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

Felicia M Page [Corresp., 1] , **James Manning** [2] , **Lesley Howard** [1] , **Ryan Healey** [1] , **Nancy E Karraker** [1]

[1] Department of Natural Resources Science, University of Rhode Island, Kingston, Rhode Island, United States

[2] Northeast Fisheries Science Center, National Oceanic and Atmospheric Administration, Woods Hole, Massachusetts, United States

Corresponding Author: Felicia M Page
Email address: felicia_woods@uri.edu

Every fall, juvenile sea turtles in the Northwest Atlantic Ocean 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—and eventually strand 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 understand 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 bottom 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 bottom 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.

1 **Manuscript Title**

3 Developing bottom drifters to better understand the stranding locations of cold-stunned sea
4 turtles in Cape Cod Bay, Massachusetts
5

7 *Felicia M. Page[1], James P. Manning[2], Lesley E. Howard[1], Ryan M. Healey[1], Nancy E. Karraker[1]*
8
9 *[1] University of Rhode Island, Kingston, Rhode Island, USA*
10 *[2] National Oceanic and Atmospheric Administration's Northeast Fisheries Science Center,*
11 *Woods Hole, Massachusetts, USA*

13 **Corresponding Author:**

14 Felicia Page
15 1 Greenhouse Road, Kingston, Rhode Island, 02881, USA
16 Email address: Felicia_Woods@uri.edu

Abstract

Every fall, juvenile sea turtles in the Northwest Atlantic Ocean 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—and eventually strand 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 understand 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 bottom 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 bottom 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 (Bouchard and Bjorndal, 2000), yet six of the seven extant species are considered vulnerable, threatened, or critically endangered

39   (IUCN, 2020). Since 1978, extensive conservation efforts have been underway to bring Kemp's

40   ridley sea turtles (*Lepidochelys kempii*)—the world's smallest and most endangered sea turtle

41   species—back from the brink of extinction (Shaver, 2005; Caillouet et al., 2015; Shaver &

42   Caillouet, 2015; Wibbels & Bevan, 2019). Bi-national and multi-agency collaborative programs

43   such as the Kemp's Ridley Sea Turtle Restoration and Enhancement Program and the Sea Turtle

44   Stranding and Salvage Network (STSSN) have brought communities together to rescue and

45   protect sea turtles for over 40 years. After a decline of over 99% in nest production from

46   historical records (1947–1985), the efforts of these conservation programs have resulted in an

47   increase from 702 nests recorded in 1985 to nearly 25,000 recorded in 2017 (National Research

48   Council, 1990; Spotila, 2004; Shaver et al., 2005; Bevan et al., 2016; Wibbles & Bevan, 2019).

49   Although these endeavors have shown promising results, Kemp's ridley sea turtles remain

50   critically endangered (Wibbels & Bevan, 2019).

51   Since Kemp's ridley sea turtles have the most restricted distribution of all sea turtles and

52   have historically nested almost entirely in the Gulf of Mexico (for exceptions see Johnson et al.,

53   1999; National Park Service, 2018), conservation-related research has primarily focused on

54   addressing threats contributing to declines in adults and nests—e.g., equipping fishing vessels

55   with turtle excluder devices, protecting nests from poachers and predators, and translocating eggs

56   (National Research Council, 1990; Shaver, 2005). Juvenile sea turtles have received little

57   attention in previous decades but are currently a focus for sea turtle conservation in the

58   northeastern United States. The nutrient-rich waters of the Northwest Atlantic Ocean serve as an

59   important foraging ground for juvenile Kemp's ridley sea turtles (Lazell, 1980; Morreale &

60   Standora, 2005), where thousands of individuals may congregate in the Gulf of Maine to feed

61   during warmer months (Spotila, 2004). The region is also notorious for unpredictable weather—

62   such as nor'easters and frequent cold snaps—during the late summer and fall months. As a

63   result, these juvenile turtles engage in a risky tradeoff between optimizing foraging during a

64   crucial developmental phase and the threat of hypothermia if they delay migration to southern

65   overwintering habitats (Spotila, 2004; Morreale & Standora, 2005).

