Supplementary information 1

Supplementary Methods

Location estimation from light-level loggers

Estimated timings of sunrise and sunset (twilight transition times) were computed from light data using TransEdit2 (British Antarctic Survey/BAS, Cambridge, UK), and the `twilightCalc` function (GeoLight package; Lisovski & Hahn 2012) in R 3.3.3 (R Development Core Team 2017) for BAS, Migrate Technology and Biotrack loggers. Transition times were visually inspected for loggers retrieved during 2014-2017 by the same person. Lotek loggers did not retain raw light intensity data, but rather calculated and recorded latitudes and longitudes based on an on-board algorithm which has been shown to be biased (Frederiksen et al. 2016). Therefore we used these threshold method (Lisovski & Hahn 2012) derived positions to back calculate transition times using the `lotek_to_dataframe` function (probGLS package; Merkel et al. 2016). Daily experienced sea surface temperature (SST) was estimated from raw logged temperature data using the `sst_deduction` function (`probGLS` package) with a possible range of -2 to 20°C for Lotek loggers and -2 to 40°C for all other brands.

A most probable track for each individual and tracking year was calculated using an iterative method utilizing probability sampling detailed in Merkel et al. (2016) and implemented in the `prob_algorithm` function (`probGLS` package). Input data were logger recorded transition times, salt water immersion data as well as calculated daily recorded SST data. Daily optimal interpolated high resolution satellite derived SST, SST uncertainty estimates and sea ice concentration data for the algorithm with a 0.25° resolution were provided by NOAA (Boulder, Colorado, US; Reynolds et al. 2007). To improve precision we included land avoidance, an inability to enter the Baltic Sea (except for Common guillemots from the Isle of May) and an evasion of heavy pack ice (>90% sea ice concentration). Each movement path incorporated parameters based on the ecology of the species and the oceanographic conditions in the North Atlantic (table S1.1). Usually, it is not possible to estimate latitude during times of equinox as day length (the proxy for latitude) is very similar everywhere on earth. However, this methodology is able to estimate locations also during times of equinox by among other things utilizing the recorded temperature data and comparing them to satellite derived sea surface temperature (SST) fields. Due to small north-south gradients in SST in certain areas of the North Atlantic (e.g. the Gulf Stream along the Norwegian coast) we limited the boundary box parameter in

`prob_algorithm` for certain individuals and colonies after initial assessment of their movement track (table S1.1). Each computed track was afterwards visually inspected and erroneous locations particularly around polar night and midnight sun were removed (<1 % of all locations).

Environmental parameters

All chosen environmental parameters used to calculate the environmental space and their rational are listed in table S1.3. Fronts in sea surface temperature (SST) and sea surface height anomaly fields were calculated using a canny edge detector (package `imager`, low & high threshold at 90% & 98%, respectively). Bathymetry was log-transformed and all distance measurements were capped at 500 km as well as square root-transformed. Predictability in SST was calculated as the sum of constancy and contingency following Colwell (1974) over a ten year time period (2007-2016) with 10 equal bins using the `hydrostats` package (figure S1.1). All variables have been standardized (variance = 1, mean = 0).

Mantel correlation analysis

Following Cohen et al. (2018) we calculated species-specific Mantel correlations to validate our migratory connectivity results with an independent method. All individual annual tracks were split into 10 day bins starting 1 July. A resolution of 10 days was chosen to retain a sufficient number of locations for each bin for further analysis. Migratory connectivity for each species was quantified using Mantel correlation tests with 1000 permutations (Ambrosini et al. 2009). More specifically, the distance between individual breeding locations was compared to the distance between their current locations throughout the non-breeding season for each 10 day bin (as central location in each 10 day bin). For this analysis only data from the last three years of tracking was used (2014/15 - 2016/17) due to the uneven sampling across colonies in earlier years. To avoid pseudo-replication only one year of tracking for each repeat track individual was used (randomly chosen). Further, ecoregion- and season-specific Mantel correlation tests were computed - for ecoregions with individuals from more than one population present during the focal time period - to assess the area and season specific connectivity for each species. Results are illustrated in figure S1.3.

