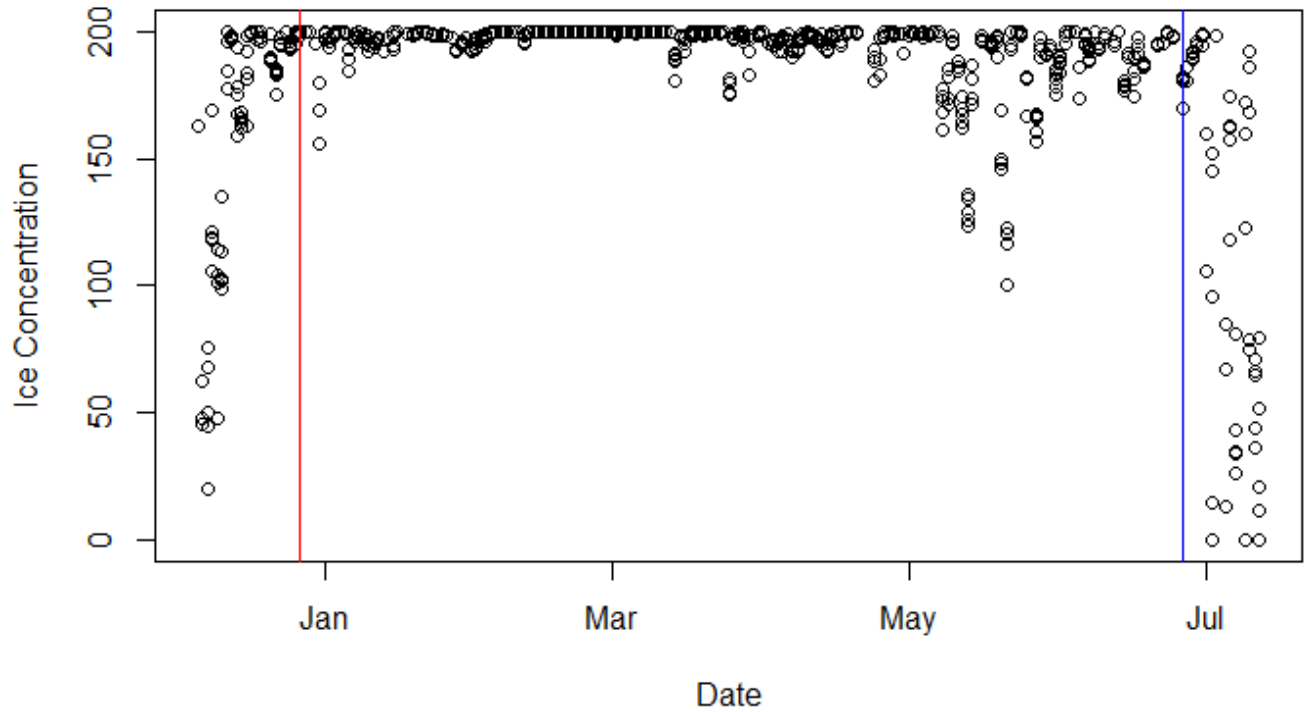Figure 1. Map of Hudson Bay and Western Hudson Bay polar bear population range.

Figure 2. Example of how a piecewise regression calculated the break point dates to define the freeze-up and the break-up season for female polar bears in western Hudson Bay tracked from 2004-2017. Break point dates were calculated per bear using the ice concentration at each of the individual bear's telemetry locations. The first break point to define freeze-up season is in red (December 27), while the second break point to define break-up season is in blue (June 26).