66   The biggest threat to juvenile sea turtles in the Gulf of Maine and its southernmost

67   embayment—Cape Cod Bay, Massachusetts—is severe hypothermia, commonly referred to as

68   cold stunning. Cold stunning occurs when water temperatures drop below roughly 10°C and

69   cause physiological processes to begin shutting down (Still et al., 2005; Shaver et al., 2017; Liu

70   et al., 2019). Once cold-stunned, sea turtles are unable to actively swim and may die from

71   prolonged exposure to the cold temperatures, whether in the water or on the beach, or by

72   drowning because they cannot raise their heads out of the water (Shaver et al., 2017). It is

73   believed, following a sudden cold snap, that some proportion of turtles become incapacitated and

74   remain buoyant at the surface either because of a lack of ability to dive or because gases build up

75   from undigested food in the gut (B Still, 2018, pers. comm.). Other sea turtles either dive below

76   the surface—where the water temperature is more stable—and remain there or lose their ability

77   to swim and sink to the bottom. Observations of injuries and shell conditions showed that many

78   turtles drag along the bottom before washing up. Mortality rate among cold-stunned Kemp's

79   ridley sea turtles in Cape Cod Bay is approximately 40–50% and largely affects turtles 0.75–4

80   years old, with straight-line carapace lengths of 20–30 cm (Avens et al., 2020). Although cold

81   stunning is not a threat unique to temperate waters (e.g., Witherington & Ehrhart, 1989; Shaver

82   et al., 2017), it impacts hundreds of threatened and endangered sea turtles in Cape Cod Bay

83   every fall—including Kemp's ridleys, loggerheads (*Caretta caretta*), and green turtles (*Chelonia*

84 *mydas*)—of which Kemp's ridley sea turtles comprise the majority of those recovered (see

85 Supplemental Information).

86   For several decades, the STSSN has collaborated with the Wellfleet Bay Wildlife

87 Sanctuary of the Massachusetts Audubon Society in the U.S. and has trained volunteers to patrol

88 Cape Cod Bay beaches by foot in search of stranded sea turtles. Cold-stunned sea turtles are

89 carried toward the beaches by winds and currents, where they are typically found by these search

90 teams shortly after high tide when the water is receding. However, the Cape Cod beaches where

91 sea turtles strand extends over 100 km, which requires that volunteers search large areas to find

92 cold-stunned sea turtles as quickly as possible to reduce exposure time. Over 1,000 stranded

93 turtles were recovered from Cape Cod beaches in 2014 and 2020, and stranding numbers are

94 expected to increase with a changing climate (Griffin et al., 2019; Moise, 2021). It is also

95 important to note that population recovery—estimated to be rebounding by as much as 19% per

96 year because of conservation efforts (Spotila, 2004)—will increase the number of sea turtles

97 exposed to threats (Putman, Hawkins, & Gallaway, 2020) and coincidentally increase the

98 number of sea turtles that strand from cold-stun events. Reducing the amount of time that cold-

99 stunned sea turtles are exposed to potentially lethal air temperatures is crucial to recovery, and

100 the ability to predict where sea turtles are likely to strand in each storm event or cold snap may

101 help focus search efforts and increase the likelihood of survival.

102   Previous research on cold stunning in the Northwest Atlantic Ocean examined the

103 importance of environmental correlates, such as temperature and wind direction, as spatial and

104 temporal drivers of sea turtle cold-stunning and stranding locations (Burke et al., 1991; Morreale

105 et al., 1992; Still et al., 2005; Liu et al., 2019). Other studies have estimated circulation patterns

106 in Cape Cod Bay based on sediment transport from Massachusetts Bay (Beşiktepe et al., 2003;

107 Warner et al., 2008) and particle tracking models (Liu et al., 2019), but information is limited on

108 the effects of these currents on sea turtles themselves. With the exception of research by Liu et

109 al. (2019), wind direction has been the primary variable used to estimate the locations of sea

110 turtle strandings in Cape Cod Bay.

111 Wind is a principal driver of water currents at or near the ocean's surface (i.e., surface

112 currents) and is often used to estimate the trajectory of objects floating in the water (Garrison,

113 2013). However, other factors contribute to the flow of water, especially in shallow water

114 embayments like Cape Cod Bay. For example, the effects of waves and tidal oscillation are not

115 captured when wind direction is the sole driver used to model drifting objects. Ocean currents are

116 often studied using drifters—oceanographic instruments used to track ocean currents via satellite

117 telemetry—to analyze these trajectories over time (Novelli et al., 2017) and offer a more accurate

118 representation of ocean circulation patterns.

