Effects of Sea Surface Temperature on the Distribution of Short-finned Pilot Whales (*Globicephala macrorhynchus*) in the Western North Atlantic Ocean

By

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TABLE OF CONTENTS

EXECUTIVE SUMMARY 1
INTRODUCTION 2
METHODS 3
Study area 3
Field methods 3
Analysis 3
Temperature sampling 4
Habitat selection 4
RESULTS 5
DISCUSSION 6
Spatial range 7
Lower temperature extent 7
Habitat selection 7
Management implications 7
Future research 8
ACKNOWLEDGEMENTS 8
REFERENCES 9

EXECUTIVE SUMMARY

Two species of pilot whales inhabit the western North Atlantic Ocean: short-finned pilot whales, *Globicephala macrorhynchus*; and long-finned pilot whales, *G. melas*. The two species are morphologically similar and difficult to differentiate in the field, so the National Marine Fisheries Service (NMFS) uses an algorithm based on sea surface temperature (SST) and water depth to determine species identity for stock assessment surveys and fishery bycatch records. NMFS assumes that short-finned pilot whales are found in waters warmer than 22°C, while long-finned pilot whales are typically found in waters colder than 25°C, with an overlap between the two species in waters from 22°C to 25°C. This area of overlap occurs primarily between latitudes 38°N and 40°N during summer months.

My analysis used satellite telemetry data from short-finned pilot whales to examine the thermal preferences of the species. In the area of overlap with long-finned pilot whales only 7.4% of the locations of tagged animals occurred in waters below 22°C, and my analysis demonstrated that SST is an important component of short-finned pilot whale habitat selection. Additionally, only a few animals moved north of the previously observed spatial extent of the range of the species in the western North Atlantic. Individual animals traveled as far as 85 km in a day, indicating that short-finned pilot whales have the potential to cover considerable distances in a short time period.

My results will inform future pilot whale stock assessments in the western North Atlantic Ocean and assist in determining species identity of Atlantic pelagic longline fishery bycatch records. Accurate estimates of abundance and identification of bycatch events are of particular importance for short-finned pilot whales as bycatch levels exceed Potential Biological Removal, a biological reference point that indicates the number of animals that can be removed from a stock without it falling below the optimum sustainable level.

Additionally, my results can assist managers in further defining areas where short-finned pilot whales are likely present and provide a baseline for assessing potential range shifts in the western North Atlantic Ocean. Understanding current and future ranges will aid in management of the Atlantic pelagic longline fishery to minimize interactions with pilot whales.

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INTRODUCTION

Due to habitat overlap and morphological similarity, it is difficult to differentiate between long-finned and short-finned pilot whales in the field (NOAA Fisheries 2017). A method for photo-based identification has been established by Rone and Pace (2012), although this method does not allow for immediate identification at sea and high-quality photographs are necessary for the analysis. Instead, data reported during visual surveys (vessel-based and aerial) and by fishery observers typically only identify the whales to the genus level, *Globicephala* sp. (NOAA Fisheries 2017). To determine species identity, the National Marine Fisheries Service (NMFS) uses a model based on sea surface temperature (SST) and water depth (Garrison and Rosel 2017, NOAA Fisheries 2017). This model indicates that short-finned pilot whales are more likely to occur in warmer, deeper water than long-finned pilot whales (NOAA Fisheries 2017). Garrison and Rosel (2017) suggest that time of year is also an important distinguishing factor, however time of year is not currently used in the model (NOAA Fisheries 2017).

The two species overlap between ~35°N and ~40°N (Payne and Heinemann 1993, Garrison and Rosel 2017) and specifically between 38°N and 40°N during the warmer months of the year (Garrison and Stokes 2016). However, estimates of the degree of overlap vary (NOAA Fisheries 2017), and the exact overlap between the two species is still unclear. The NMFS model uses mtDNA sequences conducted on biopsy samples to determine species identity (Garrison and Rosel 2017, NOAA Fisheries 2017). This research indicates an area of overlap between the two species in waters with SSTs between 22°C and 25°C (NOAA Fisheries 2017), although Garrison and Rosel (2017) observed overlap in waters as cold as 20°C (Garrison and Rosel 2017).

