Important declarations

Please remove this info from manuscript text if it is also present there.

Associated Data

Data supplied by the author:
The raw data include the (1) satellite and GPS data for the drifters, (2) weather data (wind speed, direction, etc), and (3) 2019 cold-stunned sea turtle stranding locations. Codes include python algorithms used to calculate (1) the direction and (2) the distance the drifters traveled to estimate the heading and speed.

Required Statements

Competing Interest statement:
The authors declare that they have no competing interests.

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Developing subsurface drifters to better predict the stranding locations of cold-stunned sea turtles in Cape Cod Bay, Massachusetts

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Every fall, critically endangered sea turtles are threatened by rapidly declining water temperatures. When sea turtles become hypothermic, or cold-stunned, they lose mobility—either at the surface, subsurface, or the bottom of the water column—eventually stranding at the shoreline where rescue teams associated with the Sea Turtle Stranding and Salvage Network may search for them. Understanding the effects of ocean currents on the potential stranding locations of cold-stunned sea turtles is essential to better predict stranding hotspots and increase the probability of successful discovery and recovery of turtles before they die in the cold temperatures. Traditional oceanographic drifters—instruments used to track currents—have been used to examine relationships between current and stranding locations in Cape Cod Bay, but these drifters are not representative of sea turtle morphology and do not assess how subsurface currents affect stranding locations. To address these knowledge gaps, we designed new drifters that represent the shape and dimensions of sea turtles—one that can float at the surface and one that sinks to the bottom—to track both surface and subsurface currents in Cape Cod Bay. We found a marked difference between the trajectories of our new drifter models and those that were previously used for similar research. These findings bring us one step closer to identifying the transport pathways for cold-stunned sea turtles and optimizing cold-stunned sea turtle search and rescue efforts in Cape Cod.

Manuscript Title

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Abstract

Every fall, critically endangered sea turtles are threatened by rapidly declining water temperatures. When sea turtles become hypothermic, or cold-stunned, they lose mobility—either at the surface, subsurface, or the bottom of the water column—eventually stranding at the shoreline where rescue teams associated with the Sea Turtle Stranding and Salvage Network may search for them. Understanding the effects of ocean currents on the potential stranding locations of cold-stunned sea turtles is essential to better predict stranding hotspots and increase the probability of successful discovery and recovery of turtles before they die in the cold temperatures. Traditional oceanographic drifters—instruments used to track currents—have been used to examine relationships between current and stranding locations in Cape Cod Bay, but these drifters are not representative of sea turtle morphology and do not assess how subsurface currents affect stranding locations. To address these knowledge gaps, we designed new drifters that represent the shape and dimensions of sea turtles—one that can float at the surface and one that sinks to the bottom—to track both surface and subsurface currents in Cape Cod Bay. We found a marked difference between the trajectories of our new drifter models and those that were previously used for similar research. These findings bring us one step closer to identifying the transport pathways for cold-stunned sea turtles and optimizing cold-stunned sea turtle search and rescue efforts in Cape Cod.

Introduction

The ecological significance of sea turtles extends well beyond their roles as predator and prey and their contributions to the health of the world's oceans (Wilson et al., 2010), yet six of the seven extant species are at risk of extinction (IUCN, 2020). Since 1978, extensive conservation efforts have been underway to bring Kemp's ridley sea turtles (*Lepidochelys kempii*)—the world's smallest and most endangered sea turtle species—back from the brink of extinction (Shaver, 2005; Caillouet et al., 2015; Shaver et al., 2015; Wibbels & Bevan, 2019). Bi-national, multi-agency collaborative programs such as the Sea Turtle Stranding and Salvage Network (STSSN) and the Kemp's Ridley Sea Turtle Restoration and Enhancement Program have brought communities together to rescue and protect sea turtles for over 40 years. After a decline of over 99% in nest production from historical records (1947–1985), the efforts of these conservation programs have resulted in an increase from 702 nests recorded in 1985 to nearly 25,000 recorded in 2017 (National Research Council, 1990; Spotila, 2004; Shaver et al., 2005; D Shaver, 1985–2017, unpublished data). Although these endeavors have shown promising results, Kemp's ridley sea turtles remain critically endangered (Wibbels & Bevan, 2019).

Since Kemp's ridley sea turtles have the most restricted distribution of all sea turtles and have historically nested almost entirely in the Gulf of Mexico (for exceptions see Johnson et al., 1999; National Park Service, 2018), conservation-related research has primarily focused on addressing threats contributing to declines in adults and nests—e.g. equipping fishing vessels with turtle excluder devices, protecting nests from poachers and predators, and translocating eggs (National Research Council, 1990; Shaver, 2005). Juvenile sea turtles have received little attention in previous decades but are currently a focus for sea turtle conservation in the Northeastern United States. The nutrient-rich waters of the Northwestern Atlantic Ocean serve as an important foraging ground for juvenile Kemp's ridley sea turtles (Lazell, 1980; Shoop & Kenney, 1992; Morreale & Standora, 2005), where thousands of individuals congregate in the Gulf of Maine to feed during warmer months (Spotila, 2004). The region is also notorious for unpredictable weather—such as Nor'easters and frequent cold snaps—during the late summer and fall months. As a result, these juvenile turtles engage in a risky tradeoff between optimizing foraging during a crucial developmental phase and the threat of hypothermia if they delay migration to southern overwintering habitats (Spotila, 2004; Morreale & Standora, 2005).

The biggest threat to juvenile sea turtles in the Gulf of Maine and its southernmost embayment—Cape Cod Bay, Massachusetts—is severe hypothermia, commonly referred to as cold stunning. Cold stunning occurs when water temperatures drop below roughly 10°C and cause physiological processes to begin shutting down (Still et al., 2005; Shaver et al., 2017; Liu et al., 2019). One cold-stunned, sea turtles are unable to actively swim and may die from prolonged exposure to the cold temperatures, whether in the water or on the beach, or by drowning because they cannot raise their heads out of the water (Shaver et al., 2017). It is believed, following a sudden cold snap, that some proportion of turtles becomes incapacitated and remain buoyant at the surface either because of a lack of ability to dive or because gases building up from undigested food in the gut (B Still, 2018, pers. comm.). Another proportion either dives below the surface, where the water temperature is more stable, and remains there or loses its ability to swim and sinks to the bottom. Records of injuries and shell conditions show that many turtles drag along the bottom before washing up (STSSN, 2017, unpublished data). Mortality rate among cold-stunned Kemp's ridley sea turtles is approximately 40–50% and largely affects turtles between 2–7 years old, with a straight-line carapace length of 20–30 cm (Sampson, 2019). Although cold stunning is not a threat unique to temperate waters (e.g., Witherington & Ehrhart, 1989; Shaver et al., 2017), it impacts hundreds of endangered sea turtles in Cape Cod Bay every fall—including Kemp's ridleys, loggerheads (*Caretta caretta*), and green turtles (*Chelonia mydas*)—of which Kemp's ridley sea turtles comprise the majority of those recovered (STSSN, 2019, unpublished data).