119 To simulate ocean currents in Cape Cod Bay, Liu et al. (2019) compared data from

120 moorings, sea turtle stranding locations, and satellite-tracked ocean surface drifters to validate a

121 model that investigated the cause and transport of cold-stunned turtles. Their study addressed

122 questions regarding the impact of wind-driven surface currents on potential sea turtle stranding

123 hotspots but the effect of currents on cold-stunned sea turtles that have sunk to deeper waters is

124 still largely speculative. It is unknown whether the buoyancy of cold-stunned sea turtles changes

125 once they are immobilized—they may float at the surface of the water (positively buoyant),

126 below the surface (neutrally buoyant), or sink to the bottom (negatively buoyant).

127 Previous research has modeled potential stranding hotspots by examining the influences

128 of wind-driven surface currents on drifters that float on or just below the surface, but poorly

129 represented the size and shape of the sea turtles that typically cold stun (see drifter dimensions in

130   Table 1 below). Research that has incorporated the use of satellite-tagged sea turtle carcasses, in

131   addition to wooden effigy drifters, has shed light on the seasonal variability in stranding patterns

132   (Reneker, Cook, & Nero, 2018; Cook et al., 2021), has developed backtracking models to

133   estimate the location of at-sea mortality (Nero et al., 2013), and assessed how decomposition rate

134   impacts sea turtle drift (Reneker, Cook, & Nero, 2018; Nero et al., 2022). Although these studies

135   provided a useful foundation, we have little understanding of how other environmental factors

136   influence stranding patterns, particularly for turtles that have sunk below the surface. The

137   objectives of our study were to (1) design new drifter models that are morphologically

138   representative of sea turtles, (2) examine the effects of surface and bottom currents in Cape Cod

139   Bay on the transport of these drifters, and (3) compare drifter stranding hotspots to sea turtle

140   stranding hotspots during the cold-stunned sea turtle stranding season. This research may help

141   focus search and rescue teams on beaches with higher stranding potential under cold stunning

142   conditions, reduce the exposure time for stranded turtles, and ultimately improve the chances of

143   rescue and recovery of cold-stunned sea turtles.

144   **Methods**

145   To quantify differences between surface and bottom currents and determine how those

146   currents influence stranding locations, we documented trajectories and endpoints of four types of

147   drifter models in Cape Cod Bay, Massachusetts. No animals were involved in the sampling, so

148   no special permissions were required for this research.

149 **Study Site**

150   Cape Cod Bay is a semi-enclosed embayment surrounded by the hook-shaped peninsula

151 of Cape Cod, Massachusetts. The bay is approximately 1,564 km^2 and reaches a maximum depth

152 of 62.8 m. Currents in the bay tend to flow counterclockwise but are driven largely by wind

153 patterns and vary by season. Although the waters of the bay are stratified in the summer, they are

154 well mixed from late fall through the winter months because of strong seasonal winds (Signell &

155 List, 1999).

156 **Drifter Designs**

157   We designed a set of drifters to serve as more realistic models of sea turtles and deployed

158 them simultaneously with traditional drifters to target currents at different depths throughout the

159 bay. A deployment group consisted of a standard Davis-style drifter (Davis, 1985), sea turtle-

160 shaped surface drifters (three were used in case one or more did not collect consistent data), a

161 drogued sea turtle-shaped bottom drifter, and an unmanned miniature sailboat. Each drifter was

162 outfitted with a satellite transmitter (Globalstar SmartOne Asset Tracker) or a GPS data logger

163 (Canmore GT-730FL-S SiRF IV edition) that allowed us to record the drifter's path.

164   ***Davis-Style Surface Drifter***—An aluminum-framed adaptation of the Davis-style drifter

165 (hereafter "Davis drifter") is a standard model used in oceanographic research to track ocean

166 currents. Like the Coastal Ocean Dynamics Experiment "CODE" drifter (see Poulain, 1999; Liu

167 et al., 2019), the body of the Davis drifter consisted of an aluminum central mast, four spars, and

168 four canvas cloth sails, in addition to an acorn buoy and platform to hold the satellite

169 transmitter—programmed with a one-hour sampling rate—above the water (Fig. 1). This design,

170 with the aluminum frame, was selected because of the low cost to refurbish and reuse on

171 subsequent deployments.