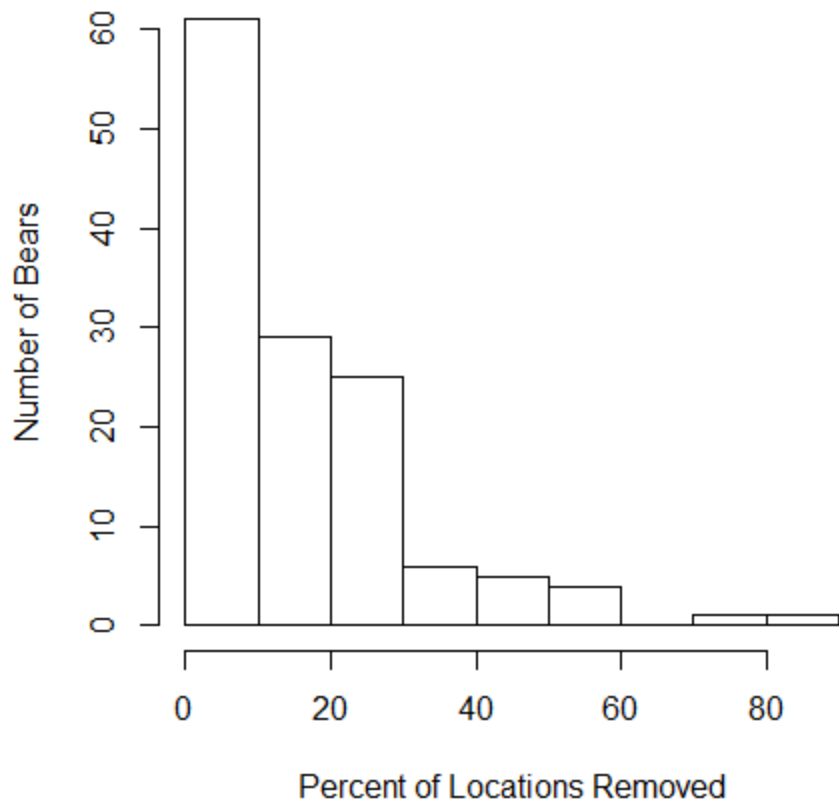
Figure 3. Percent of adult female polar bear telemetry locations removed using a 24-h moving window and removing locations, where ≤ 4 locations occurred during a 24-h time span. Data were removed for statistical precision when estimating daily movement metrics for our 4-h resolution telemetry data collected in western Hudson Bay during 2004-2016.
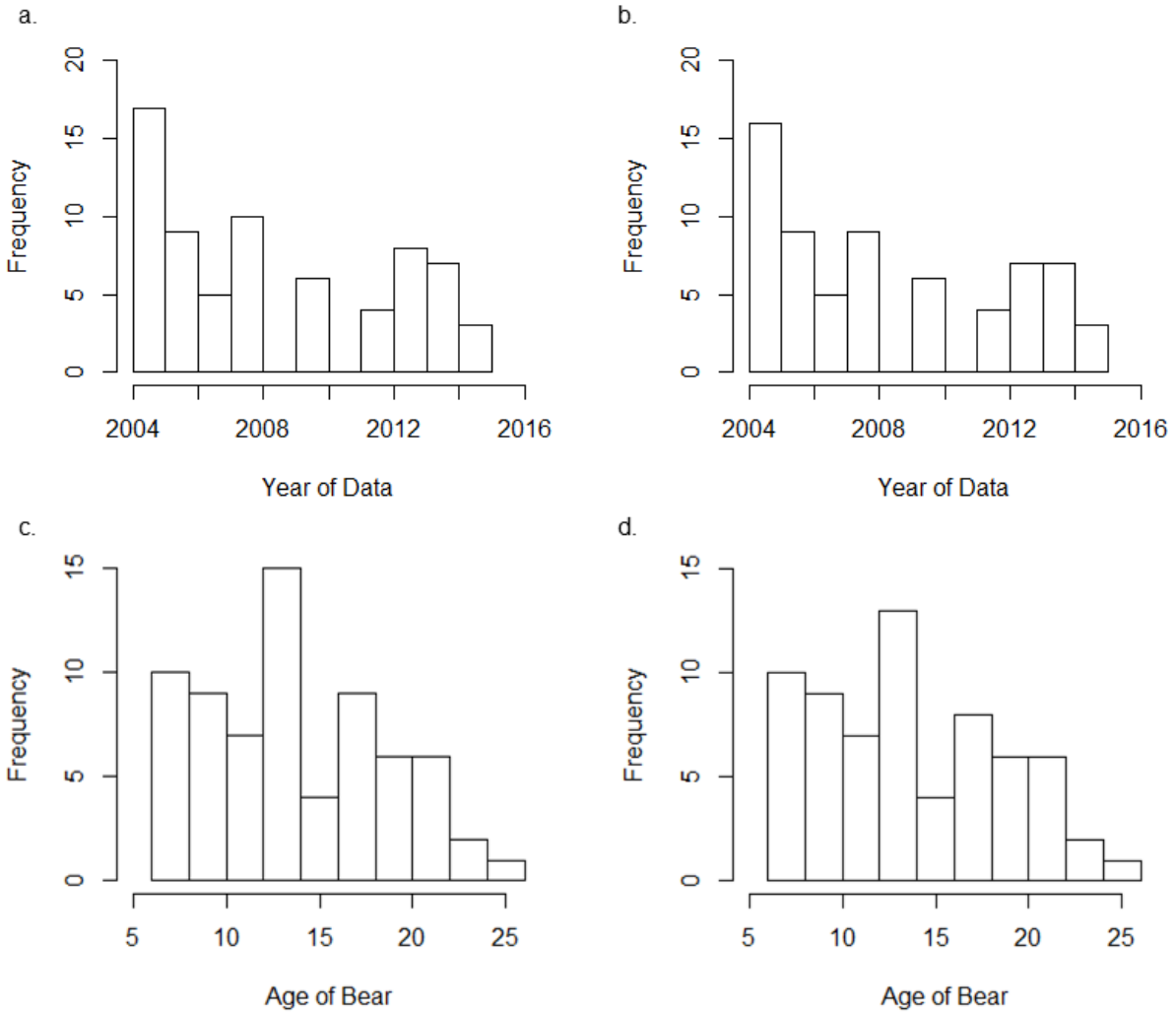