For several decades, the STSSN has collaborated with the Wellfleet Bay Wildlife Sanctuary of the Massachusetts Audubon Society in the U.S. and has trained volunteers to patrol Cape Cod Bay beaches by foot in search of stranded sea turtles. Cold-stunned sea turtles are carried toward the beaches by winds and currents where they are typically found by these search teams shortly after high tide when the water is receding. However, the portion of the Cape Cod beaches where sea turtles strand extends over 100 km, requires that volunteers search large areas to find cold-stunned sea turtles as quickly as possible to reduce exposure time. Over 1,000 stranded turtles were recovered from Cape Cod beaches in 2014 and 2020, and stranding numbers are expected to increase with a changing climate (Griffin et al., 2019; Moise, 2021). Reducing the amount of time cold-stunned sea turtles are exposed to potentially lethal air temperatures is crucial to recovery, and the ability to predict where sea turtles are likely to strand in each storm event or cold snap may help focus search efforts and increase the likelihood of survival.

Previous research on cold stunning in the Northwest Atlantic Ocean examined the importance of environmental correlates, such as temperature and wind direction, as spatial and temporal drivers of sea turtle cold-stunning and stranding locations (Burke et al., 1991; Morreale et al., 1992; Still et al., 2005; Liu et al., 2019). Other studies have estimated circulation patterns in Cape Cod Bay based on sediment transport from Massachusetts Bay (Beşiktepe et al., 2003; Warner et al., 2008) and particle tracking models (Liu et al., 2019), but information is limited on the effects of these currents on sea turtles themselves. With the exception of research by Liu and colleagues (2019), wind direction has been the primary variable used to estimate the locations of sea turtle strandings in Cape Cod Bay.

Wind is a principal driver of water currents at or near the ocean's surface (surface currents) and is often used to estimate the trajectory of objects floating in the water (Garrison, 2013). However, other factors contribute to the flow of water, especially in shallow water embayments like Cape Cod Bay. For example, the effects of waves, tidal oscillation, and thermohaline circulation are not captured when wind direction is the sole driver used to model drifting objects. Ocean currents are often studied using drifters—oceanographic instruments used to track ocean currents via satellite telemetry—to analyze these trajectories over time (Novelli et al., 2017) and offer a more accurate representation of ocean circulation patterns.

To simulate ocean currents in Cape Cod Bay, Liu and colleagues (2019) compared data from moorings, sea turtle stranding locations, and satellite-tracked ocean surface drifters to validate a model that investigated the cause and transport of cold-stunned turtles. This study addressed questions regarding the impact of wind-driven surface currents on potential sea turtle stranding hotspots but the effect of currents on cold-stunned sea turtles that have sunk to deeper waters is still largely speculative. It is unknown whether the buoyancy of cold-stunned sea turtles changes once they are immobilized, and they may float at the surface of the water (positively buoyant), below the surface (neutrally buoyant), or sink to the bottom (negatively buoyant).

Previous research has modeled potential stranding hotspots by examining the influences of wind-driven surface currents on drifters that float on or just below the surface, but poorly represented the size and shape of the sea turtles that typically cold stun (see drifter dimensions in Table 1 below). Although this research has provided a useful foundation, we have little understanding of how other environmental factors influence stranding patterns, particularly for turtles that have sunk below the surface. The objectives of our study were to (1) design new drifter models morphologically representative of sea turtles, (2) examine the effects of surface and subsurface currents in Cape Cod Bay on the transport of these drifters, and (3) compare drifter stranding hotspots to sea turtle stranding hotspots during the cold-stunned sea turtle stranding season. This research may help focus search and rescue teams on beaches with higher stranding potential under cold stunning conditions, reduce the exposure time for stranded turtles, and ultimately improve the chances of rescue and recovery of cold-stunned sea turtles.

Methods

To quantify differences between surface and subsurface currents and determine how those currents influence stranding locations, we documented trajectories and endpoints of four drifter models in Cape Cod Bay, Massachusetts. No animals were involved in the sampling, so no special permissions were required for this research.

Study Site

Cape Cod Bay is a semi-enclosed embayment surrounded by the hook-shaped peninsula of Cape Cod, Massachusetts. The bay spans approximately 1,564 km^2 and reaches a maximum depth of 62.8 m. Currents in the bay tend to flow counterclockwise but are driven largely by wind patterns and vary by season. Although the waters of the bay are stratified in the summer, they are well mixed from late fall through the winter months because of strong seasonal winds (Signell & List, 1999).

Drifter Designs

We designed a set of drifters to serve as more realistic models of sea turtles and deployed them simultaneously with traditional drifters to target currents at different depths throughout the bay. A deployment group consisted of a standard Davis-style drifter (Davis, 1985), three sea turtle-shaped surface drifters, a drogued sea turtle-shaped subsurface drifter, and an unmanned miniature sailboat. Each drifter was outfitted with a satellite transmitter (sends and receives satellite signal) or a GPS data logger (only receives satellite signal) that allowed us to record the drifter's path.

Davis-Style Surface Drifter—An aluminum-framed adaptation of the Davis-style drifter (hereafter "surface drifter") is a standard model used in oceanographic research to track ocean currents. Like the "CODE" (Coastal Ocean Dynamics Experiment) drifter (see Poulain, 1999; Liu et al., 2019), the body of the surface drifter consists of an aluminum central mast, four spars, and four canvas cloth sails, in addition to an acorn buoy and platform to hold the satellite transmitter above the water (Fig. 1). This design, with the aluminum frame, was selected because of the low cost to refurbish and reuse on subsequent deployments.

Sea Turtle Surface Drifter—The sea turtle surface drifters were designed to mimic juvenile Kemp's ridley sea turtles in size (20–30 cm straight-line carapace length), shape, and weight (3–5 kg). Similar to those used by Santos et al. (2018), the drifter bodies were built from plywood and polystyrene foam board, with a hole cut in the center to add ballast before deploying, and GPS data loggers were housed in small plastic bottles attached to the drifter bodies (Fig. 2). Just enough ballast was added to partially sink the drifters below the surface while maintaining positive buoyancy (Fig. 2c).

Sea Turtle Subsurface Drifter— To form the sea turtle subsurface drifter, we made a plaster mold using the carcass of a cold-stunned Kemp ridley sea turtle that had died and was loaned by New England Aquarium. The plaster mold was used to prepare a secondary silicone mold before creating the final cast of the body, which consisted of lightweight polyurethane casting resin safe for marine use (Fig. 3). The drifter had a hollowed "belly" to add ballast at the release location to compensate for changes in daily salinity, using only enough weight to create negative buoyancy (4–6 kg total). A retractable tether—adapted from an outdoor retractable PVC clothesline—was used to anchor the sea turtle subsurface drifter to the buoy-mounted satellite tracker (Fig. 3e). The retractable tether helped keep the floating transmitter as close as possible to the submerged drifter while floating through shallower waters.