Short-finned pilot whales are the marine mammal species taken most frequently in the Atlantic pelagic longline fishery (National Marine Fisheries Service 2016, Garrison and Rosel 2017). Management measures to "reduce serious injury and mortalities of pilot whales and Risso's dolphins"(US OFR 2009) in the fishery were finalized in the Atlantic Pelagic Longline Take Reduction Plan (PLTRP), implemented June 18, 2009. The management measures in the PLTRP, produced by the Atlantic Pelagic Longline Take Reduction Team, are intended to reduce the serious injury and mortality of these populations to "insignificant levels approaching a zero mortality and injury rate within five years of implementation" (16 USC 1387) as required by the Marine Mammal Protection Act. Insignificant levels are defined as "less than 10% of the PBR [(Potential Biological Removal)]"(US OFR 2004). Despite implementation of the PLTRP in 2009, short-finned pilot whale mortality exceeds the PBR of 159 animals (NOAA Fisheries 2017, Hayes et al. 2018).

Previous studies have called for additional analyses of the relationship between pilot whale occurrence and oceanographic variables, such as SST, to help management efforts in the Atlantic pelagic longline fishery (Stepanuk et al. 2018). In the present study, I attempt to understand the influence of sea surface temperature on short-finned pilot whale habitat selection in the western North Atlantic Ocean. This study has the potential to inform future stock assessments, Atlantic pelagic longline fishery management, fishery bycatch records, and future short-finned pilot whale habitat selection as these waters warm.

METHODS

Study area

The northern extent of the range of *G. macrorhynchus* is approximately 40°N in the western North Atlantic Ocean (Payne and Heinemann 1993, Garrison and Stokes 2016, Garrison and Rosel 2017). The study area (Figure 1) includes the area within 38°N to 42°N, and -61°W to -74°W.

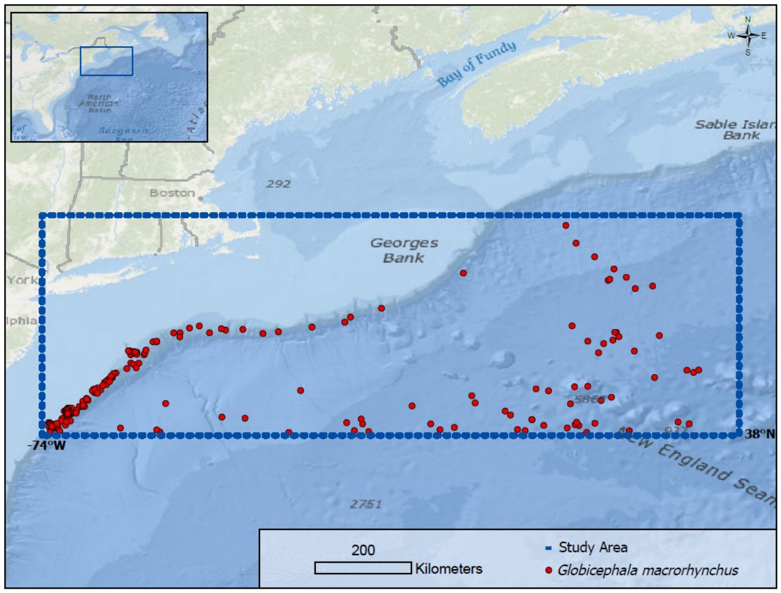

Figure 1: The study area, outlined in blue, includes 38°N to 42°N, and -61°W to -74°W. Red points indicate locations of tagged short-finned pilot whales.

Field methods

Satellite tags were deployed on 62 short-finned pilot whales off Cape Hatteras, North Carolina from 2014 to 2018 following methods described in Thorne et al. (2017). Most of the animals were tagged during the late spring (May) and summer, however, a few animals were tagged later in the year.

