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Spatial Use of Cuvier's Beaked Whales and Short-finned Pilot Whales Satellite Tagged off Cape Hatteras, North Carolina: 2018 Annual Progress Report



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Cuvier's beaked whale (*Ziphius cavirostris*) off Cape Hatteras. Photographed by Andrew J. Read, Duke University, taken under NOAA Scientific Permit No. 14809 (Douglas Nowacek) and NOAA General Authorization Letter of Confirmation 19903 held by Duke University.

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Table of Contents

Acronyms and Abbreviations	v
1. Introduction.....	1
2. Methods.....	1
3. Results.....	3
4. Discussion	5
5. Acknowledgments	6
6. Literature Cited	6

Appendices

Appendix A.

Figures

- FIGURE 1. ALL FILTERED LOCATIONS OF CUVIER'S BEAKED WHALE ZCTAG069 OVER THE 38.9-DAY TAG-ATTACHMENT DURATION, 24 MAY – 2 JULY 2018.
- FIGURE 2. ALL FILTERED LOCATIONS OF CUVIER'S BEAKED WHALE ZCTAG070 OVER THE 12.5-DAY TAG-ATTACHMENT DURATION, 25 MAY–6 JUNE 2018.
- FIGURE 3. ALL FILTERED LOCATIONS OF CUVIER'S BEAKED WHALE ZCTAG071 OVER THE 34.3-DAY TAG-ATTACHMENT DURATION, 5 AUGUST–8 SEPTEMBER 2018.
- FIGURE 4. ALL FILTERED LOCATIONS OF CUVIER'S BEAKED WHALE ZCTAG072 OVER THE 42.9-DAY TAG-ATTACHMENT DURATION, 5 AUGUST–17 SEPTEMBER 2018.
- FIGURE 5. ALL FILTERED LOCATIONS OF CUVIER'S BEAKED WHALE ZCTAG073 OVER THE 43.6-DAY TAG-ATTACHMENT DURATION, 5 AUGUST–18 SEPTEMBER 2018.
- FIGURE 6. ALL FILTERED LOCATIONS OF CUVIER'S BEAKED WHALE ZCTAG075 OVER THE 41.4-DAY TAG-ATTACHMENT DURATION, 8 AUGUST–16 SEPTEMBER 2018.
- FIGURE 7. ALL FILTERED LOCATIONS OF CUVIER'S BEAKED WHALE ZCTAG076 OVER THE 44.4-DAY TAG-ATTACHMENT DURATION, FROM 6 AUGUST–17 SEPTEMBER 2018.
- FIGURE 8. ALL FILTERED LOCATIONS OF A CUVIER'S BEAKED WHALE ZCTAG077 OVER THE 23.7-DAY TAG-ATTACHMENT DURATION, 6-30 AUGUST 2018.
- FIGURE 9. ALL FILTERED LOCATIONS OF CUVIER'S BEAKED WHALE ZCTAG078 OVER THE 23.2-DAY TAG-ATTACHMENT DURATION, 6-29 AUGUST 2018.
- FIGURE 10. ALL FILTERED LOCATIONS OF CUVIER'S BEAKED WHALE ZCTAG079 OVER THE 43.3-DAY TAG-ATTACHMENT DURATION, 7 AUGUST–19 SEPTEMBER 2018.
- FIGURE 11. ALL FILTERED LOCATIONS OF CUVIER'S BEAKED WHALE ZCTG080 OVER THE 12.8-DAY TAG-ATTACHMENT DURATION, 7 AUGUST–20 SEPTEMBER 2018.
- FIGURE 12. ALL FILTERED LOCATIONS OF CUVIER'S BEAKED WHALE ZCTAG081 OVER THE 57.2-DAY TAG-ATTACHMENT DURATION, 7 AUGUST–3 OCTOBER 2018.
- FIGURE 13. ALL FILTERED LOCATIONS OF CUVIER'S BEAKED WHALES TAGGED IN 2018 ($N=12$), WITH CONSECUTIVE LOCATIONS JOINED BY A LINE.

FIGURE 14. ALL FILTERED LOCATIONS OF CUVIER'S BEAKED WHALES TAGGED IN 2014 ($N=3$), 2015 ($N=6$), 2016 ($N=6$), 2017 ($N=14$), AND 2018 ($N=12$).

FIGURE 15. A PROBABILITY-DENSITY REPRESENTATION OF CUVIER'S BEAKED WHALE LOCATION DATA, USING ONLY A SINGLE INDIVIDUAL FROM EACH PAIR WHERE INDIVIDUALS WERE ACTING IN CONCERT.

FIGURE 16. ALL FILTERED LOCATIONS OF SHORT-FINNED PILOT WHALE GMTAG197 TAGGED OFF NORTH CAROLINA OVER A 27.0-DAY PERIOD, 11 MAY–7 JUNE 2018.

FIGURE 17. ALL FILTERED LOCATIONS OF SHORT-FINNED PILOT WHALE GMTAG198 TAGGED OFF NORTH CAROLINA OVER A 19.5-DAY PERIOD, 22 MAY–10 JUNE 017.

FIGURE 18. ALL FILTERED LOCATIONS OF SHORT-FINNED PILOT WHALE GMTAG199 TAGGED OFF NORTH CAROLINA OVER A 7.6-DAY PERIOD, 24–31 MAY 2018.

FIGURE 19. ALL FILTERED LOCATIONS OF SHORT-FINNED PILOT WHALE GMTAG200 TAGGED OFF NORTH CAROLINA OVER A 11.3-DAY PERIOD, 24 MAY–4 JUNE 2018.

FIGURE 20. ALL FILTERED LOCATIONS OF SHORT-FINNED PILOT WHALE GMTAG201 TAGGED OFF NORTH CAROLINA OVER A 27.5-DAY PERIOD, 30 MAY–26 JUNE 2018.

FIGURE 21. ALL FILTERED LOCATIONS OF SHORT-FINNED PILOT WHALE GMTAG202 TAGGED OFF NORTH CAROLINA OVER A 25.6-DAY PERIOD, 30 MAY–25 JUNE 2017.

FIGURE 22. ALL FILTERED LOCATIONS OF SHORT-FINNED PILOT WHALE GMTAG203 TAGGED OFF NORTH CAROLINA OVER A 17.4-DAY PERIOD, 31 MAY–17 JUNE 2018.

FIGURE 23. ALL FILTERED LOCATIONS OF SHORT-FINNED PILOT WHALE GMTAG204 TAGGED OFF NORTH CAROLINA OVER A 30.2-DAY PERIOD, 31 MAY–30 JUNE 2017.

FIGURE 24. ALL FILTERED LOCATIONS OF SHORT-FINNED PILOT WHALE GMTAG205 TAGGED OFF NORTH CAROLINA OVER A 27.3-DAY PERIOD, 31 MAY–27 JUNE 2018.

FIGURE 25. ALL FILTERED LOCATIONS OF SHORT-FINNED PILOT WHALE GMTAG206 TAGGED OFF NORTH CAROLINA OVER A 31.6-DAY PERIOD, 31 MAY–1 JULY 2018.

FIGURE 26. ALL FILTERED LOCATIONS OF SHORT-FINNED PILOT WHALE GMTAG207 TAGGED OFF NORTH CAROLINA OVER A 10.2-DAY PERIOD, 5-15 AUGUST 2018.

FIGURE 27. ALL FILTERED LOCATIONS OF SHORT-FINNED PILOT WHALE GMTAG208 TAGGED OFF NORTH CAROLINA OVER A 10.5-DAY PERIOD, 5–15 AUGUST 2018.

FIGURE 28. ALL FILTERED LOCATIONS OF SHORT-FINNED PILOT WHALE GMTAG210 TAGGED OFF NORTH CAROLINA OVER A 20.5-DAY PERIOD, 6–26 AUGUST 2018.

FIGURE 29. ALL FILTERED LOCATIONS OF SHORT-FINNED PILOT WHALE GMTAG211 TAGGED OFF NORTH CAROLINA OVER A 18.0-DAY PERIOD, 6–24 AUGUST 2018.

FIGURE 30. ALL FILTERED LOCATIONS OF SHORT-FINNED PILOT WHALE GMTAG216 TAGGED OFF NORTH CAROLINA OVER A 13.0-DAY PERIOD, 26 AUGUST–8 SEPTEMBER 2018.

FIGURE 31. ALL FILTERED LOCATIONS OF SHORT-FINNED PILOT WHALE GMTAG217 TAGGED OFF NORTH CAROLINA OVER A 27.5-DAY PERIOD, 26 AUGUST–22 SEPTEMBER 2018.

FIGURE 32. ALL FILTERED LOCATIONS OF SHORT-FINNED PILOT WHALE GMTAG218 TAGGED OFF NORTH CAROLINA OVER A 21.7-DAY PERIOD, 26 AUGUST–17 SEPTEMBER 2017.

FIGURE 33. ALL FILTERED LOCATIONS OF SHORT-FINNED PILOT WHALES TAGGED OFF NORTH CAROLINA IN 2018.

FIGURE 34. ALL FILTERED LOCATIONS OF SHORT-FINNED PILOT WHALES TAGGED OFF NORTH CAROLINA IN 2014 ($N=17$), 2015 ($N=19$), 2016 ($N=9$), 2017 ($N=11$), AND 2018 ($N=17$), AND OFF JACKSONVILLE, FLORIDA, IN 2016 ($N=4$).

FIGURE 35. A PROBABILITY-DENSITY REPRESENTATION OF SHORT-FINNED PILOT WHALE LOCATION DATA, INCLUDING INDIVIDUALS TAGGED OFF NORTH CAROLINA IN 2014 ($N=14$), 2015 ($N=17$), 2016 ($N=5$), 2017 ($N=9$) AND 2018 ($N=15$), AS WELL AS JACKSONVILLE, FLORIDA, IN 2016 ($N=2$).

Tables

- TABLE 1. SUMMARY DETAILS OF SATELLITE TAG DEPLOYMENTS ON CUVIER'S BEAKED WHALES OFF CAPE HATTERAS, NORTH CAROLINA, DURING 2018
- TABLE 2. SUMMARY DETAILS OF SATELLITE TAG DEPLOYMENT ON SHORT-FINNED PILOT WHALES OFF CAPE HATTERAS, NORTH CAROLINA, DURING 2018
- TABLE 3. DISTANCES BETWEEN PAIRS OF CUVIER'S BEAKED WHALES WITH TEMPORALLY OVERLAPPING TAG DATA. DISTANCES ARE CALCULATED WHEN LOCATIONS ARE RECEIVED DURING THE SAME SATELLITE OVERPASS. LIST IS ORDERED BASED ON THE TIMING OF TAGGING FOR COMPARISON PURPOSES.
- TABLE 4. DISTANCES BETWEEN PAIRS OF SHORT-FINNED PILOT WHALES WITH TEMPORALLY OVERLAPPING TAG DATA. DISTANCES ARE CALCULATED WHEN LOCATIONS ARE RECEIVED DURING THE SAME SATELLITE OVERPASS.
- TABLE 5. CHARACTERISTICS OF MOVEMENTS IN RELATION TO TAGGING DISTANCE FOR SATELLITE-TAGGED CUVIER'S BEAKED WHALES TAGGED OFF NORTH CAROLINA IN 2018
- TABLE 6. CHARACTERISTICS OF MOVEMENTS IN RELATION TO TAGGING DISTANCE FOR SATELLITE-TAGGED SHORT-FINNED PILOT WHALES TAGGED OFF NORTH CAROLINA IN 2018
- TABLE 7. DEPTHS AND DISTANCES FROM SHORE AND THE 200-M ISOBATH FROM GIS ANALYSIS OF FILTERED SATELLITE-TAG LOCATIONS FROM CUVIER'S BEAKED WHALES TAGGED IN 2018
- TABLE 8. DEPTHS AND DISTANCES FROM SHORE AND THE 200-M ISOBATH FROM GIS ANALYSIS OF FILTERED SATELLITE-TAG LOCATIONS FROM SHORT-FINNED PILOT WHALES TAGGED IN 2018
- TABLE 9. SUMMARY OF BEHAVIOR DATA FROM LOCATION-DEPTH TAGS WITH ONE DAY OR MORE OF DIVE DATA PRIOR TO CONTROLLED EXPOSURE EXPERIMENTS (CEE) OR TO TRANSDUCER FAILURE. TAGS COLLECTING ONLY A TIME SERIES OF DIVE DEPTHS ARE NOT INCLUDED. FOR SHORT-FINNED PILOT WHALES, DIVES THAT EXCEEDED 75 M AND 30 SEC WERE RECORDED, WHILE FOR CUVIER'S BEAKED WHALES DIVES THAT EXCEEDED 50 M AND 33 MIN WERE RECORDED.

Acronyms and Abbreviations

BRS	Behavioral Response Study
CEE	controlled exposure experiment
CRC	Cascadia Research Collective
km	kilometer(s)
km ²	square kilometer(s)
LIMPET	Low-Impact Minimally Percutaneous External-electronics Transmitter
m	meter(s)
min	minute(s)
photo-ID	photo-identification
sec	second(s)
U.S.	United States

1. Introduction

In 2014 a collaborative study between Cascadia Research Collective (CRC) and Duke University was initiated off the coast of Cape Hatteras, North Carolina, to examine the spatial use and diving behavior of multiple odontocete species using remotely deployed Low-Impact Minimally Percutaneous External-electronics Transmitter (LIMPET) satellite tags. This work builds upon and complements longer-term studies of movements and site fidelity of both Cuvier's beaked whales (*Ziphius cavirostris*) and short-finned pilot whales (*Globicephala macrorhynchus*) off the North Carolina coast using photo-identification (photo-ID) ([Swaim et al. 2014](#), [Foley et al. 2015](#), [2016](#), [2017](#)). While the primary focus has been on Cuvier's beaked whales and short-finned pilot whales, in the first three years a number of other species were tagged as well. From 2014 through 2017, satellite-tag data were obtained from 96 individuals of seven species: 29 Cuvier's beaked whales, 52 short-finned pilot whales, 10 common bottlenose dolphins (*Tursiops truncatus*), 2 common dolphins (*Delphinus delphis*), 1 Risso's dolphin (*Grampus griseus*), 1 Clymene dolphin (*Stenella clymene*), and 1 sperm whale (*Physeter macrocephalus*), ranging over periods from 1.3 to 354 days ([Baird et al. 2015](#), [2016](#), [2017](#), [2018](#); [Thorne et al. 2017](#); Stepanuk et al. 2018).

In May and August 2018, additional field efforts were undertaken focusing on Cuvier's beaked whales and short-finned pilot whales as part of the Atlantic Behavioral Response Study (BRS), a collaborative effort between Duke University, Southall Environmental Associates, the University of St. Andrews, and CRC. Satellite tags were deployed on both Cuvier's beaked whales and short-finned pilot whales in each of the periods, prior to scheduled controlled-exposure experiments (CEEs). Given the CEEs and their potential influence on fine-scale movements and diving behavior, this report summarizes results from satellite tagging, focusing on large-scale spatial use by tagged individuals as well as diving behavior prior to the CEEs. Detailed analyses of fine-scale movements and diving behavior in relation to the CEEs can be found in [Southall et al. \(2019\)](#).

2. Methods

During the 2018 field efforts, the primary tags used were location and depth SPLASH10 tags (produced by Wildlife Computers, Redmond, Washington) with the extended-depth-range option, in the LIMPET configuration (Andrews et al. 2008). A small number of SPLASH10-F tags were also used to provide Fastloc-GPS locations instead of, or in addition to, dive data. Tags deployed on both species were set to transmit every day, 21 hours per day for Cuvier's beaked whales and 17 hours per day for short-finned pilot whales. Prior to each field effort, satellite pass predictions were executed using the Argos website to determine the best hours of the day for transmissions given satellite overpasses for the approximate 2-month period starting at the beginning of each deployment period.

For short-finned pilot whales, SPLASH10 tags were programmed to provide dive statistics (e.g., start and end time, maximum depth, and duration) in "behavior" files for any dives that exceeded 75 meters (m) and 30 seconds (sec). SPLASH10-F tags deployed on short-finned pilot whales were programmed to provide Fastloc-GPS locations and behavior data (three tags), or only

Fastloc-GPS locations (one tag). For those tags programmed to provide both Fastloc-GPS locations and behavior data, tags were set with Fastloc-GPS locations as highest priority and behavior (i.e., dive data) as lowest priority, with a two-day buffer. For Cuvier's beaked whales, SPLASH10 tags were programmed to provide dive statistics (three tags) for any dives that exceeded 50 m and 33 minutes (min), or time series (seven tags), with depth values recorded once every 5 min. During the May field effort, only a single time-series tag was deployed as a proof of concept, while during the August effort the majority of tags deployed on this species were programmed for time series, with a smaller number of tags recording dive statistics, as their theoretical maximum data-collection life is longer. This allowed for a balance of higher-resolution, shorter-term dive data with lower-resolution, longer-term data, to increase the probability of successfully collecting dive data before, during, and after exposures.

Tags were remotely deployed using a DAN-INJECT JM 25 pneumatic projector (DanWild LLC, Austin, Texas), and were attached with two 6.8-centimeter surgical-grade titanium darts with backward-facing petals. The target area for tag attachment was the dorsal fin or base of the fin. In some encounters, after deploying the first tag, an Argos Goniometer¹ (CLS America, Lanham, Maryland) was used to help re-locate the tagged individual, allowing us to deploy additional tags on other members of the group.

Photographs were taken of target and companion individuals prior to and at the time of tagging for contribution to the long-term Duke University photo-ID catalogs. Age class (i.e., adult, sub-adult) and sex were noted in the field based on body size and morphology, and photographs also were used to confirm sex for Cuvier's beaked whales based on the presence of erupted teeth and scarring patterns (McSweeney et al. 2007).

Locations of tagged individuals were estimated by the Argos system using the least-squares method and were assessed for plausibility using the Douglas Argos-filter version 8.5 to remove unrealistic locations, following protocols previously used (Schorr et al. 2009; Baird et al. 2010). Filtered location data were processed with R 3.2.2 (packages *sp* 1.2-2, *rgeos* 0.3-15, *raster* 2.5-2) to determine depth, distance from shore, and distance from the 200 m isobath. Depth values were generated from 3 arc-second data from the United States (U.S.) Coastal Relief Model for regions off the U.S. Atlantic coast ([NE Atlantic](#) and [SE Atlantic](#)) where available, and with 30 arc-second data from the General Bathymetric Chart of the Oceans 2014 (www.gebco.net/) in other areas. The 200m isobath dataset used was from the "Data Basin" on-line mapping tool (databasin.org). Given the inherent lack of precision associated with Argos-derived locations, combined with the steep continental shelf-edge and slope topography, we report median and maximum depths of tagged animal locations. Maximum depths are less likely to be influenced by Argos location quality or the steep slope given that the deepest locations of most tagged individuals were well seaward of the continental shelf (see **Section 3, Results**).

When more than one tag was deployed on the same species during the same time periods, we assessed whether individuals were acting in concert during the period of overlap by measuring the straight-line distances between pairs of individuals when locations were obtained during a single satellite overpass (approximately 10 min). We used both the mean distances between

¹<https://www.clsamerica.com/argos-goniometer>

pairs of individuals and the maximum distance between pairs to assess whether individuals were acting independently, following protocols described by [Schorr et al. \(2009\)](#) and [Baird et al. \(2010\)](#). For Cuvier's beaked whales, given the low quality of Argos locations received from this species, individuals were presumed to remain associated if the mean distance apart was less than 15 kilometers (km) and the maximum distance apart was less than 30 km. For short-finned pilot whales, since a greater proportion of high-quality Argos locations are obtained (cf. Costa et al. 2010), we used mean distances apart of 5 km as a cutoff for individuals remaining associated.

Probability-density maps were generated using all filtered satellite-tag data for individuals of each species excluding individuals thought to be acting in concert, with data from all five years (2014–2018) incorporated. Kernel-density polygons corresponding to the 50, 95, and 99 percent densities were generated using the R package *adehabitatHR* version 0.4.11². Bandwidth (h) values used were $h=37290$ for short-finned pilot whales and $h=10163$ for Cuvier's beaked whales. Polygons were plotted in Google Earth Pro version 7.3.2.5495.

To assess whether potential pressure transducer issues may have influenced dive depth recordings, we examined the status file from each tag deployment. The depth value noted in a status message represents the last value recorded immediately prior to the tag transmitting, so it is typically within 1 to 2 m of zero, although in extreme cases of linear drift, values within 10 m of zero have been observed and may be considered to be within an acceptable range (R.D. Andrews, Marine Ecology and Telemetry Research, pers. comm.). We considered cases where more than one value exceeded ± 10 m as indicative of potential transducer failure issues. It is not possible to determine whether such transducer issues reflect a simple baseline shift, which should be corrected with the zero offset correction feature of the tags, or represent a change in the linearity of depth readings and therefore prevent an accurate estimate of the actual dive depth. In addition, the manufacturer of the pressure transducers notes that the transducers may fail if subject to depths exceeding 3,000 m, so for any tags with depths approaching this we also assessed minimum rates of ascent and descent, by dividing twice the dive depth by the dive duration. Rates of descent and ascent for deep (>800 m) dives from time-depth recorder deployments on Cuvier's beaked whales are less than 2 m/sec and 1 m/sec, respectively (Baird et al. 2008), so we used an average of 2 m/sec as an indicator of pressure transducer issues.

Most of the tagged individuals were subjects of the controlled-exposure experiments (see [Southall et al. 2019](#)), and we only present dive data from behavior logs prior to CEEs. For those tags with potential pressure transducer issues, only dive data for the period prior to evidence of the potential issues are presented.

3. Results

Field efforts were undertaken for tagging in May and August 2018. Thirty-one tags were deployed (**Table 1, 2**)—13 on Cuvier's beaked whales and 18 on short-finned pilot whales. One tag on a Cuvier's beaked whale hit the leading edge of the fin with only a single dart (ZcTag074), and the tag fractured on impact, leaving a single dart in the fin. One tag on a short-

² <https://www.movebank.org/node/14620>

finned pilot whale (GmTag206) likely was removed by a conspecific shortly after deployment. Of the 12 remaining tags deployed on Cuvier's beaked whales, 11 were deployed in the dorsal fin or at the base of the dorsal fin, and one was deployed below the base of the fin. No dive data were obtained from this latter deployment (ZcTag071), likely due to the location of the tag influencing transmissions to the satellite. Tag transmitting durations for Cuvier's beaked whales for the 12 tags ranged from 12.5 to 57.3 days, with a median attachment duration of 41.6 days. One Fastloc-GPS tag was deployed on a Cuvier's beaked whale (ZcTag077). After filtering, there were 44 Argos locations and 179 Fastloc-GPS locations obtained from this deployment. No dive data were recorded by this tag. Of the 17 remaining tags deployed on short-finned pilot whales, all were deployed on the fin or at the base of the fin. Tags on short-finned pilot whales transmitted from 7.6 to 46.7 days, with a median of 21.7 days.

