Supplementary material

Warming sea surface temperatures are linked to lower shorebird migratory fuel loads

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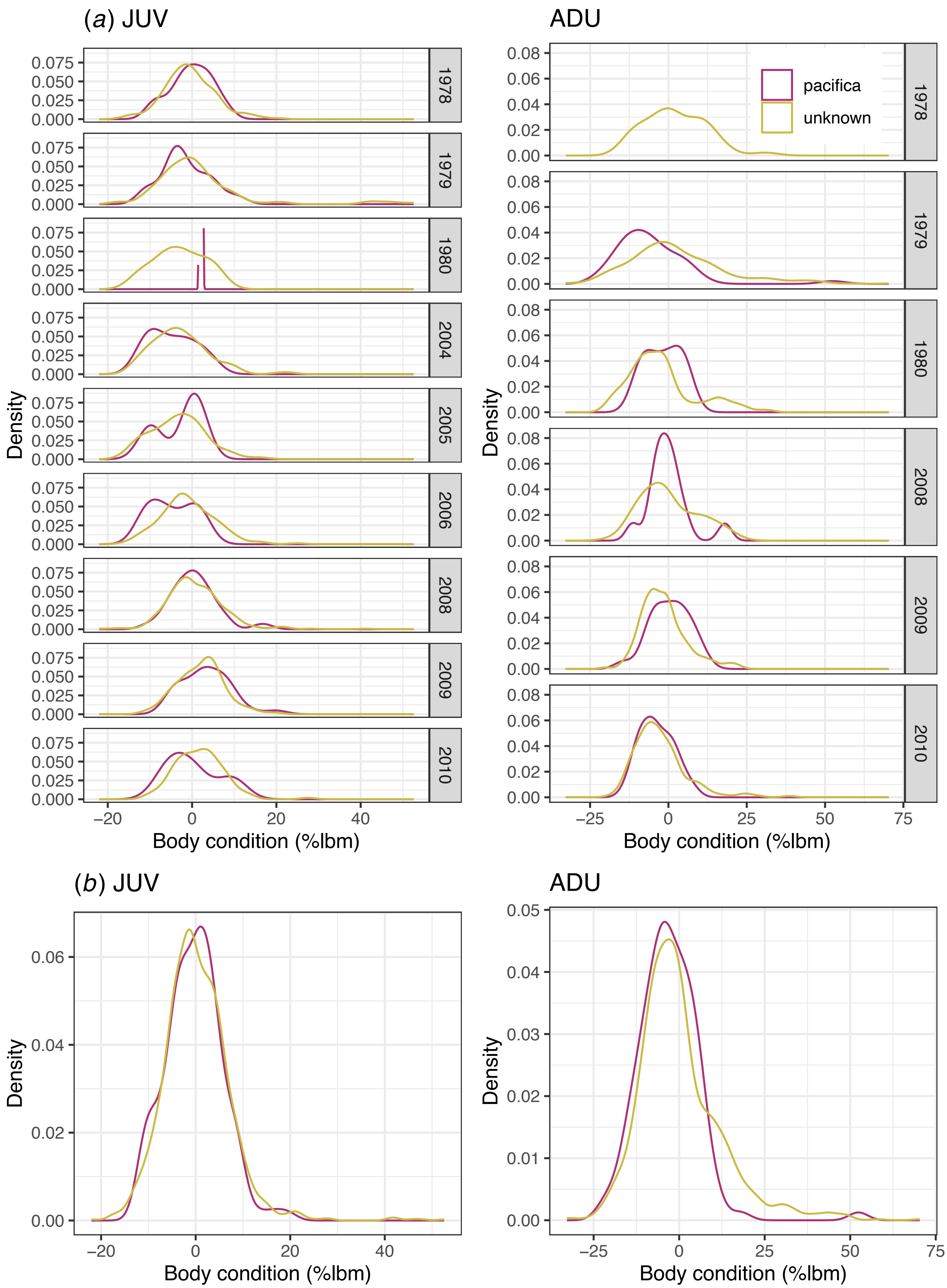


(a) JUV
ADU
pacifica
unknown
1978
1979
1980
2004
2005
2006
2008
2009
2010
Density
Body condition (%lbm)
(b) JUV
ADU
Density
Body condition (%lbm)

Figure S1. (a) Density plots of juvenile (JUV; n = 1,459) and adult (ADU; n = 1,122) Dunlin pre-migratory body conditions during the southbound migratory fueling period (22 August–22 September) in Angyoyaravak Bay, Yukon–Kuskokwim Delta, Alaska, by year and subspecies (*pacifica* and unknown; see text). (b) Density plots of juvenile (*n* = 173 *pacifica* and 1,286 unknown) and adult (*n* = 113 *pacifica* and 1,009 unknown) pre-migratory body conditions during the southbound migratory fueling period by subspecies (years combined).