Analysis

Telemetry data were first filtered using a Douglas Filter, as described in Thorne et al. (2017) and then filtered to remove locations outside of the study area. I sorted these data by Location Class and further filtered the data to include only the first location per animal, per day of the best quality. After this series of filtering steps, 264 locations from 22 of the 62 animals tagged off Cape Hatteras remained in the data set.

I downloaded MODIS Level-3 sea surface temperature data for the study area from the Aqua satellite at a 4km spatial resolution from May 2014 to June 2018. The Aqua satellite provides the best SST data for the Northwest Atlantic Ocean (Feng and Hu 2016). I used the "Create Rasters for PO.DAAC MODIS L3SST" tool in the NASA JPL PO.DAAC, MODIS Global Level 3 Mapped SST tool within ArcMap's Marine Geospatial Ecology Toolbox. The tool automatically masks cloud coverage and was set to temporally aggregate the data to an 8-day composite.

Temperature sampling

I sampled each pilot whale location in the study area for SST from the 8-day composite rasters. If SST data was filtered as cloud coverage from any cells directly next to the cell overlapping with the sample location, the values were excluded. One location, with a sampled SST of 14.68°C, was removed from the analysis as seven of eight surrounding cells had been filtered out as cloud coverage. I filtered locations with SSTs below the 22°C threshold believed to be the lower SST for short-finned pilot whales and calculated the proportion of the total number of locations with SST values below that threshold.

Habitat selection

I then filtered the locations within the study area to select those from tagged whales that occurred over two consecutive days (Figure 2). I considered the distance between each set of two consecutive points as "one day of travel." I created a "one day of travel" buffer around each initial location and sampled sea surface temperature on 10 randomly selected buffer vertices (considered to be potential second-day locations) for each initial location (Figure 2). Finally, I compared SSTs of the potential locations to the realized SST for each second day. Locations with no SST data were excluded from the analysis; however, locations were not excluded if SST data was filtered as cloud coverage from cells directly next to the cell overlapping with the sample location.

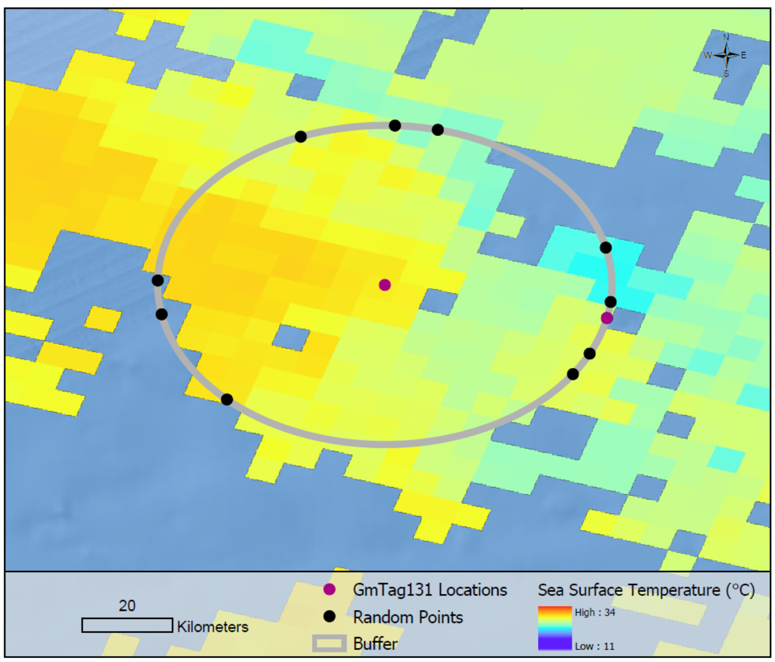

Figure 2: Habitat selection methodology. The purple point in the center of the buffer perimeter (grey circle) denotes an initial location (day 1) for GmTag131. The purple point on the buffer perimeter indicates the realized location (day 2). The distance between "day 1" and "day 2" was considered "one day of travel." Black points indicate potential locations sampled.

I binned the potential locations into 2°C bins based on SST and ran a chi-squared test to determine whether the distribution of realized locations differed from the potential locations. Finally, I calculated the average distance traveled per day for each animal.

