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Loggerhead turtles are good ocean-observers in stratified mid-latitude regions

Samir H. Patel[a,*], Susan G. Barco[b], Leah M. Crowe[c], James P. Manning[d], Eric Matzen[d], Ronald J. Smolowitz[a], Heather L. Haas[d]

[a] Coonamessett Farm Foundation, 277 Hatchville Road, East Falmouth, MA, 02536, USA
[b] Virginia Aquarium & Marine Science Center, 717 General Booth Boulevard, Virginia Beach, VA, 23451, USA
[c] Integrated Statistics Under Contract to the Northeast Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 166 Water Street, Woods Hole, MA, 02543, USA
[d] Northeast Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 166 Water Street, Woods Hole, MA, 02543, USA

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ABSTRACT

Since 2009, we have deployed 167 satellite tags on loggerheads within the U.S. Mid-Atlantic Bight of the Northwest Atlantic Ocean. These tags collect and transmit location, temperature and depth information and have yielded 18,790 temperature-depth profiles during the highly stratified season (01 June –04 October) for the region. This includes 16,371 profiles exceeding the mixed-layer depth, and, of those, 11,591 full water column profiles reaching the ocean floor. The US MAB is a dynamic ecosystem that is difficult to model due to a combination of complex seasonal water masses and currents and a limited set of tools for taking *in situ* measurements. This region is also prime foraging habitat for loggerhead sea turtles during the late-spring to summer months. Here we suggest that the habitat usage of loggerhead turtles in the Mid-Atlantic Bight make them good ocean observers within this difficult to model, highly stratified region. The use of turtle-borne telemetry devices has the potential to improve resolution of *in situ* temperature through depth data and in turn improve oceanographic model outputs. It is imperative that model outputs are continuously updated, as they are regularly used to inform management and conservation decisions.

1. Introduction

Mid-latitude seasonally stratifying shelf seas (~30°–60°) represent a small portion of the global ocean (Cox et al., 2018), but they represent a vitally important component of the larger ecosystem because of their disproportionately high contribution to global productivity (Muller-Karger et al., 2005; Simpson and Sharples, 2012), their importance to commercial fisheries (Kroodsma et al., 2018), their role in supporting coastal economies (Small and Nicholls, 2003), their support of charismatic megafauna (Avila et al., 2018; Sala et al., 2017), and their climatic influence on areas with major populations centers of the world (Glenn et al., 2016; Lutjeharms and De Ruijter, 1996). The physical features of these stratified mid-latitude shelf areas make them highly dynamic (Cox et al., 2018), and their oceanography is therefore difficult to model accurately (Saba et al., 2016). Here we examine the Mid-Atlantic Bight (MAB) of the Northeast U.S. Continental Shelf Large Marine Ecosystem (NES LME) as an example of a mid-latitude seasonally stratified continental shelf sea, and we present a unique and replicable multidisciplinary approach to studying the oceanography of continental shelf waters.

The Mid-Atlantic Bight is a highly dynamic marine environment influencing coastal communities and major population centers along the east coast of the United States from North Carolina through New York. Environmental conditions in the MAB influence the productivity of regional fisheries, including portions of the Atlantic sea scallop and American lobster fishery, which have revenues exceeding hundreds of millions of dollars annually (Gaichas et al., 2016; National Marine Fisheries Service, 2017; Schofield et al., 2008; Sullivan et al., 2005).

Abbreviations: MAB, United States Mid-Atlantic Bight; NES LME, Northeast U.S. Continental Shelf Large Marine Ecosystem; MLD, Mixed-Layer Depth; CPW, Cold Pool Water; MARACOOS, Mid-Atlantic Regional Association of Coastal Ocean Observing Systems; XBT, Expendable Bathythermograph; SCL, straight carapace length; CCL, Curved Carapace Length; SRDL, Satellite Relay Data Logger; ESA, United States Endangered Species Act

[*] Corresponding author.

E-mail addresses: spatel@cfarm.org (S.H. Patel), sgbarco@virginiaaquarium.com (S.G. Barco), leah.crowe@noaa.gov (L.M. Crowe), james.manning@noaa.gov (J.P. Manning), eric.matzen@noaa.gov (E. Matzen), rjsmolowitz@cfarm.org (R.J. Smolowitz), heather.haas@noaa.gov (H.L. Haas).

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The oceanography of MAB also influences weather systems affecting upwards of 40 million people in the Washington D. C., Philadelphia, New York metropolitan corridor (www.census.gov; Glenn et al., 2016). Thermal properties are key oceanographic features that are changing relatively rapidly for the MAB (Saba et al., 2016) and are associated with fluctuations in ecological processes (Munroe et al., 2016; Nye et al., 2014) and major weather events (Glenn et al., 2013).

The MAB thermal properties (sea surface temperature (SST), mixed-layer depth (MLD), and bottom temperature) are difficult to model. SST is routinely estimated from high resolution satellite data (Reynolds and Chelton, 2010), but when cloud cover inhibits measurements, estimating the environmental conditions within this narrow region becomes difficult. Remotely sensed SST values of the MAB can have spatial inconsistencies and differ from *in situ* measurements by 1°–2 °C (Cervone, 2013) and on occasion by as much as 15 °C (Warden, 2011). Mixed-layer and bottom temperatures are difficult to predict due to contrasting currents, specifically the northward movement of the Gulf Stream in contrast to the coastal, southward moving cold water from Georges Bank (Lentz, 2017). These counter-currents yield a strong thermocline that develops during the summer across most of the Mid-Atlantic shelf and one of the largest seasonal temperature fluctuations of any ocean region (Coakley et al., 2016). In turn, the MAB develops an annual Cold Pool that forms in late May (Lentz, 2017). During the summer months, the Cold Pool water (CPW) mass warms and evolves, typically settling on the bottom between the 30-m and 70-m isobaths before dissipating in October during the autumn turnover (Lentz, 2017). Modelled water temperature in the summer at mid-depth has had relatively high errors, possibly because of the difficulty of modeling variability at this depth range during the strong summer thermocline (Li et al., 2017; Wilkin and Hunter, 2013). Ocean forecast models are regularly used for management and conservation decisions; however consequences can be dire when models are wrong (Tommasi et al., 2017).

