Migratory behaviour of humpback whales in the Southeastern Pacific under climate change

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Supplementary Information

Figure S1. Duration of emission for 42 humpback whales of the BSG tagged in three sites whithin breeding grounds in Panama (n = 16), Costa Rica (n = 4) and Ecuador (n = 22) and across five distinct years. Whales that remained in their breeding ground and did not initiate their migration during the study are represented in red, and migrating whales in blue. In each panel, the average departure date per year is indicated by a vertical dashed line.

Figure S2. Step length in km **(A)** and turning angle in radian **(B)** characterizing the movement behaviour exhibited by 42 whales from the Breeding Stock G in their breeding grounds of Panama, Costa Rica and Ecuador and during their southward migration along the west coast of the south American continent. Observed data are displayed on the histogram, while the modeled data are displayed with a line colored by behavioural state. The stationary state-space model had a maximum likelihood of 5743.14 and an AIC of -11466. Modeled track with locations colored by movement behaviour state for individual ID 149467 exhibiting a transiting behaviour **(C)** and individual ID 149462 exhibiting an Area Restricted Search behaviour **(D)**. State1: Area Restricted Search behaviour (colored in orange), State2: Transiting (colored in blue).

Figure S3. Oceanic conditions between May and September of each year of tracking data **(A)** Oceanic Niño Index (3-months sea-surface temperature anomalies). The dotted lines mark the thresholds for El Niño/La Nina conditions. An ONI value above +0.5 indicates El Niño conditions (weak in 2009 and strong in 2015), while an ONI index below -0.5 indicates La Niña; **(B)** Average daily sea surface temperature (SST (°C)) and daily chlorophyll-a level (chloro-a (mg/m3) at 4,000 random locations drawn in the breeding grounds of humpback whales by year and tagging area (North: Panama and Costa Rica, South: Ecuador). Points have been jittered to improve visualization and the lines connect the seasonal averages **(C)** daily sea surface temperature (°C): Average daily Sea Surface Temperature with the seasonal average indicated by a dashed line; **(D)** daily chloro-a (mg/m3): Daily Chlorophyll-a concentration with the seasonal average indicated by a dashed line.

Figure S4. **(A)** Study area and tracks of 24 humpback whales that initiated their southward migration during the study; **(B)** Chlorophyll-a concentration (mg/m3) and **(C)** Sea surface temperature (°C) extracted at the locations and timestamps along the migratory tracks. Base maps were created in R **[59]**, using the *sf* **[64]** and *rnaturalearth* **[70]** packages.

Figure S5. Oceanic conditions between November 1st and March 31st preceding the southward migration for each year of tracking data at 4,000 random locations drawn in the feeding grounds of humpback whales. **(A)** Daily sea ice concentration (%) with the seasonal average indicated by a dashed line; **(B)** Sea surface temperature (°C) with the seasonal average indicated by a dashed line.

Figure S6. Random point locations (4,000) drawn in the northern breeding grounds of the Breeding Stock G of humpback whales (**A:** Costa Rica and Panama), in the southern breeding ground (**B:** Ecuador), and in the feeding ground off the Western Antarctic Peninsula **(C)**. Base maps were created in R **[59]**, using the *sf* **[64]** and *rnaturalearth* **[70]** packages.

Figure S7. Contribution on the principal component axes of the variables used to characterize the oceanic conditions in the breeding grounds **(A, B)**, during migration **(C)** and in the feeding ground **(D)**. Breeding grounds: *ONI* (Oceanic Niño Index), mean*_daily_chloro_breeding* (mean chlorophyll-a level), *mean_daily_chloro_lag_breeding* (mean chlorophyll-a level with a 30-day time lag), *chloro_anomaly_breeding* (anomaly in chlorophyll-a level compared to the 2009 to 2016 average), *mean_daily_sst_breeding* (mean sea surface temperature), *sst_anomaly_breeding* (anomaly in sea surface temperature compared to the 2009 to 2016 average), *max_sst_breeding* (maximum value of daily sea surface temperature), *julian_day_max_sst_breeding* (earliest date at which the mean daily sea surface temperature peaked to a maximum); Migration route: *chloro_avg_migr* (mean daily chlorophyll-a level), *chloro_lag_avg_migr* (mean daily chlorophyll-a level with a 30-day time lag), *sst_avg_migr* (mean sea surface temperature); Feeding ground: *mean_sst_feeding* (mean sea surface temperature), *sst_anomaly_feeding* (anomaly in sea surface temperature compared to the 2009 to 2016 average), *max_sst_feeding* (maximum value of daily sea surface temperature), *mean_sic* (mean value of daily sea ice concentration), *max_sic* (maximum in sea ice concentration), *day_start_melting* (earliest date at which the daily sea ice concentration reached 0).