Supplementary references

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Supplementary Tables and Figures

Table S1.1. `probGLS` algorithm input parameters used to compute locations. standard deviation = sd

algorithm parameter	description	value used
`particle.number`	number of particles computed for each point cloud	2000
`iteration.number`	number of track iterations	100
`loess.quartile`	remove outliers in transition times based on local polynomial regression fitting processes (Lisovski & Hahn 2012)	used with k = 10
`sunrise.sd & sunset.sd`	shape, scale and delay values describing the assumed uncertainty structure for each twilight event following a log normal distribution	2.49/ 0.94/ 0[1]
`range.solar`	range of solar angles used	-7° to -1° (except for C250 logger from SK: -4° to -2°)
`boundary.box`	the range of longitudes and latitudes likely to be used by tracked individuals	90°W to 120°E & 40°N to 81°N; except for 91% COGU tracks from IM with 40°N to 62°N; all COGU from BI and 94% COGU SK tracks with 60°N to 77°N; 6% SK tracks with 50°N to 77°N
`day.around.spring.equinox` & `days.around.fall.equinox`	number of days before and after an equinox event in which a random latitude will be assigned	spring: 21 days before & 14 days after autumn: 14 days before & 21 days after
`speed.dry`	fastest most likely speed, speed sd and maximum speed allowed when the logger is not submerged in sea water	17/ 4/ 30 m/s[2]
`speed.wet`	fastest most likely speed, speed sd and maximum speed allowed when the logger is submerged in sea water	1/ 1.3/ 5 m/s[3]
`sst.sd`	logger-derived sea surface temperature (SST) sd	0.5°C[4]
`max.sst.diff`	maximum tolerance in SST variation	3°C
`east.west.comp`	compute longitudinal movement compensation for each set of twilight events (Biotrack 2013)	used

[1] These parameters are chosen as they resemble the twilight error structure of open habitat species in Lisovski et al. (2012).
[2] inferred from GPS tracks (unpublished data) and (Elliott & Gaston 2005)
[3] North Atlantic current speed up to fast current speeds (i.e. East Greenland current) (Lumpkin & Johnson 2013) as the tagged animal is assumed to not actively move when the logger is immerged in seawater
[4] logger temperature accuracy

Table S1.2. Proportion of locations missing in each season mainly due to lack of twilight events caused by midnight sun (seasons: autumn and spring) or polar night (early and late winter) for each breeding population as well as mean and standard deviation (sd) across populations. Breeding populations: SNZ = Southern Novaya Zemlya, NNZ = Northern Novaya Zemlya, ESP = Eastern Spitsbergen, WSP = Western Spitsbergen, BI = Bjørnøya, SBS = Southern Barents Sea, HJ = Hjelmsøya, SK = Sklinna, JM = Jan Mayen, IC = Northeast Iceland, FA = Faroe Islands, IM = Isle of May

species	season	breeding populations											mean	sd
		IM	FA	SK	IC	JM	WSP	HJ	BI	SBS	ESP	SNZ	NNZ		
BRGU	autumn	-	-	-	15 %	13 %	39 %	-	29 %	15 %	58 %	11 %	47 %	29 %	17 %
	early winter	-	-	-	6 %	1 %	1 %	-	5 %	36 %	100 %	20 %	97 %	33 %	39 %
	late winter	-	-	-	0 %	2 %	1 %	-	3 %	4 %	29 %	1 %	8 %	6 %	9 %
	spring	-	-	-	30 %	45 %	73 %	-	63 %	45 %	91 %	51 %	81 %	60 %	19 %
COGU	autumn	1 %	2 %	10 %	0 %	8 %	-	12 %	14 %	4 %	-	-	-	6 %	5 %
	early winter	1 %	1 %	9 %	0 %	5 %	-	51 %	34 %	39 %	-	-	-	18 %	19 %
	late winter	1 %	0 %	1 %	1 %	3 %	-	2 %	5 %	2 %	-	-	-	2 %	2 %
	spring	4 %	12 %	14 %	31 %	46 %	-	44 %	48 %	27 %	-	-	-	28 %	16 %

Table S1.3. Parameter chosen to describe the environmental space.