***Unmanned Miniature Sailboat*—**An unmanned miniature sailboat (hereafter mini-boat, Fig. 4) was provided by Educational Passages (Kennebunk, Maine, USA) and the Gulf of Maine Lobster Foundation (Kennebunk, Maine, USA) and was used to track flow directly above the surface of the water. This device was instrumental in providing a more accurate estimate of the wind conditions nearest to the water's surface succeeding the drifter deployments and helped guide search efforts for recovering the GPS-equipped sea turtle surface drifters once they stranded. Since location data was not being transmitted to the satellites for the GPS-equipped drifters, we estimated the landing sites based on the relationship between wind direction and mini-boat landing.

Observed Drifter Data

A total of six drifter deployments, each including a set of all four drifter types, were conducted throughout Cape Cod Bay, Massachusetts between 31 October and 26 November 2019. Drifter deployments took place ahead of storm fronts when temperatures were expected to drop below the cold stunning threshold (10°C; Spotila et al., 1997; Milton & Lutz, 2003) for sea turtles and winds were expected to exceed 5 m/s (sustained). Drifters were deployed from the eastern side of Cape Cod Bay (near 41.8999°N, -70.1202°E) where the bay was approximately 11 m deep at mean low tide. This location was selected because the depth did not exceed the length of the retractable tether attached to the subsurface drifter, allowing it to reach the bottom of the bay. We provided contact information on all drifters and mini-boats in the event that stranded equipment was encountered by beach walkers.

***Data collection*—**Data for the satellite-tracked drifters (surface drifters, sea turtle subsurface drifters) and mini-boat were maintained and accessed through the ORBCOMM telecommunications network. Since the sea turtle surface drifters were equipped with GPS data loggers, rather than satellite transmitters, data tracks were downloaded once the units were recovered from the beaches. Satellite information was used to direct the drifter recovery teams to the satellite transmitter-equipped drifters and the mini-boat, and GPS-equipped drifters were primarily recovered by beach walkers and STSSN volunteers while searching for cold-stunned sea turtles.

We observed the data remotely via ORBCOMM for the sea turtle subsurface drifters regularly to determine if the drifter had detached from the buoy, or if the drifter became entangled. Following the guidance of Haza and colleagues (2018), we observed drift patterns in the satellite data looking for spans of missing data points and changes in drift velocity. Missing data points indicated that the buoy may have flipped over, submerging the satellite transmitter, and detached buoys or entangled drifters responded to wind forcing differently than properly functioning drifters (i.e., detached floating drifters moved faster and entangled drifters showed less movement).

Hourly data for environmental correlates were retrieved from the National Oceanic and Atmospheric Administration's National Data Buoy Center and a weather station at Provincetown Municipal Airport (Provincetown, MA, USA). These data were used to estimate the mean wind speed around the time, and immediately after, the drifters were deployed.

Data Analysis**—**The initial drifter speed was determined using the distance traveled over the time interval between location points—i.e., $\Delta distance/\Delta time = m/s$. Location data were also used to calculate the compass direction (cardinal and degrees) for the initial direction of travel (Table 2). We focused the analysis on the first few hours after deployment, limited by the time it took for the mini-boat to strand.

Comparing hotspots of drifter strandings to sea turtle strandings

The Sea Turtle Stranding and Salvage Network collects data each winter on cold-stunned sea turtles, including location and condition (dead/alive), as rescue teams recover stranded turtles. Data for the 2019 Cape Cod Bay sea turtle stranding season were provided by the Massachusetts Audubon Society. A total of 299 cold-stunned sea turtles, dead and alive, were recovered from the beaches of Cape Cod Bay during the 2019 stranding season—from 9 November 2019 to 3 April 2020.

Locations of high-density stranding locations (hotspots) were identified using a kernel density analysis in ArcGIS, for both the stranded sea turtles and the drifters. Drifter stranding data were grouped by deployment date and drifter type, and the deployment dates were compared to the 2019 sea turtle stranding data. Since drift time varied by deployment date, sea turtle stranding data were restricted to either the latest date the drifters stranded or by one week—whichever was more restrictive.

Results

Drifter Designs

Except for two surface drifters, nearly all drifters were recovered after stranding. Two surface drifters were swept out of the bay and lost at sea—one deployed during a pilot study on 31 October 2018 (F Page, 2018, unpublished data), and the second deployed on 31 October 2019. GPS-equipped sea turtle surface drifters were recovered by beach walkers over an 8-month period.

Drift time differed between drifter types. We documented that, on average, drift time was 10 times longer for Davis-style surface drifters than for sea turtle surface drifters (Table 1). Similarly, drift time was 10 times longer for sea turtle subsurface drifters than sea turtle surface drifters (Table 1).

Observed Drifter Data

Three of the six deployment clusters produced sufficient data for comparison—at least one of each drifter model transmitted consistently from these three clusters. The mean wind velocity (5.32 m/s) used for this analysis was calculated using four hourly readings for the period after the drifters were deployed. Although the effects of currents varied by wind conditions (Table 2), there were marked differences in the trajectories of the traditionally used Davis-style surface drifters, sea turtle surface drifters, and sea turtle subsurface drifters.

The sea turtle surface and subsurface drifters moved in distinctly different patterns throughout the duration of drift from deployment to stranding (Fig. 5). Although the difference in depth was much greater between the two sea turtle-shaped drifters, we observed more separation between the Davis-style surface drifter and the sea turtle surface drifter than between the two (surface and subsurface) sea turtle drifter models (Fig. 5). The degree of divergence between the tracks varied under different wind conditions, but, regardless of date of deployment, the data exhibited noticeable differences in the trajectories of the four drifter models. Hotspots for the strandings of the sea turtle subsurface drifters were south of the hotspots of the sea turtle surface drifters.

Comparing hotspots of drifter strandings and sea turtle strandings

Several drifter sets were deployed during the week with peak stranding numbers associated with cold stunning in 2019. A total of 299 sea turtles stranded during the winter of 2019, a majority of which were recovered in Barnstable, MA (n=69, 23% of the total) and other hotspots (Fig. 6a).

The stranding hotspot for all drifter models (Fig. 6b) was centered in Truro, MA, northeast of our deployment site. The stranding hotspot for the sea turtle surface drifters (Fig. 7a) was also in Truro, ~12 km north of the sea turtle subsurface drifter hotspot (Fig. 7b) in Wellfleet, MA.