Figure S1


Migrating (Y/N N Y
Panama, Costa Rica, Ecuador - 2009-2016
Aug-17 Aug-31 Sep-14 Sep-28 Oct-12 Oct-26 Nov-09 Nov-23 Dec-0
Panama - 2009
tag_id
87743 87742 87741 87740 87739 87738 87736 87734 87727 87726 87725 87723 87721
Aug-19 Aug-24 Aug-29 Sep-03 Sep-08 Sep-13 Sep-18
Panama - 2014
tag_id
138214 138203 138202
Sep-12 Sep-17 Sep-22 Sep-27 Oct-02
Costa Rica - 2015
tag_id
149462 149459 149456 149455
Sep-12 Sep-22 Oct-02 Oct-12 Oct-22 Nov-01 Nov-11
Ecuador - 2013
tag_id
131591 131590 131589 131588 131587 131586 131585 131584 129276 129275 129273 129271 129268 129267 129264
Aug-13 Aug-23 Sep-02 Sep-12 Sep-22 Oct-02 Oct-12 Oct-22
Ecuador - 2016
tag_id
157390 157389 157386 157384 149473 149467 149465
Oct-06 Oct-16 Oct-26 Nov-05 Nov-15 Nov-25 Dec-

Figure S2

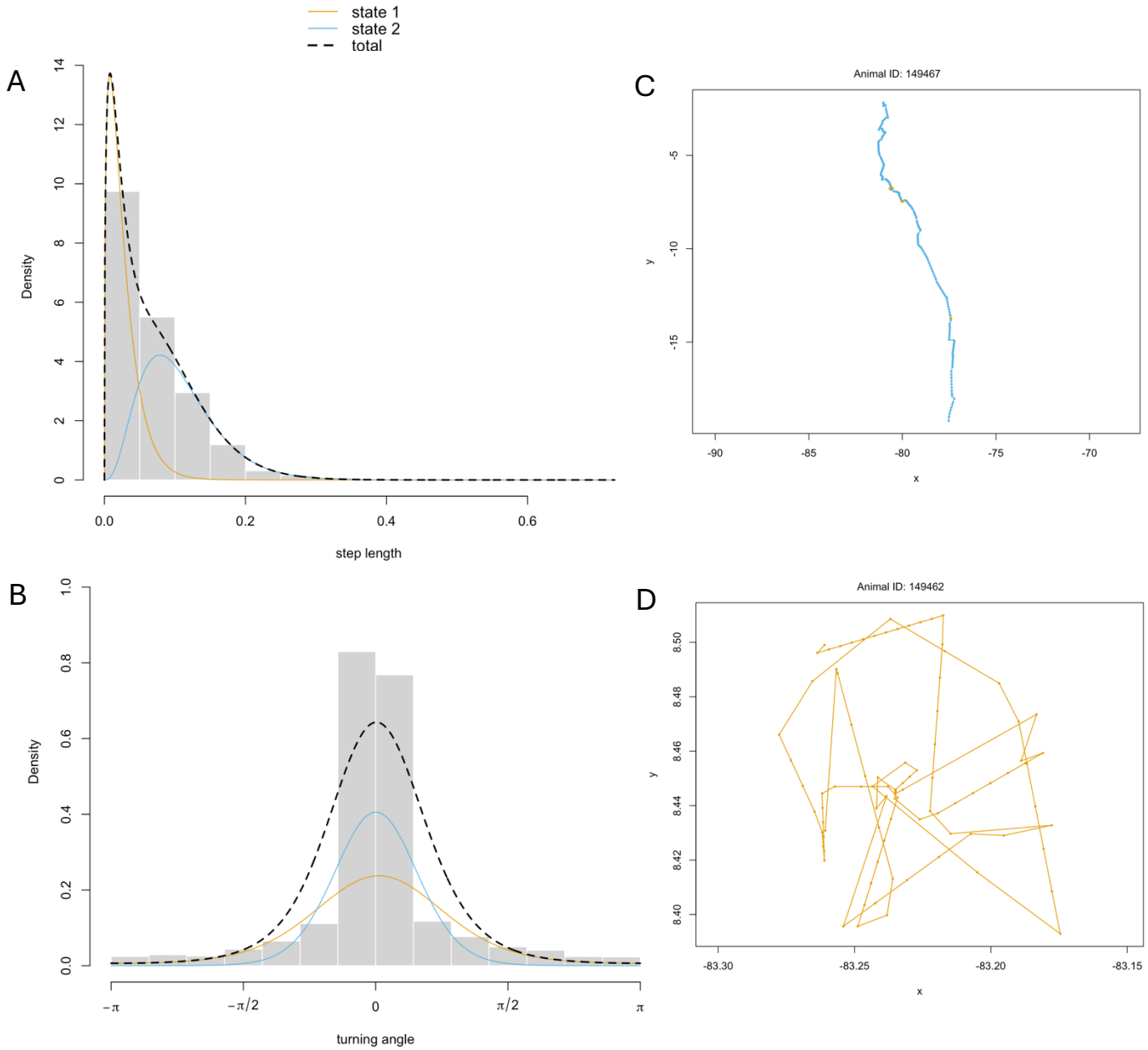

A
state 1
state 2
total
Density
step length
B
Density
turning angle
C
Animal ID: 149467
y
x
D
Animal ID: 149462
y
x

Figure S3

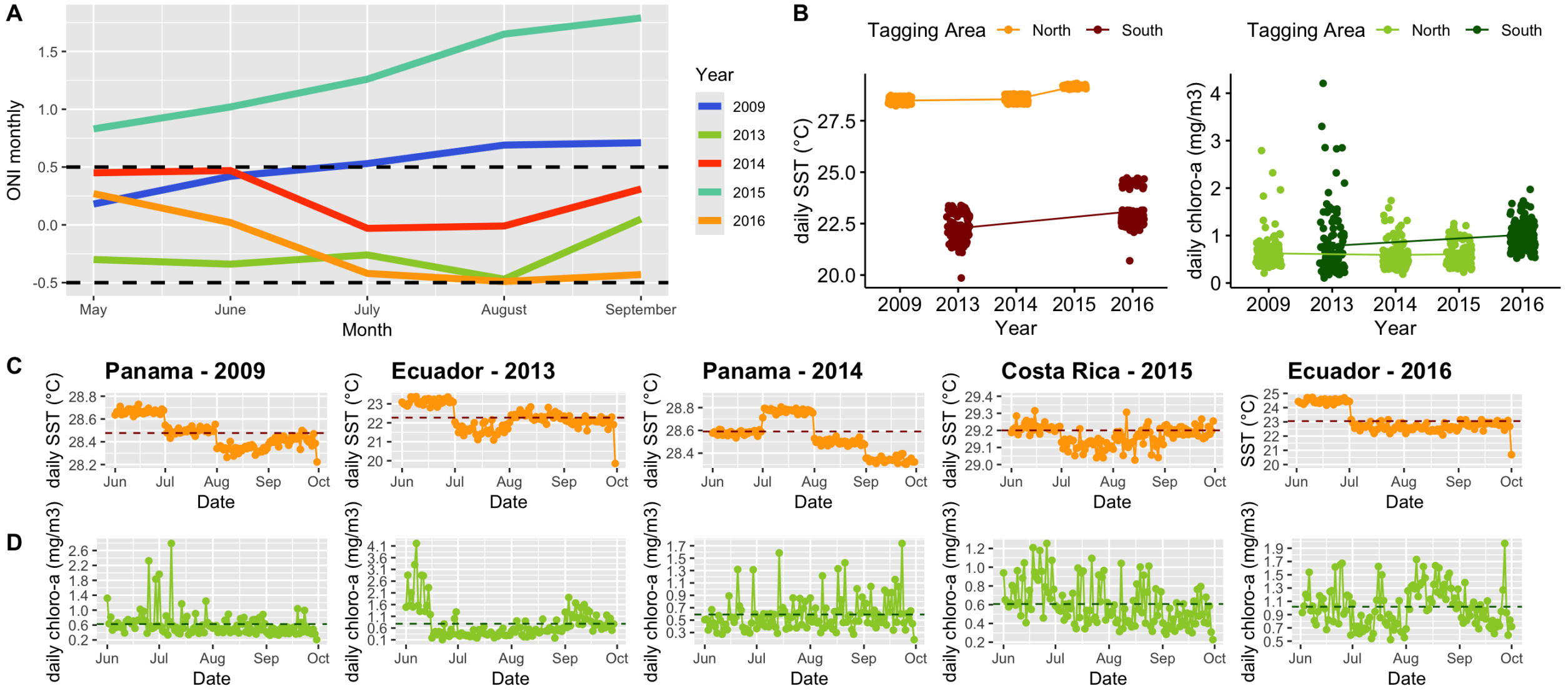

A
ONI monthly
1.5
1.0
0.5
0.0
-0.5
May
June
July
August
September
Month
Year
2009
2013
2014
2015
2016
B
Tagging Area
North
South
daily SST (°C)
27.5
25.0
22.5
20.0
2009
2013
2014
2015
2016
Year
Tagging Area
North
South
daily chloro-a (mg/m3)
4
3
2
1
0
2009
2013
2014
2015
2016
Year
C
Panama - 2009
Ecuador - 2013
Panama - 2014
Costa Rica - 2015
Ecuador - 2016
daily SST (°C)
SST (°C)
Jun
Jul
Aug
Sep
Oct
Date
D
daily chloro-a (mg/m3)
Jun
Jul
Aug
Sep
Oct
Date