RESULTS

The animals included in the analysis traveled as far north as 41.9°N. The mean daily distance traveled varied greatly among individuals, with the highest mean of 85 km per day, and the shortest mean of 8 km per day. Mean distances traveled by each animal are included in Table 1.

Table 1: Daily distances traveled by each animal. Data for GmTag122 and GmTag201 only included two consecutive days, or one day of travel, as noted in the Frequency column. Daily distances traveled were only calculated for animals with locations reported over consecutive days.

Tag Number	Mean (km)	Minimum (km)	Max (km)	Range (km)	Standard Deviation (km)	Median (km)	Variance (km)	Frequency
GmTag87	55.95	7.20	125.42	118.22	44.78	53.60	2005297.11	10
GmTag88	38.19	9.99	85.70	75.71	32.87	21.60	1080482.06	7
GmTag90	50.82	47.60	54.05	6.45	4.56	50.82	20806.23	2
GmTag94	31.53	7.79	70.58	62.79	21.73	27.84	472282.84	6
GmTag95	19.89	4.34	35.55	31.21	13.08	19.83	171029.05	4
GmTag122	20.41	20.41	20.41	0.00	0.00	20.41	0.00	1
GmTag126	33.33	5.50	67.21	61.71	16.29	36.73	265285.59	11
GmTag130	8.03	0.51	41.11	40.60	11.10	3.58	123237.09	46
GmTag131	61.21	0.80	180.50	179.70	47.70	42.34	2275606.44	22
GmTag139	85.08	35.48	118.31	82.84	33.37	94.09	1113677.78	5
GmTag157	21.85	0.87	75.70	74.82	26.62	6.04	708861.82	16
GmTag160	46.14	9.63	90.15	80.51	40.78	38.63	1662917.48	3
GmTag201	16.66	16.66	16.66	0.00	0.00	16.66	0.00	1
GmTag206	36.73	23.99	49.47	25.48	18.02	36.73	324664.70	2

Seven of the 22 animals entered waters below 22°C in a total of 16 days, or 7.4% of days sampled. Table 2 includes all sampled SSTs below 22°C. The coldest sampled SST was 18.06°C from GmTag87 (other than the point that was determined to be cloud coverage that passed through the filter). GmTag126, GmTag139 and GmTag157, were found in water below 22°C most frequently.

Table 2: Locations initially sampled with SSTs below 22℃. Some of these locations did not occur at times when data was available over two consecutive days, therefore they were not sampled in the habitat selection portion of the analysis.

Tag Number	Date	Longitude (°W)	Latitude (°N)	SST (°C)
GmTag87	11/8/2014	-72.97907	38.73482	18.06
GmTag87	10/14/2014	-67.67756	40.31937	18.46
GmTag126	6/17/2015	-72.72415	39.05546	20.57
GmTag126	6/15/2015	-72.67744	39.10274	20.58
GmTag126	6/14/2015	-72.91741	38.79873	21.20
GmTag126	6/16/2015	-73.01133	38.81554	21.23
GmTag126	6/23/2015	-72.07243	39.54154	21.44
GmTag126	6/26/2015	-72.30532	39.50477	21.76
GmTag137	10/27/2015	-73.79168	38.10991	21.07
GmTag138	11/14/2015	-73.83794	38.06999	21.17
GmTag139	11/10/2015	-62.14399	38.19999	21.51
GmTag139	10/27/2015	-73.68219	38.03581	21.56
GmTag139	10/26/2015	-72.54800	38.08700	21.76
GmTag157	10/4/2016	-72.70023	39.05285	20.74
GmTag157	7/2/2016	-73.88870	38.18836	20.89
GmTag157	9/30/2016	-72.63168	39.11487	21.82

Tagged pilot whales selected SSTs that deviated significantly from those available to the animals (Chi-square test, $p = 0.0004$, 2°C bins). The animals avoided the coldest temperatures and demonstrated a slight preference against the warmest temperatures (Figure 3, Figure 4). Due to the limited sample, it was not possible to examine temperature selection for individual whales.