When comparing the drifter strandings to the cold-stunned sea turtle strandings for the season (Fig. 8, 9, and 10), we saw an overlap in stranding locations but not necessarily the hotspots. For example, the stranding locations for the drifters deployed on 26 November were centered in the outer Cape (Fig. 10a), while the sea turtle strandings for the week of 26 November were centered in the mid-Cape (Fig. 10b). Of the four drifter models, the sea turtle subsurface drifter stranding hotspots were closest to the 2019 stranding hotspot for cold-stunned sea turtles.

Discussion

Expanding on previous research by Liu et al. (2019) and Santos et al. (2018), we incorporated sea turtle shaped surface and subsurface (drogued) drifters that were more representative in size and shape of individuals in the study population into our study of the currents in Cape Cod Bay. We found that the new sea turtle-shaped drifter models behaved distinctly different from the traditionally used Davis-style surface drifters. However, as the distance between the drifters increased, so did the variability between the trajectories of the surface and subsurface drifters. For example, if the surface drifter entered the longshore current while others were still in deeper water, we could no longer compare their paths directly since they were in very different regions and water masses. This is the reason we chose to limit our analysis to roughly the first four hours after deployment.

Our analysis showed an overlap between the stranding locations of the sea turtles and drifters, although the proximity of the drifter deployment location to the shore likely added to the difference in stranding hotspots (i.e., drifters vs. turtles). We also noted that the stranding hotspots for the sea turtle subsurface drifters were south of the hotspots of the sea turtle surface drifters. These results consistent with what we generally know about variation in currents with depth in the Northern hemisphere, that, because of friction, deeper currents flow to the right of the wind direction in a process called Ekman Transport.

Experiments of this sort in the future might include deployment locations throughout the bay. While we do not know where in the bay sea turtles lost mobility, there were several days when cold-stunned sea turtles were found near both surface and subsurface sea turtle drifters when team members were sent to recover them. Also, while searching for stranded turtles, rescue teams found beached sea turtle surface drifters nearby.

It is also interesting to note that two drifters deployed on 31 October—one during a pilot study (F Page, 2018, data unpublished) and one during this study—drifted out of Cape Cod Bay and into the Atlantic Ocean. On both occasions, they were deployed during the cold stun stranding season, which begins mid-October, but prior to the first dramatic seasonal change in weather. This could indicate that, even if cold stunning occurs early in the season, some turtles may be pushed out into the open waters of the Atlantic Ocean rather than becoming trapped in the bay.

As described by Liu and colleagues (2019), particle tracking can be conducted through numerical ocean models to estimate the origin of cold-stunned turtles. However, more experiments need to be conducted with particles in different layers of the water column. As shown in our study, water parcels, and therefore free-drifting turtles, will be transported to different regions of the coast depending on the depth of water at their point of origin.

Conclusion

Previous research on the relationship between drifter data and stranding locations addressed several knowledge gaps but did not wholly capture the conditions experienced by cold-stunned sea turtles. However, this study developed and tested new drifter models that more closely simulate the movement of immobilized cold-stunned sea turtles in Cape Cod Bay and serves to advance our understanding of sea turtle drift trajectories, particularly for the individuals that sink to the bottom upon stunning, a group that has received little attention. This new information may help to inform conservation efforts focused on the recovery of cold-stunned sea turtles in Cape Cod Bay.

The variability of the currents in Cape Cod Bay make it inherently difficult to predict stranding locations for turtles not floating at the surface, but the information gathered by this study will help expand search efforts. Also, taking into consideration the differences we observed in stranding hotspots for drifters and sea turtles, further research is needed to compare stranding locations to different drifter deployment locations throughout the bay, ideally to simulate different cold stunning locations, including where turtles are located before they cold stun. Understanding the environmental correlates driving sea turtle strandings, both at the surface and subsurface, will increase the likelihood of more quickly recovering cold-stunned sea turtles in Cape Cod Bay, thereby increasing the chances of survival.

While cold stunning is only one of the many threats to critically endangered Kemp's ridley sea turtles, it is one of the most crucial threats to the thousands of juvenile sea turtles foraging in the Northwest Atlantic region. The information gathered by this research brings us closer to identifying the pathways of transport for cold-stunned turtles through both the surface and subsurface currents—one puzzle piece at a time.

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sea turtle carcass used to model the drifters for this research, permitted under U.S. Fish and Wildlife Service Recovery Permit #1150C-1.

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Table 1(on next page)

Dimension and mean drift time for drifters deployed during the 2019 stranding season for cold-stunned sea turtles.

***Drift depth refers to the deepest point the drifter reaches. For the mini-boat, this is the height of the sail rather than the portion that is submerged below the water.**

Drifter Design	Height (m)	Length (m)	Drift Depth* (m)	Number of Drifters (n)	Drift Time Mean (hrs)	Range (hrs)	Drift Time SD (hrs)
Miniature Sailboat	1.36	1.52	0.91	5	5	3–6	±1.30
Davis-style Surface	1.88	1.22	-1.55	6	174	58–325	±112.90
Sea Turtle Surface	0.13	0.36	0.00	4	16	8–24	±8.16
Sea Turtle Subsurface	0.13	0.36	-11.5	4	160	44–371	±150.34

Table 1: Dimension and mean drift time for drifters deployed during the 2019 stranding season for cold-stunned sea turtles.

****Drift depth refers to the deepest point the drifter reaches. For the mini-boat, this is the height of the sail rather than the portion that is submerged below the water.***

Figure 1

Davis-style surface drifter used to track currents in Cape Cod Bay, Massachusetts.

(a) Drifter before deployment to show size comparison. (b) Deployed surface drifter shows main body submerged. Photo credit: Chip Carroll (a) and Felicia Page (b).