Table S1. Linear mixed models considered for estimating structural lean body masses of Dunlin (*n* = 1,577) captured in Angyoyaravak Bay, Yukon–Kuskokwim Delta, Alaska (1–21 August, 1978–80, 2005–06, 2008–09).

Model	*k*	AIC	ΔAIC	*w*
Mass at capture ~ Culmen length * Age + (1|Year)	6	8132	0	1.00
Mass at capture ~ Culmen length + Age + (1|Year)	5	8186	54	0.00
Mass at capture ~ Culmen length + (1|Year)	4	8199	67	0.00
Mass at capture ~ 1 + (1|Year)	3	8607	475	0.00

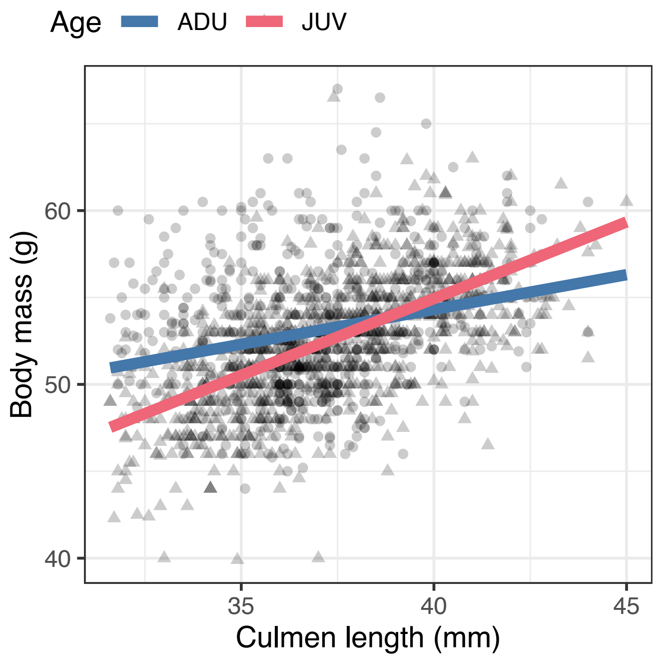


Figure S2. Linear regression of body mass by culmen length for adult (ADU; n = 690; circular data points) and juvenile (JUV; n = 887; triangular data points) Dunlin captured during the pre-fueling period (1–21 August, 1978–80, 2005–06, 2008–09) in Angyoyaravak Bay, Yukon–Kuskokwim Delta, Alaska.

Table S2. Number of juvenile and adult Dunlin captured by 8-day sampling period and year in Angyoyaravak Bay, Yukon–Kuskokwim Delta, Alaska. Bolded values are the minimum number of age-specific captures per sampling period–year combination (see text).

	1978	1979	1980	2004	2005	2006	2008	2009	2010
Sampling period 1: 22–29 August									
Juvenile	169	**85**	2	0	13	26	169	**164**	69
Adult	**6**	211	**1**	**0**	**0**	**0**	**57**	183	**47**
Sampling period 2: 30 August–6 September									
Juvenile	18	18	**24**	1	39	47	106	66	**43**
Adult	**5**	**3**	72	**0**	**0**	**0**	**24**	**24**	122
Sampling period 3: 7–14 September									
Juvenile	40	**12**	**0**	75	17	29	87	17	**9**
Adult	**32**	47	4	**1**	**1**	**2**	**30**	**5**	31
Sampling period 4: 15–22 September									
Juvenile	**0**	**13**	**0**	**0**	**2**	67	32	0	0
Adult	0	193	19	0	5	**2**	**6**	**0**	**0**
Balanced totals: 22 August–22 September									
Juvenile	43	113	25	1	3	4	117	193	99
Adult	43	113	25	1	3	4	117	193	99

Table S3. Number of juvenile and adult Dunlin captured by year in Angyoyaravak Bay, Yukon–Kuskokwim Delta, Alaska.