Tags were deployed on more than one individual in the same encounter on a number of different days (**Table 3, 4**). For Cuvier's beaked whales, distance between individuals for six dyads indicated that individuals may have remained associated or become associated for extended periods, although for one of the six only a single location was obtained overlapping on the same satellite overpass (**Table 3**) so these individuals were likely not associated. Of the remaining five dyads, four dyads were tagged on different dates (**Table 3**).

Movement patterns of the Cuvier's beaked whales varied, with 9 of the 12 individuals remaining within 100 km of the location where they were tagged (**Table 5**). Most of the tagged individuals remained largely on the continental slope (**Figures 1, 2, 3, 4, 8, 9, 10, 11, 12; Table 5**), with only occasional movements off the slope (e.g., **Figures 5, 6, 7**). Overall movements (**Figure 13**) were within the range of movements of animals tagged in previous years (**Figure 14**). A probability-density distribution from tag data obtained from all five years, accounting for pseudoreplication, suggests that the core range for individuals tagged off the coast of Cape Hatteras is relatively small (50 percent core area = 1,600 square kilometers [km²]; **Figure 15**).

Two tags (ZcTag072, ZcTag081, both programmed for time series) had pressure transducer issues partway through the deployments, and two more (ZcTag073, ZcTag079, also programmed for time series) had anomalies in the data stream. After excluding data subsequent to evidence of transducer failure, as well as periods post-CEEs, 42 days of behavior data were obtained from Cuvier's beaked whale tags, with approximately 100 percent coverage for both tags (**Table 9**). Maximum dive depths documented for both individual Cuvier's beaked whales prior to CEE exposure were 2,927.5 and 2,543.5 m, and maximum dive durations were 131.8 and 64.1 min, respectively (**Table 9**). Median depths at locations of these tagged individuals were 1,639.7 and 1,554.5 m, respectively (maximums of 2,815.8 and 2,349.7 m; **Table 6**), suggesting that many of the dives were likely to, or close to, the sea floor.

Eighteen satellite tags were deployed on short-finned pilot whales (**Table 2**) during 15 different encounters. In two of the three encounters where pairs were tagged the individuals acted independently, while in one of the three (GmTag206 and GmTag207) the individuals appeared to remain closely associated during the period of tag overlap (**Table 4**).

Mean and maximum distances moved varied considerably among individual short-finned pilot whales (**Table 6**), as did the typical depths used (**Table 8**), suggesting considerable variability in movement patterns and habitat use among short-finned pilot whale groups off the U.S. Atlantic

coast. Several individuals remained strongly associated with the shelf edge and shelf break over the entire duration of tag attachment (**Figures 16, 17, 20 through 27, 30, 31, 32**), while others had excursions off the shelf (GmTag199 and GmTag200, **Figures 18, 19**; GmTag210 and GmTag211, **Figures 28, 29**). The timing of movements of these individuals offshore appeared to be unrelated to the CEEs.

A map showing combined track and location data from all short-finned pilot whales tagged off the coast of North Carolina in 2014 ($n=17$), 2015 ($n=19$), 2016 ($n=5$), 2017 ($n=11$), and 2018 ($n=17$) as well as individuals tagged off Jacksonville, Florida, in 2016 ($n=4$) is shown in **Figure 34**. A probability density map incorporating all five years, but with only a single individual from each pair when individuals were acting in concert, shows that the core area for this population is small (19,668 km²) and centered off North Carolina and Virginia (**Figure 35**). The 99 percent probability density based on all five years covers a broad area (740,172 km²), ranging from Florida to New York and into Canadian and international waters. It should be noted that the 95 and 99 percent probability polygons include considerable areas not known to be habitat for short-finned pilot whales (i.e., shallow-water shelf and even some estuarine habitats). This inclusion of shallow shelf and estuarine habitats in the probability density maps is an artifact of the preference for this species to use the very steep slope waters adjacent to a broad shelf area along much of the eastern United States, combined with uncertainty associated with Argos locations and the bandwidth used in the probability density calculations.

4. Discussion

Efforts in 2018 have continued to build on what is known about the spatial use and behavior of Cuvier's beaked whales and short-finned pilot whales along the eastern coast of the United States, adding to work begun in 2014 ([Baird et al. 2015](#), [2016](#), [2017](#), [2018](#); [Shearer et al. 2019](#); [Stepanuk et al. 2018](#); [Thorne et al. 2017](#)). The combined efforts represent the first dedicated satellite tagging on free-ranging, medium-sized odontocetes off the U.S. Atlantic coast. Tag deployments have provided additional long-distance movement information for Cuvier's beaked whales off the U.S. Atlantic coast, as well as long-distance movements of short-finned pilot whales in the area, information that prior to 2014 had only been obtained from stranded and rehabilitated individuals released off Florida (Wells et al. 2013). Importantly, tag deployments of both species have also allowed for examining behavioral responses as part of the Atlantic BRS (Southall et al. 2019).

With data from 12 Cuvier's beaked whales satellite tagged in 2018, the sample size of movement data for this species off the U.S. Atlantic coast has increased by 41 percent, and the combined sample of location data now represents 1,596 days of locations, the largest collection of satellite-tag data for this species anywhere in the world. The large number of tags deployed in 2018 reflects in part the high density of Cuvier's beaked whales off Cape Hatteras ([McLellan et al. 2018](#)). The primary factor limiting an even greater number of tag deployments on Cuvier's beaked whales off Cape Hatteras is suitable sea conditions for finding, approaching, and tagging this species. All of the tagged Cuvier's beaked whales spent all or most of their time in or near the core area occupied by the animals tagged in previous years (**Figures 13, 14**), along the continental slope off Cape Hatteras, with only two (**Figures 1, 4**) moving to any degree along the shelf edge, further emphasizing the importance of the area to this species.

While the photo-ID work suggests that short-finned pilot whales display a high degree of site fidelity off Cape Hatteras, satellite tagging demonstrates that these animals can cover a significant range north and south along the continental slope, and occasionally into offshore waters (**Figure 34**). In 2018 four individuals were documented moving far offshore (**Figures 18, 19, 28, 29**), primarily using pelagic waters, although in all four cases the individuals returned (or were returning) to slope waters. The considerable variability in movement patterns and habitat use likely reflects patterns that vary by social group and by responses to ephemeral oceanographic conditions ([Thorne et al. 2017](#)). Understanding site fidelity and association patterns determined through photo-ID will help in interpreting such variability.

Even though short-finned pilot whales cover a much larger range, their core range (**Figure 35**) appears to be centered in the same area as Cuvier's beaked whales (**Figure 15**), although it is approximately 15 times larger than that of Cuvier's beaked whales. Although more study is necessary to determine the demographic structure and habitat use of these stocks, the importance of the continental slope to the east of Cape Hatteras (North Carolina) is becoming increasingly apparent as sample sizes increase.

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A

Figures



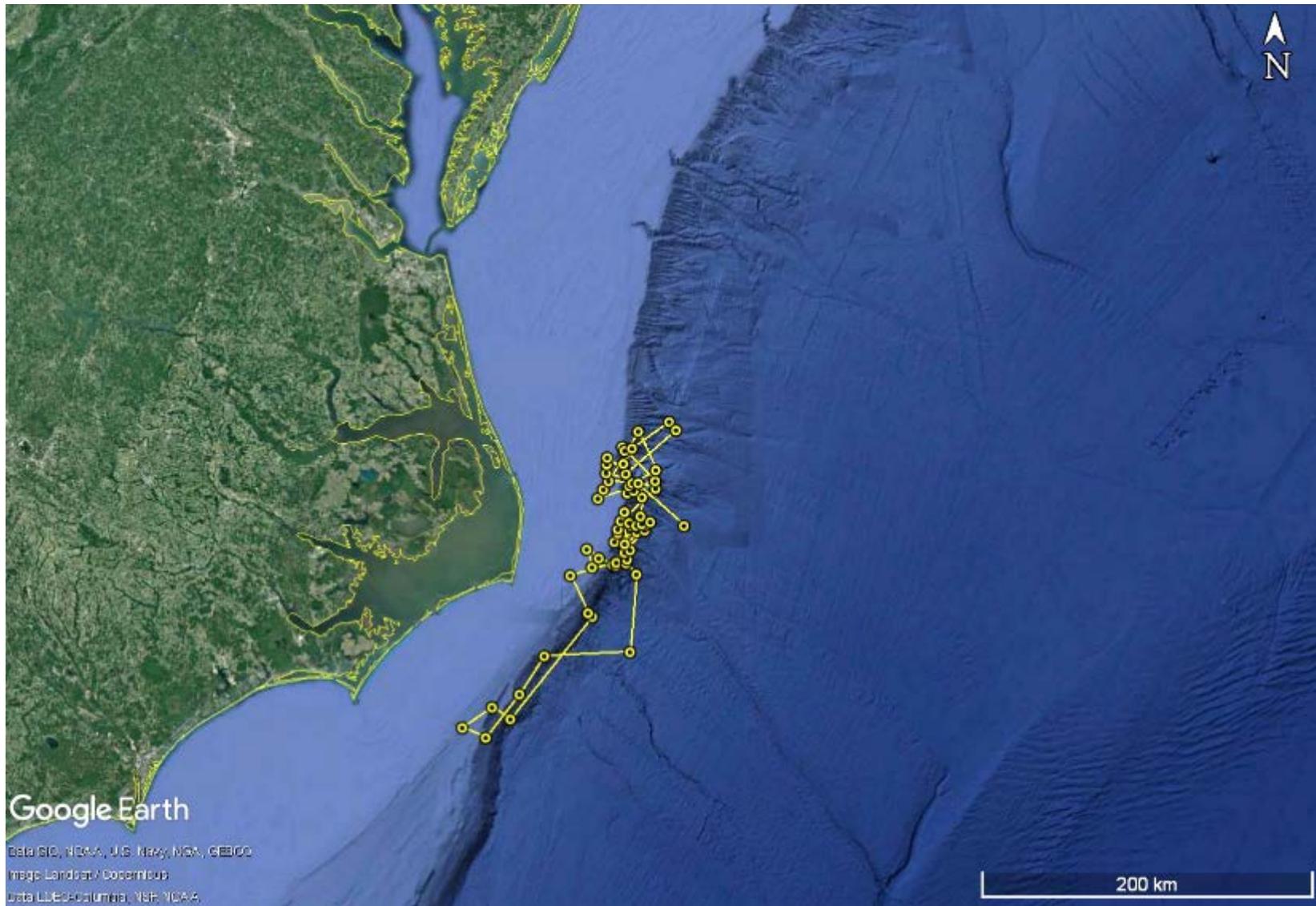


Figure 1. All filtered locations of Cuvier's beaked whale ZcTag069 over the 38.9-day tag-attachment duration, 24 May–2 July 2018, with consecutive locations joined by a line. This individual was one of the subjects of the controlled-exposure experiments.



Figure 2. All filtered locations of Cuvier's beaked whale ZcTag070 over the 12.5-day tag-attachment duration, 25 May–6 June 2018, with consecutive locations joined by a line. This individual was one of the subjects of the controlled-exposure experiments.

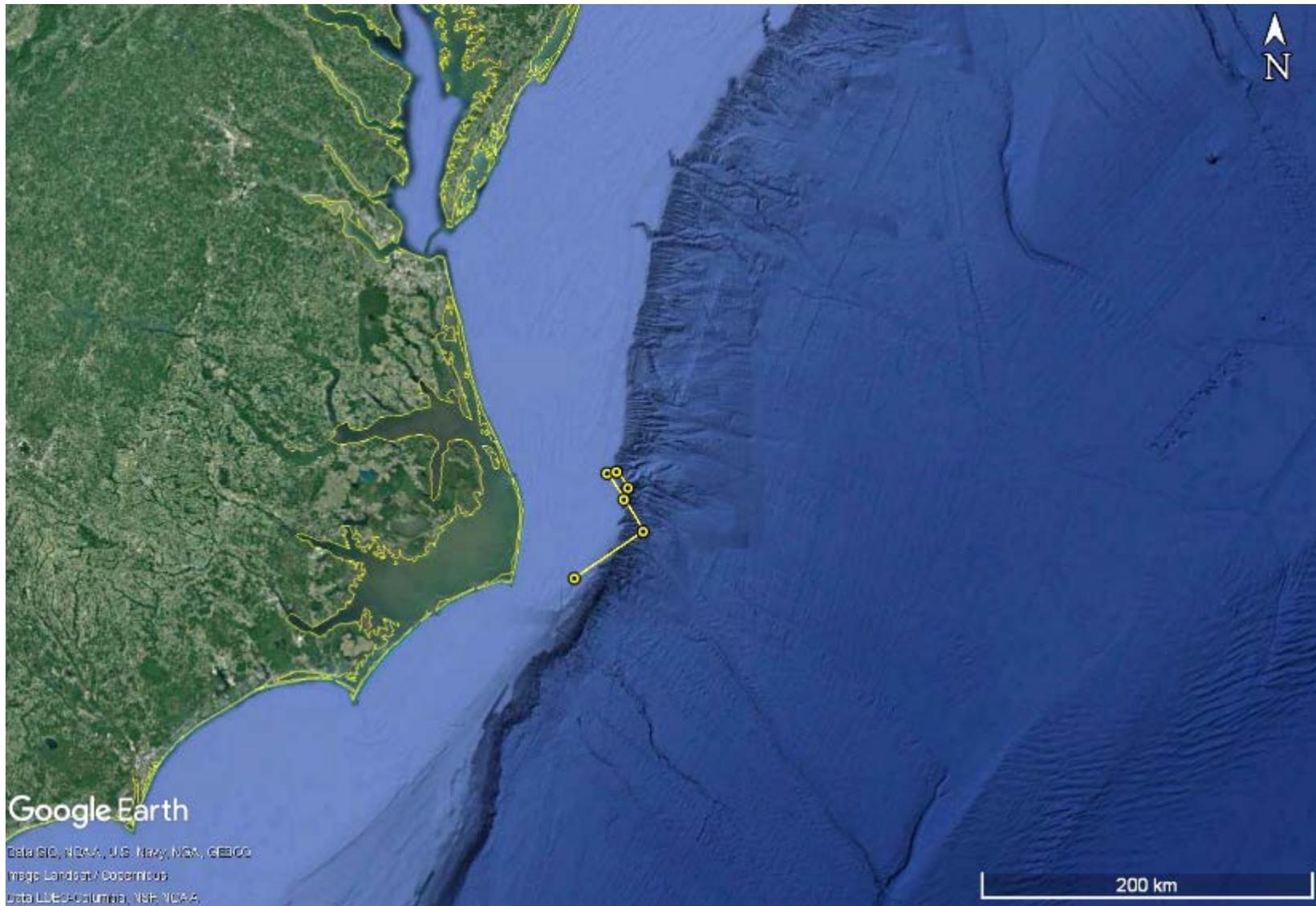


Figure 3. All filtered locations of Cuvier's beaked whale ZcTag071 over the 34.3-day tag-attachment duration, 5 August–8 September 2018, with consecutive locations joined by a line. This individual was one of the subjects of the controlled-exposure experiments. ZcTag071 was tagged in the same encounter as ZcTag072 (Figure 4).

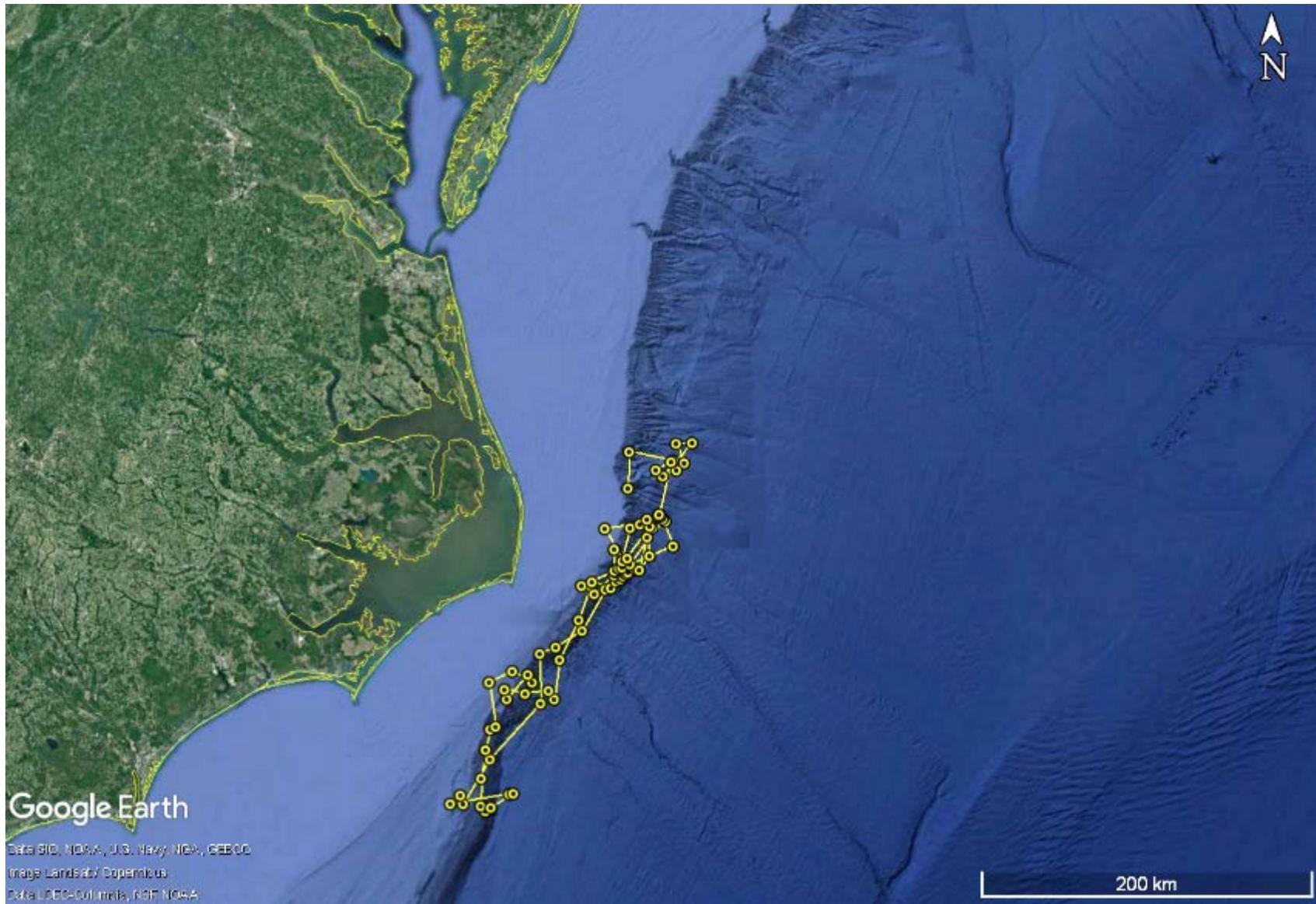


Figure 4. All filtered locations of Cuvier's beaked whale ZcTag072 over the 42.9-day tag-attachment duration, 5 August–17 September 2018, with consecutive locations joined by a line. This individual was one of the subjects of the controlled-exposure experiments. ZcTag072 was tagged in the same encounter as ZcTag071 (Figure 3).

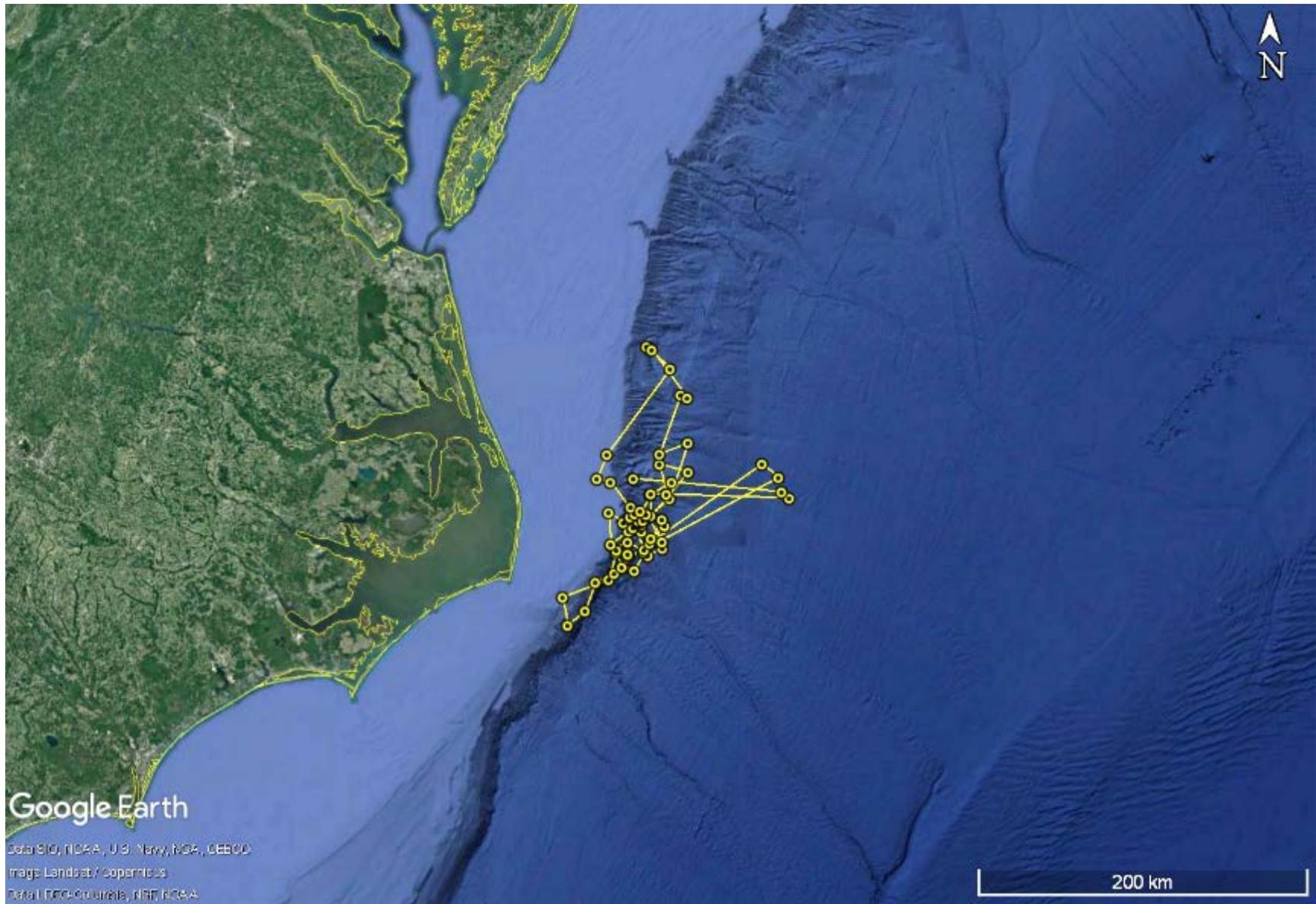


Figure 5. All filtered locations of Cuvier's beaked whale ZcTag073 over the 43.6-day tag-attachment duration, 5 August–18 September 2018, with consecutive locations joined by a line. This individual was one of the subjects of the controlled-exposure experiments.