parameter	**temporal resolution**	**spatial resolution**	**rational**	**data source**
bathymetry	static	0.25°	predictable productivity on continental shelfs	ETOPO1 & IBCAO[1]
surface air temperature	daily	0.75°	influences energy requirements[2]	ECMWF[3]
sea surface temperature (SST)	daily	0.25°	water mass indicator & physiological constraint[2]	NOAA OI SST V2[4]
SST predictability (figure S1.2)	static	0.25°	identifier of spatially variable SST features across seasons and years (e.g. persistent frontal systems[5])	NOAA OI SST V2[4]
minimum distance to 15%, 50% & 90% sea ice concentrations	daily	0.25°	descriptor of marginal sea ice zone	NSIDC[6]
sea surface height (SSH)	daily	0.25°	descriptor of the locations of large-scale features such as gyres and fronts	AVISO[7]
distance to SSH anomaly gradients	daily	0.25°	distance to meso-scale eddies as spatially dynamic sources of upwelling	AVISO[7]
distance to SST gradient	daily	0.25°	distance to meso- and large-scale temperature fronts[5]	NOAA OI SST V2[4]

[1] (Amante & Eakins 2009, Jakobsson et al. 2012), [2] (Fort et al. 2009), [3] (Berrisford et al. 2011), [4] (Reynolds et al. 2007), [5] (Scales et al. 2014), [6] (Cavalieri et al. 1999), [7] Aviso, with support from Cnes (http://www.aviso.altimetry.fr/)

Table S1.4. Large-scale movement network metrics. P-values derived by two tailed t-tests. Displayed values denote mean ± standard deviation (minimum & maximum in brackets), if not labelled otherwise. df = degree of freedom

network metric	COGU	BRGU	p-value	df
# of nodes	24	25	-	-
# of populations present at a node	2.7 (1-7)	3.5 (1-6)	0.13	46
node size	17±14% (2-56%)	16±20% (0.4-75%)	0.89	42
node size by population	**49±40% (1-100%)**	**37±38% (1-100%)**	**0.05**	**134**
total degrees (connections per node)	**6.9 (2-21)**	**10.8 (2-26)**	**0.03**	**60**
edge size	7±8% (0.2-38%)	5±8% (0.1-55%)	0.14	157
edge size by population	**36±38% (1-100%)**	**22±32% (1-100%)**	**0.001**	**202**
# of unique ecoregions used by population	3.5 (2-6)	4.8 (2-8)	0.24	12
# of unique ecoregions used by individuals	**1.5±0.7 (1-4)**	**2.3±0.9 (1-4)**	**<0.001**	**156**

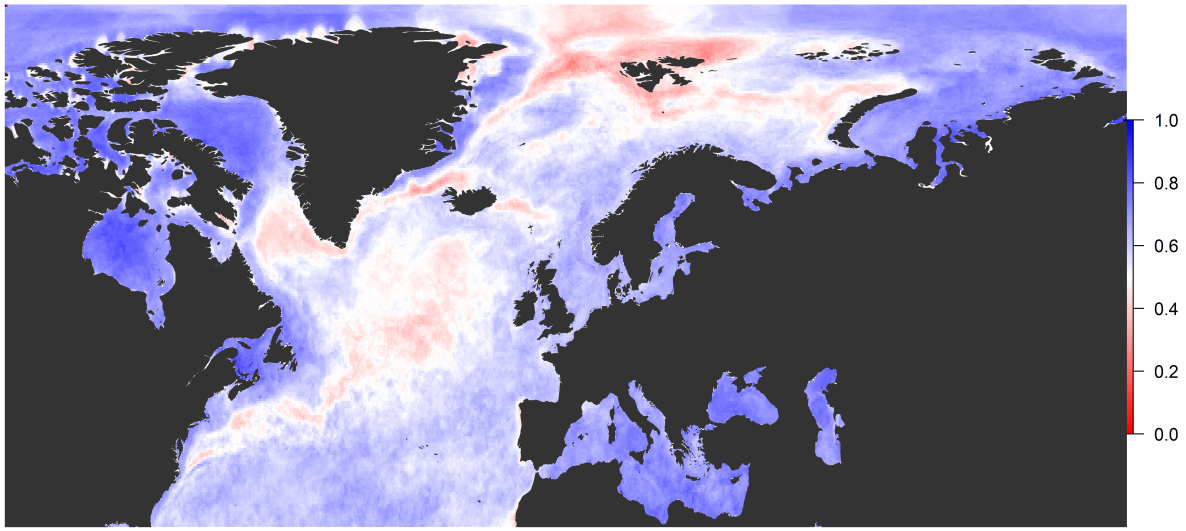

Figure S1.1. Distribution of SST predictability in the North Atlantic with a scale from 0 (no predictability) to 1 (very predictable).