Figure S4

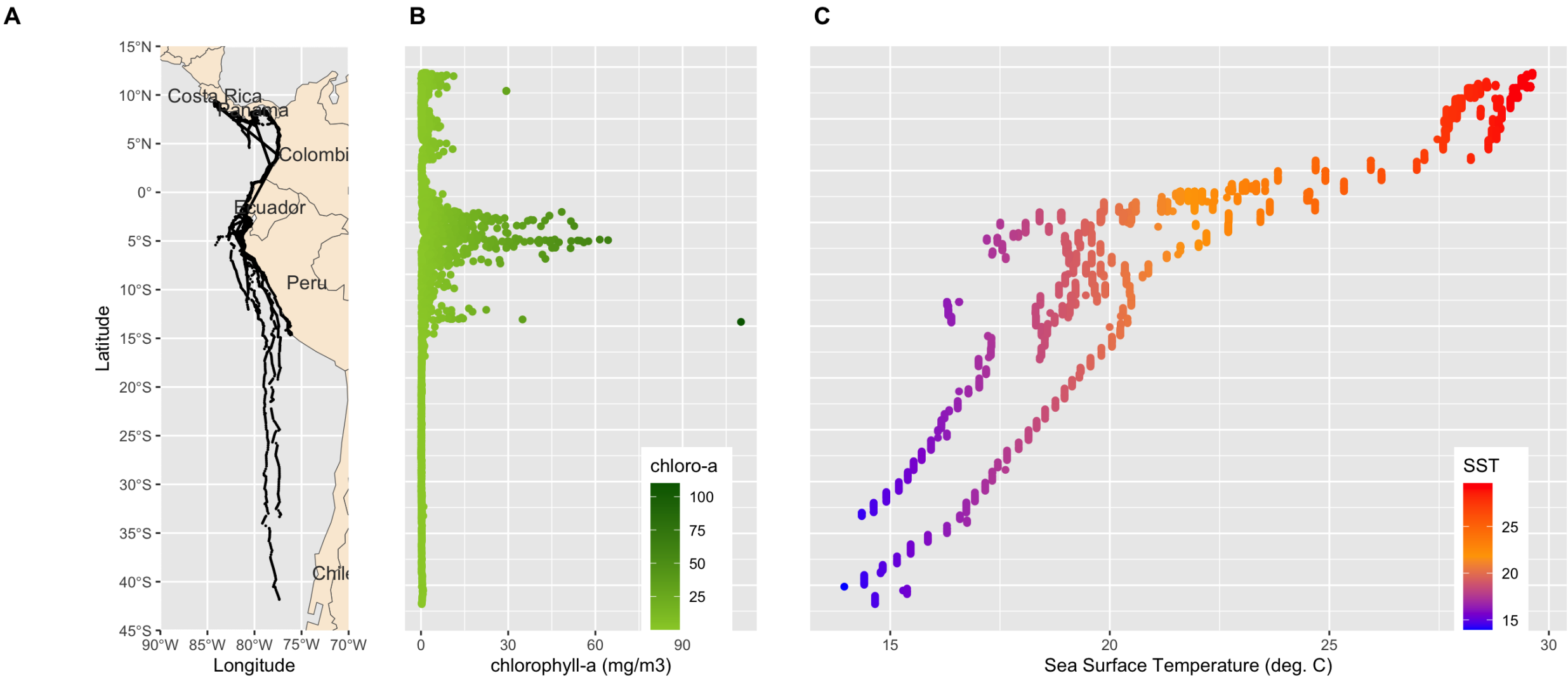

A
B
C
15°N
10°N
5°N
0°
5°S
10°S
15°S
20°S
25°S
30°S
35°S
40°S
45°S
Latitude
Costa Rica
Panama
Colombi
Ecuador
Peru
Chile
90°W
85°W
80°W
75°W
70°W
Longitude
chloro-a
100
75
50
25
0
30
60
90
chlorophyll-a (mg/m3)
SST
25
20
15
15
20
25
30
Sea Surface Temperature (deg. C)

Figure S5


A
2009
2013
2014
2015
2016
Daily sea ice concentration (%)
0.0
0.2
0.4
0.6
Nov
Dec
Jan
Feb
Mar
Apr
Date
B
Daily sea surface temperature (C)
-1
0
1
2
3