Figure 4. Comparison of adult female polar bear data in the freeze-up season before and after duplicate bears were removed to avoid pseudoreplication. There were 69 bears initially and removal resulted in 61 bears. The distribution of years of bear data (a) before and (b) after removing the second occurrence of the same bear. The distribution of bear age (c) before and after (d) data removal. Data was collected in western Hudson Bay during 2004-2016.

Figure 5. Comparison of adult female polar bear data in the early winter season before and after duplicate bears were removed to avoid pseudoreplication. There were 85 bears initially and removal resulted in 71 bears. The distribution of years of bear data (a) before and (b) after removing the second occurrence of the same bear. The distribution of bear age (c) before and after (d) data removal. Data was collected in western Hudson Bay during 2004-2016.
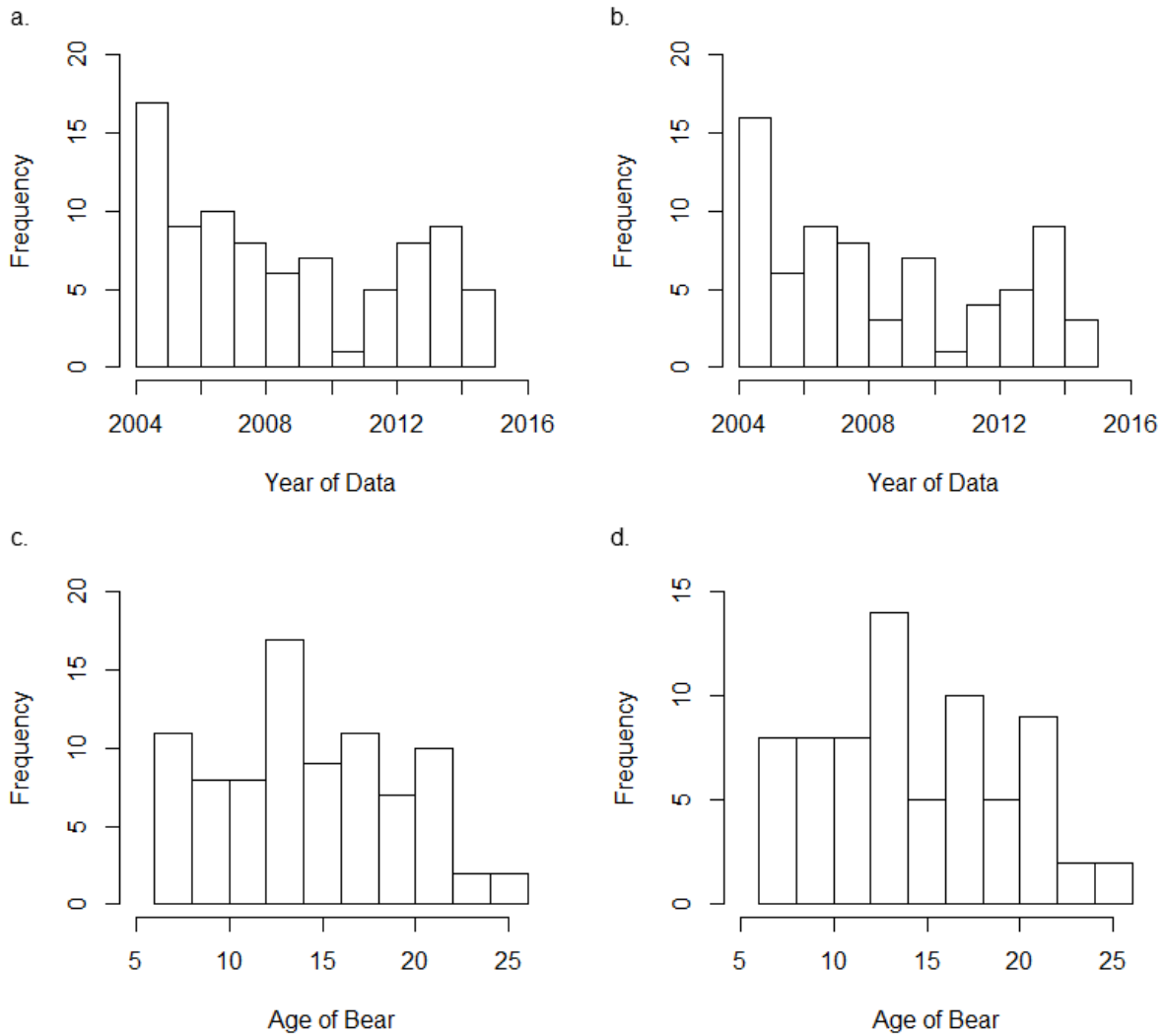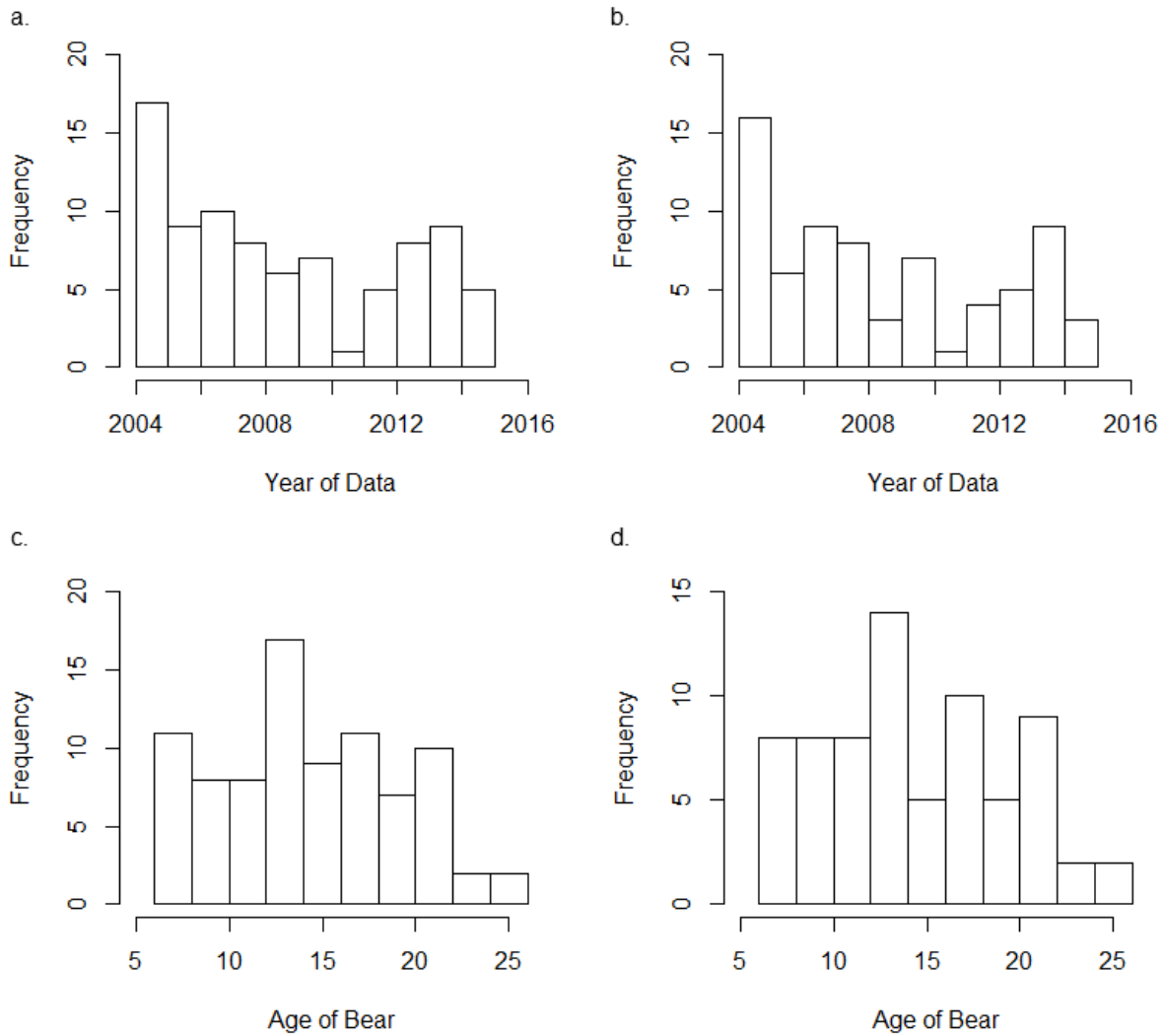
Figure 6. Comparison of adult female polar bear data in the late winter season before