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

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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

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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-