Figure S6

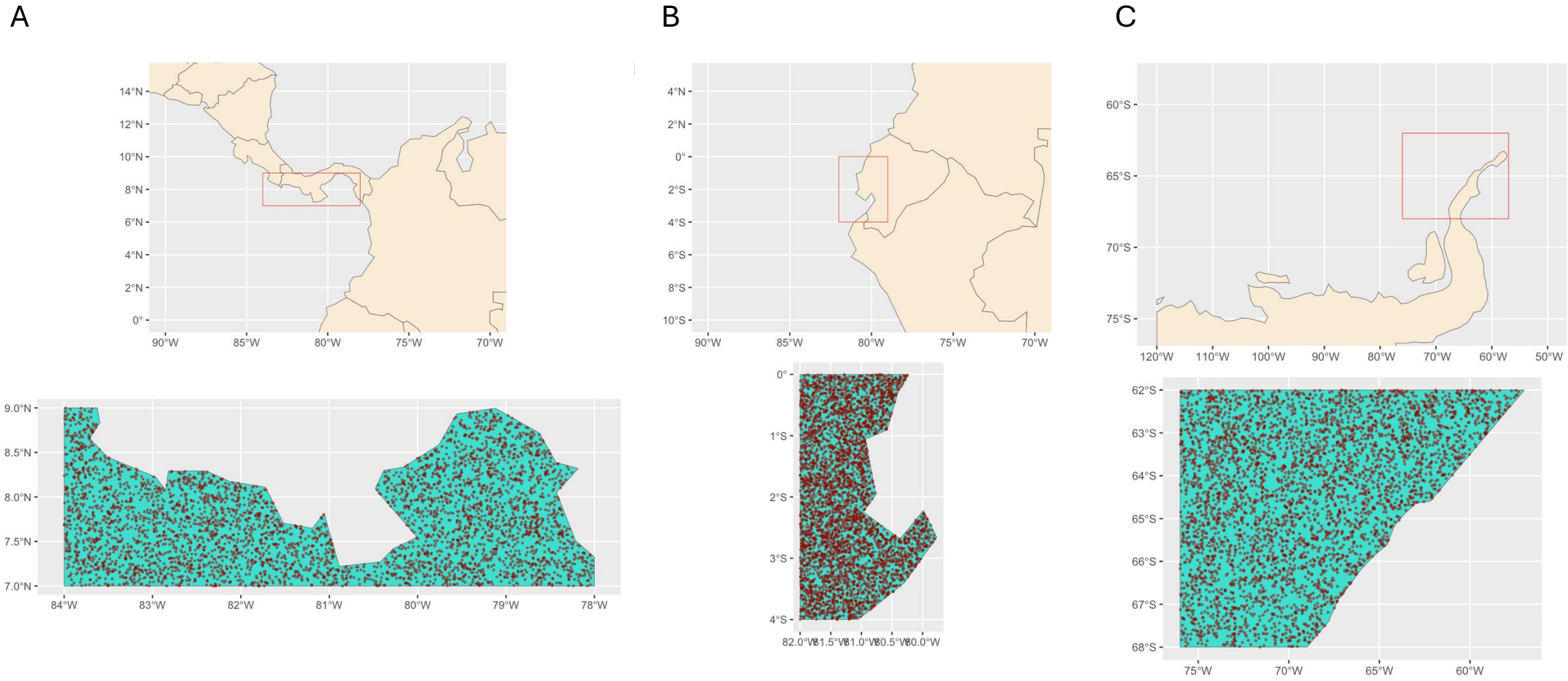
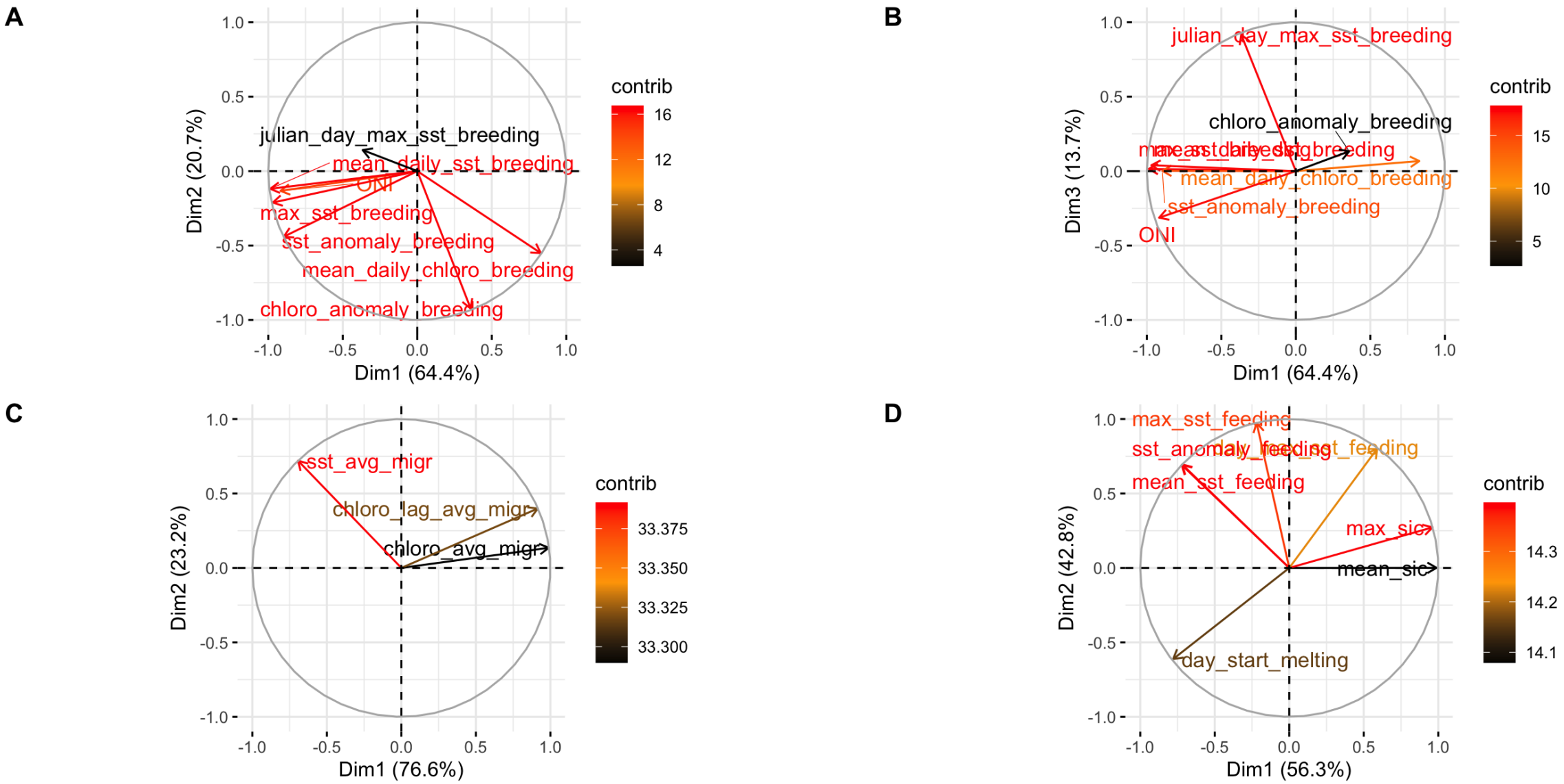