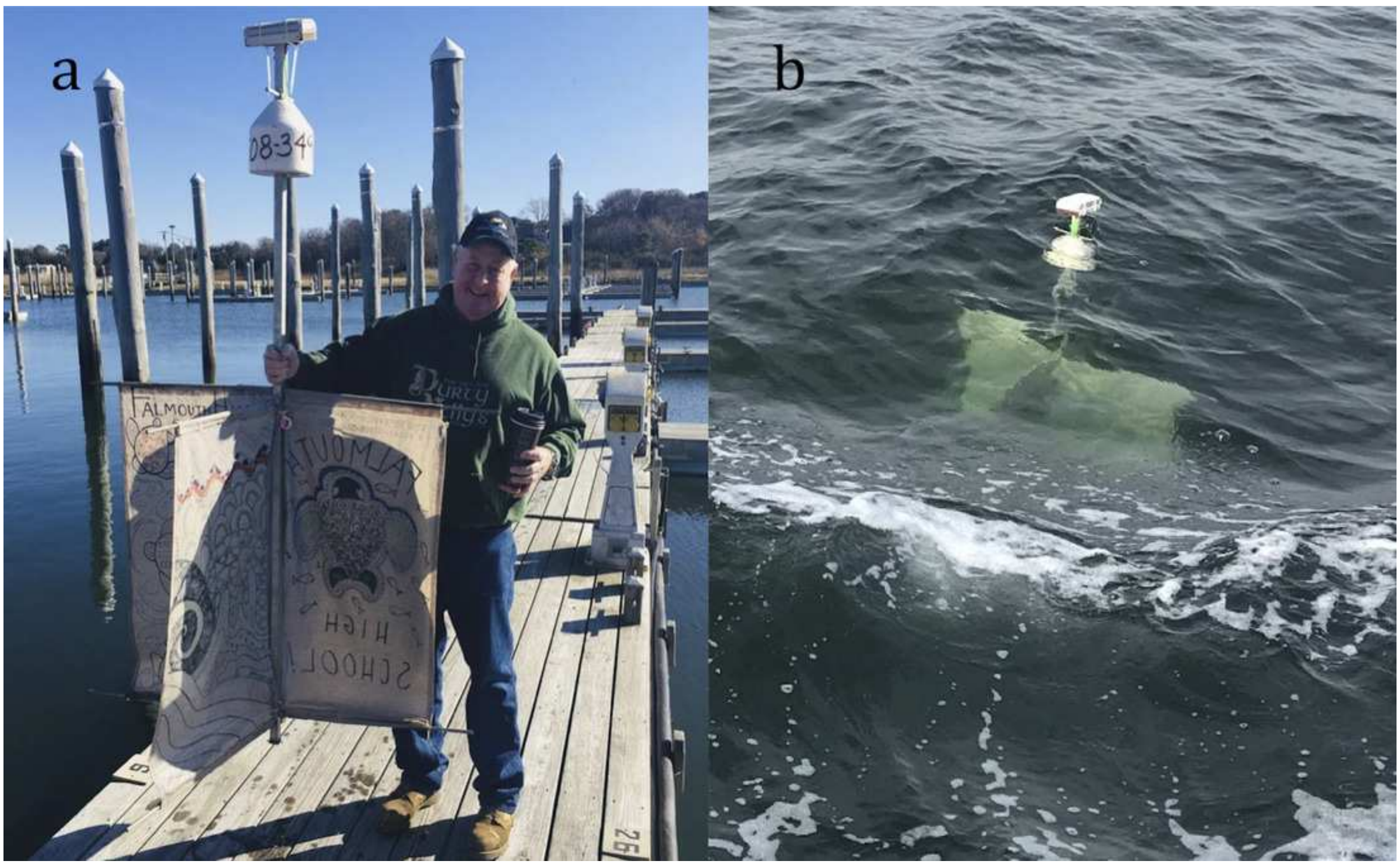


Figure 2

Sea turtle surface drifter with 25 cm straight-line carapace length used to model sea turtle stranding locations in Cape Cod Bay, Massachusetts.

(a) Bottom of the drifter with ballast compartment. (b) Decorated carapace of drifter with bottle attached for GPS logger housing. (c) Deployed sea turtle surface drifters. Photo credit: Felicia Page.

Figure 3

Making the sea turtle subsurface drifters used to model sea turtle stranding locations in Cape Cod Bay, Massachusetts.

(a) Plaster mold of deceased cold-stunned Kemp’s ridley sea turtle. (b) Silicone casts of sea turtle. (c) Polyurethane resin in mold. (d) Assembled subsurface sea turtle drifter. (e) Deploying the tethered subsurface drifter. *Photo credit: Felicia Page.*

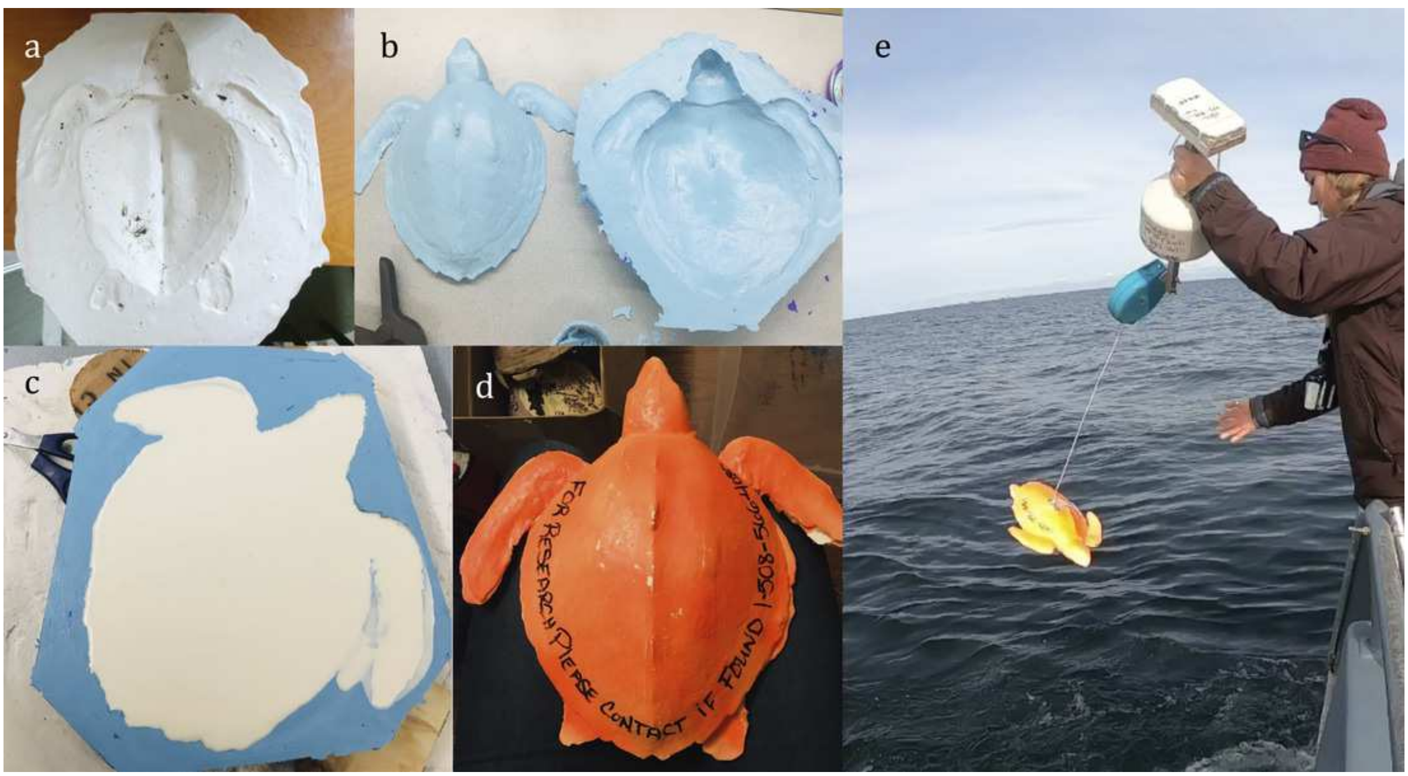


Figure 4

Unmanned miniature sailboat documented wind conditions in Cape Cod Bay, Massachusetts.