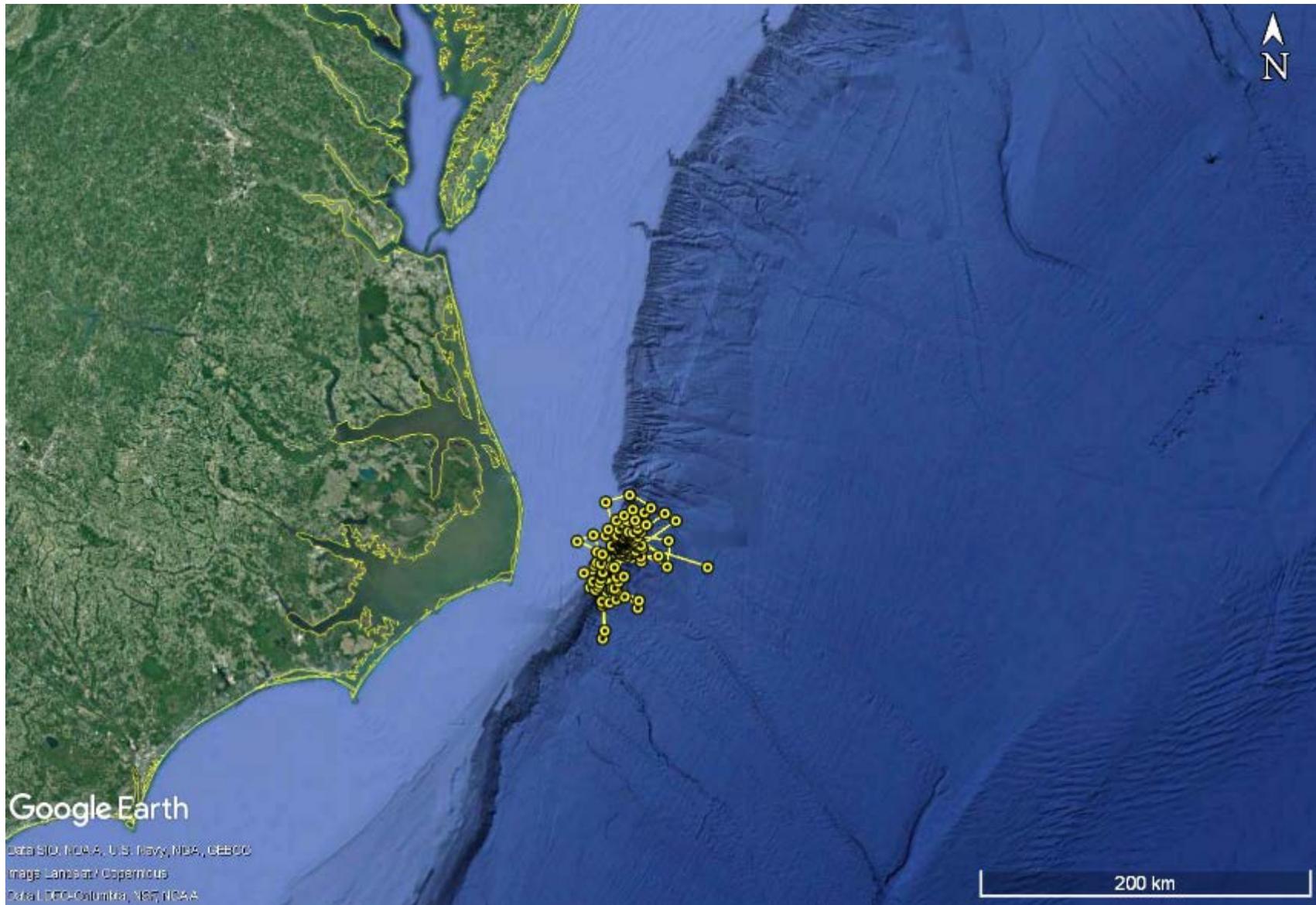


Figure 6. All filtered locations of Cuvier's beaked whale ZcTag075 over the 41.4-day tag-attachment duration, 8 August–16 September 2018, with consecutive locations joined by a line. This individual was one of the subjects of the controlled-exposure experiments. ZcTag075 was tagged in the same encounter as ZcTag076 (Figure 7).

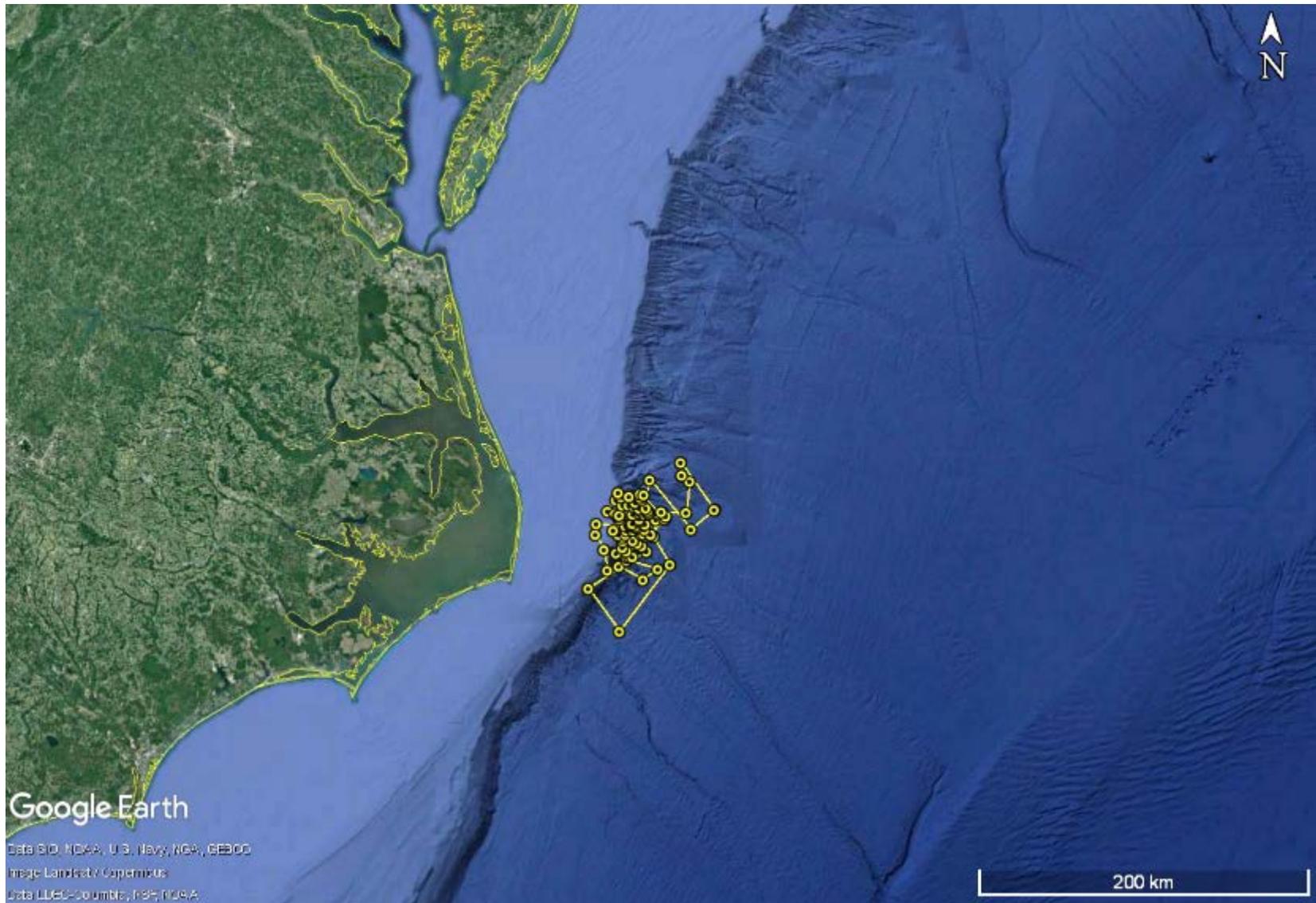


Figure 7. All filtered locations of Cuvier's beaked whale ZcTag076 over the 44.4-day tag-attachment duration, 6 August–17 September 2018, with consecutive locations joined by a line. This individual was one of the subjects of the controlled-exposure experiments. ZcTag076 was tagged in the same encounter as ZcTag065 (Figure 6).

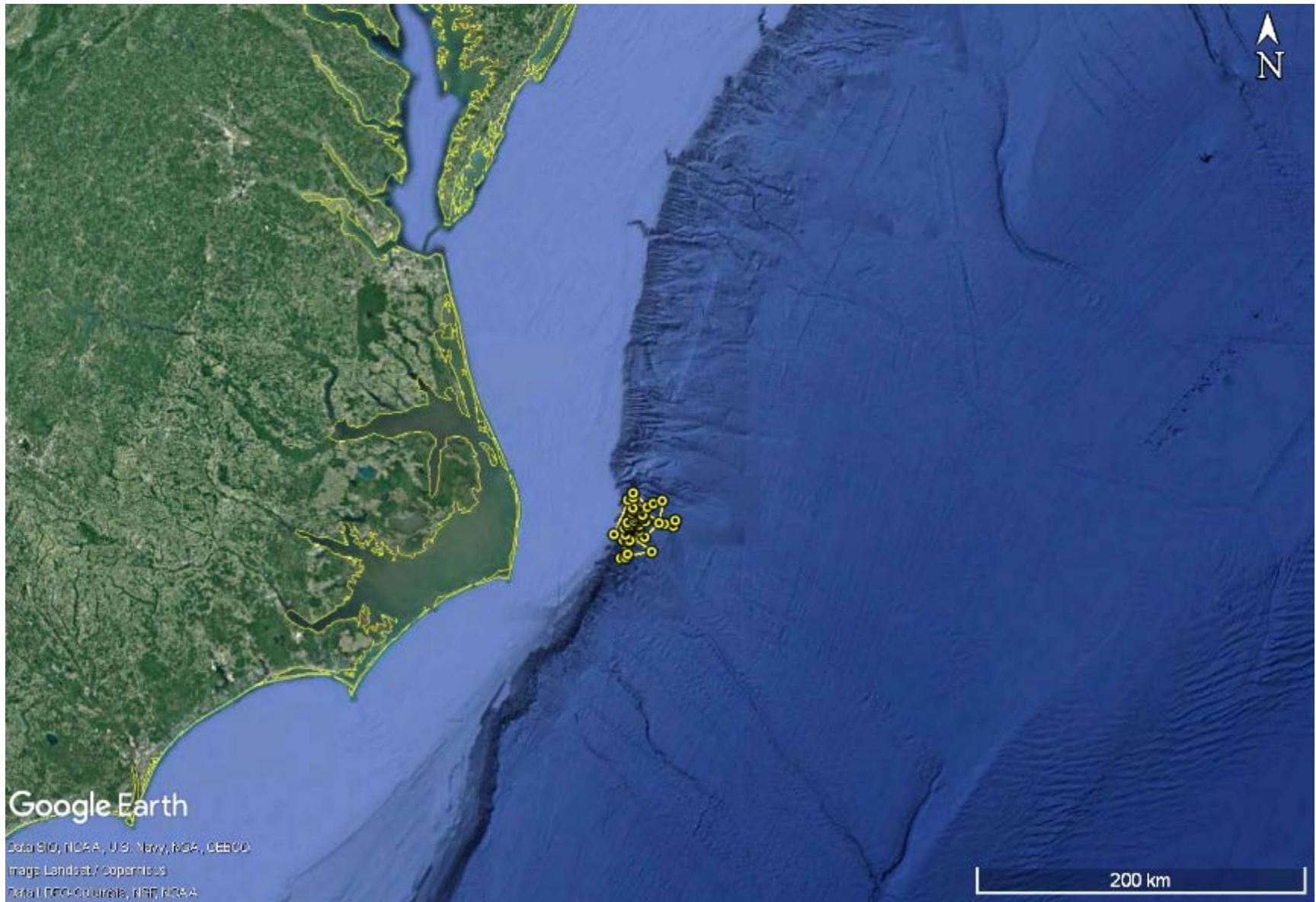


Figure 8. All filtered locations of a Cuvier's beaked whale ZcTag077 over the 23.7-day tag-attachment duration, 6–30 August 2018, with consecutive locations joined by a line. This individual was one of the subjects of the controlled-exposure experiments.

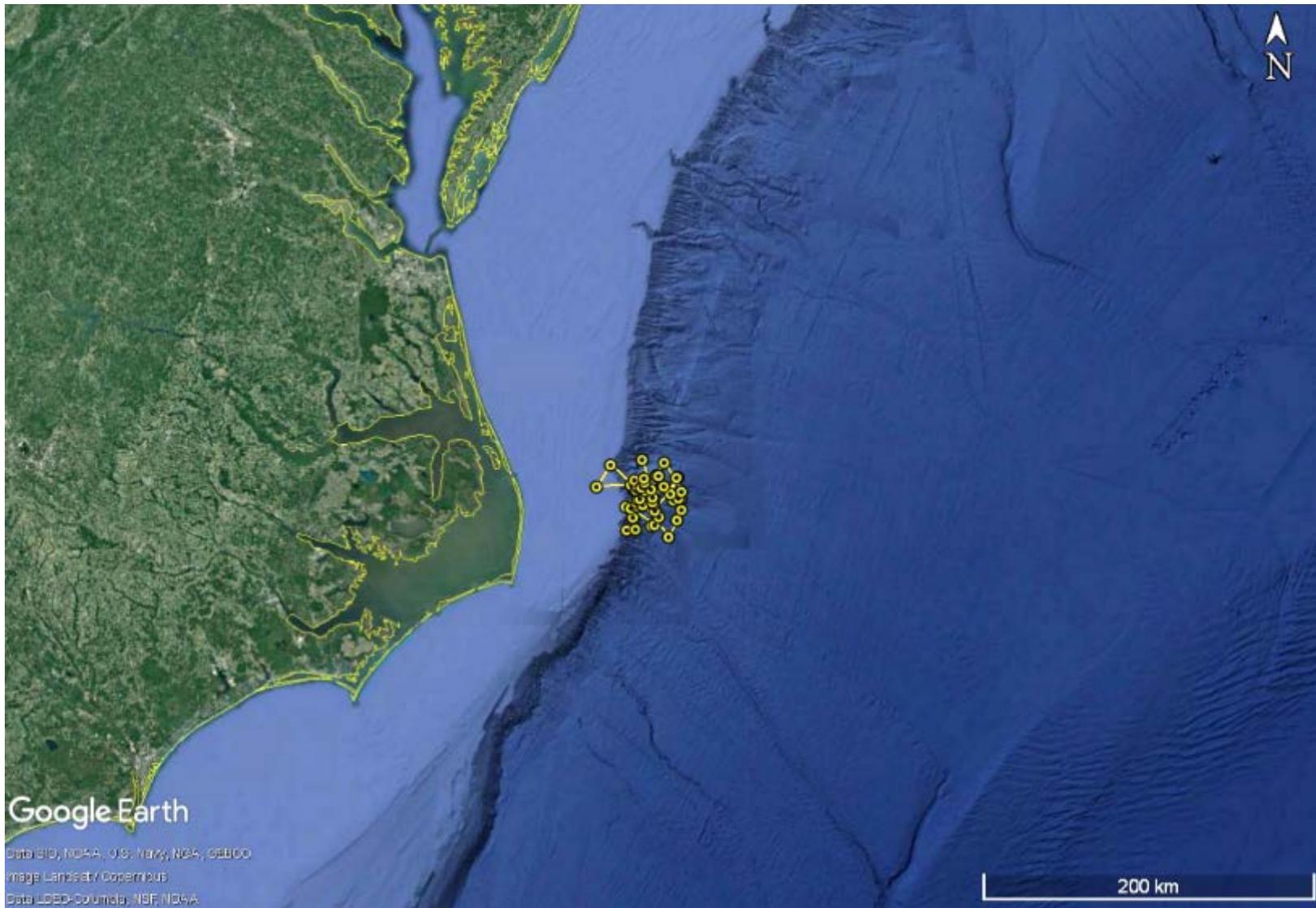


Figure 9. All filtered locations of Cuvier's beaked whale ZcTag078 over the 23.2-day tag-attachment duration, 6–29 August 2018, with consecutive locations joined by a line. This individual was one of the subjects in the controlled-exposure experiments.



Figure 10. All filtered locations of Cuvier's beaked whale ZcTag079 over the 43.3-day tag-attachment duration, 7 August–19 September 2018, with consecutive locations joined by a line. This individual was one of the subjects in the controlled-exposure experiments.

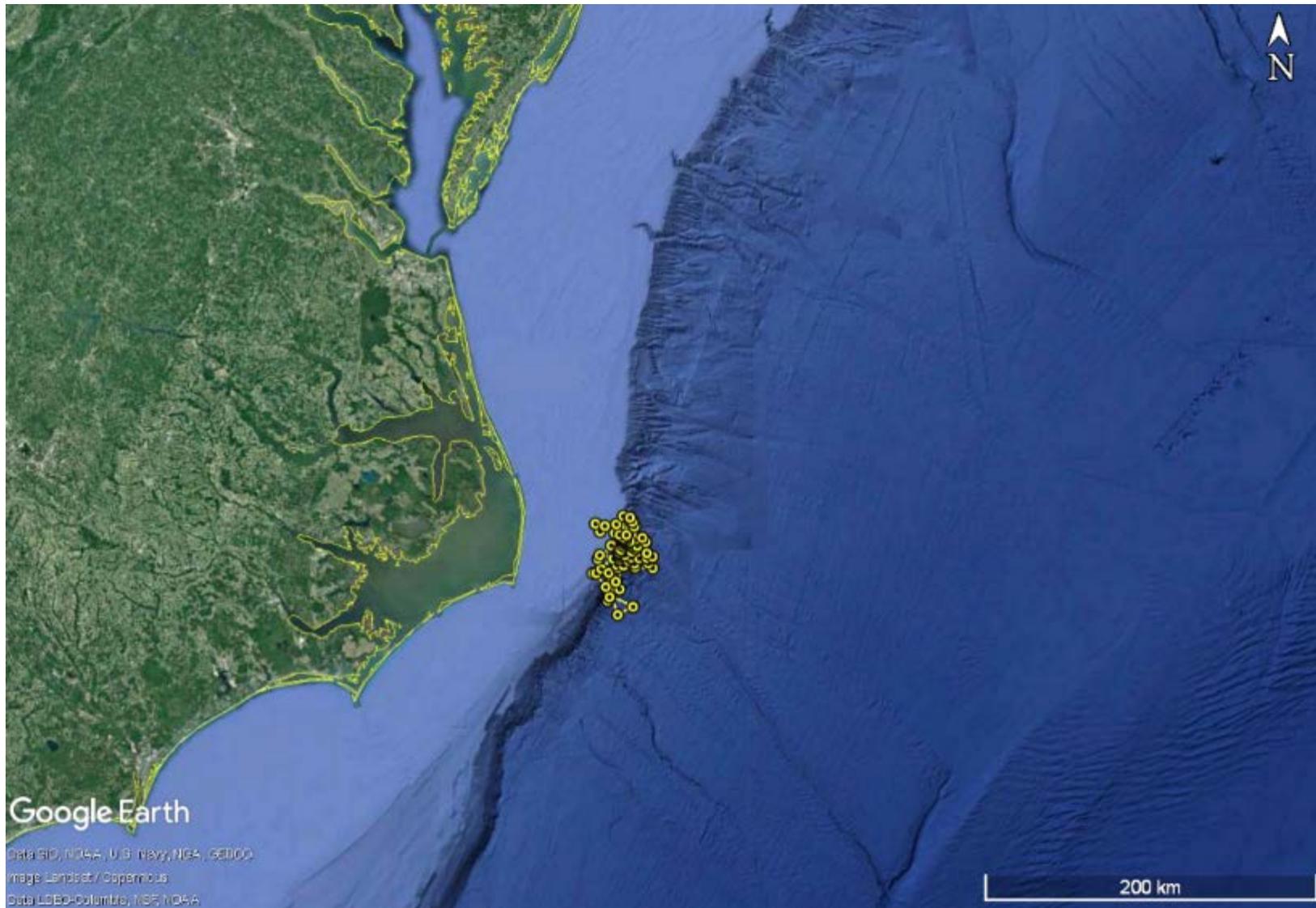


Figure 11. All filtered locations of Cuvier's beaked whale ZcTg080 over the 12.8-day tag-attachment duration, 7 August–20 September 2018, with consecutive locations joined by a line. This individual was one of the subjects in the controlled-exposure experiments. This individual was tagged in the same group as ZcTag081 (Figure 12).