Despite the highly dynamic environment and socio-economic importance, the NES LME has relatively minimal real-time oceanographic thermal monitoring to inform the numerical ocean models. Global programs such as Argo, have not deployed floats within the shelf waters of the MAB (www.argo.ucsd.edu). Locally, the Mid-Atlantic Regional Association of Coastal Ocean Observing Systems (MARACOOS) have limited offshore moorings, and primarily rely on glider deployments, drifting buoys, and boats outfitted with sensing equipment for offshore oceanographic data (http://oceansmap.maracoos.org/). There are also a few programs that are restricted in geographic and temporal scope. There is a 40-year time series from the Oleander Project of a near-monthly expendable bathythermograph (XBT) transect across the shelf (Rossby and Gottlieb, 1998), and in the past few years, both the Ocean Observatory Initiative with their Pioneer Array (http://oceanobservatories.org/array/coastal-pioneer/) and the Commercial Fisheries Research Foundation and Woods Hole Oceanographic Institute in collaboration with commercial fishing vessels (http://www.cfrfoundation.org/shelf-research-fleet/) began routinely sampling a section of the shelf edge within Southern New England waters.

In recent years, various data loggers affixed to marine animals have supplemented temperature data obtained from satellites, ships, fixed buoys, and gliders. The reliability of the oceanographic data from animal-borne loggers is well-documented (e.g. Boehme et al., 2009; Fedak, 2004, 2013; Nordstrom et al., 2013), including from leatherback sea turtles (McMahon et al., 2005). Data from animal-borne sensors, including on occasion human-borne (Brewin et al., 2017), are making significant contributions to oceanographic research by capturing fine-scale variability, illustrating novel oceanographic features, reducing errors in ocean models, and improving knowledge of ocean circulation in polar regions (Boehme et al., 2008; Carse et al., 2015; Grist et al., 2011; Sala et al., 2017; Wilmers et al., 2015). Many successful applications of bio-logging technology have occurred in the higher latitudes where oceanographic sampling can be challenging (Boehme et al., 2008, 2009; Charrassin et al., 2010; Fedak, 2013; Roquet et al., 2013, 2014; Simonite, 2005). For example in the far Southern Ocean, animal platforms, primarily marine mammals, now provide over half of all oceanographic profiles available (Fedak, 2013).

Sea turtles are ideal candidates as ocean observers (McMahon et al., 2005). Unlike marine mammals, the turtles' hard shell allows a strong attachment which lasts for several months and these animals exhibit only a mild stress response if handled appropriately (Allen et al., 2018), rebounding well after capture (Mangel et al., 2011). The loggerhead carapace is comprised of bone covered by keratinous scutes (Wyneken and Witherington, 2001). The vertebral scutes of late stage juvenile and adult loggerheads are well suited for tag attachment because a) they can be easily cleaned without harming the turtle, b) their proteins adhere well to epoxy, and c) uneven keels disappear by ~58 cm straight carapace length (SCL) (Brongersma, 1972 in Dodd, 1988). In addition, as loggerheads grow, vertebral scutes increase in length rather than width so that most of their vertebral scutes eventually become longer rather than wider (Brongersma, 1972 in Dodd, 1988). This means that a data logging tag can be placed within a single scute (avoiding the dynamic growth area at scute junctions) while having the narrow aspect of the tag facing forward in the most hydrodynamic position.

Regarding their at-sea habitat usage, sea turtles inhabit a large swath of the world's oceans and predictably occupy certain regions (Luschi et al., 2003). This can yield consistent long-term data from the same regions year after year. Additionally, sea turtles utilize most or all of the water column when in continental shelf waters. For example, loggerheads typically maintain residency within shelf waters, spending time foraging or resting on the sea floor (Bjorndal, 1997; Patel et al., 2016a), while leatherbacks have been known to dive to over 1000 m (Houghton et al., 2008). Finally, sea turtles exhibit individual level phenotypic variability in their at-sea behavior (Robinson et al., 2016) which means that deploying tags on a few turtles has the potential to return oceanographic data from many unique locations allowing for a more comprehensive assessment of a region.

In this paper, we examine loggerhead turtles and temperature data from attached satellite-relay data loggers to evaluate this species as a platform for ocean observation in a mid-latitude, seasonally-stratified, continental shelf region. The primary hypotheses of this research were a) loggerheads fit the physical requirements for affixing animal-borne data loggers, b) loggerhead diving behavior in the MAB yields a large quantity of full water column profiles within this difficult to model, highly stratified region, and c) increasing the number of data logger deployments on loggerheads improves resolution of monitoring MAB thermal properties. We propose the turtle-bourne data collection as an addition to our local observing system. The data described here are especially useful in that they provide an otherwise difficult to acquire assessment of the thermal structure of the highly dynamic MAB and can be easily integrated to improve regional temperature models.

2. Methods

2.1. Loggerhead capture and instrumentation

Between 2009 and 2017, we captured loggerhead turtles in the Mid-Atlantic either by the use of a large dip net from a small inflatable boat or during controlled testing of experimental fishing gear (trawl and gillnet) aboard a commercial fishing boat. Dip net captures occurred between May and September, while the experimental fishing gear captures occurred in February off of North Carolina. Once netted, turtles were brought aboard larger vessels (fisheries research vessels or chartered commercial fishing boats) for processing. Turtles were weighed and/or their length was measured to ensure compliance with the United States Endangered Species Act (ESA) permitting requirements that the total combined weight of all transmitter attachments was less than 5% of the turtle's body mass. Turtles were held on deck while we attached a satellite tag to the carapace of each turtle using a two-