	1978	1979	1980	2004	2005	2006	2008	2009	2010	Total
Pre-fueling period, 1–21 August										
Juvenile	166	147	39	0	396	57	70	12	0	887
Adult	12	404	2	0	109	128	33	2	0	690
Southbound migratory fueling period, 22 August–22 September										
Juvenile	227	128	26[a]	76	71	169	394	247	121	1,459
Adult	43	454	96[a]	1	6	4	117	212	200	1,133

[a]6 additional juveniles and 5 adults were captured on 4 October 1980. We removed 1 of the juvenile capture records from further analysis because its fuel load measurement (%lbm) was 20% greater than all other fuel load measurements.

Table S4. Values of model variables used to predict maximum flight ranges of Dunlin departing Angyoyaravak Bay, Yukon–Kuskokwim Delta, Alaska, on southbound migration. Flight range predictions were generated using program *Flight* (see text).

Model variable	Value	Reference
Altitude of flight	717 m	Hedenström and Alerstam 1992
Air density	1.1429 kg/m^3	Standard air density at 717 m
Flight speed	Constant	Pennycuick and Battley 2003
Specific work	Constant	Pennycuick and Battley 2003
Minimum energy from protein	5%	Pennycuick and Battley 2003
Induced power factor	0.9	Pennycuick et al. 2013
Body drag coefficient	0.06	Pennycuick et al. 2013
Ratio: air speed–minimum power speed at start	1.98	See text
Wing span[a]	0.346 m	Pennycuick et al. 2013
Wing area[a]	0.0147 m^2	Pennycuick et al. 2013
Airframe mass at start[a]	0.0477 kg	Pennycuick et al. 2013
Lean-mass fraction of departure fuel load	0.24	Pennycuick and Battley 2003

[a]Value is for Dunlin that occur in southern Sweden and are smaller than Dunlin that occur in western Alaska. Flight range predictions are not sensitive to differences in size, but rather differences in shape (Pennycuick 1975), which are minimal between the populations (Engelmoer and Roselaar 1998).

Table S5. Departure-fuel-load adjustment factors (% structural lean body mass; %lbm) by year, age, and average sea surface temperature in the previous year (SST $year_{i-1}$; 11–24 June) for Dunlin departing Angyoyaravak Bay, Yukon–Kuskokwim Delta, Alaska, on southbound migration.

	1978	1979	**1980**	2004	2005	2006	2008	2009	2010
Adjustment factor (%lbm)[a]									
Juvenile	+2.14	+3.69	**0**	-0.66	-0.70	+1.36	+3.38	+4.91	+4.23
Adult	+4.39	+4.00	**0**	–	–	–	+2.30	+0.90	-0.57
Average SST $year_{i-1}$ (11–24 June; °C) by year									
	2.98	5.30	**2.68**	7.56	7.51	6.91	4.03	4.03	4.47
Adjustment factor (%lbm)[b]									
Juvenile	+0.83	+3.37	**0**	-0.84	-0.68	+1.04	+2.84	+2.84	+3.26

[a]Adjustment factors by year represent the difference in mean annual pre-migratory body condition between each year and 1980 (see Figure 2).
[b]Adjustment factors by average SST $year_{i-1}$ (11–24 June) represent the difference in mean climatic effect between the range of $year_{i-1}$ SSTs 1978–2022 (i.e., 1.31°C–10.74°C) and that of 1980 (i.e., 2.68°C). We only present the adjustment factors for the years that Dunlin were captured (see Figure 3a). Climatic effects were identified using sliding window analyses (see text).