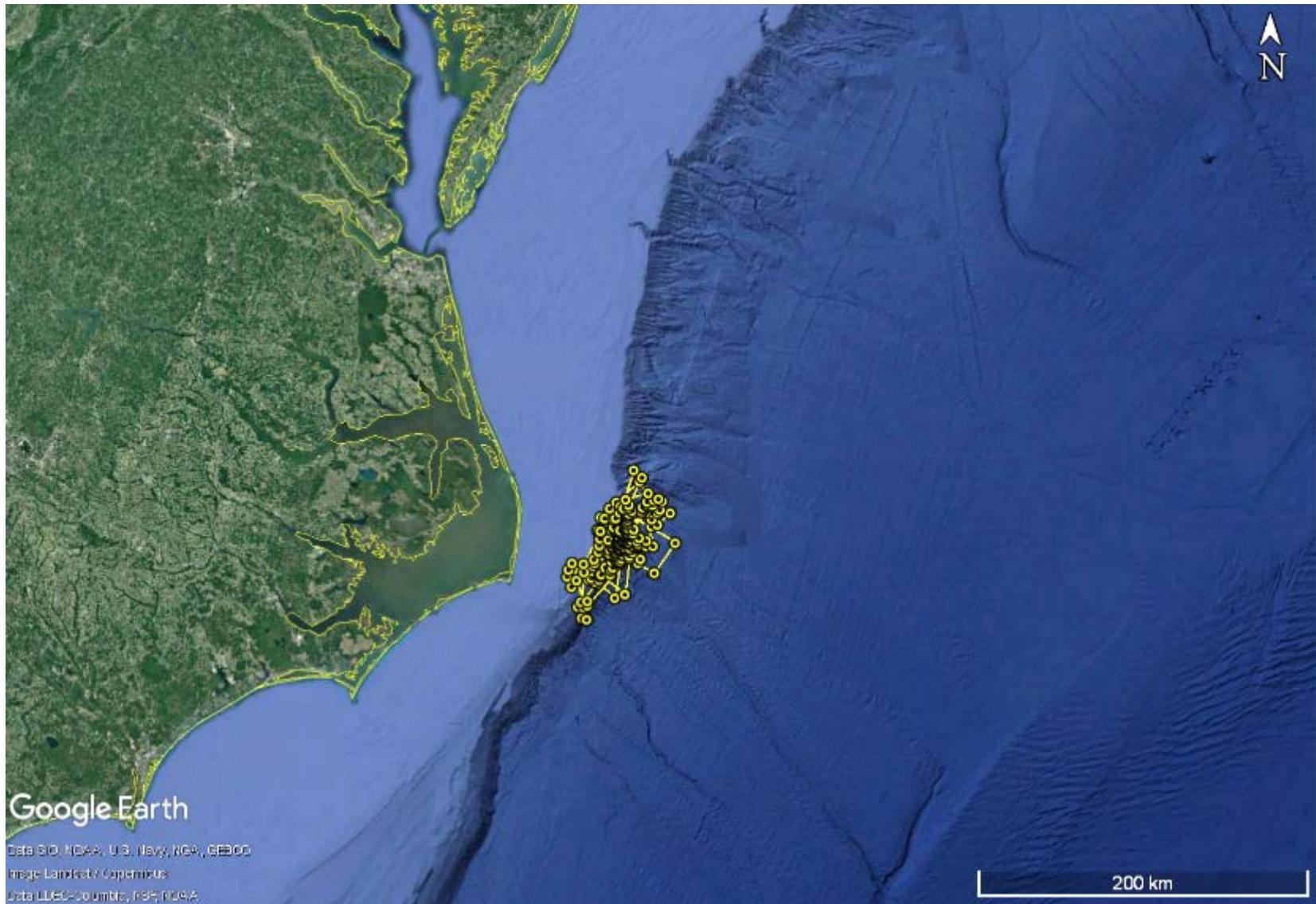


Figure 12. All filtered locations of Cuvier's beaked whale ZcTag081 over the 57.2-day tag-attachment duration, 7 August–3 October 2018, with consecutive locations joined by a line. This individual was one of the subjects in the controlled-exposure experiments. This individual was tagged in the same group as ZcTag080 (Figure 11).

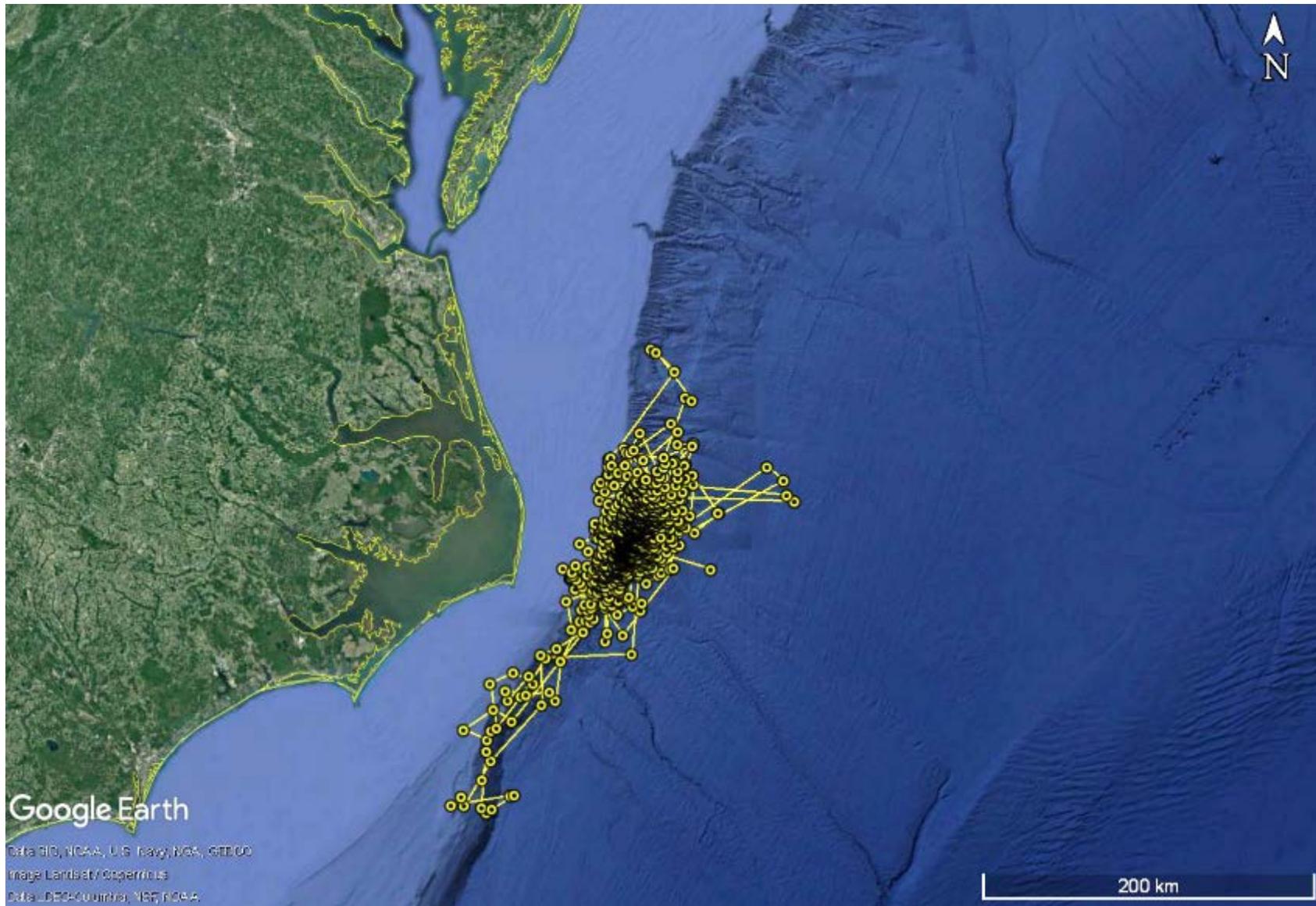


Figure 13. All filtered locations of Cuvier's beaked whales tagged in 2018 ($n=12$), with consecutive locations of each individual joined by a line.

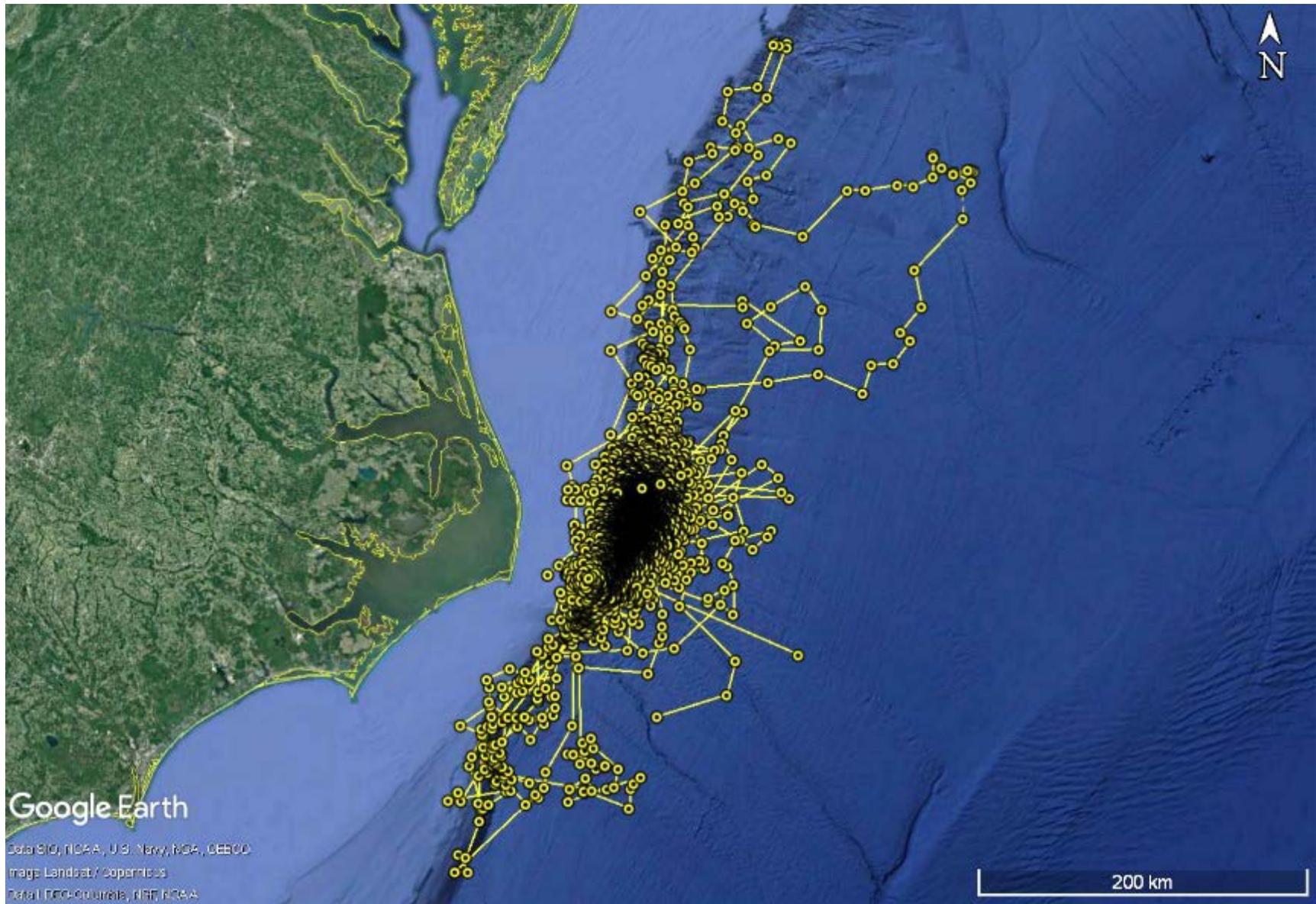


Figure 14. All filtered locations of Cuvier's beaked whales tagged in 2014 ($n=3$), 2015 ($n=6$), 2016 ($n=6$), 2017 ($n=14$), and 2018 ($n=12$) with consecutive locations of each individual joined by a line.

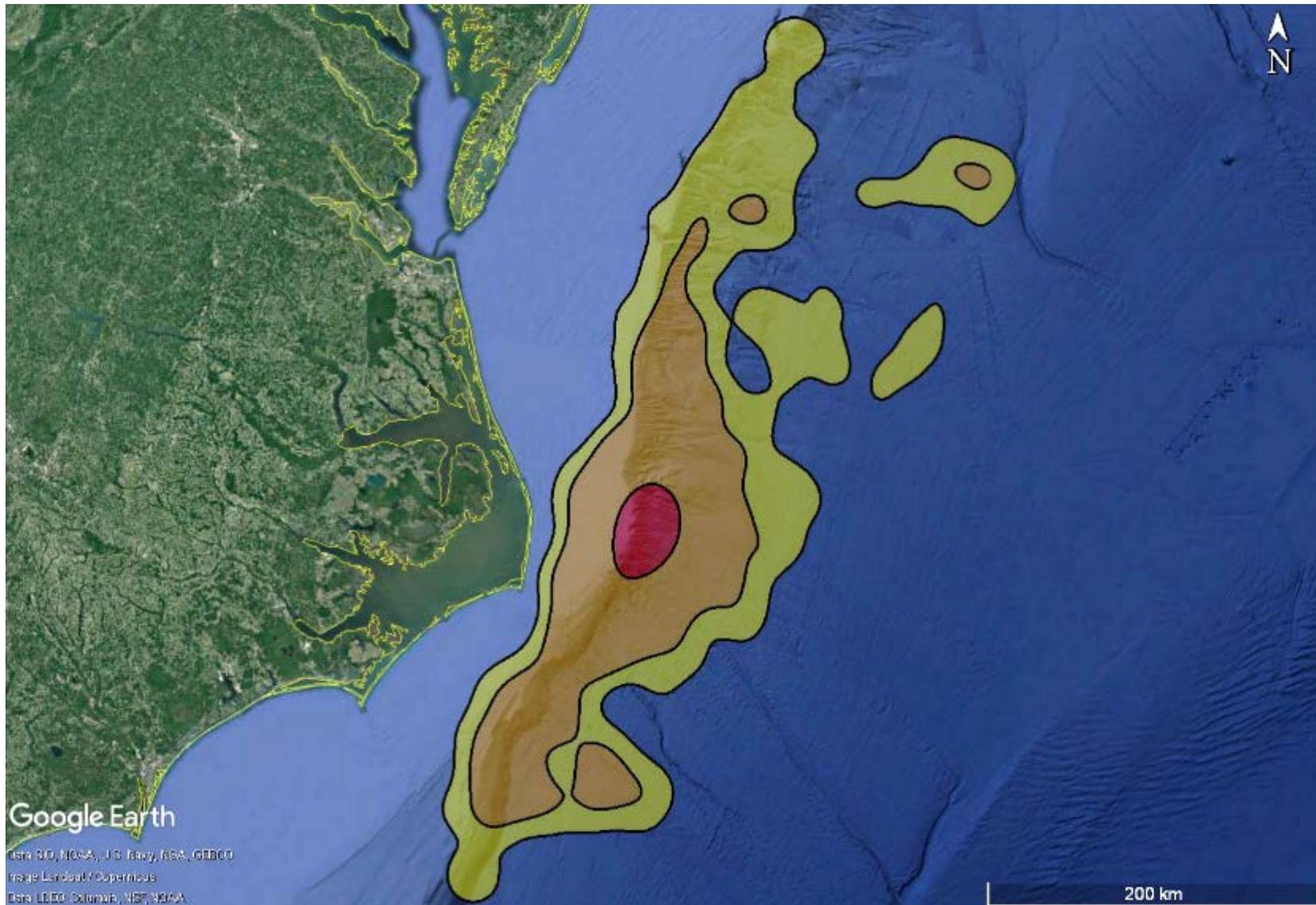


Figure 15. A probability-density representation of Cuvier's beaked whale location data, using only a single individual from each pair where individuals were acting in concert. The sample includes data from 34 individuals tagged off North Carolina: 2014 ($n=3$), 2015 ($n=6$), 2016 ($n=5$), 2017 ($n=10$), 2018 ($n=10$). The red area indicates the 50 percent density polygon (the "core range"), the orange represents the 95 percent polygon, and the yellow represents the 99 percent polygon.

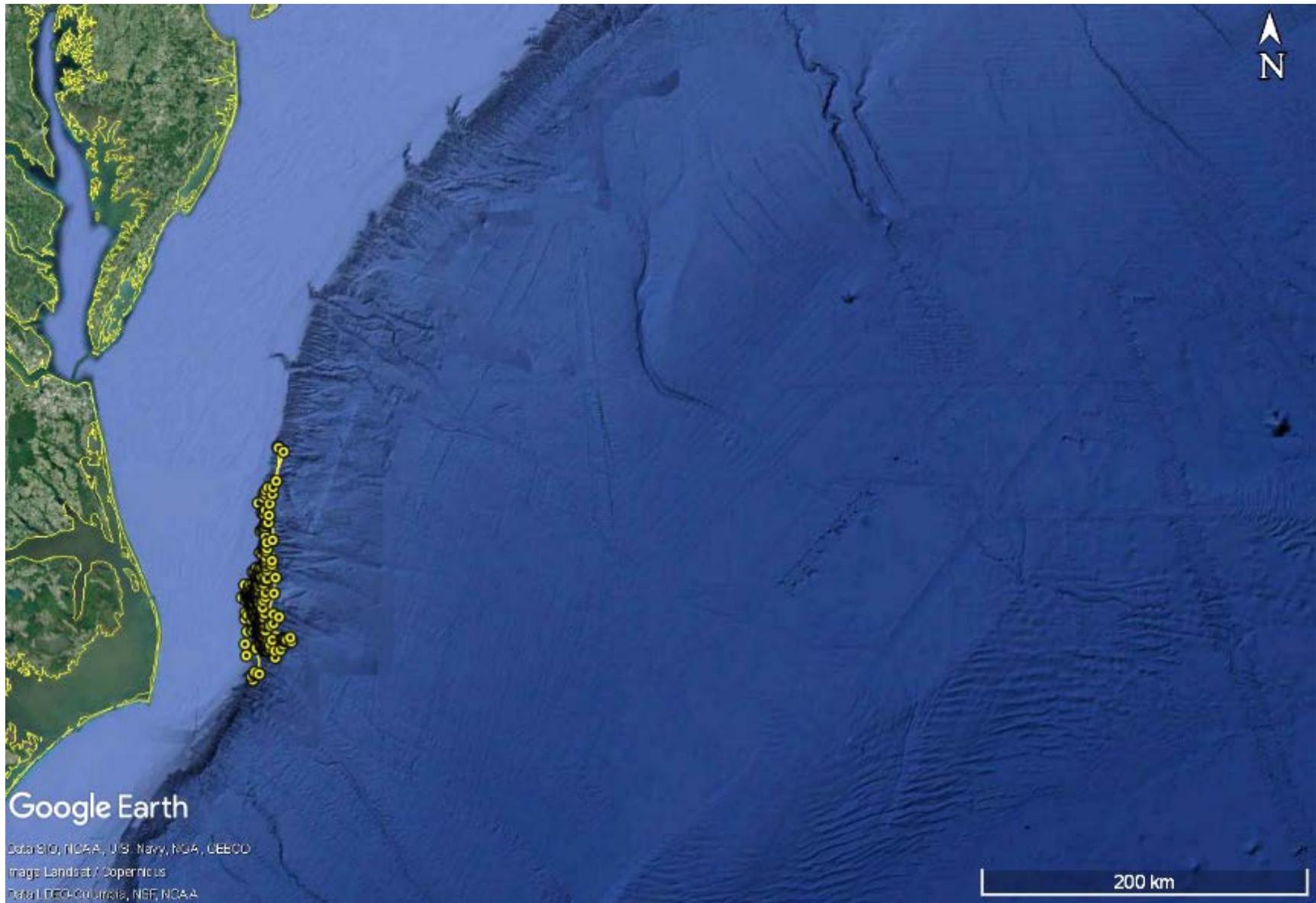


Figure 16. All filtered locations of short-finned pilot whale GmTag197 tagged off North Carolina over a 27.0-day period, 11 May–7 June 2018, with consecutive locations joined by a line. This individual was one of the subjects of the controlled-exposure experiments.

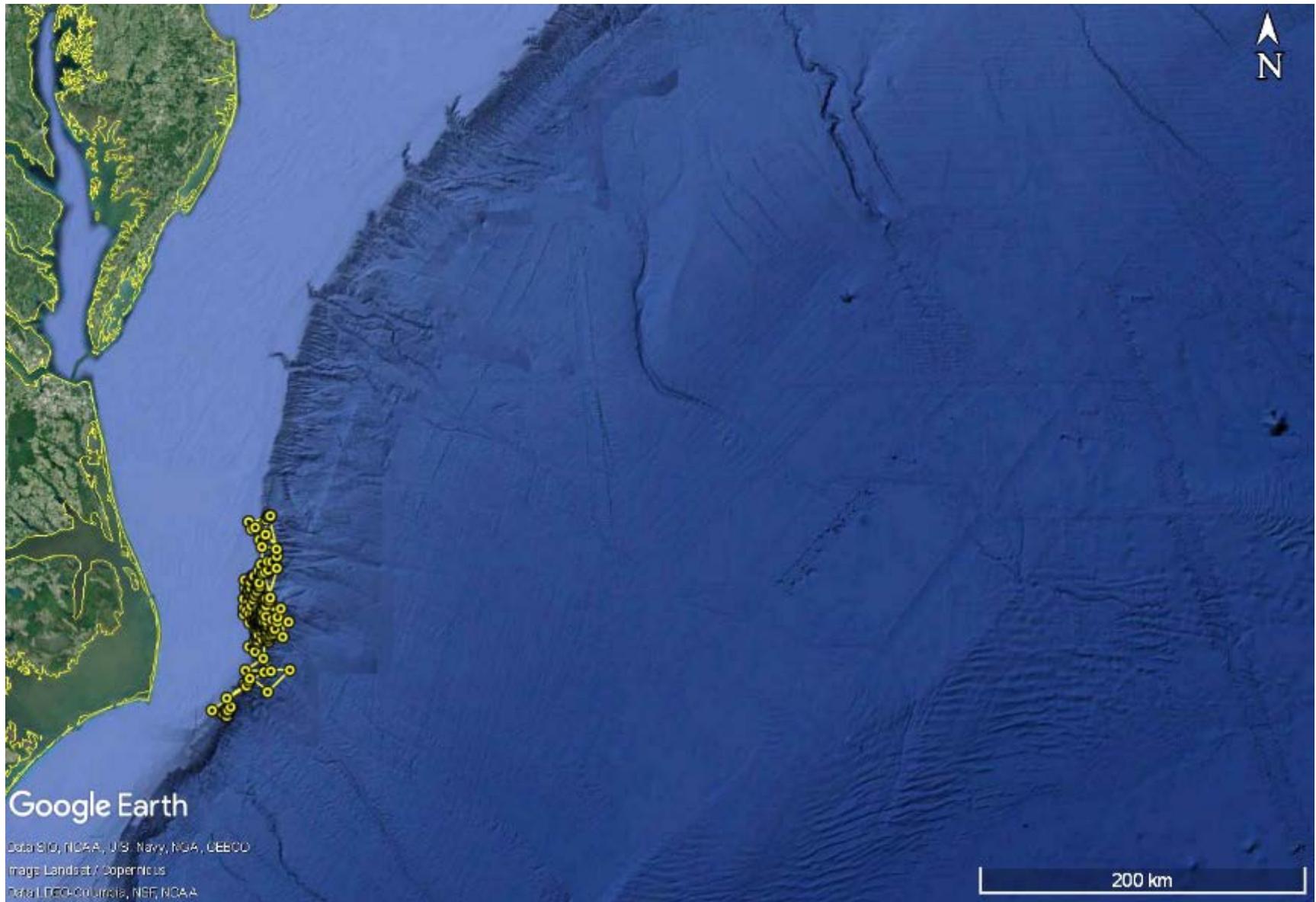


Figure 17. All filtered locations of short-finned pilot whale GmTag198 tagged off North Carolina over a 19.5-day period, 22 May–10 June 2018, with consecutive locations joined by a line. This individual was one of the subjects of the controlled-exposure experiments.