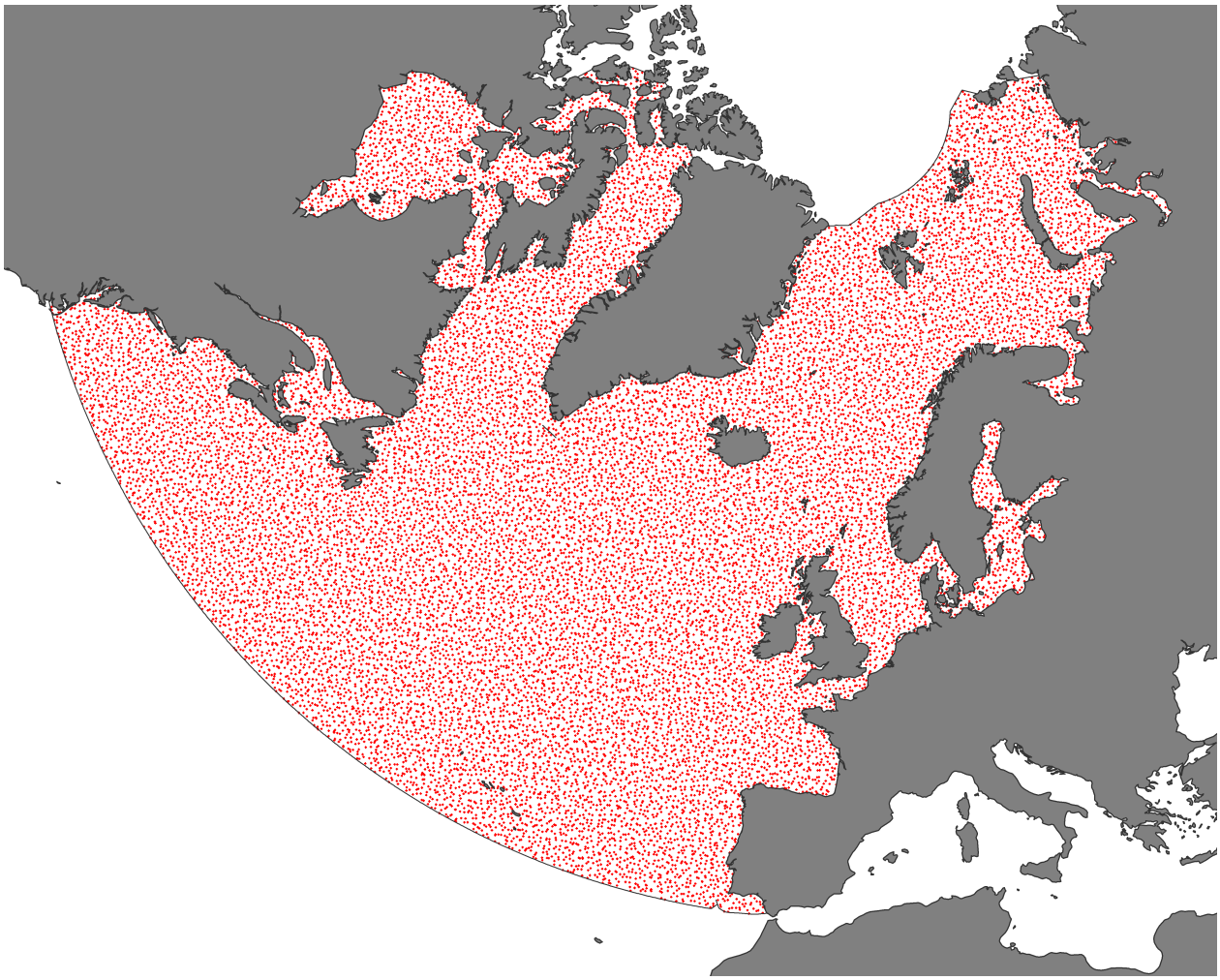

Figure S1.2. Map (in polar stereographic projection) displaying the study region including the 20000 random locations (in red) used to estimate the available environmental space.