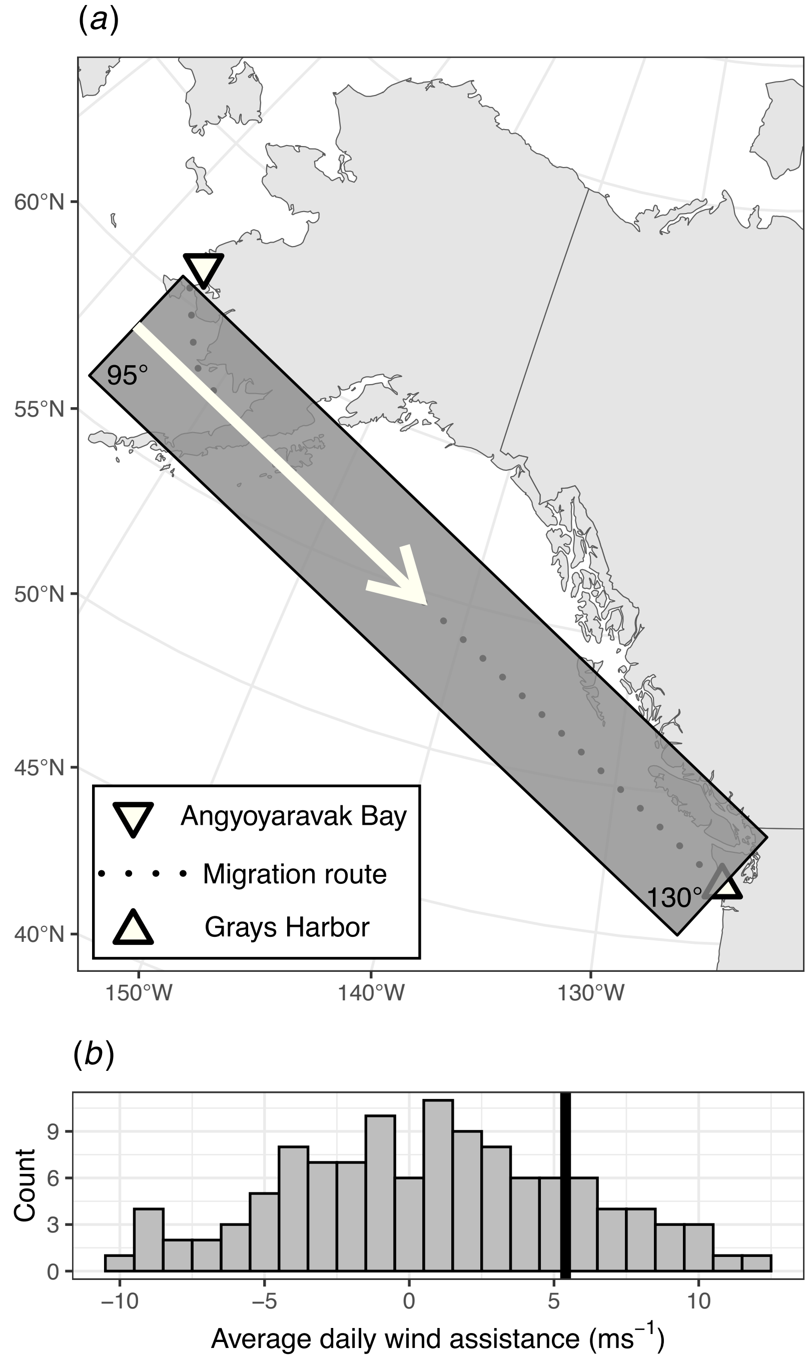