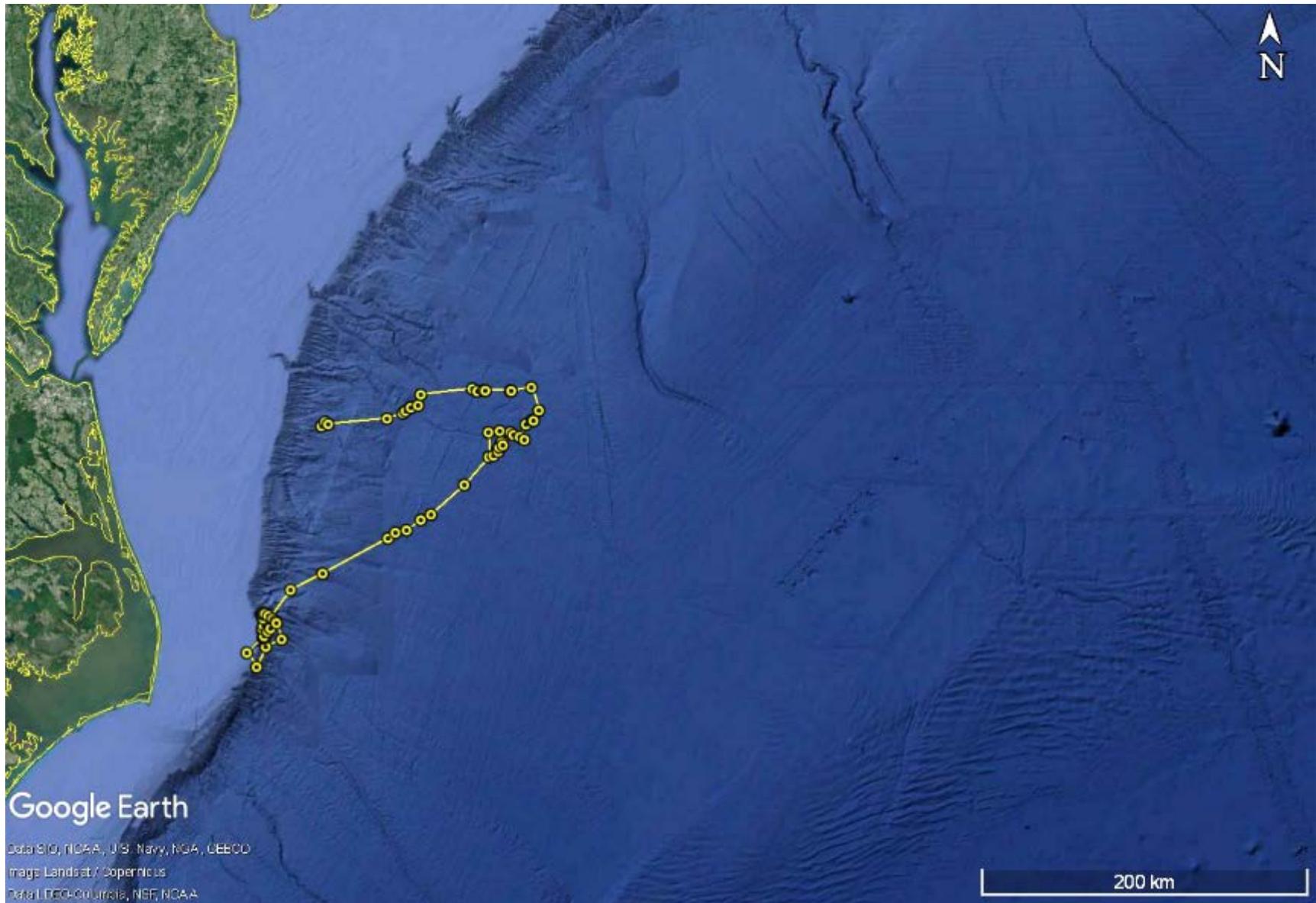


Figure 18. All filtered locations of short-finned pilot whale GmTag199 tagged off North Carolina over a 7.6-day period, 24–31 May 2018, with consecutive locations joined by a line. This individual was one of the subjects of the controlled-exposure experiments.

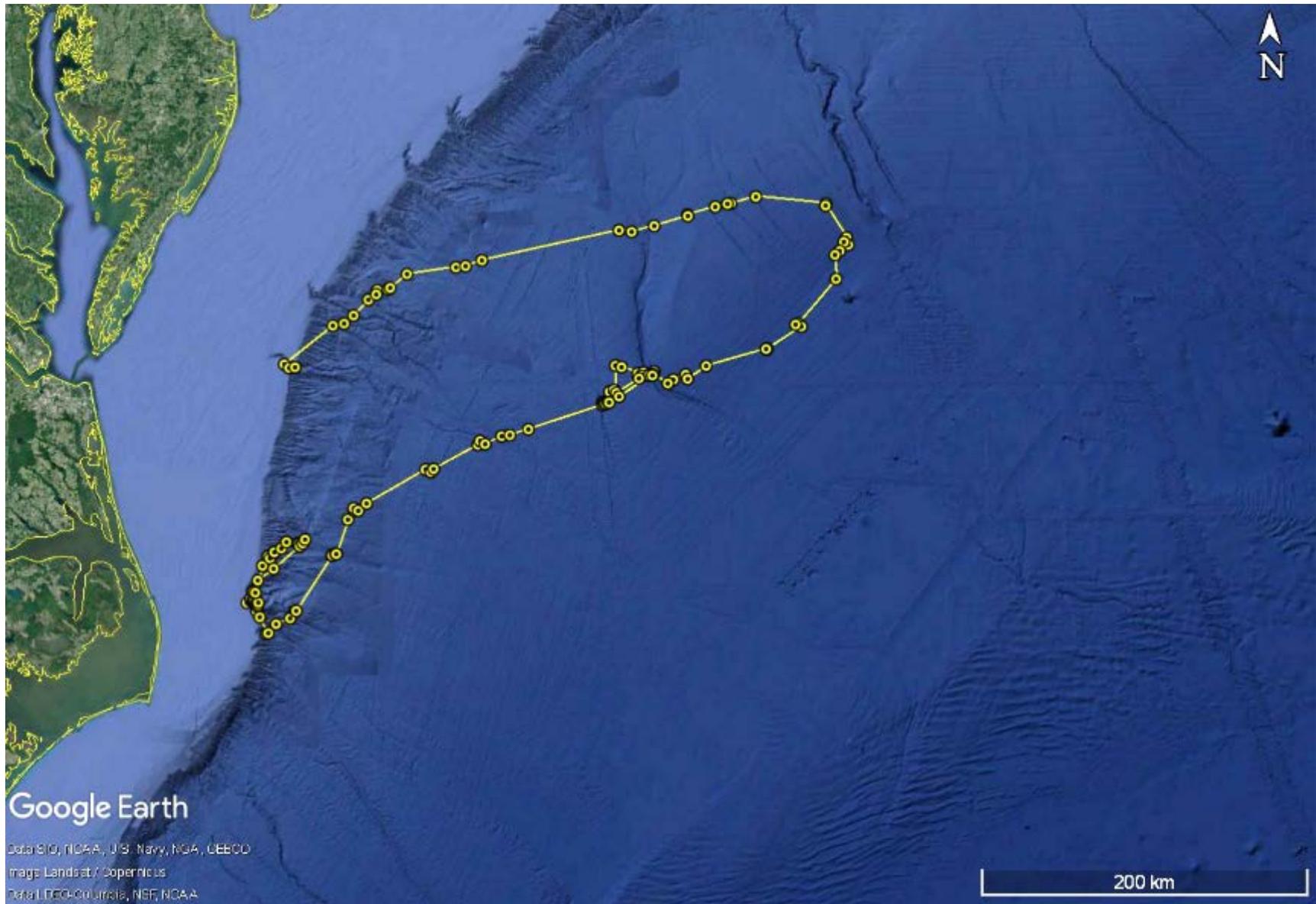


Figure 19. All filtered locations of short-finned pilot whale GmTag200 tagged off North Carolina over a 11.3-day period, 24 May–4 June 2018, with consecutive locations joined by a line. This individual was one of the subjects of the controlled-exposure experiments.

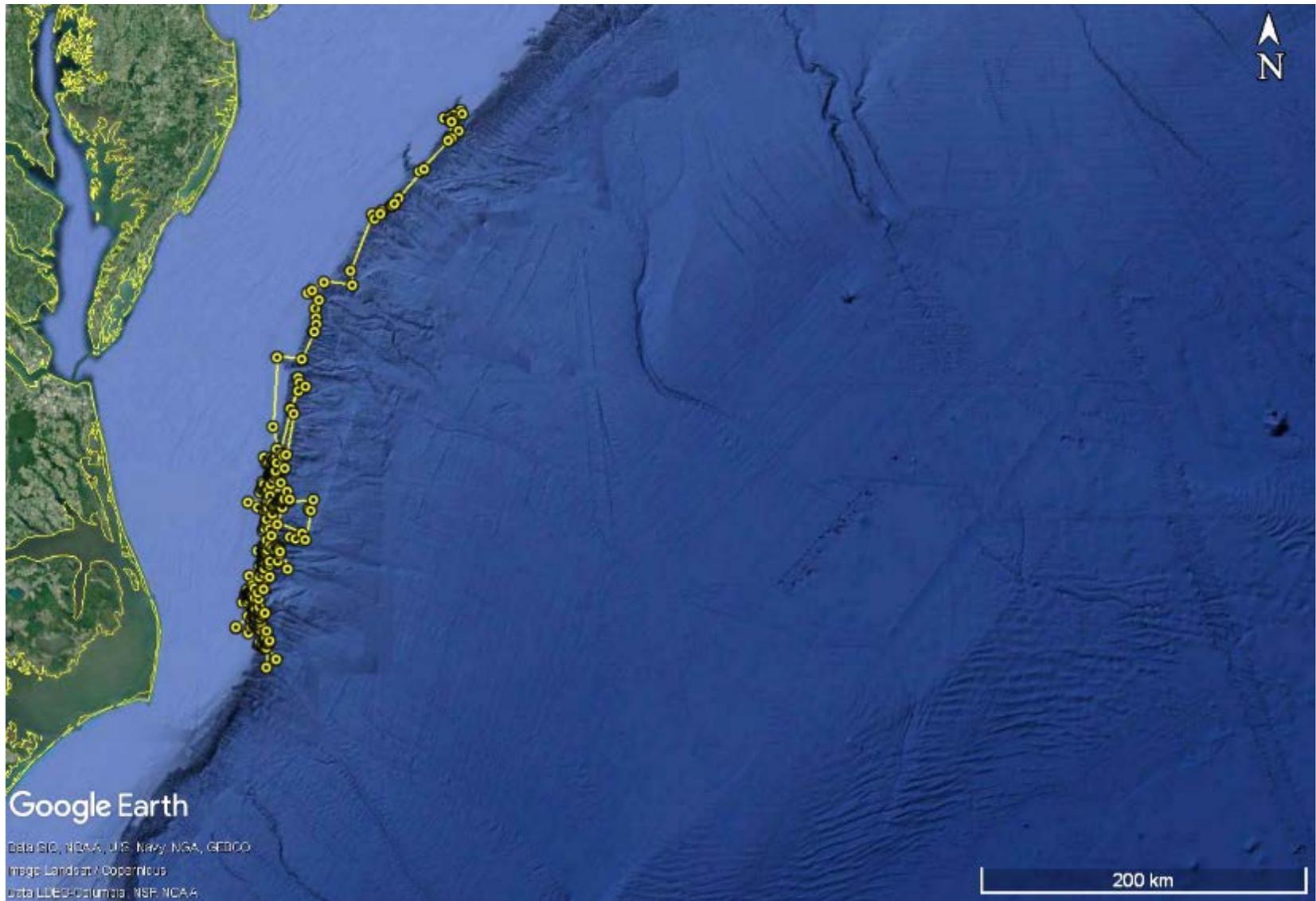


Figure 20. All filtered locations of short-finned pilot whale GmTag201 tagged off North Carolina over a 27.5-day period, 30 May–26 June 2018, with consecutive locations joined by a line. This individual was one of the subjects of the controlled-exposure experiments.

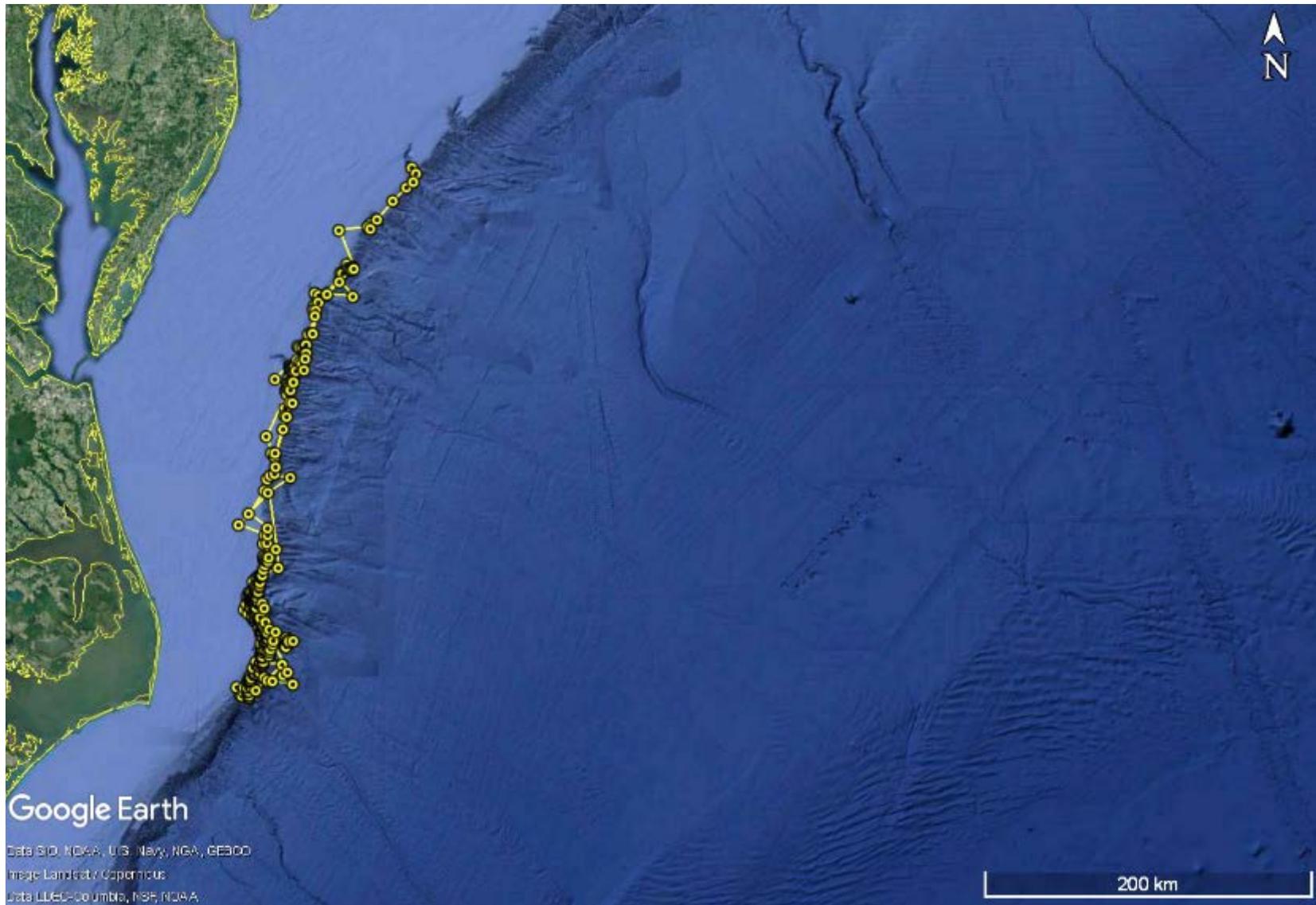


Figure 21. All filtered locations of short-finned pilot whale GmTag202 tagged off North Carolina over a 25.6-day period, 30 May–25 June 2018, with consecutive locations joined by a line. This individual was one of the subjects of the controlled-exposure experiments.

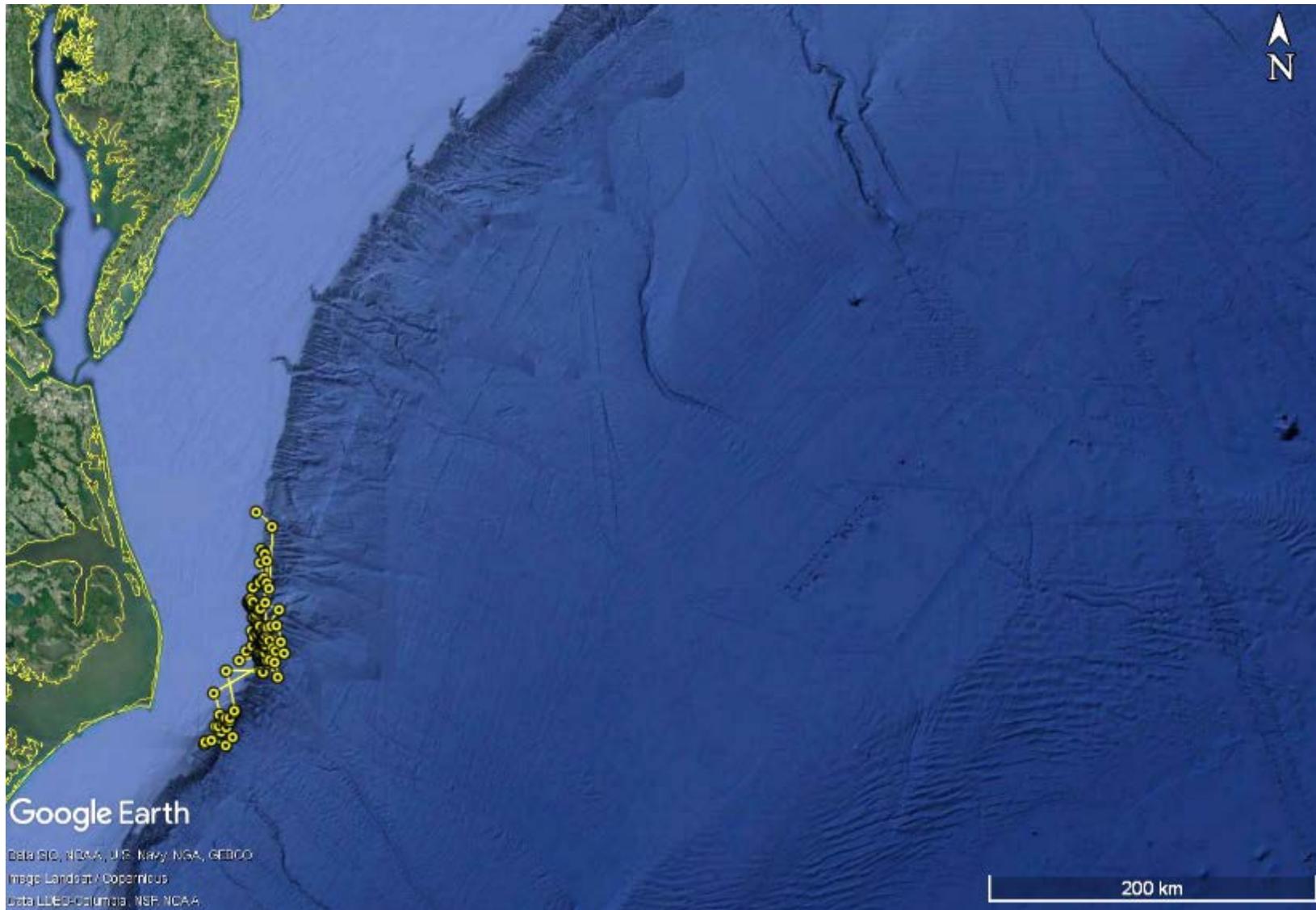


Figure 22. All filtered locations of short-finned pilot whale GmTag203 tagged off North Carolina over a 17.4-day period, 31 May–17 June 2018, with consecutive locations joined by a line. This individual was one of the subjects of the controlled-exposure experiments. GmTag203 was tagged in the same group as GmTag204 (Figure 23).

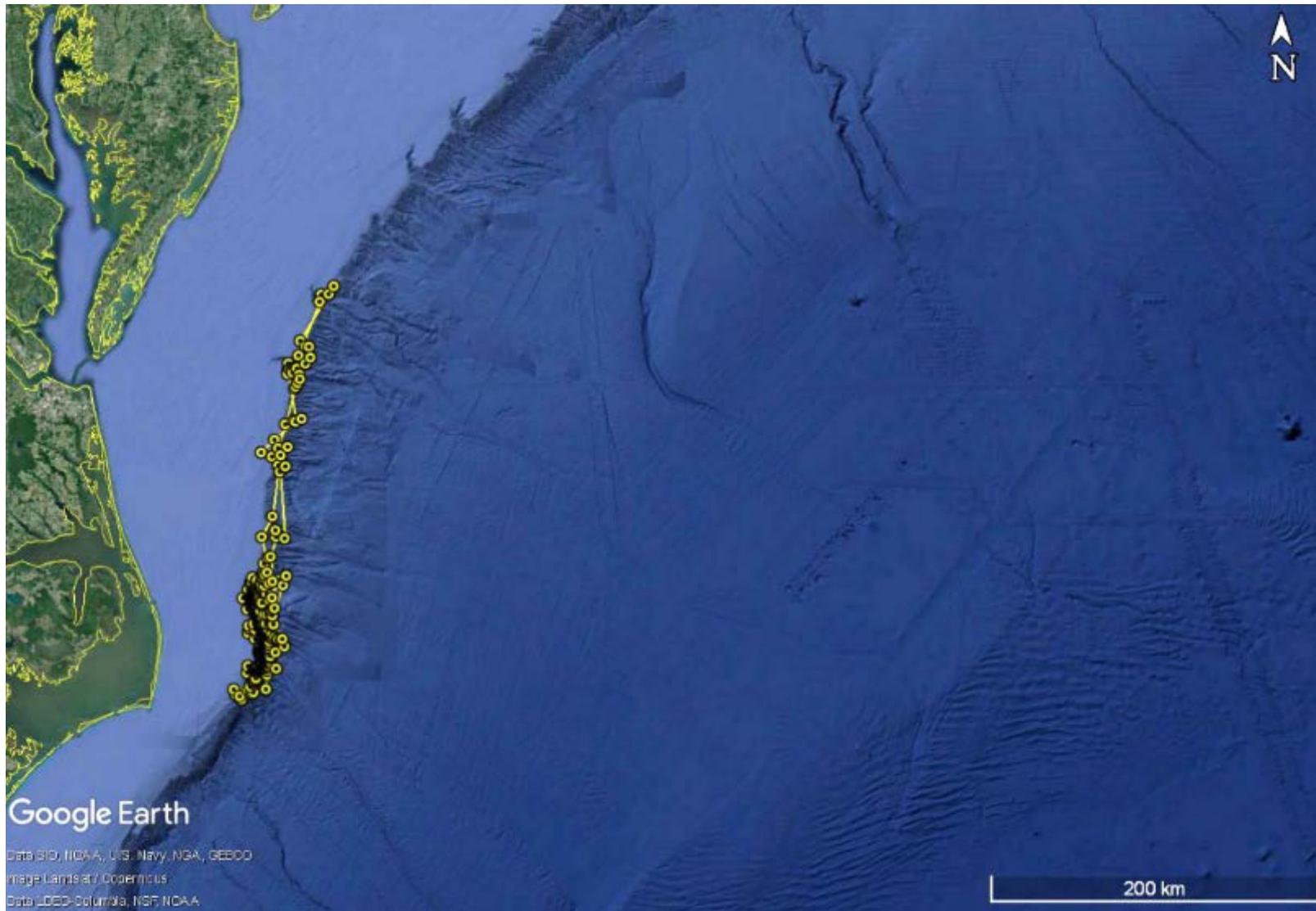


Figure 23. All filtered locations of short-finned pilot whale GmTag204 tagged off North Carolina over a 30.2-day period, 31 May–30 June 2018, with consecutive locations joined by a line. This individual was one of the subjects of the controlled-exposure experiments. GmTag204 was tagged in the same group as GmTag203 (Figure 22).