A
14°N
12°N
10°N
8°N
6°N
4°N
2°N
0°
90°W
85°W
80°W
75°W
70°W
9.0°N
8.5°N
8.0°N
7.5°N
7.0°N
84°W
83°W
82°W
81°W
80°W
79°W
78°W
B
4°N
2°N
0°
2°S
4°S
6°S
8°S
10°S
90°W
85°W
80°W
75°W
70°W
0°
1°S
2°S
3°S
4°S
82.0°W
81.5°W
81.0°W
80.5°W
80.0°W
C
60°S
65°S
70°S
75°S
120°W
110°W
100°W
90°W
80°W
70°W
60°W
50°W
62°S
63°S
64°S
65°S
66°S
67°S
68°S
75°W
70°W
65°W
60°W

Figure S7


A
julian_day_max_sst_breeding
mean_daily_sst_breeding
ONI
max_sst_breeding
sst_anomaly_breeding
mean_daily_chloro_breeding
chloro_anomaly_breeding
Dim1 (64.4%)
Dim2 (20.7%)
contrib
16
12
8
4
B
julian_day_max_sst_breeding
chloro_anomaly_breeding
mean_daily_chloro_breeding
sst_anomaly_breeding
ONI
Dim1 (64.4%)
Dim3 (13.7%)
contrib
15
10
5
C
sst_avg_migr
chloro_lag_avg_migr
chloro_avg_migr
Dim1 (76.6%)
Dim2 (23.2%)
contrib
33.375
33.350
33.325
33.300
D
max_sst_feeding
mean_sst_feeding
max_sic
mean_sic
day_start_melting
Dim1 (56.3%)
Dim2 (42.8%)
contrib
14.3
14.2
14.1

TableS1. Track Description for 42 BSG humpback whales; whales that initiated migration during the study (n=24) are in bold. Duration: number of days when the tag transmitted the whale location; Date Begin: first date of tag transmission; Date End: last date of tag transmission; Total Distance: total distance covered (km); Distance to Shore: average distance from the shoreline (km); Average Speed: average speed (km/day).