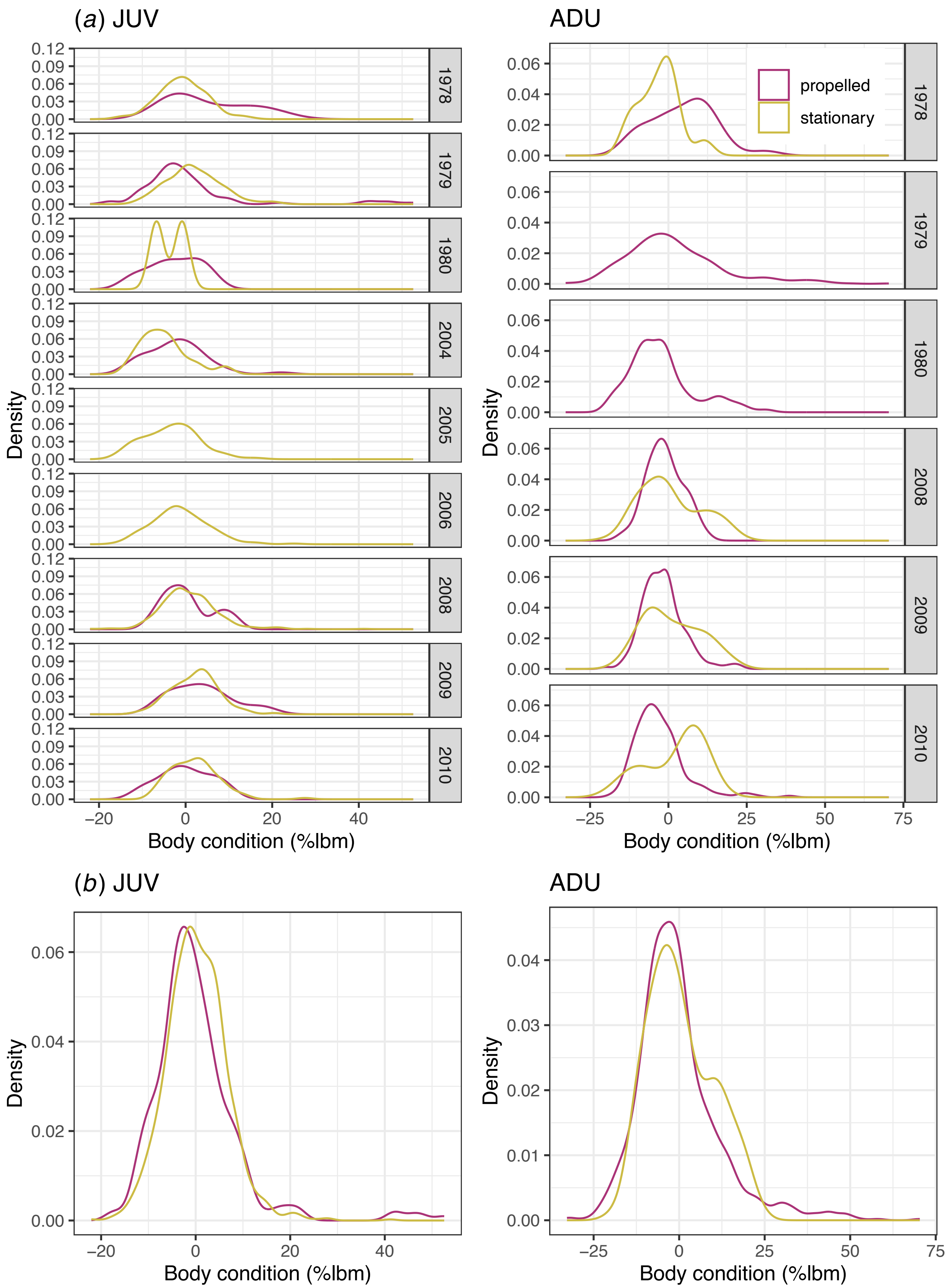