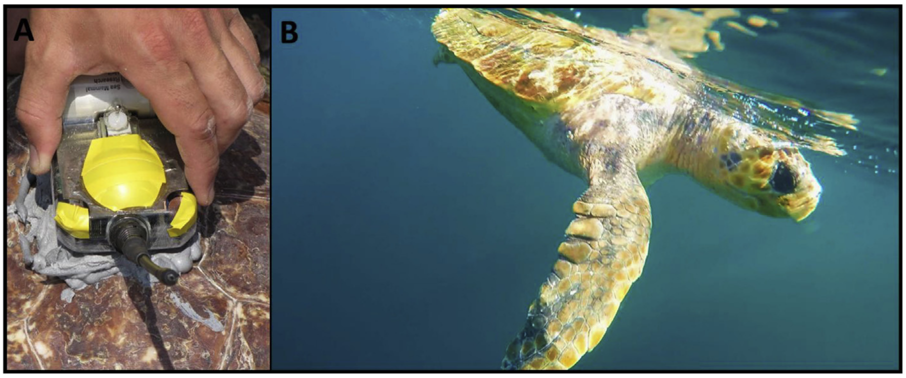

Fig. 1. A) Attachment of Sea Mammal Research Unit Satellite Relay Data Logger (SRDL) used to collect movement and oceanographic data from the turtle. B) Loggerhead turtle carapace breaching the water surface.

part epoxy. See Patel et al. (2016b) and Barco and Lockhart (2017) for full details on capture and handling protocols.

The satellite relay data loggers (SRDL) we deployed were manufactured by Sea Mammal Research Unit at University of St Andrews Scotland (Fig. 1a). Each tag reported location (GPS for the first 3 months of deployment and ARGOS for the remainder), depth and temperature. The transmission duty cycle was set to deliver ~1 complete temperature-depth profile per day from a deep dive. The tag sampled temperature and pressure at a 4-second rate. The pressure sensors were accurate to 1% of the depth range (Boehme et al., 2009). McMahon et al. (2005) compared the thermistor of the SMRU SRDL to relevant ARGO float data, and found no differences. Additionally, given a very small temperature time response of ~1 s, the tags were capable of recording an accurate water column profile (Roquet et al., 2011). The ascending temperature-depth profile was reduced to 10 values using a combination of fixed depths and “broken-stick” inflection point selection algorithm as described in Fedak et al. (2002), and only the ascending profile was transmitted. We removed some profiles to ensure data quality.

Tag data were analyzed to investigate individual tag performance, specifically, how often tags last longer or failed sooner than expected. Each tag was programmed to last thirteen months in a tradeoff of longevity versus finer scale data collection and transmission abilities. Tag duration was gathered from all tags deployed between August 2009 and September 2016. The tag start time was the time the tagged turtle was deployed from the ship. The end date was either the time where an event occurred to terminate natural behavior (turtle was known to be dead, injured or sick or the tag was recovered separate from the turtle) or the last transmission from the tag.

2.2. Loggerhead distribution within the MAB

For loggerheads to be good MAB ocean observers, they would need to be present in the MAB in times and areas with CPW and strong thermoclines, as these are strata where the water column is difficult to model accurately. We defined the MAB as north of 35.2° N, east of −76.0° W, south of 41.1° N, and west of −70.0° W (Ecosystem Assessment Program, 2012). In all cases where we compared tag data to bathymetry, we used the ETOPO1 Ice Surface Global Relief Model (National Centers for Environmental Information/NOAA). Because ETOPO1 is a 1 arc-minute global model, we expect there to be variations between actual and modelled bathymetry values due to fine scale variations in bathymetry, and we expect variation between true and modelled depth in regions of extreme bathymetric changes, such as Hudson Canyon. To account for these expected variations, we identified bottom depth as any depth value within 15% of modelled bathymetry. Temperature-depth profiles that included a temperature from the bottom were considered full water column profiles.

To identify the time period influenced by CPW, we plotted the surface and bottom temperatures from the profiles within the 30-m to 70-m isobaths region (Lentz, 2017). We selected a broad temporal window (Julian day 121–304, 01 May to 31 October) which generally coincides with the stratified season within the MAB (Schofield et al., 2008). We defined the surface temperature as the shallowest temperature reported in the profile. Average depth of surface temperature was 2.0 m. We defined the bottom temperature as the deepest temperature from a full water column profile. We then used the time period with strong separation between surface and bottom temperatures as a temporal envelope for evaluating loggerhead distribution within the MAB.

To evaluate whether loggerhead distribution provided sampling throughout the water column, we first examined a cross section of the of the MAB continental shelf waters in an area (from 39° N to 40° N) with frequent CPW (Lentz, 2017). We plotted profiles in relationship to bathymetry and longitude for profiles collected within the stratified season between 2009 and 2017. We estimated the bathymetry as the maximum ETOP1 depth at every 0.01° of longitude between 39° N and 40° N latitude. We also assessed whether temperature sampling occurred throughout the water column in the larger MAB by examining data from dives that exceed the MLD and/or reached the bottom. For each collected profile position, MLD was obtained from the HYCOM Global Analysis model (GLBa0.08). Profiles were analyzed to determine if they had reached below the MLD. All profiles reaching the bottom, were also considered to have exceeded the MLD. We examined the spatio-temporal distribution of deep sampling dives by mapping the location of full water column profiles per month. We do not show maps for profiles that went through the MLD because they were similarly distributed as the full water column profiles.

2.3. Sample size considerations

In order to explore the number of turtle-borne data loggers that would be needed to achieve consistent monitoring of MAB thermal properties, we investigated how frequently tags provided at least one complete profile per week. We plotted the percent of tags that had at least one profile meeting the depth threshold (MLD or bottom), and we identified the percent of tags that had at least one qualifying profile in every week within the stratified season. Because our tags were programmed to last longer than a year and to allocate more transmission time to behavioral data than oceanographic monitoring, this represents the low end of what could be achieved with a tag parameterized for a shorter overall time period or a tag parameterized with more emphasis on oceanographic data collection.

3. Results

The temperature, depth, and location data from the turtle-borne

Table 1
Summary table of sample sizes of usable tag deployments and temperature-depth profiles within the MAB from Julian day 152–277.