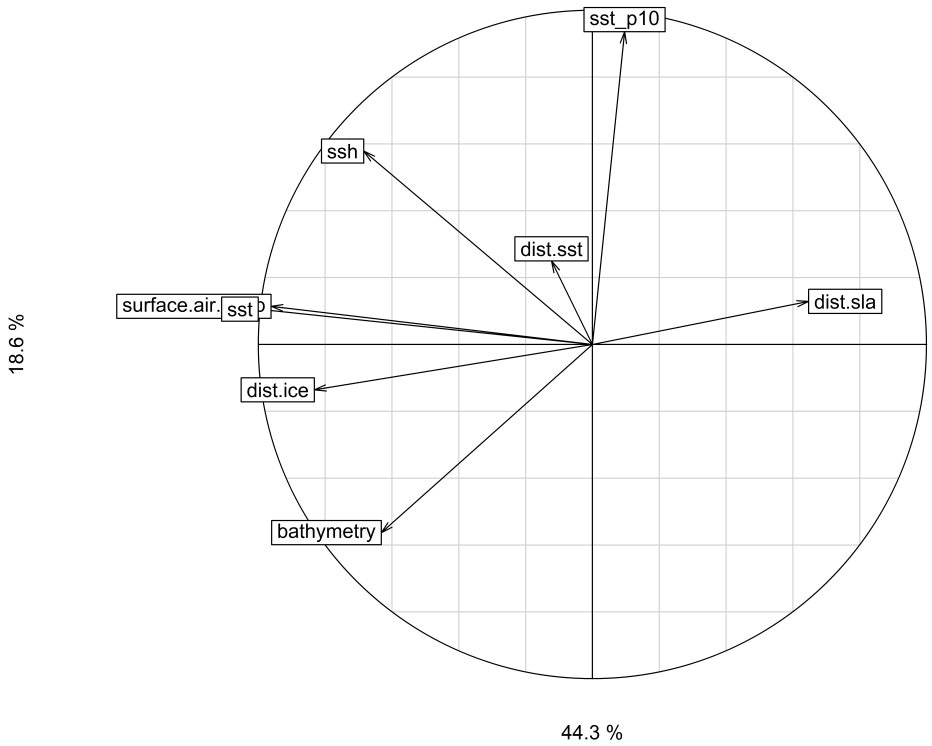

Figure S1.3. PCA correlation circle for the environmental space representing the North-Atlantic over the entire study period. dist.sla = distance to mesoscale eddies, dist.ice = distance to the marginal sea ice zone, surface.air.temp = surface air temperature, sst = sea surface temperature, ssh = sea surface height, dist.sst = distance to SST fronts, sst_p10 = SST predictability