Figure S3. (*a*) Approximate bearing of the shortest migratory route upon departing Angyoyaravak Bay, Yukon–Kuskokwim Delta, Alaska (95°), and upon arriving in the northern extent of the species' primary wintering grounds on the Pacific coast of North America (130°; average bearing: 112.5°). The shaded rectangle represents the region in which average daily wind assistance values were calculated (see text). (*b*) Histogram of average daily wind assistance values (meters per second [ms^{-1}]) from 29 September to 11 October 1978–80, 2004–06, and 2008–10 (n = 117). The vertical bar represents the 80th percentile of wind assistance values.



(a) JUV
ADU
propelled
stationary
Density
Body condition (%lbm)
1978
1979
1980
2004
2005
2006
2008
2009
2010
(b) JUV
ADU

Figure S4. (*a*) Density plots of juvenile (JUV; n = 1,459) and adult (ADU; n = 1,122) Dunlin pre-migratory body conditions during the southbound migratory fueling period (22 August–22 September) in Angyoyaravak Bay, Yukon–Kuskokwim Delta, Alaska, by year and capture method (propelled and stationary). (*b*) Density plots of juvenile and adult pre-migratory body conditions during the southbound fueling period by capture method (years combined).

Table S6. Top models for weather variables used to assess annual variation in juvenile Dunlin (*n* = 1,459) pre-migratory body condition during the southbound migratory fueling period (22 August–22 September, 1978–80, 2004–06, 2008–10) in Angyoyaravak Bay, Yukon–Kuskokwim Delta, Alaska. Model sets were constructed using a sliding window approach (see text) and contained models with linear and quadratic response functions (*n* = 153 models per response function). ΔAICc values are relative to a baseline model with no weather variables. We selected models with the lowest AICc and considered models with ΔAICc < 2 to have equal support. We considered top models with a P_C value < 0.10 to represent a real climate signal (models in bold; see text).

Weather variable	Response function	ΔAICc	P_C	Climate window
Avg air temp	Quadratic	-8.13	0.30	–
Avg SST	Linear	-6.71	0.41	–
Avg SST year$_{i-1}$	**Quadratic**	**-17.88**	**0.05**	**11–24 June**
Avg precip	**Quadratic**	**-11.69**	**0.04**	**4 June–29 July**

Table S7. Linear mixed models considered for estimating climatic effects on pre-migratory body condition (PMBC) of juvenile Dunlin (*n* = 1,459) captured in Angyoyaravak Bay, Yukon–Kuskokwim Delta, Alaska (22 August–22 September, 1978–80, 2004–06, 2008–10). Average SST in the previous year (SST $year_{i-1}$; 11–24 June) and average precipitation in the year of capture (precip; 4 June–29 July) were identified as influential predictors of juvenile pre-migratory body condition using a sliding window approach (see text).

Model	*k*	AICc	ΔAICc	*w*
PMBC ~ SST $year_{i-1}$ + SST $year_{i-1}^2$ + (1|Year)	5	9744	0	0.81
PMBC ~ (SST $year_{i-1}$ + SST $year_{i-1}^2$) * (precip + $precip^2$) + (1|Year)	11	9748	4	0.15
PMBC ~ precip + $precip^2$ + (1|Year)	5	9750	6	0.04
PMBC ~ 1 + (1|Year)	3	9762	18	0.00

Table S8. SST $year_{i-1}$ models and parameter values used to estimate the effect of SST $year_{i-1}$ on pre-migratory body condition of juvenile Dunlin (n = 1,459) captured in Angyoyaravak Bay, Yukon–Kuskokwim Delta, Alaska (22 August–22 September, 1978–80, 2004–06, 2008–10). SST $year_{i-1}$ models were identified using a sliding window approach (see text; n = 153 candidate models). ΔAICc values are relative to a baseline model with no weather variables. Model-averaged parameter values are in bold.

Intercept	Linear term	Quadratic term	ΔAICc	*w*	Climate window
-14.012	6.533	-0.679	-17.88	0.331	11–24 June
-14.482	6.294	-0.619	-16.63	0.177	11 June–1 July
-13.830	5.969	-0.571	-14.99	0.078	18–24 June
-17.653	6.924	-0.630	-14.32	0.056	11 June–8 July
-14.436	**6.433**	**-0.645**	–	–	–

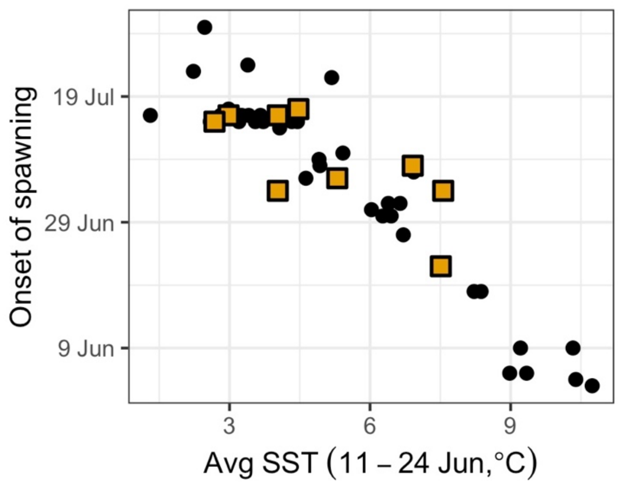


Figure S5. Predicted date of onset of spawning of *Limecola balthica* clams by average SST (11–24 June) in the central Yukon–Kuskokwim Delta (YKD), Alaska, 1977–2022. Date of onset of spawning is the date central YKD SST values exceeded 8.3 °C (Philippart et al. 2003). Gold squares represent the relevant values for the years that Dunlin were captured.

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