Year	Sample size (n)			
	Tags Deployed	Total profiles	Profiles to MLD	Profiles to bottom
2009	2	563	360	100
2010	14	1356	1082	775
2011	26	3485	3022	2062
2012	32	3950	3633	2638
2013	18	2740	2423	1786
2014	18	2078	1852	1348
2015	9	626	575	420
2016	21	1643	1435	1038
2017	22	2349	1989	1424
TOTAL	162	18,790	16,371	11,591

sensors described below are available for download at this website: https://www.nefsc.noaa.gov/psb/turtles/.

3.1. Loggerhead capture and instrumentation

Since 2009 we captured and tagged 167 loggerheads within the MAB. While tagged, one of these turtles spent time in the MAB only outside the stratified season, and four of the tags did not transmit after deployment. This reduced our usable sample size to 162 tags (Table 1).

All captured loggerheads were large enough to carry a substantial data logger. The lightest turtle was 19.0 kg, which is ESA permitted to carry up to a 950-g tag-attachment combination. Most loggerheads were much heavier (mean = 64.6 kg) and large enough (mean curved carapace length [CCL] = 78.0 cm; SCL = 73.2 cm) that vertebral keels were not present. Some of the vertebral scutes of the six loggerheads shorter than 58 cm SCL had the slight appearance of keels still present, but they were so minimal that it did not interfere with tag placement. Fig. 1b shows a tagged loggerhead resting with the head, flippers, and most of the body submerged, but with the most dorsal part of the carapace and the entire tag above the water line. This allowed for regular communication of the SRDL with the overhead satellites.

Mean tag duration (for the subset of usable tags deployed between 2009 and 2016, *n* = 144) was 340.2 days, and total duration ranged between 23.3 days and 703 days (Fig. 2). Within monthly bins, the tag durations peaked at 13 months (*n* = 18), 12 months (*n* = 16) and 14 months (*n* = 14). About a fifth (18.8%) of the tags did not last longer than six months, but almost half (44.4%) of tags did last the programmed 13 months (395 days).

3.2. Loggerhead distribution within the MAB

Tagged loggerheads were present in the MAB and diving to the bottom during periods with strong CPW signals. Between 01 May and 31 October (across all years), we collected 11,498 profiles in the CPW zone of 30–70 m. The mean number of profiles per yearday throughout the whole water column in this time and area was 62.5 (± 33.7 SD). Mean surface temperature for these profiles was 22.3° (± 2.8 °C SD), and mean bottom temperature was 11.0° (± 2.8 °C SD).

The period of Julian day 152 (01 June in non-leap years) and ending on Julian day 277 (04 October in non-leap years) between 2009 and 2017 had large temperature differences between surface water and bottom water (Fig. 3), so we used this temporal window as an envelope for strong stratification in the MAB and for examining loggerhead distribution within the MAB. Our temperature sampling within the MAB prior to 01 June is relatively infrequent due to our cruise schedule for tag deployment and also due to turtle migration patterns. We selected the end date to be prior to the autumn mixing events and to equally divide the season into 7-day bins. During this highly stratified season, 162 tagged loggerheads were present in the MAB and collected 18,790 profiles (Table 1).

Examining cross sections of the MAB shelf in regions of CPW formation (Fig. 4) revealed that the tagged turtles were sampling throughout the water column in June through September, particularly between 73° and 74° W. There were fewer samples west of 73°, partially because it represents a smaller area but also because the turtle distribution was centered further offshore (Winton et al., 2018). East of 73° W, Hudson Canyon dropped below 80 m and we did not receive temperature data from depths greater than 80 m.

Deep sampling dives were distributed across the MAB, particularly between the 30 and 70-m isobaths (Fig. 5). Fewer bottom dives occurred north of Hudson Canyon early (June) and late (September) in the foraging season. Loggerheads carried most data loggers through the MLD to the ocean floor. All 162 tags present in the MAB exceeded the MLD, and a total of 16,371 profiles captured this ocean feature. Most (160 of 162) tags went to the bottom recording a total of 11,591 full water column profiles. Of all the dives that did not go to the bottom (*n* = 7199), two thirds (66.6%) exceeded the MLD. The dives beyond

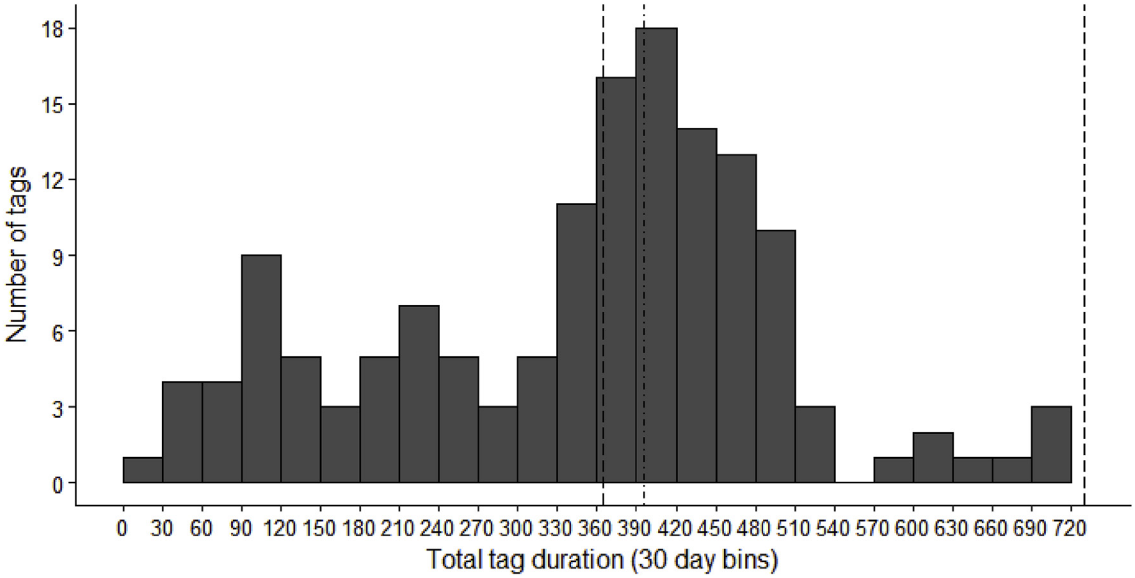

Fig. 2. Satellite tag lifespans. Long dashed lines are year demarcations, dash dot line is the 13 month mark the tags were programmed to achieve.