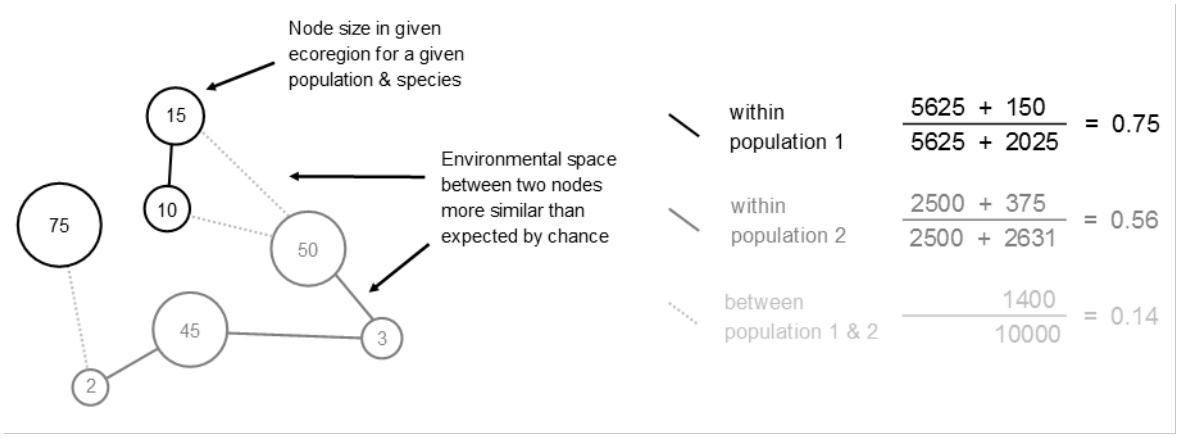

Figure S1.4. A schematic detailing the environmental similarity index (S) calculations in equation 1 (within example populations, solid lines) and equation 2 (between two example populations, dashed lines) using two example populations (in black and grey). The symbols denote ecoregion-, species- and breeding population-specific environmental space use. Its size corresponds to the proportional use as visualised in figure 1B. Lines connect environmental spaces which are similar based on the environmental niche similarity test (one way is considered sufficient, i.e. $niche\ 1 \cong \text{niche } 2 \mid \text{niche } 2 \cong \text{niche } 1$).

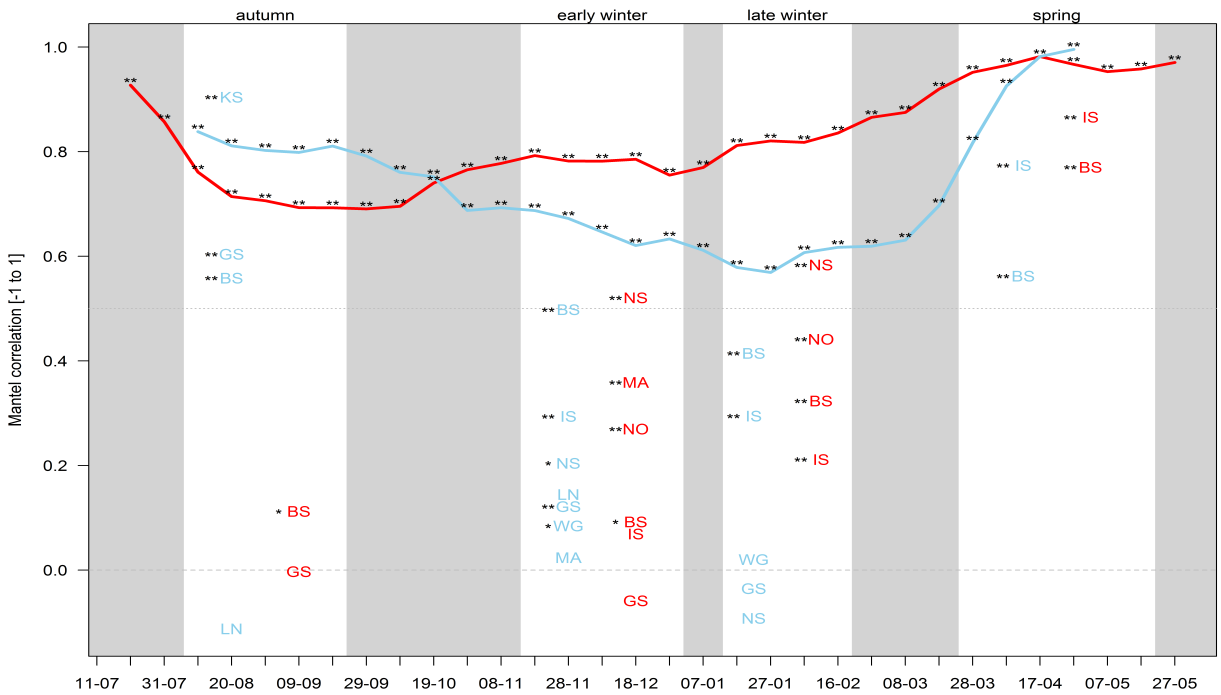

Figure S1.5. Species-specific mantel correlation through time (10 day bins) for all data from 2014-2017. BRGU in blue and COGU in red. Labels in each season (white boxes) denote season-specific mantel correlation values for each particular ecoregion with birds from more than one breeding population present. Significance levels based on 1 000 permutations: ** = <0.001, * = <0.05; Ecoregion abbreviations: BS = Barents Sea, KS = Kara Sea, GS = Greenland Sea, IS = Iceland Shelf & Sea, WG = West Greenland, NO = North Sea, MA = Central North Atlantic, NS = Norwegian Sea, LN = Labrador shelf & Newfoundland