(a) Size comparison just before deployment of mini-boat. (b) Mini-boat after deployment. (c) Mini-boat after stranding. Photo credit: Felicia Page.

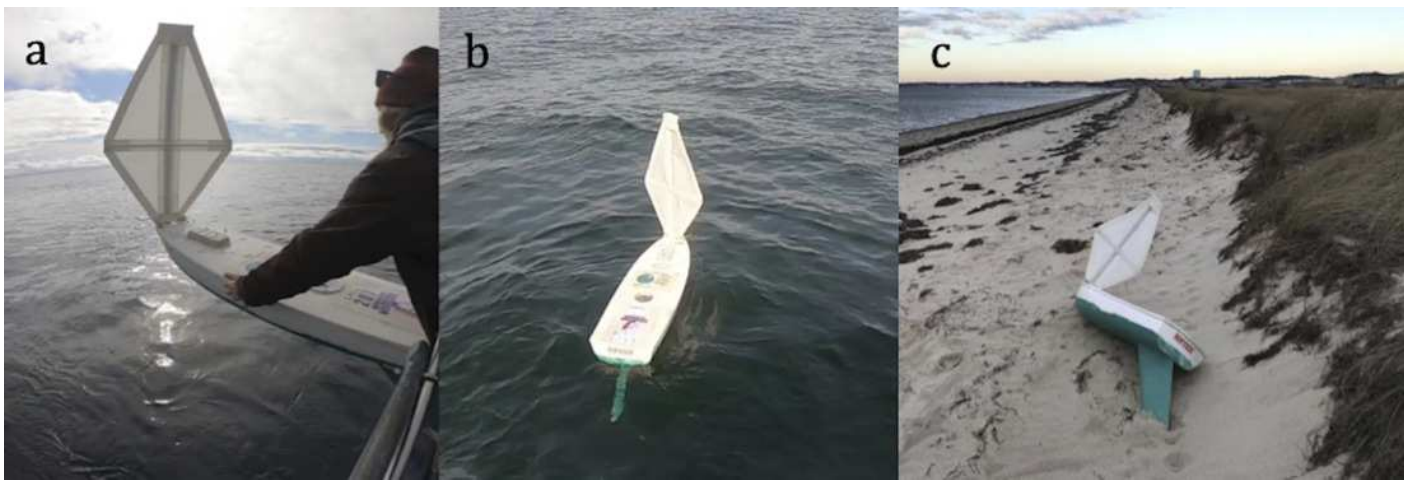


Table 2(on next page)

The initial direction of travel and speed of drifters and the corresponding wind variables.

**Wind direction reads opposite of drifter heading [origin (wind) vs. heading (drifters)].*

1

Date	Drifter	Direction* (cardinal)	Direction (degrees)	Estimated speed (m/s)
11/14/2019	WIND	SSW	198.25	4.41
11/14/2019	Mini-boat	N	4.39	0.83
11/14/2019	Sea Turtle Surface	NWN	325.93	0.11
11/14/2019	Surface	NW	312.00	0.11
11/14/2019	Sea Turtle Subsurface	NWW	305.83	0.07
11/19/2019	WIND*	WSW	245.94	2.62
11/19/2019	Mini-boat	E	86.50	0.37
11/19/2019	Sea Turtle Surface	ES	103.5	0.15
11/19/2019	Surface	SEE	119.32	0.14
11/19/2019	Sea Turtle Subsurface	ESE	114.16	0.15
11/26/2019	WIND*	SSW	207.19	8.94
11/26/2019	Mini-boat	NEN	36.63	1.01
11/26/2019	Sea Turtle Surface	NE	43.57	0.20
11/26/2019	Surface	NEE	35.06	0.22
11/26/2019	Sea Turtle Subsurface	NE	46.79	0.18

2

Table 2: Initial direction of travel and speed of drifters and the corresponding wind variables. *Wind direction reads opposite of drifter heading [origin (wind) vs. heading (drifters)].

Figure 5

Drifter tracks following the 19 November 2019 deployment in Cape Cod Bay, Massachusetts.