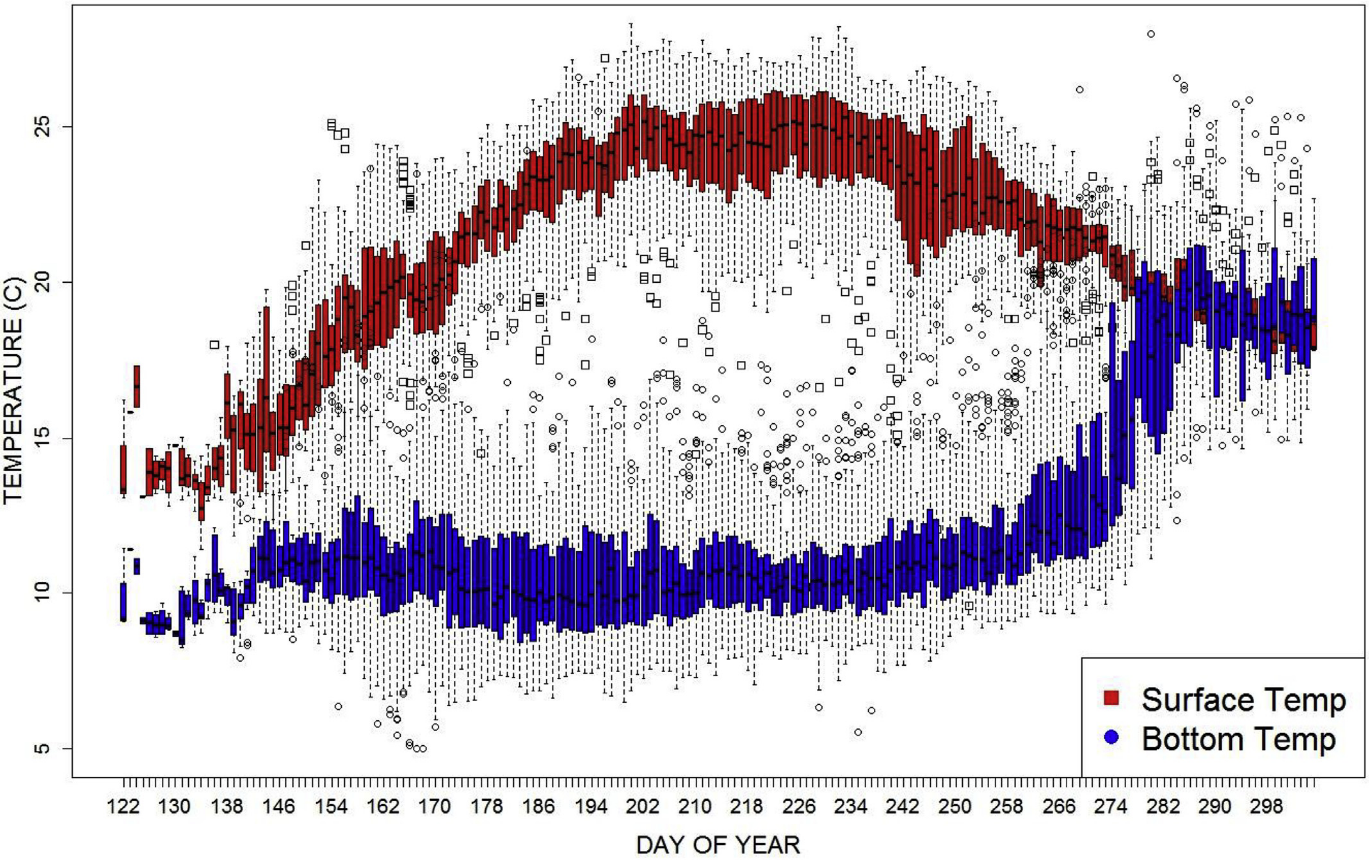

Fig. 3. Daily bin of all recorded surface and bottom temperatures from bottom dives between the 30 and 70 m isobaths from May 1 to Oct 31 for all sample years, 2009–2017. Horizontal bars = median; box = 50%; whiskers = range of observations within 1.5 times the interquartile range from edge of the box; open circles/squares = observations farther than 1.5 times the interquartile range for bottom and surface temperature respectively.

the MLD and to the bottom were widely distributed across weeks (Fig. 6).

3.3. Sample size considerations

The majority of tags sampled temperature throughout the entire water column at least once per week during the highly stratified season. Most tags that went through the MLD also sampled to the bottom. In reference to how well individual tag-turtle pairs performed, about a third of the tags returned at least one profile through the MLD (34.0%) and to the bottom (30.6%) in every week of the stratified season. Nearly half returned profiles through the MLD (48.8%) and to the bottom (41.3%) in all but one week of the stratified seasons, and over half returned profiles through the MLD (55.0%) and to the bottom (51.5%) in all but two weeks of the stratified seasons.

4. Discussion

The evaluation of our data has identified that the temperature-depth profiles obtained from turtles within the MAB regularly captured the MLD and CPW signatures. Tag durations were such that coverage within the MAB lasted the entire summer and could be used to track the evolution of the CPW and identify the autumn turnover event. Additionally, previous spatial analyses found that loggerheads tagged within the Northwest Atlantic primarily restrict their summertime distribution to the continental shelf waters and on occasion include excursions into adjacent bays and estuaries (Winton et al., 2018). Overall, environmental data collected from turtle-borne sensors can be used to improve understanding of temperature through depth within the Mid-Atlantic Bight.