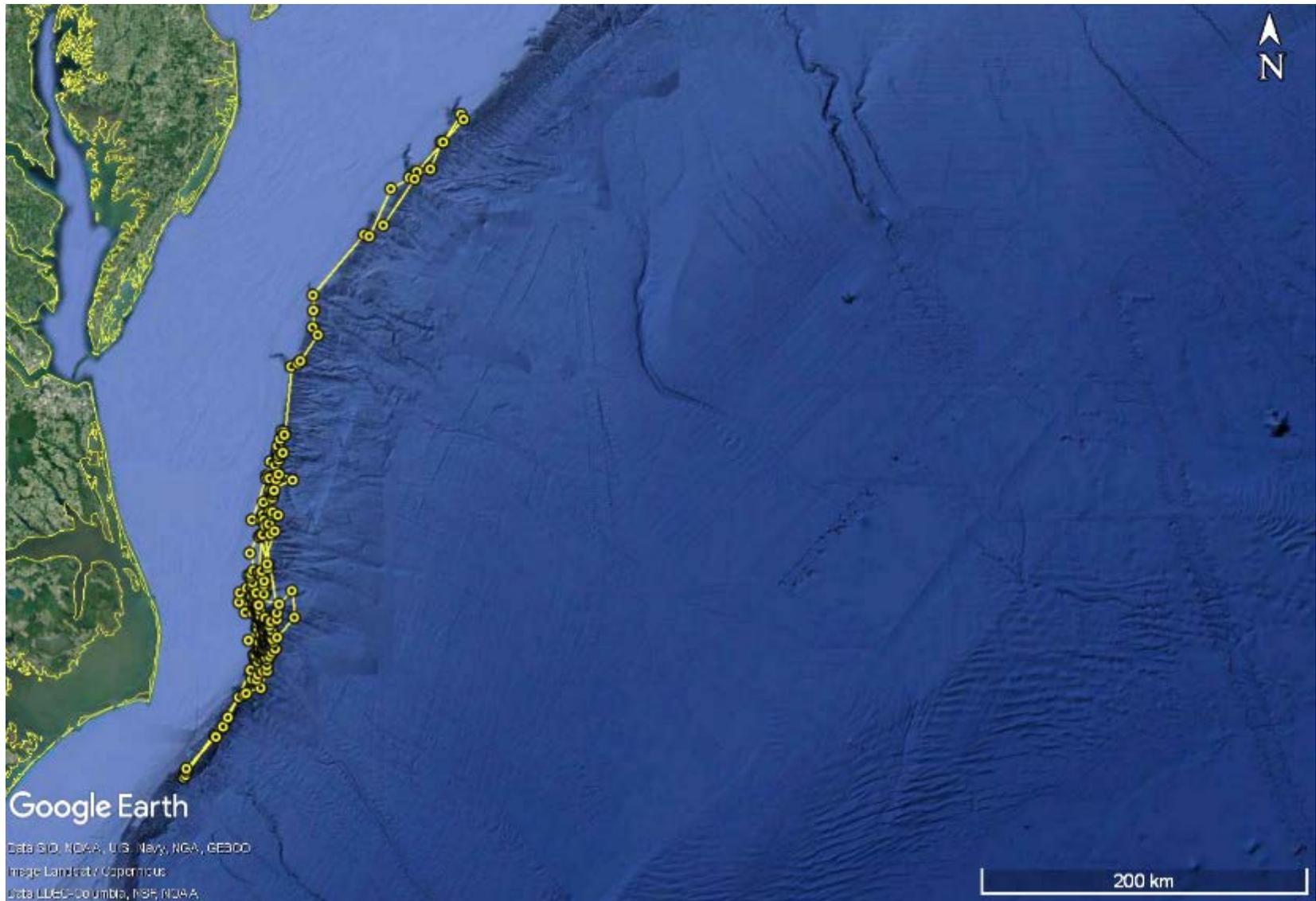


Figure 24. All filtered locations of short-finned pilot whale GmTag205 tagged off North Carolina over a 27.3-day period, 31 May–27 June 2018, with consecutive locations joined by a line. This individual was one of the subjects of the controlled-exposure experiments. GmTag205 was tagged in the same group as GmTag206 (Figure 25).

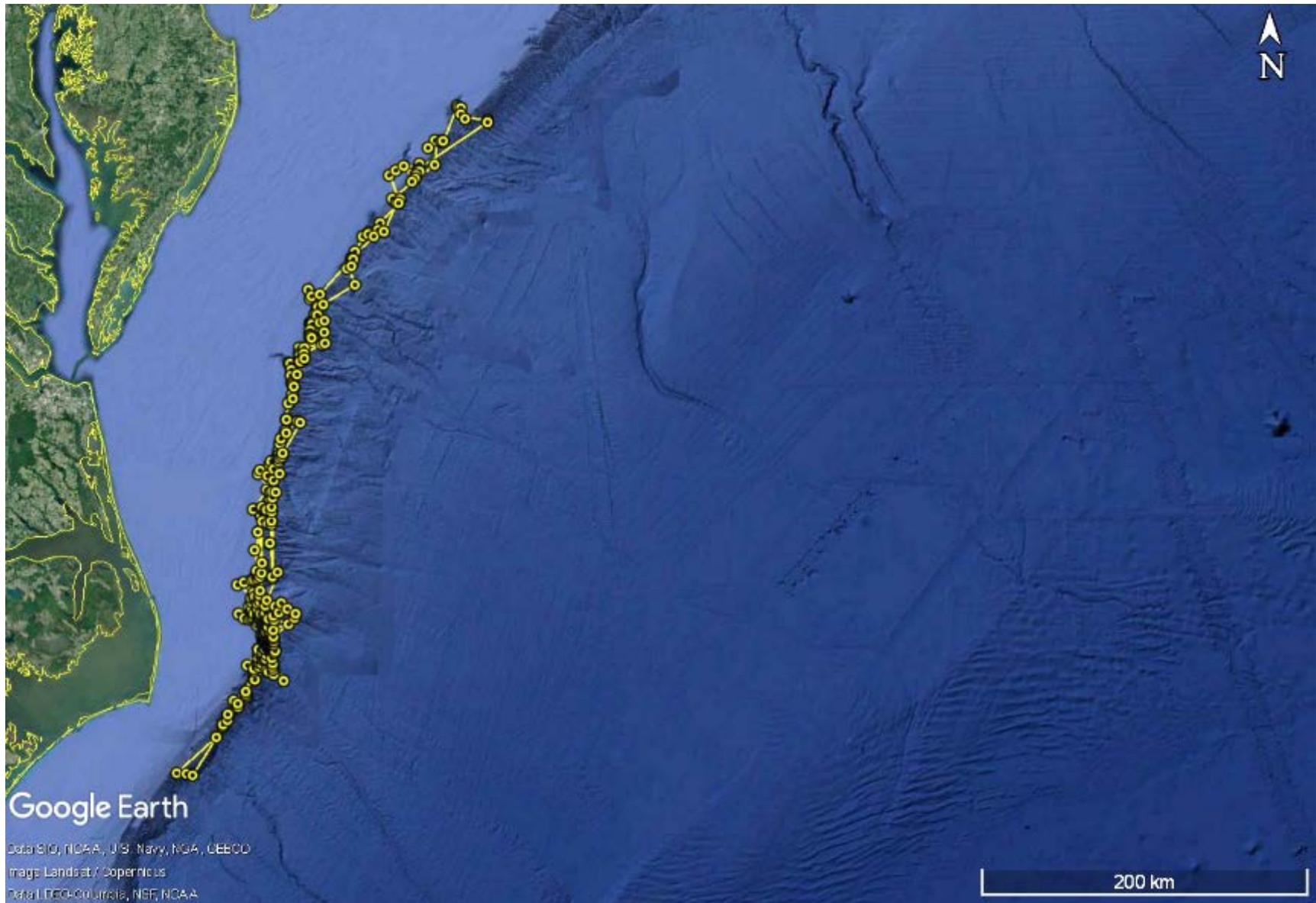


Figure 25. All filtered locations of short-finned pilot whale GmTag206 tagged off North Carolina over a 31.6-day period, 31 May–1 July 2018, with consecutive locations joined by a line. This individual was a subject for the controlled-exposure experiments. GmTag206 was tagged in the same group as GmTag205 (Figure 24).

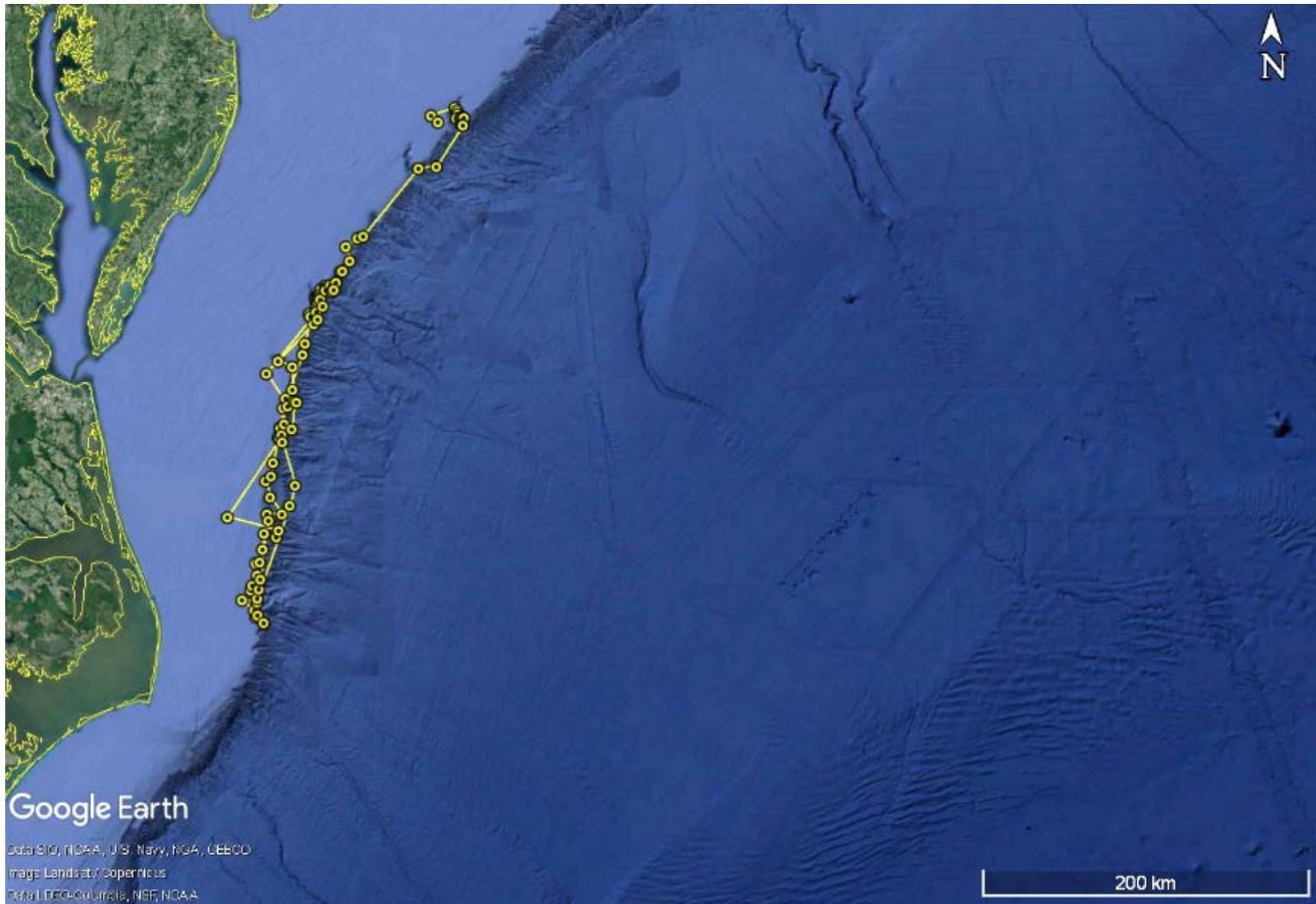


Figure 26. All filtered locations of short-finned pilot whale GmTag207 tagged off North Carolina over a 10.2-day period, 5-15 August 2018, with consecutive locations joined by a line. This individual was not a subject for the controlled-exposure experiments.

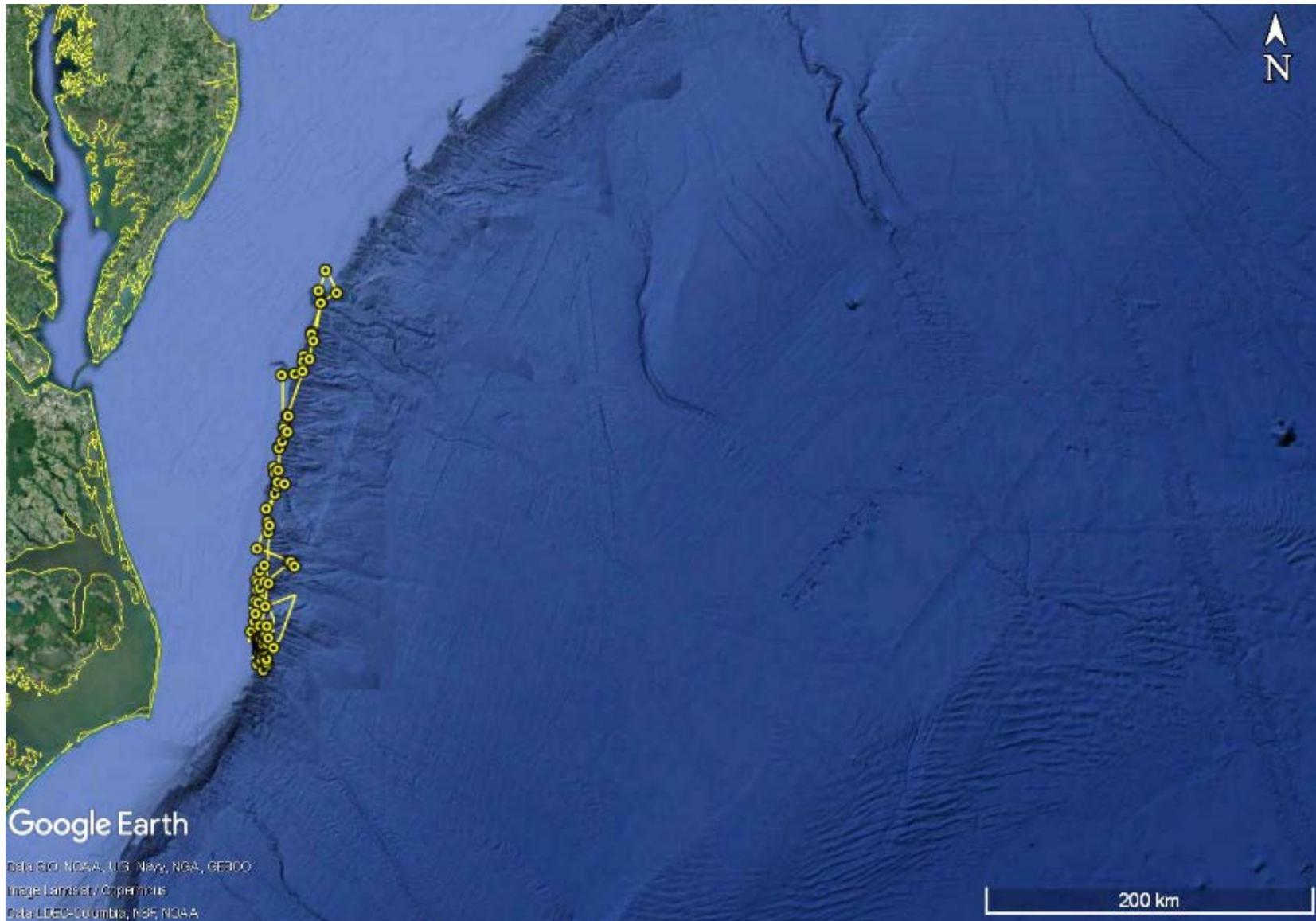


Figure 27. All filtered locations of short-finned pilot whale GmTag208 tagged off North Carolina over a 10.5-day period, 5–15 August 2018, with consecutive locations joined by a line. This individual was not a subject for the controlled-exposure experiments.

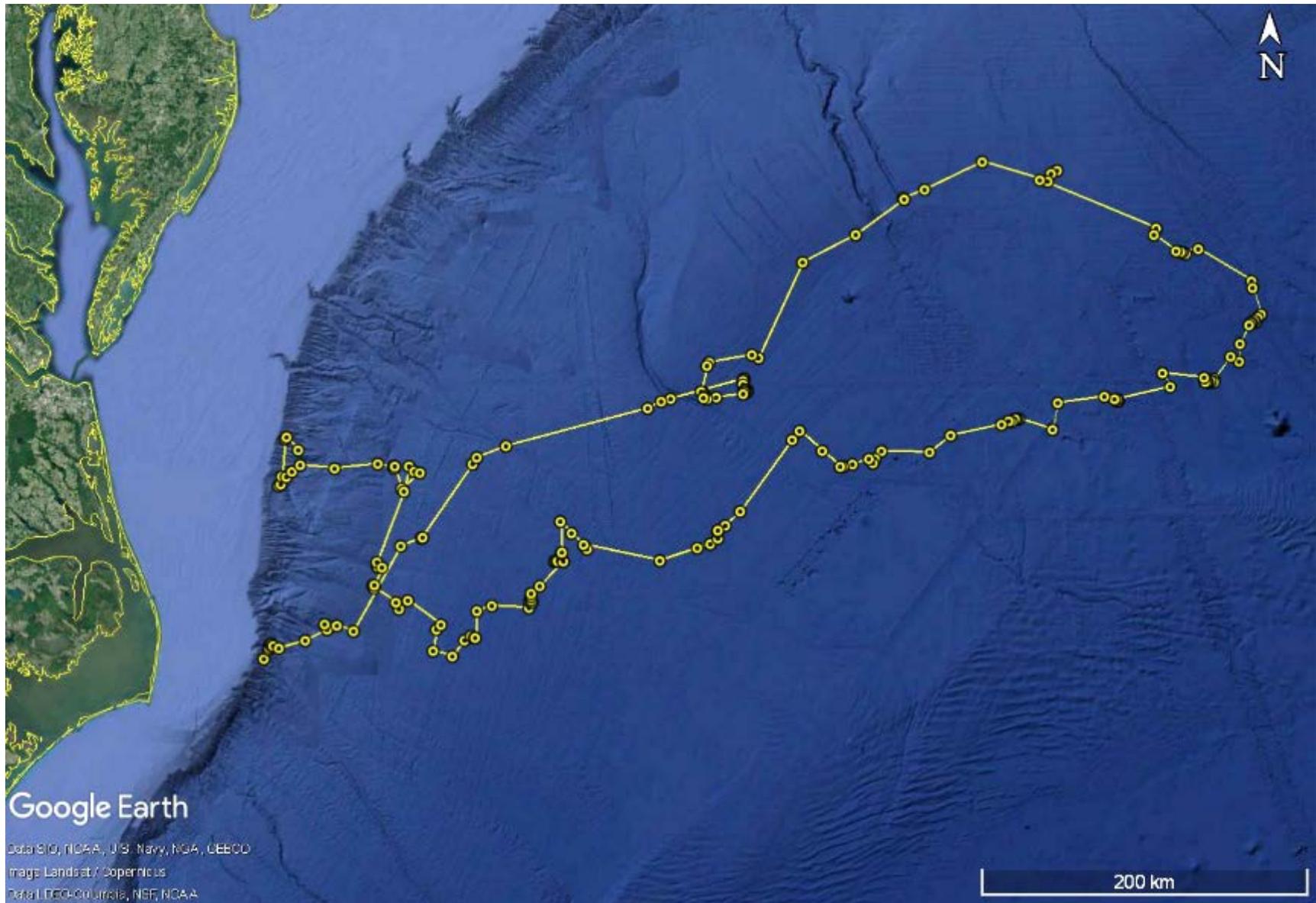


Figure 28. All filtered locations of short-finned pilot whale GmTag210 tagged off North Carolina over a 20.5-day period, 6–26 August 2018, with consecutive locations joined by a line. This individual was not a subject for the controlled-exposure experiments. GmTag210 was tagged in the same group as GmTag211 (Figure 29).