and after duplicate bears were removed to avoid pseudoreplication. There were 65 bears initially and removal resulted in 52 bears. The distribution of years of bear data (a) before and (b) after removing the second occurrence of the same bear. The distribution of bear age (c) before and after (d) data removal. Data was collected in western Hudson Bay during 2004-2016.

Figure 7. Comparison of adult female polar bear data in the break-up season before and after duplicate bears were removed to avoid pseudoreplication. There were 42 bears initially and removal resulted in 38 bears. The distribution of years of bear data (a) before and (b) after removing the second occurrence of the same bear. The distribution of bear age (c) before and after (d) data removal. Data was collected in western Hudson Bay during 2004-2016.
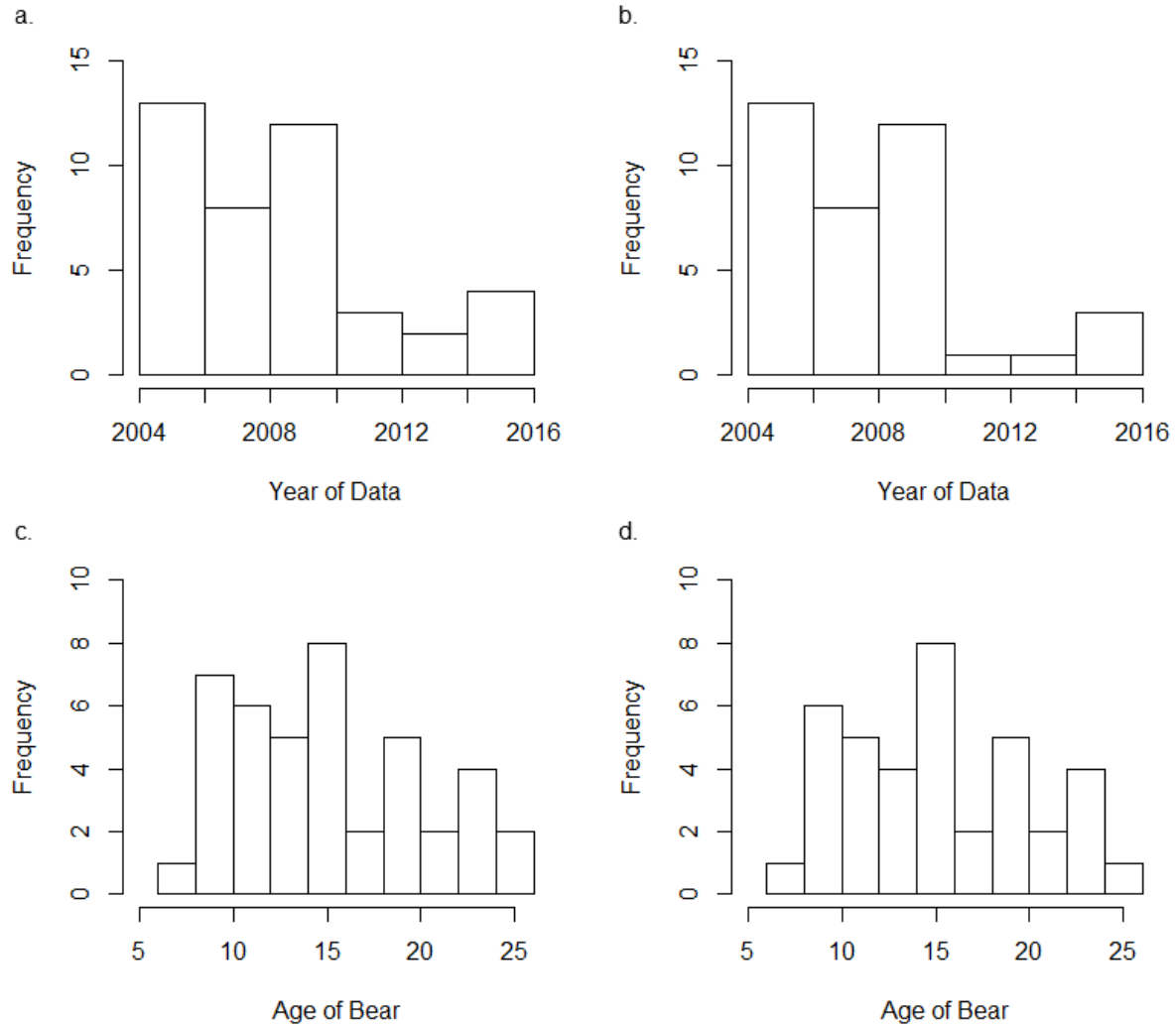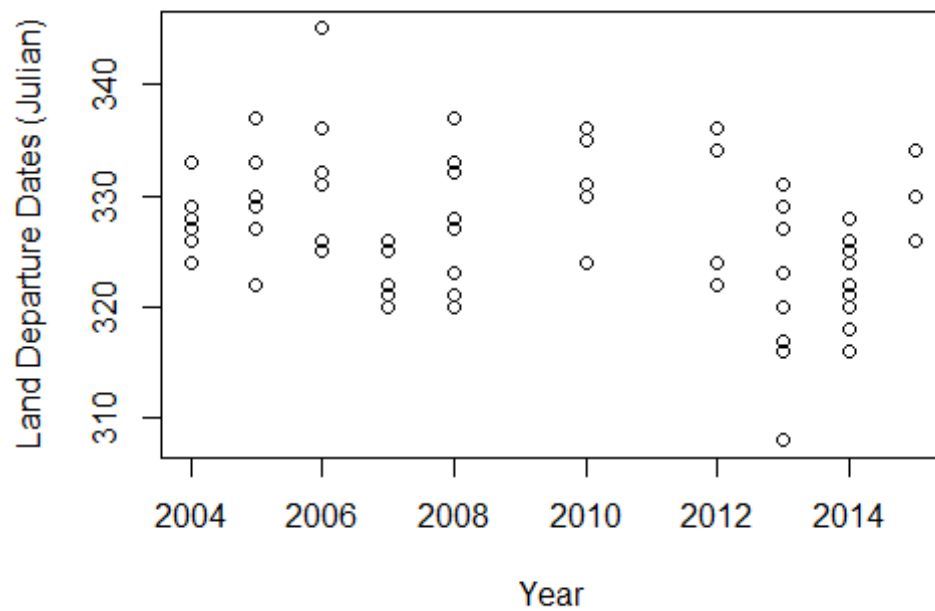
Figure 8. Land departure dates of adult female polar bears in western Hudson Bay during 2004-2015.