The realization that loggerheads can be excellent ocean observers emerged from our conservation research programs. We applied data logging tags to learn about loggerhead behavior and the environment, and we later realized an extensive oceanographic dataset was emerging as a byproduct of this effort. The tag programming and sensors can be modified to achieve oceanographic objectives. To be clear, we are not advocating that oceanographers capture protected sea turtle species to instrument them with elaborate data collection systems. Rather, we are recognizing that important synergies and strong collaborations can emerge between protected species research programs, instrument manufacturers, and oceanographers. Resulting data can be used to manage and recover loggerheads, better map the distribution and by-catch of other protected species, predict ecosystem fisheries interactions, and improve forecast modelling.

Due to the relatively large population of loggerheads and the consistent reporting from the satellite transmitters, less effort is required to obtain oceanographic data from turtles in the MAB than to obtain the same amount of data using traditional methods of shipboard CTDs, gliders and moorings. For example, one of the longest running programs within the region to collect oceanographic data is the Oleander Project, which since 1995 has contributed to at least 33 peer-reviewed publications (http://www.aoml.noaa.gov/phod/goos/oleander/index.php). This project is a partnership that started in 1977 between researchers and the MV Oleander that takes a weekly shipping route from New Jersey to the Bahamas (Rossby and Gottlieb, 1998). During this transit, researchers deploy XBTs to measure temperature through depth. Since 2000, this project has yielded between 38 and 324 profiles per year, across a narrow band within the region (http://www.aoml.noaa.gov/phod/goos/oleander/index.php). Similarly, since 2009, tagged turtles have accrued an average of ~1450 full water column

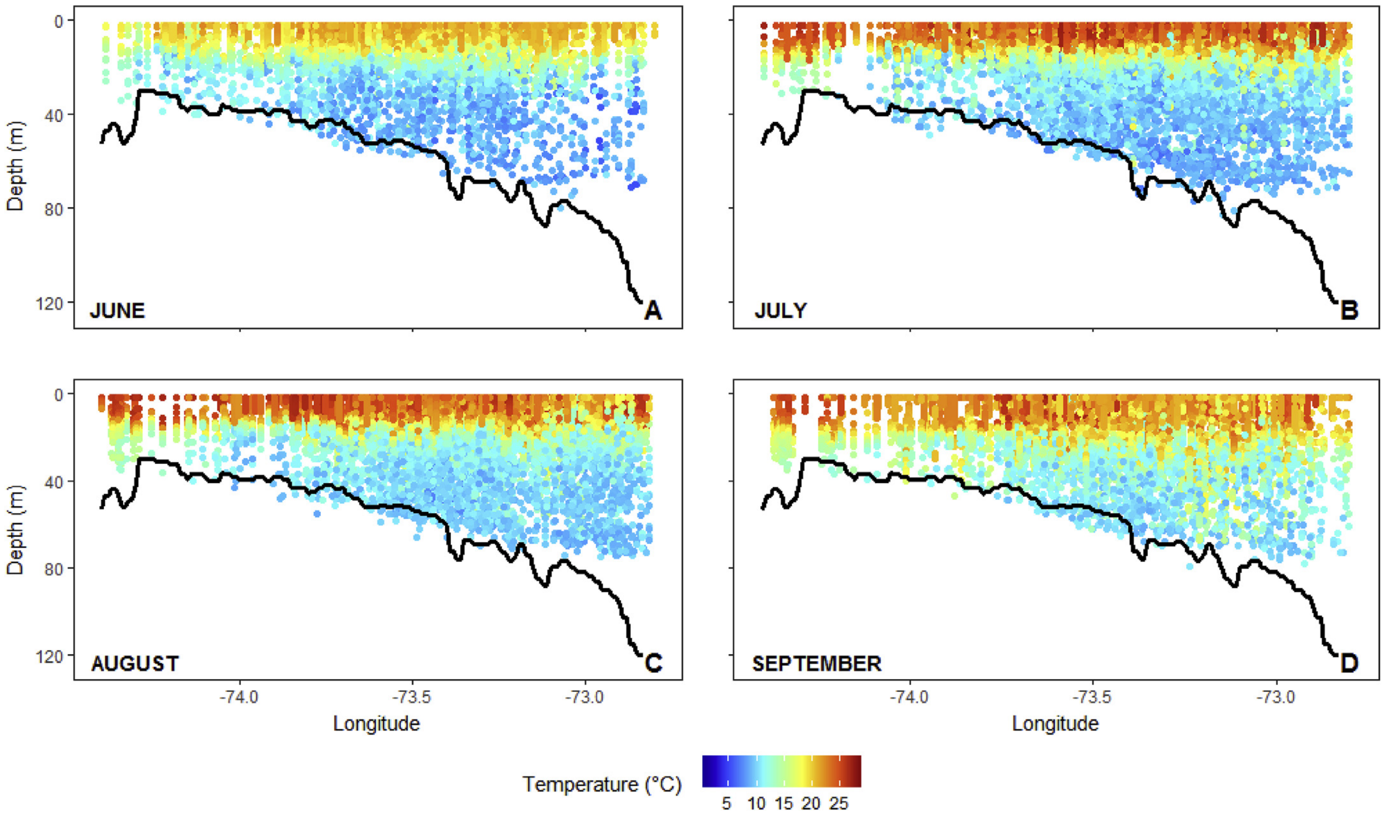

Fig. 4. Temperature-depth profiles for bottom dives occurring between latitudes 39° N and 40° N along the continental shelf. This degree of latitude tends to have the largest difference in surface and bottom temperature as a result of the seasonal CPW (Lentz, 2017). Left along the X axis for each graph is closest to shore. Solid black bathymetry line represents the maximum depth at every 0.01° of longitude between 39° N and 40° N latitude. A) Temperature-depth profiles for June 2009–2017; B) Temperature-depth profiles for July 2009–2017; C) Temperature-depth profiles for August 2009–2017; D) Temperature-depth profiles for September 2009–2017.

profiles within the MAB per year with much wider spatial coverage.