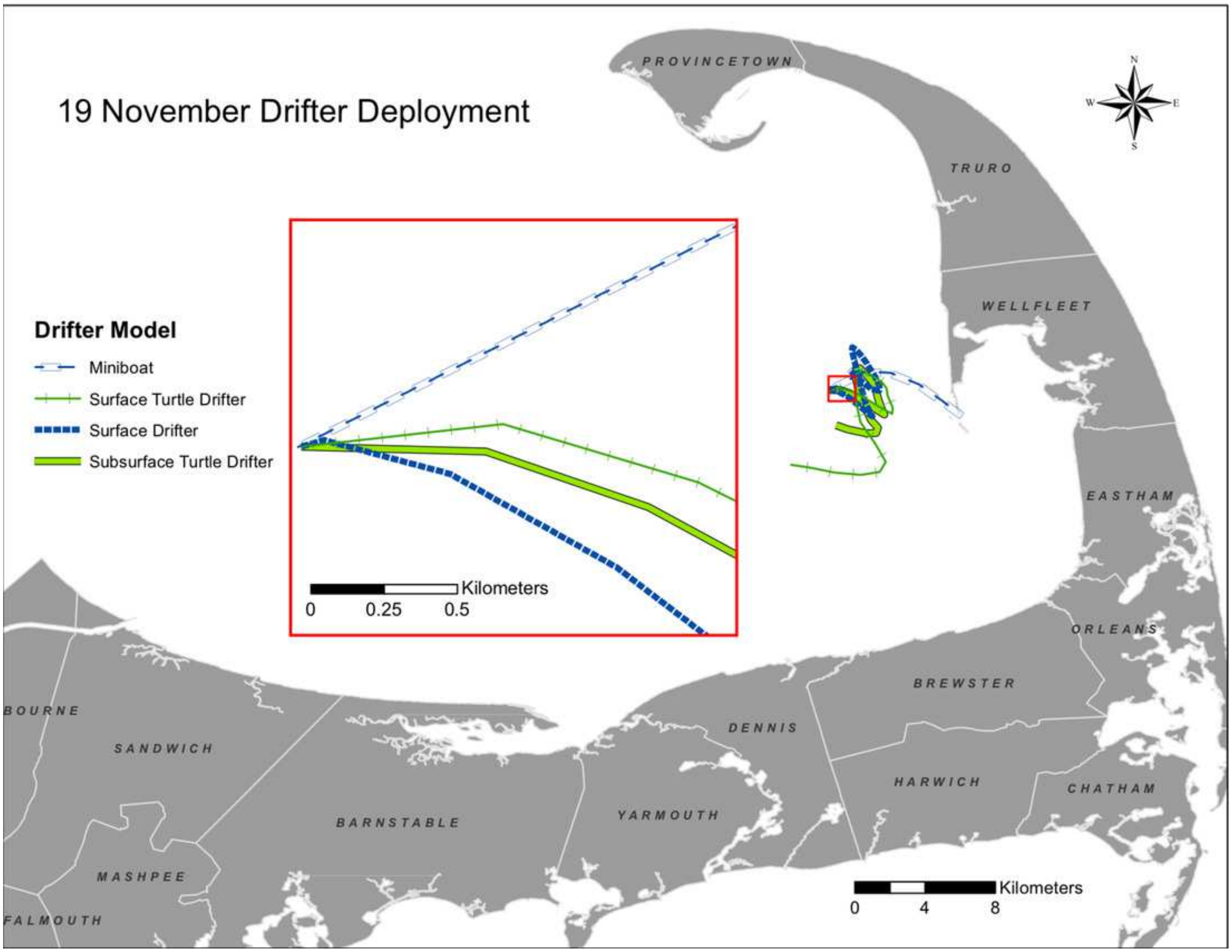


Figure 6

Stranding hotspots for the sea turtles and drifters in Cape Cod Bay, Massachusetts, 2019.

(a) Sea turtle stranding hotspots highlight areas where the largest numbers of cold-stunned sea turtles were recovered throughout the season *(b) Stranding hotspots for all drifter models.*

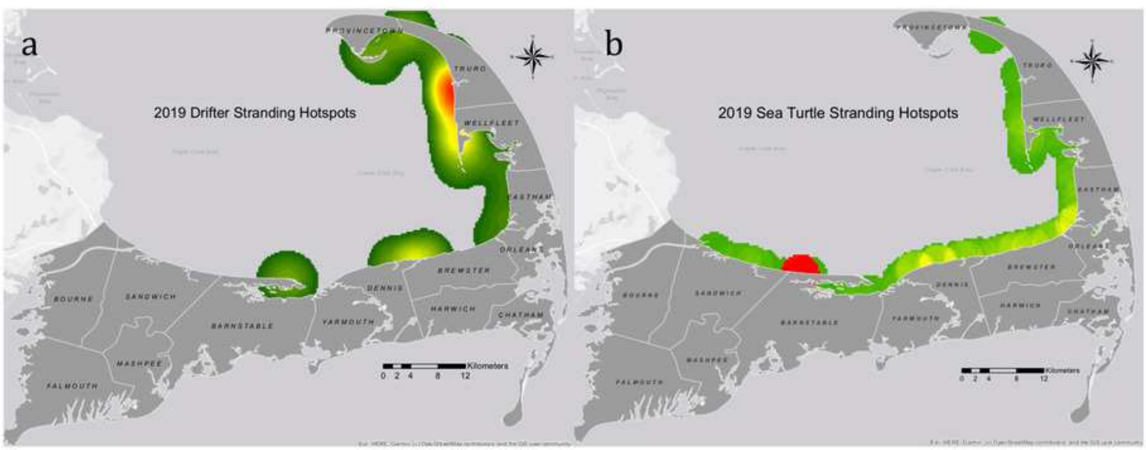

a
2019 Drifter Stranding Hotspots
PROVINCETOWN
TRURO
WELLFLEET
EASTHAM
ORLEANS
BREWSTER
DENNIS
HARWICH
CHATHAM
YARMOUTH
BARNSTABLE
SANDWICH
BOURNE
MASHPEE
FALMOUTH
Kilometers
0 2 4 8 12
b
2019 Sea Turtle Stranding Hotspots
PROVINCETOWN
TRURO
WELLFLEET
EASTHAM
ORLEANS
BREWSTER
DENNIS
HARWICH
CHATHAM
YARMOUTH
BARNSTABLE
SANDWICH
BOURNE
MASHPEE
FALMOUTH
Kilometers
0 2 4 8 12

Figure 7

Stranding hotspots for sea turtle-shaped drifters in Cape Cod Bay, Massachusetts, 2019.

(a) Sea turtle surface drifters (n=14) stranding hotspots. (b) Sea turtle subsurface drifters (n=4) stranding hotspots.

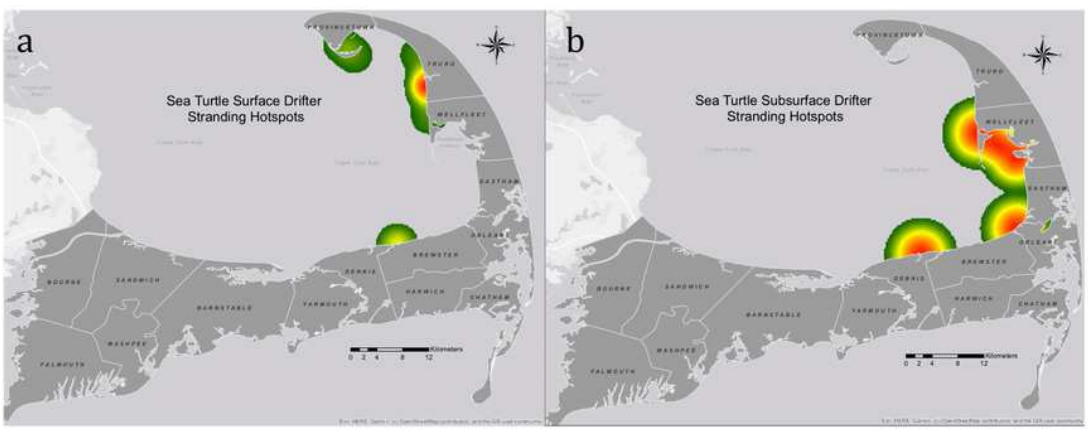

a
Sea Turtle Surface Drifter
Stranding Hotspots
b
Sea Turtle Subsurface Drifter
Stranding Hotspots

Figure 8

Comparison of drifter and cold-stunned sea turtle stranding hotspots in Cape Cod Bay, Massachusetts from 14–18 November, 2019.

(a) Drifters (n=6) deployed on 14 November. (b) Cold-stunned sea turtle strandings (n=72) from 14–18 November.