Satellite Tag ID	Year	Tagging Country	Sex	Duration (day)	Date Begin	Date End	Total Distance (km)	Distance to Shore (km)	Average Speed (km/day)
87721	2009	Panama	F	18.25	31-Aug-09	18-Sep-09	104.66	15.35	42.12
87723	2009	Panama	U	10.75	25-Aug-09	5-Sep-09	143.4	17.63	79.66
87725	**2009**	**Panama**	**F**	**7.38**	**26-Aug-09**	**3-Sep-09**	**528.78**	**11.98**	**111.94**
87726	2009	Panama	U	1.63	26-Aug-09	27-Aug-09	34.16	33.21	67.64
87727	2009	Panama	F	7.75	18-Aug-09	26-Aug-09	46.78	2.97	16.46
87734	**2009**	**Panama**	**F**	**7.75**	**26-Aug-09**	**3-Sep-09**	**597.05**	**10.69**	**94.34**
87736	2009	Panama	F	8.13	26-Aug-09	3-Sep-09	66.66	7.46	29.13
87738	**2009**	**Panama**	**U**	**10.88**	**25-Aug-09**	**5-Sep-09**	**496.5**	**21.19**	**84.70**
87739	2009	Panama	F	4.88	24-Aug-09	29-Aug-09	17.42	4.23	21.31
87740	**2009**	**Panama**	**F**	**23.75**	**26-Aug-09**	**19-Sep-09**	**421.13**	**30.07**	**53.04**
87741	2009	Panama	U	11.38	2-Sep-09	13-Sep-09	56.65	3.68	28.93
87742	2009	Panama	U	6.13	24-Aug-09	30-Aug-09	36.92	4.94	23.62
87743	2009	Panama	U	12.25	23-Aug-09	5-Sep-09	83.96	10.2	33.73
129264	**2013**	**Ecuador**	**F**	**10.13**	**10-Aug-13**	**21-Aug-13**	**150.62**	**13.67**	**43.56**
129267	2013	Ecuador	U	4.13	15-Aug-13	19-Aug-13	40.28	10.55	40.51
129268	2013	Ecuador	F	21.88	15-Aug-13	6-Sep-13	220.02	14.99	32.99
129271	**2013**	**Ecuador**	**U**	**9.88**	**14-Aug-13**	**24-Aug-13**	**312.72**	**135.01**	**59.48**
129273	**2013**	**Ecuador**	**F**	**26.25**	**13-Aug-13**	**9-Sep-13**	**551.77**	**17.22**	**50.88**
129275	2013	Ecuador	F	13.25	11-Aug-13	25-Aug-13	98.82	13.46	24.83
129276	**2013**	**Ecuador**	**U**	**7.00**	**17-Sep-13**	**24-Sep-13**	**180.45**	**19.82**	**52.81**
131584	2013	Ecuador	F	22.25	17-Sep-13	10-Oct-13	148.87	12.75	26.80
131585	**2013**	**Ecuador**	**U**	**6.25**	**14-Aug-13**	**21-Aug-13**	**309.15**	**21.44**	**81.23**
131586	**2013**	**Ecuador**	**F**	**14.00**	**19-Sep-13**	**3-Oct-13**	**527.85**	**7.66**	**50.23**
131587	2013	Ecuador	U	15.13	14-Aug-13	29-Aug-13	352	11.77	34.78
131588	**2013**	**Ecuador**	**F**	**9.75**	**14-Aug-13**	**24-Aug-13**	**658.98**	**33.74**	**107.36**
131589	**2013**	**Ecuador**	**U**	**2.00**	**11-Aug-13**	**13-Aug-13**	**112.01**	**23.41**	**72.79**
131590	2013	Ecuador	F	10.63	6-Oct-13	17-Oct-13	222.55	15.62	44.22
131591	2013	Ecuador	U	15.63	9-Oct-13	25-Oct-13	1,933.54	359.9	135.23
138202	**2014**	**Panama**	**F**	**24.63**	**9-Sep-14**	**4-Oct-14**	**367.48**	**15.13**	**41.17**
138203	**2014**	**Panama**	**F**	**24.25**	**9-Sep-14**	**4-Oct-14**	**1,478.63**	**14.64**	**73.49**
138214	2014	Panama	F	17.25	17-Sep-14	5-Oct-14	56.72	8.3	35.09
149455	**2015**	**Costa Rica**	**F**	**68.63**	**9-Sep-15**	**17-Nov-15**	**2,501.40**	**34.58**	**65.56**
149456	**2015**	**Costa Rica**	**F**	**48.13**	**13-Sep-15**	**31-Oct-15**	**296.14**	**10.4**	**36.97**
149459	**2015**	**Costa Rica**	**F**	**36.88**	**9-Sep-15**	**16-Oct-15**	**1,611.50**	**50.64**	**62.53**
149462	2015	Costa Rica	F	11.50	14-Sep-15	26-Sep-15	12.99	4.76	10.82
149465	**2016**	**Ecuador**	**F**	**28.38**	**3-Oct-16**	**31-Oct-16**	**1,164.63**	**174.7**	**67.08**
149467	**2016**	**Ecuador**	**F**	**26.63**	**5-Oct-16**	**1-Nov-16**	**1,893.45**	**85.53**	**85.25**
149473	**2016**	**Ecuador**	**F**	**16.38**	**3-Oct-16**	**19-Oct-16**	**1,123.48**	**105.61**	**81.67**
157384	**2016**	**Ecuador**	**F**	**12.13**	**8-Oct-16**	**21-Oct-16**	**390.43**	**16.52**	**60.61**
157386	**2016**	**Ecuador**	**F**	**24.00**	**7-Oct-16**	**31-Oct-16**	**1,564.96**	**121.09**	**87.57**
157389	**2016**	**Ecuador**	**U**	**56.75**	**6-Oct-16**	**2-Dec-16**	**4,445.14**	**147**	**97.56**
157390	**2016**	**Ecuador**	**F**	**42.50**	**6-Oct-16**	**17-Nov-16**	**460.01**	**24.67**	**48.36**