It is imperative that rigorous *in situ* sampling continues, as current extrapolation methods for determining temperature in this region lack appropriate resolution. This has the potential to impact a range of analyses dependent on these models, including fisheries assessments (Kleisner et al., 2017) and climate change projections (Saba et al., 2016). Recently, Forsyth et al. (2015) identified that warming in the MAB has accelerated since 2002 and Saba et al. (2016) projected that this warming is expected to continue at a rate faster than the global average. Rising SST has also been correlated with the increase in western Atlantic hurricanes; an only 0.5 °C increase in August and September SST at the main hurricane development region yielded a ~40% increase in hurricane frequency and intensity (Saunders and Lea, 2008). Additionally, this region is undergoing destabilization of the Gulf Stream, a critical feature of the entire North Atlantic (Andres, 2016). By adding new layers of resolution from the hundreds of turtle tags in the region, ocean models and climate change projections can become much more accurate. Turtles at sea have also been known to withstand and potentially collect oceanographic information during stochastic events like major storms (Dodd and Byles, 2003; Monzón-Argüello et al., 2012) when remote sensing is the only safe option for data collection.

As noted in Årthun et al., 2013, Boehme et al. (2009), and Lydersen et al. (2002) animals tend to be "adaptive samplers" in that they focus on frontal regions, places that are of most interest to oceanographers attempting to resolve fine-scale processes. Biuw et al. (2007) documented an extensive collection of dives by eighty-seven elephant seals around the entire Antarctic Ocean to investigate their body condition relative to the oceanographic states over a three year period. Nordstrom et al. (2013) compared temperature estimates from data loggers on Northern Fur Seals in the Bering Sea to shipboard CTD casts. Average temperature differences between the ship casts and seal dives were minimal (< 0.6 °C, mostly related to slight differences in positions and times of compared casts), but the seals collected an order of magnitude more data. The loggerheads in this study overlapped with the unique and difficult to model aspect of the MAB's oceanography, the Cold Pool. Turtles arrived within the MAB in late May, as the Cold Pool forms and departed in early October, as the autumn turnover causes the Cold Pool to dissipate. Most recently, Lentz (2017) assimilated 50 years of temperature profile data from the region to identify the long term trends of the Cold Pool. Although this accounted for 8000–10,000 profiles per month from March through October, data were collected non-uniformly, with spatially varying concentrations (Lentz, 2017). This turtle derived data would not only add an additional > 10,000 profiles within the MAB overlapping the Cold Pool, but also would help smooth the spatial concentrations to reduce associated biases.

The utility of the data collected from the turtle-borne instruments depends on the accuracy and parameterization of the instruments. Even though the SMRU tags we deployed were optimized to collect behavioral data, the resulting dataset appears to accurately depict oceanographic information with one notable discrepancy. About 5% of the dives appeared to be deeper than the bottom. This was either due to inaccuracies in the pressure sensor, the bottom depth smoothing of the ETOPO1 model or offset latitude and longitude readings for the precise location of the bottom depth measurement. We suspect the second two rationales are the most likely culprits as Boehme et al. (2009) discuss the accuracy and consistency of the pressure sensor in these satellite tags. First, the ETOPO1 model has a resolution of ~2 km, which invariably will result in minor discrepancies (Amante and Eakins, 2009). Second, the location data from the tags don't necessarily correspond to exactly where that turtle reached the bottom, as locations are only measured when the turtle is on the surface. To address these and other possible issues, we recommend further comparisons between these