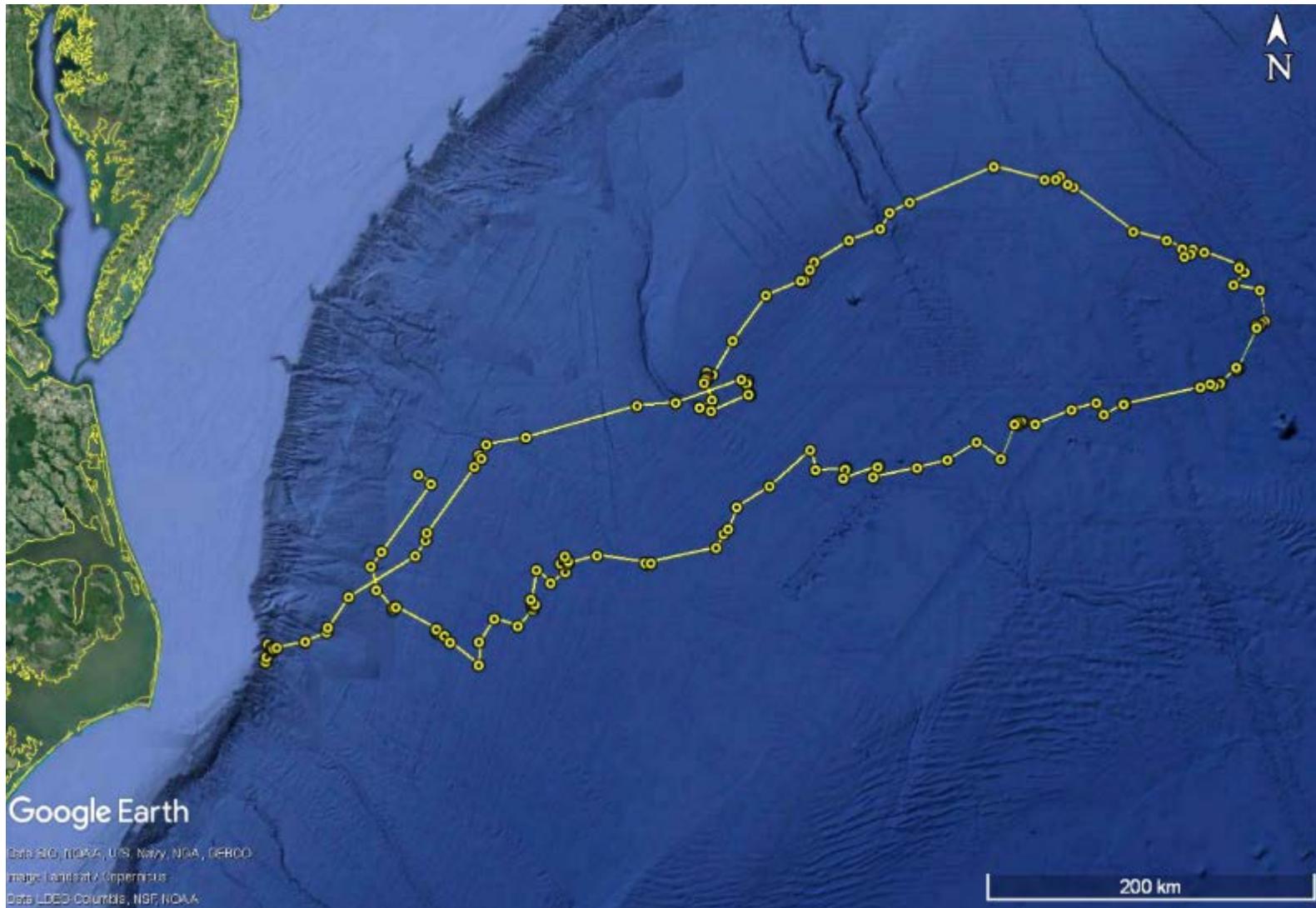


Figure 29. All filtered locations of short-finned pilot whale GmTag211 tagged off North Carolina over a 18.0-day period, 6–24 August 2018, with consecutive locations joined by a line. This individual was not a subject for the controlled-exposure experiments. GmTag211 was tagged in the same group as GmTag210 (Figure 28).

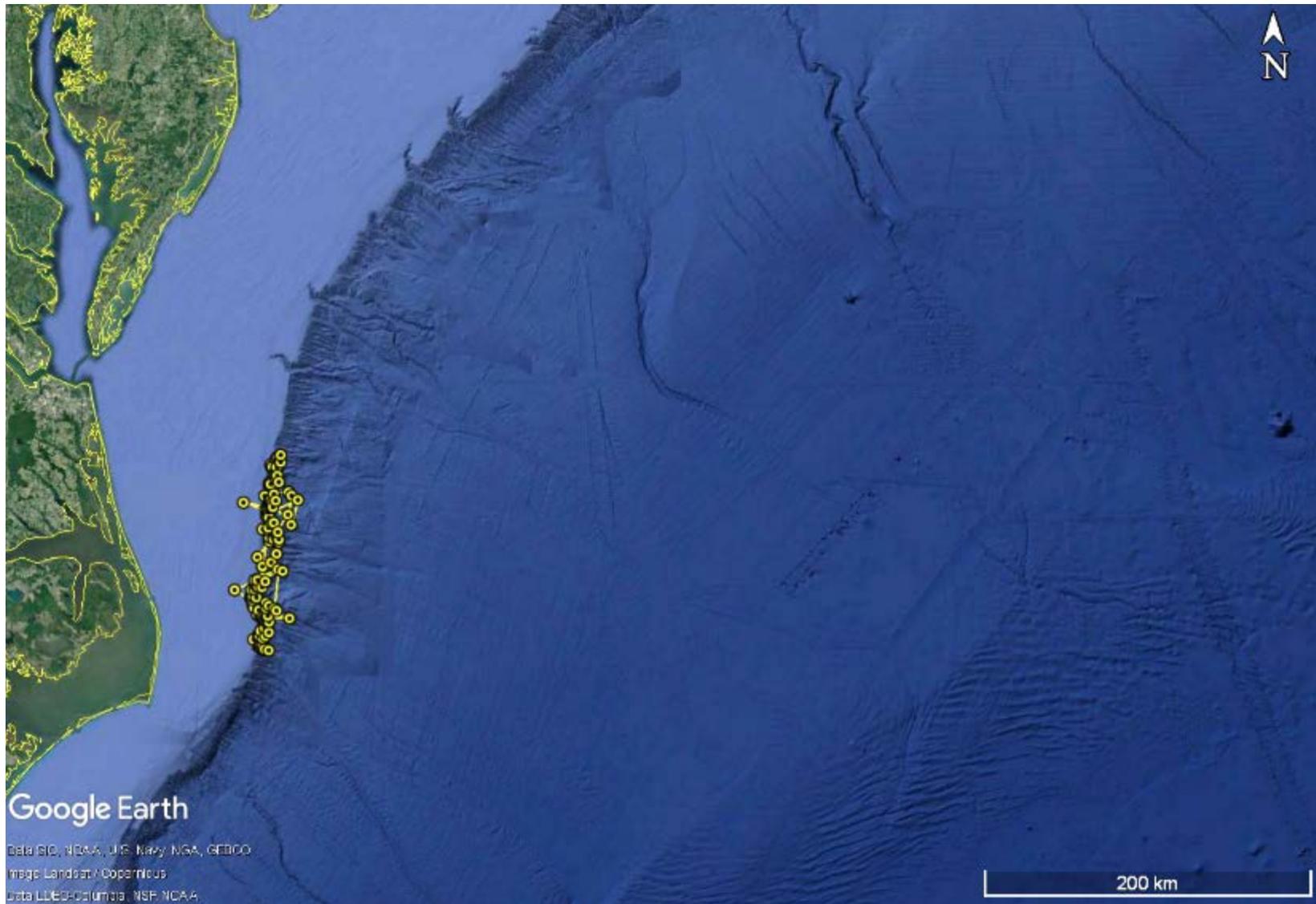


Figure 30. All filtered locations of short-finned pilot whale GmTag216 tagged off North Carolina over a 13.0-day period, 26 August–8 September 2018, with consecutive locations joined by a line. This individual was a subject for the controlled-exposure experiments.

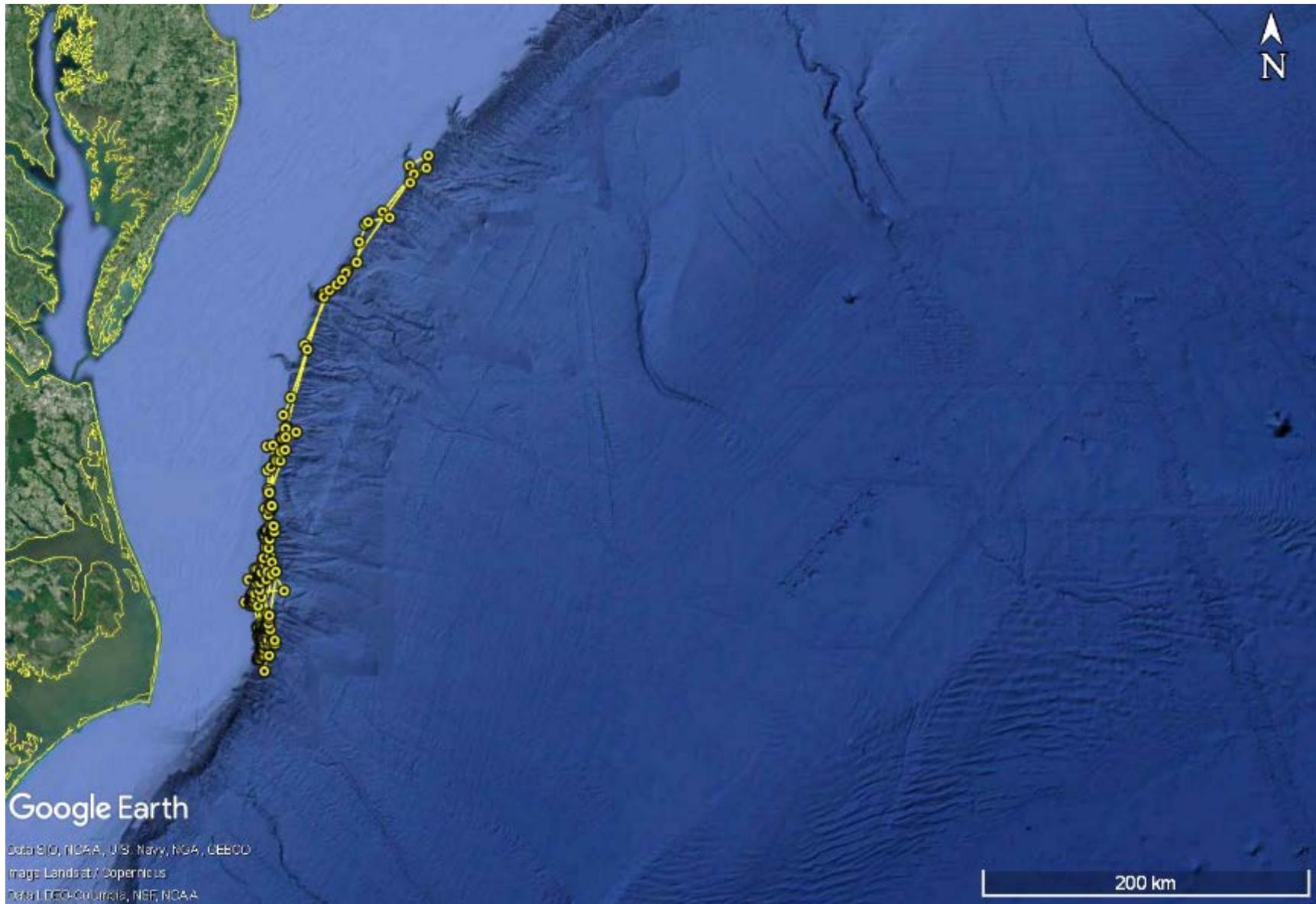


Figure 31. All filtered locations of short-finned pilot whale GmTag217 tagged off North Carolina over a 27.5-day period, 26 August–22 September 2018, with consecutive locations joined by a line. This individual was a subject for the controlled-exposure experiments.

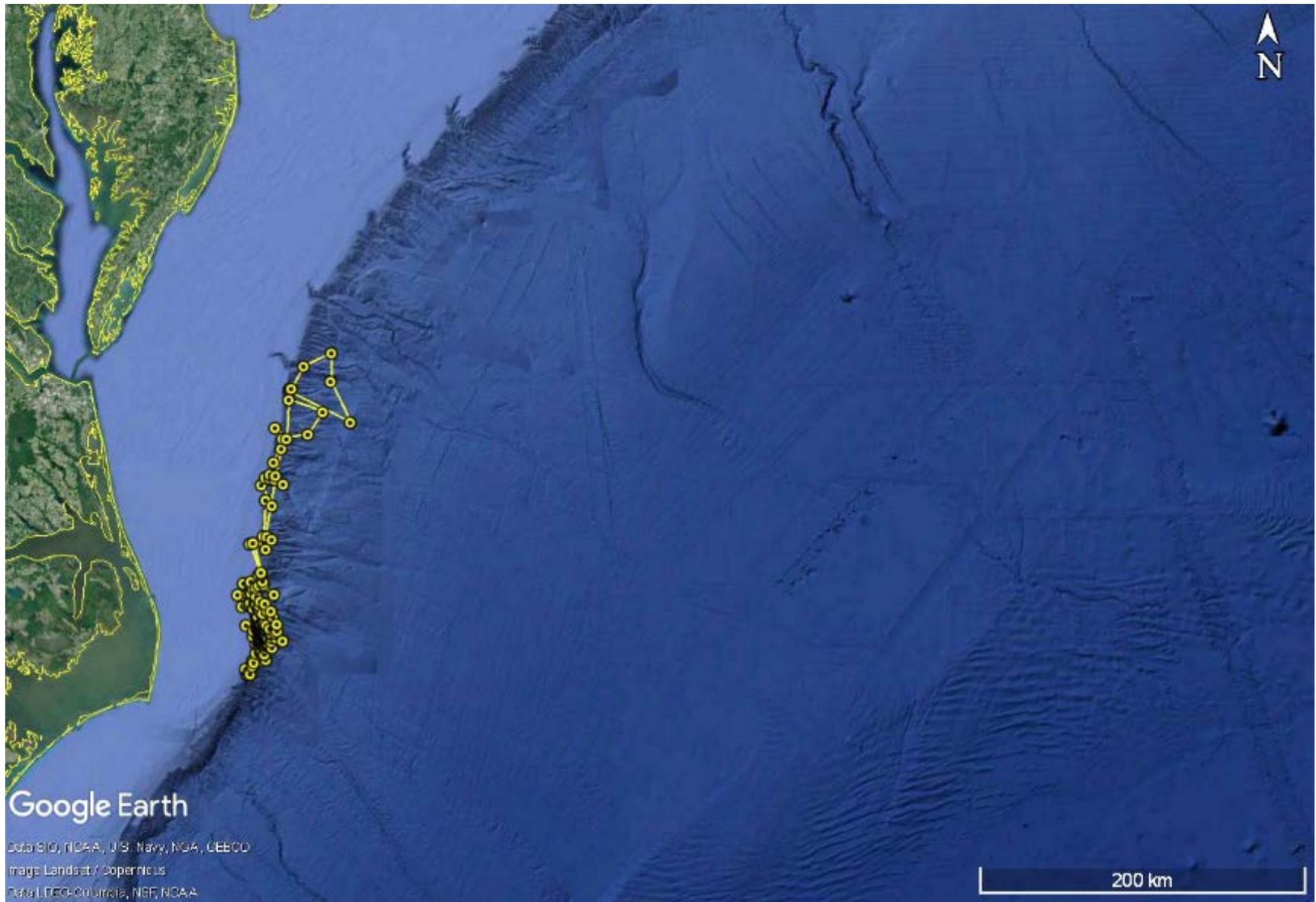


Figure 32. All filtered locations of short-finned pilot whale GmTag218 tagged off North Carolina over a 21.7-day period, 26 August–17 September 2017, with consecutive locations joined by a line. This individual was a subject for the controlled-exposure experiments.

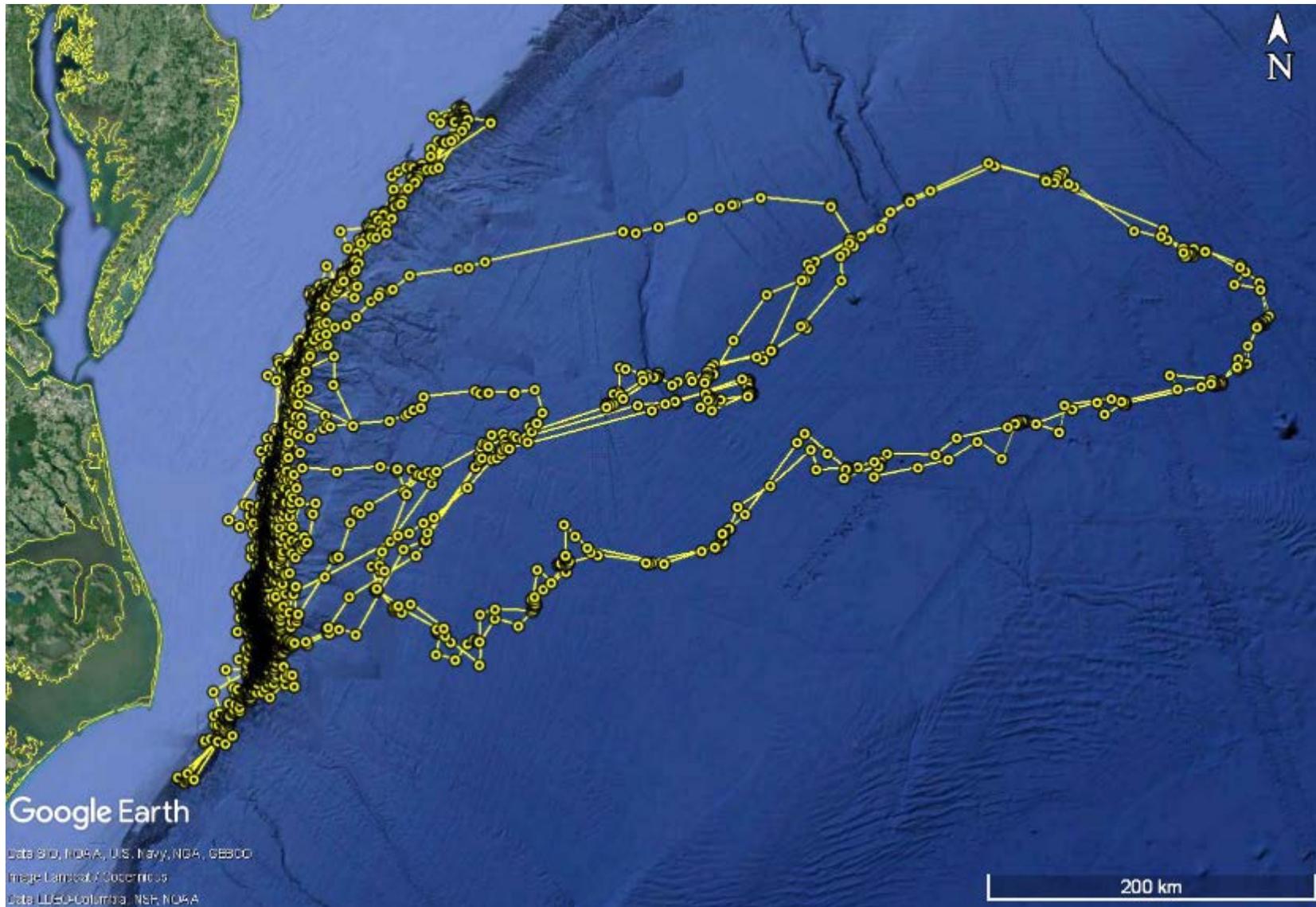


Figure 33. All filtered locations of short-finned pilot whales tagged off North Carolina in 2018, with consecutive locations of each individual joined by a line.



Figure 34. All filtered locations of short-finned pilot whales tagged off North Carolina in 2014 ($n=17$), 2015 ($n=19$), 2016 ($n=9$), 2017 ($n=11$), and 2018 ($n=17$), and off Jacksonville, Florida, in 2016 ($n=4$), with consecutive locations of each individual joined by a line. Only tag attachment durations of >1 day are shown.

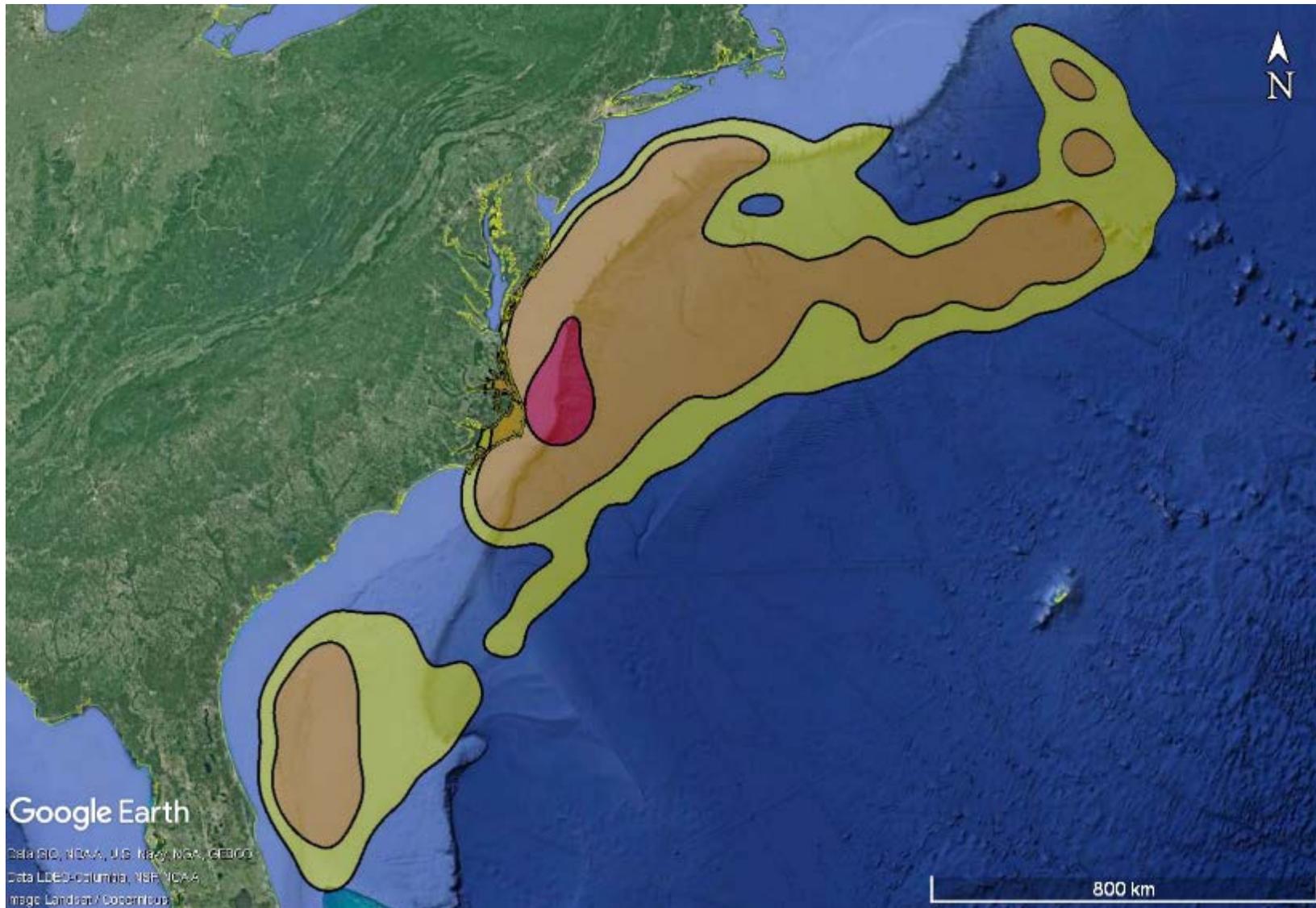


Figure 35. A probability-density representation of short-finned pilot whale location data, including individuals tagged off North Carolina in 2014 ($n=14$), 2015 ($n=17$), 2016 ($n=5$), 2017 ($n=9$), and 2018 ($n=15$), as well as Jacksonville, Florida, in 2016 ($n=2$). For pairs of individuals acting in concert, only one individual from each pair was used. Only tag attachment durations of >1 day are included. The red area indicates the 50 percent density polygon (the “core range”), the orange represents the 95 percent polygon, and the yellow represents the 99 percent polygon.