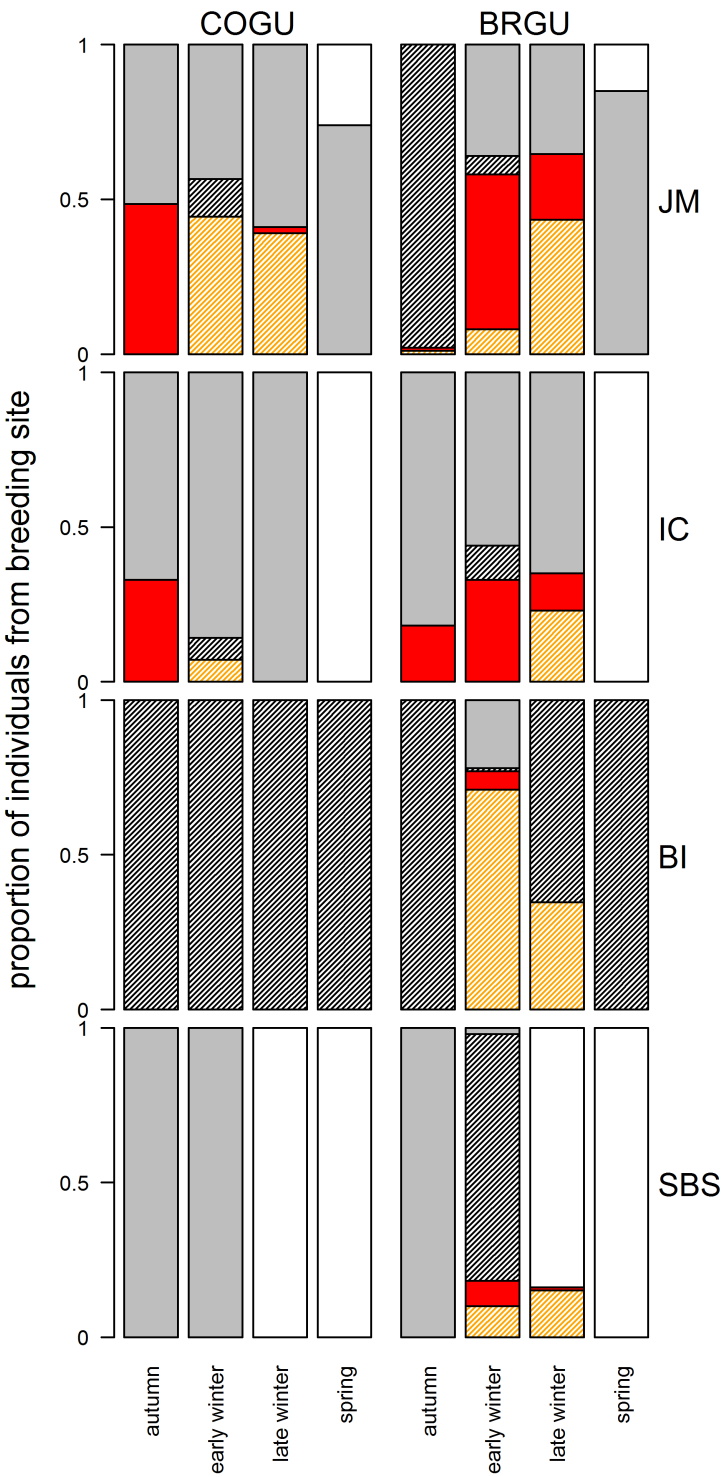

Figure S1.6. Seasonal proportional comparative space and environmental niche use between both species breeding sympatric at four breeding locations (JM = Jan Mayen, IC = North-East Iceland, BI = Bjørnøya & SBS = Southern Barents Sea). The proportion of the population occupying the same ecoregion with the other sympatric species breeding at the same location is indicated in white-grey-black colours while red-orange colours indicate different ecoregions used. Dark colours (grey & black) correspond to species-specific within ecoregion space use while white illustrates mixing between the species within ecoregions. Solid colours (white, grey & red) indicate similar environmental niches occupied while shaded colours denote distinct environments used (black & orange).