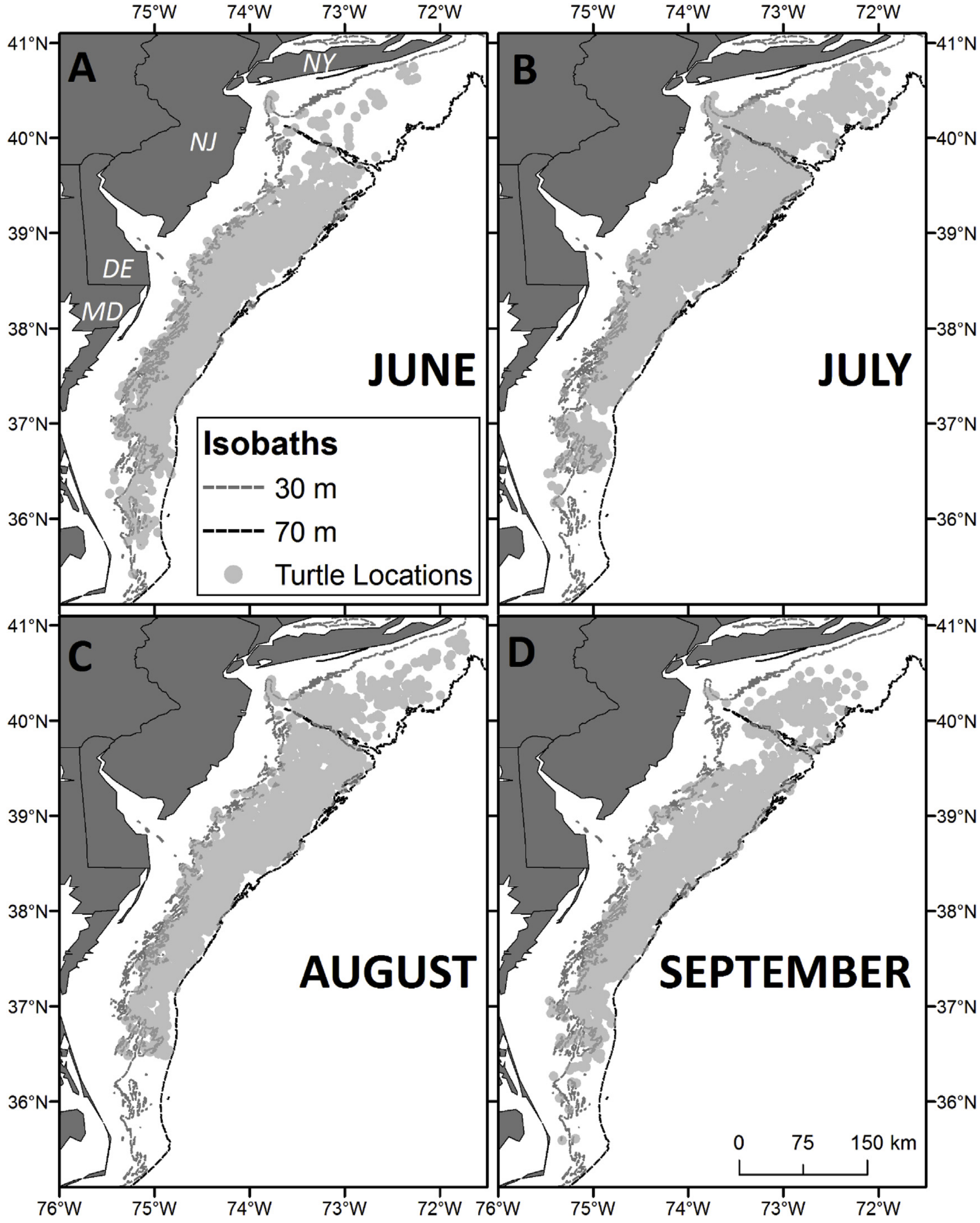

Fig. 5. Locations of all recorded bottom dives by month between 30 and 70 m isobaths within the Mid Atlantic Bight of the Northwest Atlantic Ocean. A) June: n = 2516 dives; B) July: n = 2788 dives; C) August: n = 2636 dives; D) September: n = 2368 dives.

results and other *in situ* and modeled data.

The use of environmental data collected from turtle-borne SRDLs is a unique and replicable method for studying the oceanography of mid-latitude seasonally stratified continental shelf waters. Sea turtles' morphology and behavior make them effective ocean observers due their ability to carry high yield satellite tags for long durations, their consistent annual migration and foraging behaviors, and their tendency to use a broad range of the marine environment, both horizontally and vertically through the water column. Satellite tagging of sea turtles is a relatively common method for studying the at-sea behavior of these species, and has been, and continues to be, employed throughout the world (Godley et al., 2008). There are opportunities for multidisciplinary research with turtles as ocean observers in mid-latitude coastal oceans. *In situ* data are important for improving accuracy of remote sensed ocean temperature data and climate forecasts (Reynolds et al., 2005). In the MAB, we suggest using these data to improve understanding and forecasting of the strong summer temperature stratification feature (Lentz, 2017) and stochastic events like warm core rings and major storms. In other parts of the world, we expect turtles are similarly interacting with key environmental features (Polovina et al., 2000, 2004; Dodd and Byles, 2003; Monzón-Argüello et al., 2012) and where multidisciplinary projects are warranted, turtle-borne loggers could collect *in situ* data in difficult to monitor environments like coral reef lagoons (Van Wynsberge et al., 2017) or remote continental

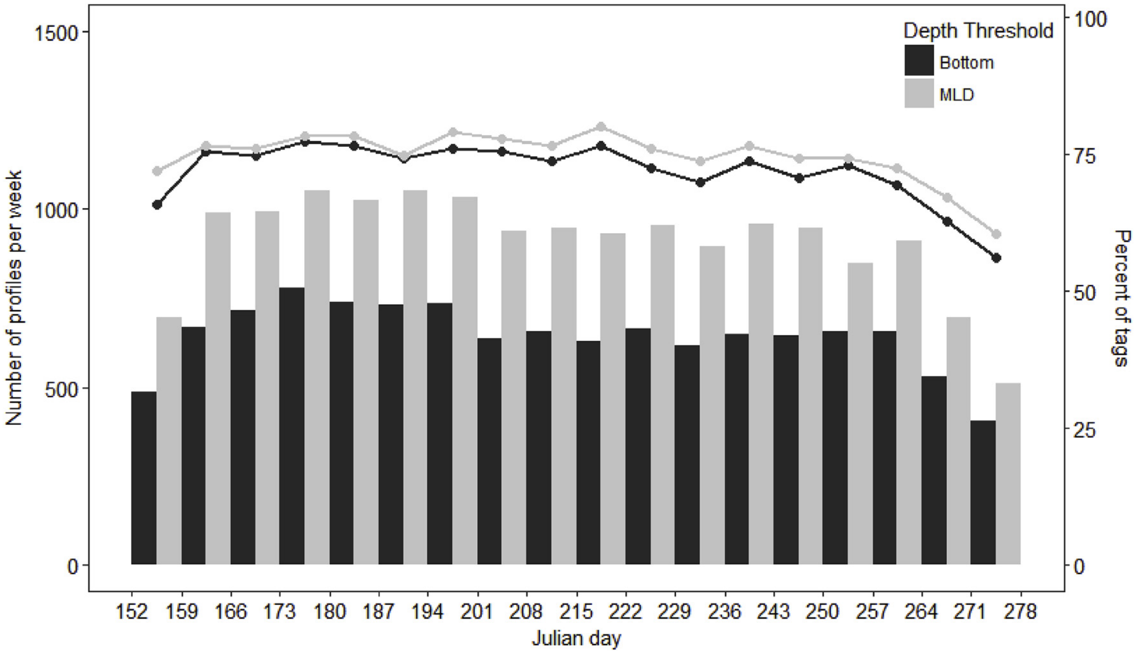

Fig. 6. Bars represent total number of profiles passing through the MLD (grey) and reaching the bottom (black), and the lines represent the percent of deployed tags (n = 167) returning profiles which meet the two depth thresholds (MLD and depth) per week across all years, 2009–2017 from Julian day 152–277.

shelf waters (Smale and Wernberg, 2009). We expect that the assimilation of over 18,000 temperature-depth profiles from the loggerheads can improve ocean models and lead to better understanding of animal growth and distribution as well as improved decision making for protecting and managing the many valuable species within the region.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.ecss.2018.08.019.

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