Table S2. Description and source for the environmental data. The chlorophyll-a concentration (mg.m-3), sea-surface temperature (°C), and sea ice concentration (%) data were downloaded using the rerddap package **[65]** and extracted using the rerddapXtracto package **[66]**.

Dataset	**erdHadISSTIce**	**erdMBchlamday_LonPM180**	**erdHadISST**
Variable	sea-ice component (%), monthly	chlorophyll-a (mg m-3), 8 day composite	sst (degree_C)
Latitude	-89.5, 89.5	-45.0, 65.0	-89.5, 89.5
Longitude	-179.5, 179.5	-180.0, 179.975	-179.5, 179.5
Time	1870-01-16T11:59:59Z, 2022-09-16T12:00:00Z	2006-02-15T00:00:00Z, 2023-03-16T12:00:00Z	1870-01-16T11:59:59Z, 2022-09-16T12:00:00Z
Resolution	1 degree	0.025 degrees	1 degree
Source	Met Office Hadley Centre	NOAA NMFS SWFSC ERD	Met Office Hadley Centre

Table S3. Oceanic variable characteristics in the breeding grounds, along the migration route, and in the feeding ground of humpback whales of the Breeding G stock.

Variable	Breeding grounds	Migration Route	Feeding Ground
chloro Chlorophyll-a level for each location/ time stamp along the track	na	From departure date until last day of emission	na
SST Sea surface temperature for each location/ time stamp along the track	na	From departure date until last day of emission	na
ONI 3 months anomaly	May – October, year of tagging	na	na
mean_chloro Mean of daily chlorophyll-a averaged across 4,000 locations	June 1st – Sept. 30th, year of tagging	na	na
mean_chloro_anomaly Anomaly in mean chlorophyll-a	June 1st – Sept. 30th, year of tagging	na	na
mean_chloro_lag Mean of daily chlorophyll-a with a 30-day time lag averaged across 4,000 locations	June 1st – Sept. 30th, year of tagging	na	na
mean_SST Mean of daily sea surface temperature averaged across 4,000 locations	June 1st – Sept. 30th, year of tagging	na	Nov. 1st – March 31st, preceding tagging
mean_SST_anomaly Anomaly in mean sea surface temperature	June 1st – Sept. 30th, year of tagging	na	Nov. 1st – March 31st, preceding tagging
max_SST Maximum value of sea surface temperature	June 1st – Sept. 30th, year of tagging	na	Nov. 1st – March 31st, preceding tagging
day_max_SST earliest date at which seas surface temperature reached a maximum	June 1st – Sept. 30th, year of tagging	na	Nov. 1st – March 31st, preceding tagging
mean_sic Mean of daily sea ice concentration averaged across 4,000 locations	na	na	Nov. 1st – March 31st, preceding tagging
max_sic Maximum value of daily sea ice concentration averaged across 4,000 locations	na	na	Nov. 1st – March 31st, preceding tagging
Day_start_melting Earliest date at which daily sea ice concentration reached a value of 0%	na	na	Nov. 1st – March 31st, preceding tagging