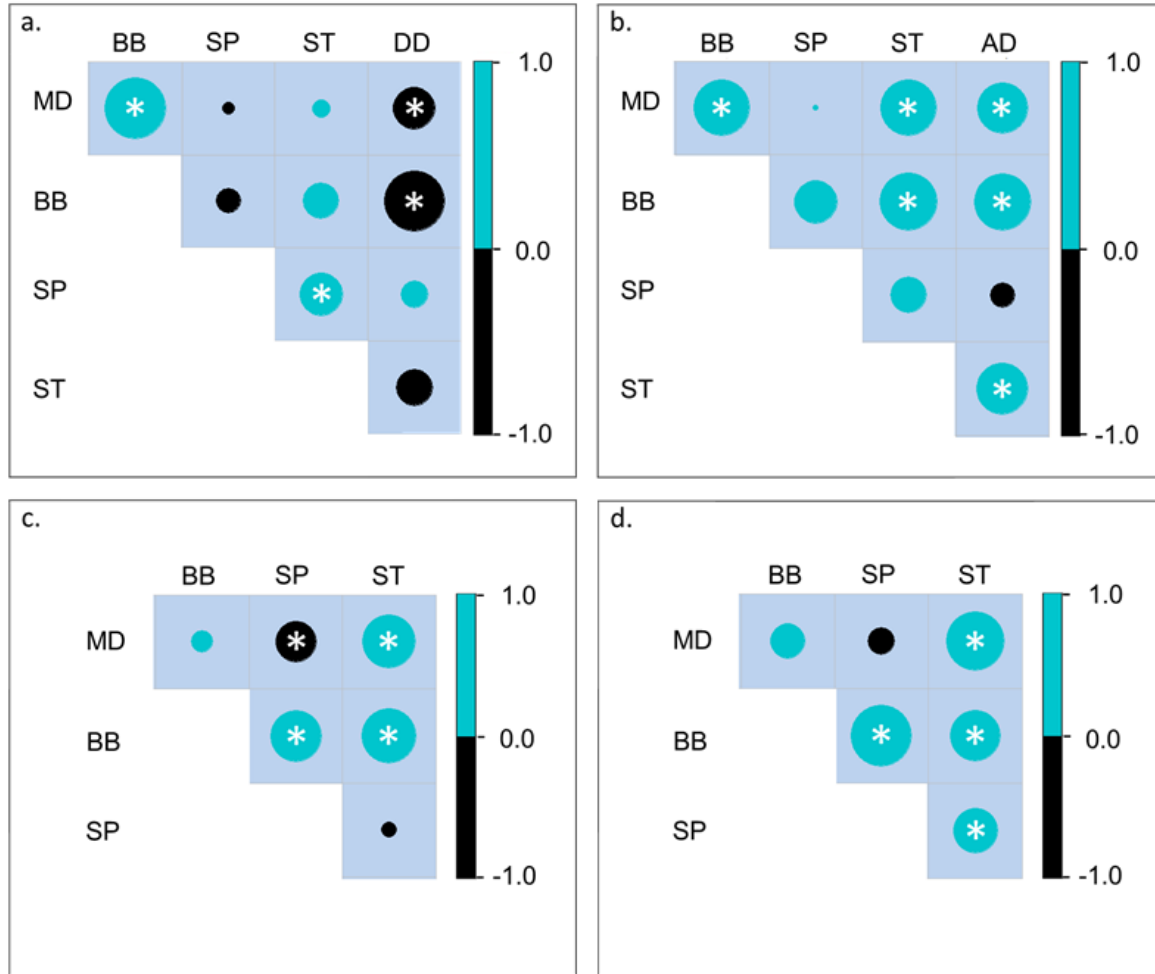
Figure 9. Migration patterns of female polar bears in western Hudson Bay based on telemetry location data collected from 2004-2016. Pearson's correlation plots of response variables in (a) freeze-up season, (b) break-up season, (c) early winter season, and (d) late winter season models. BB is the Brownian bridge home range size, SP is the median speed between consecutive locations, ST is the median daily straightness index value, DD is the departure date bears departed land and began their migration on sea ice, MD is the maximum distance to western Hudson Bay coast, and AD is the arrival date bears arrived on land from sea ice. The r values correspond with the size and colour (+/-) of the circles and significant correlations ($P<0.05$) are denoted by an asterisk (*).

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