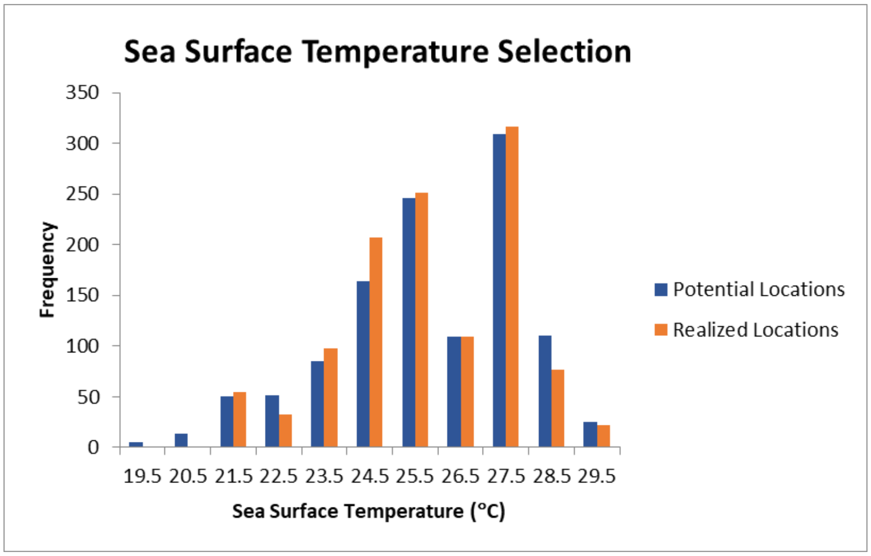

Figure 3: Frequency of available temperatures compared to the frequency of selected temperatures for all animals. The Chi-square test was run with data binned in 2°C bins.

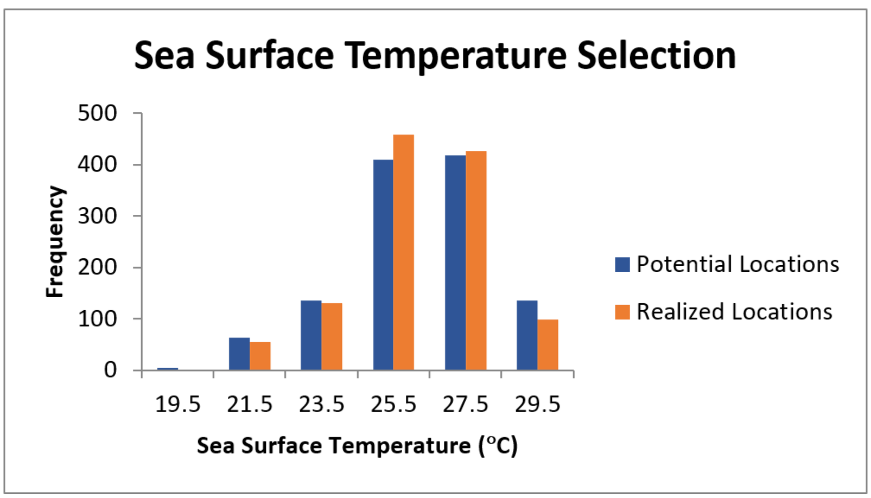

Figure 4: Frequency of available temperatures compared to the frequency of selected temperatures for all animals.

DISCUSSION

This analysis demonstrates that SST is an important determining factor of short-finned pilot whale habitat selection and is a good indicator of the species' presence within its range in the western North Atlantic Ocean. The animals avoided the coldest temperatures and showed a slight preference against the warmest temperatures, although they did not exclude the warmest temperatures entirely. The animals moved as far north as 41.9°N with some individuals traveling distances greater than 50 km per day. These findings support the use of parameters defined in the

NMFS model to distinguish between short-finned and long-finned pilot whales (Garrison and Stokes 2016, Garrison and Rosel 2017).

Spatial range

A few short-finned pilot whales moved north of the previously observed spatial boundary, but most of the sampled locations were within the current habitat, as defined by Garrison and Rosel (2017). These authors state that from May to November the "transition" area between short-finned and long-finned pilot whales is 39°N to 41°N. The points included in the present analysis fall primarily in that range, but one tagged animal moved as far north as 41.9°N. All locations of tagged whales north of 41°N were recorded in August, which is within the period when short-finned pilot whale ranges typically extend farther north (Garrison and Rosel 2017).