B

Tables



Table 1. Summary details of satellite-tag deployments on Cuvier's beaked whales off Cape Hatteras, North Carolina, during 2018.

Species ¹ / Tag ID	Sex/age class	Deployment date	Sighting #	Deployment latitude (°N)	Deployment longitude (°W)	Depth at tagging location (m)	Other data streams	Tag duration (days)
ZcTag069	Adult Male	5/24/2018	5	35.69	74.78	748	time series	38.90
ZcTag070	Adult Male	5/25/2018	1	35.54	74.77	977	behavior	12.52
ZcTag071	Adult Male	8/5/2018	9	35.73	74.78	1,031	none	34.33
ZcTag072	Adult Male	8/5/2018	9	35.72	74.78	985	time series	42.91
ZcTag073	Adult Male	8/5/2018	14	35.55	74.75	1,232	time series	43.63
ZcTag074*	Adult Male	8/6/2018	4	34.47	74.77	N/A	N/A	0
ZcTag075	Adult Male	8/6/2018	4	35.48	74.78	780	time series	41.38
ZcTag076	Adult Male	8/6/2018	4	35.47	74.78	872	behavior	41.78
ZcTag077	Adult Male	8/6/2018	6	35.51	74.75	1,181	FastGPS	23.72
ZcTag078	Adult Male	8/6/2018	7	35.57	74.74	1,240	behavior	23.23
ZcTag079	Adult Female/Sub-adult Male	8/7/2018	1	35.57	74.78	563	time series	43.32
ZcTag080	Adult Male	8/7/2018	3	35.56	74.78	513	time series	43.81
ZcTag081	Sub-adult Unknown	8/7/2018	3	35.59	74.75	1,124	time series	57.34

¹Zc = *Ziphius cavirostris*, m=meter(s), *tag failed on impact, N/A = not applicable

Table 2. Summary details of satellite tag deployment on short-finned pilot whales off Cape Hatteras, North Carolina, during 2018.

Species ^{1/} Tag ID	Sex/age class	Deployment date	Sighting #	Deployment latitude (°N)	Deployment longitude (°W)	Depth at tagging location (m)	Other data streams	Tag duration (days)
GmTag197	Adult Male	5/11/2018	2	35.69	74.78	695	behavior	27.03
GmTag198	Adult Male	5/22/2018	1	35.73	74.79	814	FastGPS/behavior	19.53
GmTag199	Adult Female/Sub-adult Male	5/24/2018	1	35.64	74.76	768	behavior	7.59
GmTag200	Adult Female/Sub-adult Male	5/24/2018	6	35.76	74.80	754	FastGPS/behavior	11.30
GmTag201	Adult Female/Sub-adult Male	5/30/2018	3	35.79	74.79	1,056	behavior	27.50
GmTag202	Adult Female/Sub-adult Male	5/30/2018	6	35.62	74.79	1,235	behavior	25.63
GmTag203	Adult Female/Sub-adult Male	5/31/2018	4	35.93	74.77	520	behavior	17.39
GmTag204	Adult Female/Sub-adult Male	5/31/2018	4	35.93	74.78	455	behavior	30.17
GmTag205	Adult Male	5/31/2018	5	35.92	74.78	604	FastGPS/behavior	27.28
GmTag206	Adult Female/Sub-adult Male	5/31/2018	5	35.92	74.79	618	behavior	31.56
GmTag207	Adult Male	8/5/2018	4	35.74	74.82	289	behavior	10.23
GmTag208	Adult Female/Sub-adult Male	8/5/2018	5	35.75	74.82	339	FastGPS	10.54
GmTag209*	Adult Female/Sub-adult Male	8/6/2018	2	35.49	74.73	N/A	N/A	0
GmTag210	Adult Male	8/6/2018	3	35.48	74.75	1,173	behavior	20.50
GmTag211	Adult Female/Sub-adult Male	8/6/2018	3	35.48	74.75	1,196	behavior	18.00
GmTag216	Adult Male	8/26/2018	1	35.61	74.79	498	behavior	13.02
GmTag217	Adult Male	8/26/2018	2	35.61	74.79	462	behavior	27.49
GmTag218	Adult Male	8/26/2018	4	35.66	74.78	464	behavior	21.69

Gm = *Globicephala macrorhynchus*; m=meter(s); *Tag gone shortly after deployment, likely due to a conspecific interaction; FastGPS=Fastloc-GPS locations

Table 3. Distances between pairs of Cuvier's beaked whales with temporally overlapping tag data. Distances are calculated when locations are received during the same satellite overpass. List is ordered based on the date of deployment.

Pair	Age/Sex of pair	Timing of tagging	Mean distance apart (km)	Max distance * apart (km)
ZcTag069, ZcTag070	Adult Male / Adult Male	Different day	27.7	27.7
ZcTag071, ZcTag072	Adult Male / Adult Male	Same group	25.9	25.9
ZcTag071, ZcTag075	Adult Male / Adult Male	Different day	28.6	35.5
ZcTag071, ZcTag077	Adult Male / Adult Male	Different day	7.9	7.9
ZcTag071, ZcTag077	Adult Male / Adult Male	Different day	18.6	18.6
ZcTag071, ZcTag080	Adult Male / Adult Male	Different day	31.5	31.5
ZcTag072, ZcTag073	Adult Male / Adult Male	Same day	63.0	114.2
ZcTag072, ZcTag075	Adult Male / Adult Male	Different day	45.9	108.0
ZcTag072, ZcTag076	Adult Male / Adult Male	Different day	52.9	187.8
ZcTag072, ZcTag077	Adult Male / Adult Male	Different day	160.4	160.4
ZcTag072, ZcTag078	Adult Male / Adult Male	Different day	96.6	192.0
ZcTag072, ZcTag080	Adult Male / Adult Male	Different day	34.8	62.0
ZcTag072, ZcTag081	Adult Male / Sub-adult Unknown	Different day	68.3	192.5
ZcTag073, ZcTag075	Adult Male / Adult Male	Different day	28.6	102.1
ZcTag073, ZcTag076	Adult Male / Adult Male	Different day	26.5	88.9
ZcTag073, ZcTag077	Adult Male / Adult Male	Different day	40.6	66.7
ZcTag073, ZcTag078	Adult Male / Adult Male	Different day	54.3	86.1
ZcTag073, ZcTag079	Adult Male / Adult Female	Different day	29.6	69.8
ZcTag073, ZcTag080	Adult Male / Adult Male	Different day	21.2	36.2
ZcTag073, ZcTag081	Adult Male / Sub-adult Unknown	Different day	34.1	91.4
ZcTag075, ZcTag076	Adult Male / Adult Male	Same group	17.1	48.2
ZcTag075, ZcTag077	Adult Male / Adult Male	Same day	22.8	38.8
ZcTag075, ZcTag078	Adult Male / Adult Male	Same day	42.8	69.0
ZcTag075, ZcTag079	Adult Male / Adult Female	Different day	17.1	35.0
ZcTag075, ZcTag080	Adult Male / Adult Male	Different day	8.9	23.6
ZcTag075, ZcTag081	Adult Male / Sub-adult Unknown	Different day	20.3	64.8

Pair	Age/Sex of pair	Timing of tagging	Mean distance apart (km)	Max distance * apart (km)
ZcTag076, ZcTag077	Adult Male / Adult Male	Same day	7.9	14.3
ZcTag076, ZcTag078	Adult Male / Adult Male	Same day	17.6	36.3
ZcTag076, ZcTag079	Adult Male / Adult Female	Different day	14.0	25.9
ZcTag076, ZcTag080	Adult Male / Adult Male	Different day	21.7	55.2
ZcTag076, ZcTag081	Adult Male / Sub-adult Unknown	Different day	19.5	38.4
ZcTag077, ZcTag078	Adult Male / Adult Male	Same day	28.6	37.2
ZcTag077, ZcTag079	Adult Male / Adult Female	Different day	9.0	15.7
ZcTag077, ZcTag080	Adult Male / Adult Male	Different day	21.2	22.3
ZcTag077, ZcTag081	Adult Male / Sub-adult Unknown	Different day	12.8	27.7
ZcTag078, ZcTag079	Adult Male / Adult Female	Different day	31.8	42.5
ZcTag078, ZcTag080	Adult Male / Adult Male	Different day	51.0	74.3
ZcTag078, ZcTag081	Adult Male / Sub-adult Unknown	Different day	36.2	50.2
ZcTag079, ZcTag080	Adult Female / Adult Male	Same day	18.2	32.2
ZcTag079, ZcTag081	Adult Female / Sub-adult Unknown	Same day	15.2	32.1
ZcTag080, ZcTag081	Adult Male / Sub-adult Unknown	Same group	18.5	26.7

Key. Zc = *Ziphius cavirostris* (Cuvier's beaked whale); km = kilometer(s); max = maximum; *When only a single set of locations were obtained for a particular pair of individuals, the mean and maximum distances apart are the same.

Table 4. Distances between pairs of short-finned pilot whales with temporally overlapping tag data. Distances are calculated when locations are received during the same satellite overpass.

Pair	Age/Sex of pair	Timing of tagging	Mean distance apart (km)	Max distance apart (km)
GmTag197, GmTag198	Adult Male / Adult Male	Different day	22.9	85.5
GmTag197, GmTag199	Adult Male / Unknown	Different day	102.1	217.0
GmTag197, GmTag200	Adult Male / Unknown	Different day	196.0	415.0
GmTag197, GmTag201	Adult Male / Unknown	Different day	55.8	126.7
GmTag197, GmTag202	Adult Male / Unknown	Different day	6.0	34.7
GmTag197, GmTag203	Adult Male / Unknown	Different day	15.9	32.1
GmTag197, GmTag204	Adult Male / Unknown	Different day	13.4	37.2
GmTag197, GmTag205	Adult Male / Adult Male	Different day	15.4	31.1
GmTag197, GmTag206	Adult Male / Unknown	Different day	15.3	40.6
GmTag198, GmTag199	Adult Male / Unknown	Different day	84.6	190.4
GmTag198, GmTag200	Adult Male / Unknown	Different day	161.3	417.5
GmTag198, GmTag201	Adult Male / Unknown	Different day	55.0	129.3
GmTag198, GmTag202	Adult Male / Unknown	Different day	14.9	47.7
GmTag198, GmTag203	Unknown / Adult Male	Different day	12.7	34.3
GmTag198, GmTag204	Unknown / Adult Male	Different day	13.8	31.3
GmTag198, GmTag205	Adult Male / Adult Male	Different day	16.8	42.0
GmTag198, GmTag206	Adult Male / Unknown	Different day	16.4	46.2
GmTag199, GmTag200	Unknown / Unknown	Same day	91.2	178.7
GmTag199, GmTag201	Unknown / Unknown	Different day	146.6	166.2
GmTag199, GmTag202	Unknown / Unknown	Different day	145.6	188.1
GmTag199, GmTag203	Unknown / Unknown	Different day	102.6	105.5
GmTag199, GmTag204	Unknown / Unknown	Different day	98.4	99.7
GmTag199, GmTag205	Unknown / Adult Male	Different day	104.0	105.1
GmTag199, GmTag206	Unknown / Unknown	Different day	101.0	101.0
GmTag200, GmTag201	Unknown / Unknown	Different day	241.0	407.0
GmTag200, GmTag202	Unknown / Unknown	Different day	273.9	421.2
GmTag200, GmTag203	Unknown / Unknown	Different day	290.3	419.6
GmTag200, GmTag204	Unknown / Unknown	Different day	285.1	413.5

Pair	Age/Sex of pair	Timing of tagging	Mean distance apart (km)	Max distance apart (km)
GmTag200, GmTag205	Unknown / Adult Male	Different day	292.5	410.6
GmTag200, GmTag206	Unknown / Unknown	Different day	296.5	416.2
GmTag201, GmTag202	Unknown / Unknown	Same day	72.1	225.2
GmTag201, GmTag203	Unknown / Unknown	Different day	67.3	148.8
GmTag201, GmTag204	Unknown / Unknown	Different day	63.9	309.0
GmTag201, GmTag205	Unknown / Adult Male	Different day	53.8	156.2
GmTag201, GmTag206	Unknown / Unknown	Different day	50.2	153.3
GmTag202, GmTag203	Unknown / Unknown	Different day	37.3	209.9
GmTag202, GmTag204	Unknown / Unknown	Different day	55.2	230.9
GmTag202, GmTag205	Unknown / Adult Male	Different day	36.4	222.8
GmTag202, GmTag206	Unknown / Unknown	Different day	30.7	217.3
GmTag203, GmTag204	Unknown / Unknown	Same group	15.7	63.4
GmTag203, GmTag205	Unknown / Adult Male	Different day	15.2	72.2
GmTag203, GmTag206	Unknown / Unknown	Different day	15.7	78.0
GmTag204, GmTag205	Unknown / Adult Male	Different day	39.9	285.4
GmTag204, GmTag206	Unknown / Unknown	Different day	59.5	307.7
GmTag205, GmTag206	Adult Male / Unknown	Same group	3.4	20.7
GmTag207, GmTag208	Adult Male / Unknown	Same Day	327.4	103.4
GmTag207, GmTag210	Adult Male / Adult Male	Different day	510.6	341.0
GmTag207, GmTag211	Adult Male / Unknown	Different day	508.1	325.4
GmTag208, GmTag210	Unknown / Adult Male	Different day	634.2	345.1
GmTag208, GmTag211	Unknown / Unknown	Different day	631.6	363.0
GmTag208, GmTag217	Unknown / Adult Male	Different day	25.8	25.8
GmTag208, GmTag218	Unknown / Adult Male	Different day	27.3	27.3
GmTag210, GmTag211	Adult Male / Unknown	Same group	30.0	4.5
GmTag210, GmTag216	Adult Male / Adult Male	Different day	114.8	114.8
GmTag210, GmTag217	Adult Male / Adult Male	Different day	95.5	95.5
GmTag210, GmTag218	Adult Male / Adult Male	Different day	114.2	114.2
GmTag216, GmTag217	Adult Male / Adult Male	Same day	200.0	97.1
GmTag216, GmTag218	Adult Male / Adult Male	Same day	89.2	31.6
GmTag217, GmTag218	Adult Male / Adult Male	Same day	176.0	58.1

Table 5. Characteristics of movements for satellite-tagged Cuvier's beaked whales tagged off North Carolina in 2018.

Tag ID	Number of locations after filtering	Mean (SD) distance from tagging location (km)	Maximum distance from tagging location (km)	Total distance traveled (km)
ZcTag069	60	40.0 (39.9)	167.9	1,033.3
ZcTag070	13	23.7 (14.7)	47.3	154.8
ZcTag071	6	20.2 (21.9)	61.7	105.7
ZcTag072	73	82.7 (62.4)	212.2	1,079.3
ZcTag073	64	31.7 (28.0)	100.7	1,241.7
ZcTag075	116	17.0 (13.5)	62.5	1,154.3
ZcTag076	85	18.6 (12.4)	57.8	1,067.0
ZcTag077	44	10.8 (7.3)	27.8	362.4
ZcTag078	48	19.4 (9.4)	36.9	458.0
ZcTag079	45	17.4 (10.2)	49.1	563.6
ZcTag080	68	21.9 (11.9)	55.3	618.6
ZcTag081	163	22.2 (14.3)	67.1	1,748.1

Key: Zc = *Ziphius cavirostris*; km = kilometer(s); SD = standard deviation

Table 6. Characteristics of movements for satellite-tagged short-finned pilot whales tagged off North Carolina in 2018.

Tag ID	Number of locations after filtering	Mean (SD) distance from tagging location (km)	Maximum distance from tagging location (km)	Total distance traveled (km)
GmTag197	278	21.4 (19.0)	102.3	1,514.9
GmTag198	143	20.3 (17.2)	66.4	931.4
GmTag199	63	111.1 (81.1)	215.8	532.0
GmTag200	118	178.2 (134.7)	415.4	1,106.3
GmTag201	260	68.4 (78.5)	315.0	1,819.9
GmTag202	280	70.4 (76.8)	289.8	1,754.6
GmTag203	136	40.3 (24.5)	105.3	836.2
GmTag204	334	40.5 (32.6)	177.4	1,844.4
GmTag205	211	55.8 (58.0)	299.3	1,719.8
GmTag206	157	41.8 (24.3)	128.9	1,097.2
GmTag207	92	133.7 (96.6)	321.4	1,095.9
GmTag208	161	38.8 (46.7)	208.7	1,176.5
GmTag210	171	302.5 (196.3)	635.9	1,901.8
GmTag211	146	326.3 (195.6)	634.7	1,730.0
GmTag216	112	49.2 (34.0)	107.7	786.2
GmTag217	171	66.8 (78.3)	302.0	1,502.7
GmTag218	168	27.5 (37.7)	166.8	1,178.6

Key: Gm = *Globicephala macrorhynchus*; km = kilometer(s); SD = standard deviation

Table 7. Depths and distances from shore and the 200-m isobath from GIS analysis of filtered satellite-tag locations from Cuvier's beaked whales tagged in 2018

Tag ID	Depth (m)		Distance from shore (km)			Distance from 200-m isobath (km)	
	Median	Max	Min	Median	Max	Median	Max
ZcTag069	1048.2	2.974.1	33.2	64.1	98.4	6.0	37.6
ZcTag070	449.4	2.070.3	27.2	53.4	70.0	4.5	22.6
ZcTag071	385.8	1.866.4	36.0	59.4	71.5	6.9	13.2
ZcTag072	1828.7	3.845.9	40.4	70.6	175.5	10.5	122.8
ZcTag073	1840.7	3.270.4	33.0	71.8	158.1	10.2	94.2
ZcTag075	1186.8	2.917.0	34.9	62.0	112.1	4.5	52.0
ZcTag076	1639.7	2.815.8	44.7	68.5	113.8	7.3	49.8
ZcTag077	1689.6	2.517.2	57.0	68.0	92.0	5.5	28.2
ZcTag078	1554.5	2.349.7	45.1	73.2	93.5	9.8	29.4
ZcTag079	1233.2	2.350.6	32.4	63.0	88.4	7.5	25.9
ZcTag080	917.2	2.665.6	42.0	59.9	78.3	5.1	22.7
ZcTag081	942.2	2.556.2	32.8	61.9	92.3	4.2	30.0

Key Zc = *Ziphius cavirostris*; km = kilometer(s); m = meter(s); Max = maximum; Min = minimum

Table 8. Depths and distances from shore and the 200-m isobath from GIS analysis of filtered satellite-tag locations from short-finned pilot whales tagged in 2018

Tag ID	Depth (m)		Distance from shore (km)			Distance from 200-m isobath (km)	
	Median	Max	Min	Median	Max	Median	Max
GmTag197	695.3	1,945.2	52.3	64.2	107.7	3.3	16.3
GmTag198	771.6	2,296.7	39.4	63.7	86.7	3.5	20.3
GmTag199	2,727.7	3,331.6	54.0	175.0	244.3	76.5	145.5
GmTag200	2,505.9	4,108.6	55.7	167.4	363.8	62.5	228.0
GmTag201	585.5	2,033.8	46.8	83.2	134.5	4.5	31.5
GmTag202	679.9	2,453.1	50.5	65.9	115.1	2.5	23.9
GmTag203	551.8	2,278.8	36.2	61.3	84.7	3.0	17.8
GmTag204	769.1	1,978.0	47.7	63.4	119.7	2.4	18.0
GmTag205	823.5	1,935.5	45.1	65.7	133.0	2.8	19.6
GmTag206	794.2	2,358.2	45.5	72.3	146.0	3.2	19.4
GmTag207	424.1	1,797.9	52.9	98.2	134.6	2.6	19.1
GmTag208	590.4	1,897.8	53.4	64.9	112.3	2.9	24.2
GmTag210	3,852.3	4,891.0	64.7	325.0	507.7	211.2	360.3
GmTag211	3,908.7	4,880.9	64.9	341.8	501.4	214.7	366.2
GmTag216	838.9	2,071.3	50.1	80.2	105.7	4.1	21.7
GmTag217	636.2	1,827.8	54.7	68.8	120.5	3.2	15.2
GmTag218	772.3	2,155.8	51.1	63.9	149.1	2.5	41.2

Key Gm = *Globicephala macrorhynchus*; km = kilometer(s); m = meter(s); Max = maximum; Min = minimum

Table 9. Summary of behavior data from location-depth tags with one day or more of dive data prior to controlled exposure experiments (CEE) or to transducer failure. Tags collecting only a time series of dive depths are not included. For short-finned pilot whales, dives that exceeded 75 m and 30 sec were recorded, while for Cuvier's beaked whales dives that exceeded 50 m and 33 min were recorded.

Tag ID	Number of days of behavior data pre-CEE or tag failure	Percent of total record	Number of dives	Max dive depth (m)	Max dive duration (min)
GmTag197*	3.80	99.5	185	911.5	21.5
GmTag198*	2.58	83.3	103	879.5	18.8
GmTag199*	1.16	100.0	38	687.5	11.7
GmTag203*	2.97	100.0	115	719.5	15.8
GmTag204*	2.94	100.0	114	719.5	16.3
GmTag205*	2.47	84.6	72	815.5	19.9
GmTag206*	2.90	100.0	80	831.5	20.5
GmTag207*	10.41	100.0	340	911.5	19.4
GmTag210	20.05	94.7	789	1,359.5	25.4
GmTag211^	16.59	52.5	376	879.5	21.1
GmTag217*	1.20	100.0	47	959.5	15.7
ZcTag076*	21.06	99.9	228	2,927.5	131.8
ZcTag078*	20.93	100.0	201	2,543.5	64.1

Key: m = meter(s); min = minute(s); Max = maximum; Gm = *Globicephala macrorhynchus*; Zc = *Ziphius cavirostris*; *Individuals that were subject to CEEs. ^Tags with potential pressure transducer issues part-way through tag attachment period.

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