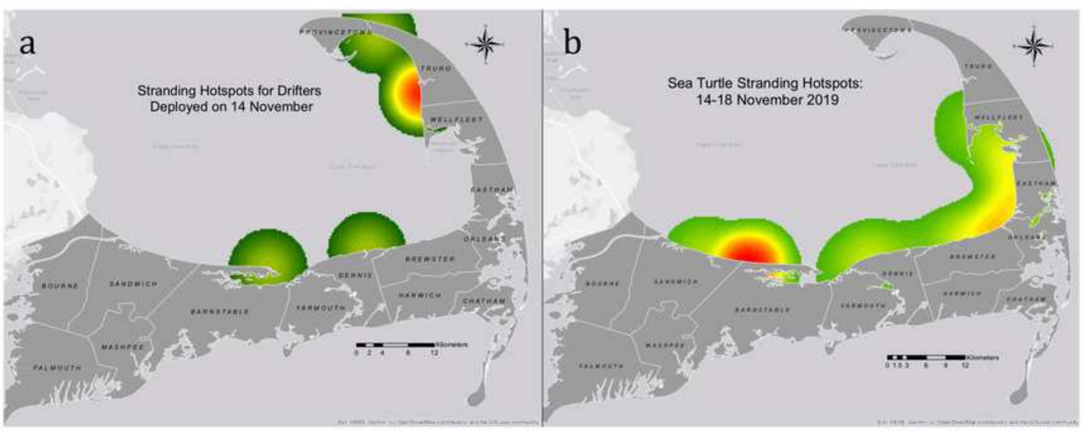

a
Stranding Hotspots for Drifters
Deployed on 14 November
PROVINCETOWN
TRURO
WELLFLEET
EASTHAM
ORLEANS
BREWSTER
DENNIS
HARWICH
CHATHAM
YARMOUTH
BARNSTABLE
SANDWICH
BOURNE
MASHPEE
FALMOUTH
Kilometers
0 2 4 8 12
b
Sea Turtle Stranding Hotspots:
14-18 November 2019
PROVINCETOWN
TRURO
WELLFLEET
EASTHAM
ORLEANS
BREWSTER
DENNIS
HARWICH
CHATHAM
YARMOUTH
BARNSTABLE
SANDWICH
BOURNE
MASHPEE
FALMOUTH
Kilometers
0 1.5 3 6 9 12

Figure 9

Comparison of drifter and cold-stunned sea turtle stranding hotspots in Cape Cod Bay, Massachusetts from 19–26 November, 2019.

(a) Drifters (n=6) deployed on 19 November. (b) Cold-stunned sea turtle strandings (n=66) from 19–26 November.

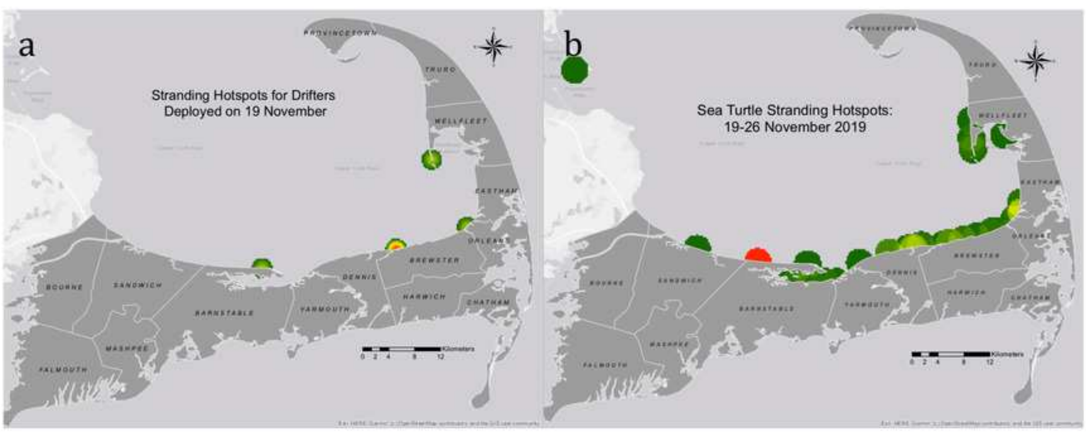
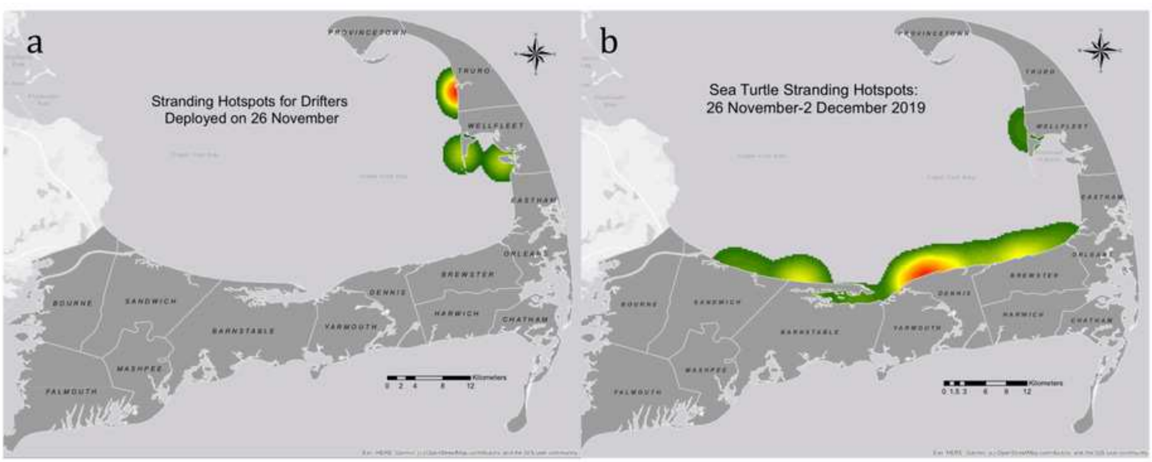

a
Stranding Hotspots for Drifters
Deployed on 19 November
PROVINCETOWN
TRURO
WELLFLEET
EASTHAM
ORLEANS
BREWSTER
DENNIS
HARWICH
CHATHAM
BOURNE
SANDWICH
BARNSTABLE
YARMOUTH
MASHPEE
FALMOUTH
0 2 4 8 12
Kilometers
b
Sea Turtle Stranding Hotspots:
19-26 November 2019
Kilometers

Figure 10

Comparison of drifter and cold-stunned sea turtle stranding hotspots in Cape Cod Bay, Massachusetts from 26 November–02 December, 2019.

(a) Drifters (n=5) deployed on 26 November. (b) Cold-stunned sea turtle strandings (n=72) from 26 November–02 December.


a
Stranding Hotspots for Drifters
Deployed on 26 November
PROVINCETOWN
TRURO
WELLFLEET
EASTHAM
ORLEANS
BREWSTER
DENNIS
HARWICH
CHATHAM
YARMOUTH
BARNSTABLE
SANDWICH
BOURNE
MASHPEE
FALMOUTH
Kilometers
0 2 4 8 12
b
Sea Turtle Stranding Hotspots:
26 November-2 December 2019
PROVINCETOWN
TRURO
WELLFLEET
EASTHAM
ORLEANS
BREWSTER
DENNIS
HARWICH
CHATHAM
YARMOUTH
BARNSTABLE
SANDWICH
BOURNE
MASHPEE
FALMOUTH
Kilometers