The mean distance traveled each day varied greatly by animal. The three greatest mean distances traveled per day were 85 km, 61 km, and 56 km, indicating that short-finned pilot whales have the potential to cover a wide range over a short time period. Previous studies report travel rates and high mobility but do not report mean distances traveled per day by individual animals (Wells et al. 2013, Thorne et al. 2017, Alves et al. 2019).

Lower temperature extent

The NOAA stock assessments for pilot whales indicate an area of overlap between the two species in waters with SSTs between 22°C and 25°C (NOAA Fisheries 2017). The SSTs of short-finned pilot whale locations in the present analysis fall mostly within that range. However, 16 of 214 locations of tagged whales were in waters below 22°C. These results align more closely with recent observations by Garrison and Rosel (2017) in which short-finned pilot whales were present in waters as cold as 20°C (Garrison and Rosel 2017). In the present study, two locations were below 20°C. However, there is potential for error with both the telemetry (Douglas et al. 2012) and SST data (Feng and Hu 2016).

Habitat selection

The SSTs selected by the short-finned pilot whales deviated significantly from the temperatures available to the animals, suggesting that SST is an important component of short-finned pilot whale habitat selection. The coldest temperature available to the animals in this part of the analysis was 18°C. The animals avoided the coldest temperatures available (Figure 3), as expected based on previous studies (Garrison and Rosel 2017). The animals also showed a slight preference against the warmest waters available, although some animals did select those temperatures (Figure 3).

Management implications

The findings of my study support recent analysis by NMFS scientists (Garrison and Rosel 2017), but it is important to note that minor differences in the SST preferences of short-finned and long-finned pilot whales could have important implications in the use of models used to distinguish between the two species in abundance surveys and observations of fishery bycatch (Garrison and Stokes 2016, Garrison and Rosel 2017).

Accurate estimates of abundance and identification of bycatch events are of particular importance for short-finned pilot whales, as the western North Atlantic stock of this species is considered strategic (Hayes et al. 2018) due to bycatch levels that exceed the PBR (16 U.S.C. 1362 , NOAA Fisheries 2017, Hayes et al. 2018). This stock frequently interacts with the Atlantic pelagic longline fishery (Garrison and Rosel 2017) and its distribution overlaps with the fishery (Garrison and Rosel 2017, Stepanuk et al. 2018). Efforts to minimize interactions and reduce the mortality and serious injury of short-finned pilot whales in this fishery are outlined in the Atlantic Pelagic Longline Take Reduction Plan (50 CFR 229.36) and subsequent recommendations by the take reduction team (National Marine Fisheries Service 2016).

The temperature preferences observed in this study can assist in minimizing interactions by further defining areas where short-finned pilot whales are likely to be present. Increased understanding of the influence of SST and other oceanographic variables on pilot whale habitat selection will increase the accuracy of models to differentiate between the two species, as well as the potential for real-time modeling of pilot whale abundance. These abundance estimates would allow for real-time management of the Atlantic pelagic longline fleet, similar to dynamic management efforts underway in other regions (Hobday et al. 2011, Howell et al. 2015, Hazen et al. 2017). Dynamic management would be particularly useful as, like many species, the western North Atlantic stock of short-finned pilot whales are expected to shift ranges as North Atlantic waters warm (MacLeod 2009). SST will be an important component in predicting future ranges as they shift.

Future research

Future analyses examining the effects of SST on short-finned pilot whale habitat selection should consider other habitat components such as water depth, sea surface height, and bathymetric features commonly used in cetacean habitat analyses (Redfern et al. 2006, Thorne et al. 2017, Becker et al. 2019) to fully understand the driving factors of habitat selection and how these may change as pilot whale ranges shift. For example, it is important to understand whether SST is the driving factor in habitat selection, or if SST appears to be the driving factor due to some other association, such as prey availability.

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