172   ***Sea Turtle Surface Drifter***—The sea turtle surface drifters (hereafter "surface drifter")

173   were designed to mimic juvenile Kemp's ridley sea turtles in size (20–30 cm straight-line

174   carapace length), shape, and weight (3–5 kg). Similar to those used by Santos et al. (2018), the

175   drifter bodies were built from plywood and polystyrene foam board, with a hole cut in the center

176   to add ballast before deploying, and GPS data loggers—with a one-minute sampling rate—were

177   housed in small plastic bottles attached to the drifter bodies (Fig. 2). Because cold-stunned sea

178   turtles are not completely rigid, the flippers were designed using a hinge to attempt to mimic

179   potential movement and resulting drag but, when observed during trials, the flippers remained

180   relatively immobile. Just enough ballast was added to partially sink the drifters below the surface

181   while maintaining positive buoyancy (Fig. 2c).

182   ***Sea Turtle Bottom Drifter***—To form the sea turtle bottom drifter (hereafter "bottom

183   drifter"), we made a plaster mold using the carcass of a cold-stunned Kemp ridley sea turtle that

184   had died (approved under U.S. Fish and Wildlife Service Recovery Permit #1150C-1). The

185   plaster mold was used to prepare a secondary silicone mold before creating the final cast of the

186   body, which consisted of lightweight polyurethane casting resin safe for marine use (Fig. 3). The

187   drifter had a hollowed "belly" to add ballast at the release location to compensate for changes in

188   daily salinity, using only enough weight to create negative buoyancy (4–6 kg total). A retractable

189   tether—adapted from an outdoor retractable PVC clothesline—was used to anchor the bottom

190   drifter to the buoy-mounted satellite tracker—programmed with a one-hour sampling rate (Fig.

191   3e). The retractable tether helped keep the floating transmitter as close as possible to the

192   submerged drifter while floating through shallower waters.

193   ***Unmanned Miniature Sailboat***—An unmanned miniature sailboat (hereafter "mini-

194   boat", Fig. 4), equipped with a satellite transmitter programmed with a one-hour sampling rate,

195   was provided by Educational Passages (Kennebunk, Maine, USA) and the Gulf of Maine Lobster

196   Foundation (Kennebunk, Maine, USA) and was used to track the flow directly above the surface

197   of the water. This device was instrumental in providing a more accurate estimate of the wind

198   conditions nearest to the water's surface during the drifter deployments and helped guide search

199   efforts for recovering the GPS-equipped surface drifters once they stranded. Since location data

200   were not being transmitted to the satellites for the GPS-equipped drifters, we estimated the

201   landing sites based on the relationship between wind direction and mini-boat landing.

202   **Observed Drifter Data**

203   Six drifter deployments, each including a set of all four drifter types, were conducted

204   throughout Cape Cod Bay, Massachusetts between 31 October and 26 November 2019. Drifter

205   deployments took place ahead of storm fronts when temperatures were expected to drop below

206   the cold stunning threshold (10 °C; Spotila et al., 1997; Milton & Lutz, 2003) for sea turtles and

207   winds were expected to exceed 5 m/s (sustained). Drifters were deployed from the eastern side of

208   Cape Cod Bay (near 41.8999 °N, 70.1202 °W) where the bay was approximately 11 m deep at

209   mean low tide. This location was selected because the depth did not exceed the length of the

210   retractable tether attached to the bottom drifter, allowing it to reach the bottom of the bay. We

211   provided contact information on all drifters and mini-boats in the event that stranded equipment

212   was encountered by beach walkers.

213   *Data collection*—Data for the satellite-tracked drifters (Davis drifters and bottom

214   drifters) and mini-boat were maintained and accessed through the ORBCOMM

215   telecommunications network. Since the surface drifters were equipped with GPS data loggers,

216   rather than satellite transmitters, data tracks were downloaded once the units were recovered

217   from the beaches. Satellite information was used to direct the drifter recovery teams to the

218   satellite transmitter-equipped drifters and the mini-boat, and GPS-equipped drifters were

219   primarily recovered by beach walkers and STSSN volunteers while searching for cold-stunned

220   sea turtles.

221   We observed the data remotely via ORBCOMM for the bottom drifters regularly to

222   determine if the drifter had detached from the buoy, or if the drifter became entangled. Following

223   the guidance of Haza et al. (2018), we observed drift patterns in the satellite data looking for

224   spans of missing data points and changes in drift velocity. Missing data points indicated that the

225   buoy may have flipped over, submerging the satellite transmitter, and detached buoys or

226   entangled drifters responded to wind forcing differently than properly functioning drifters (i.e.,

227   detached floating drifters moved faster and entangled drifters showed less movement).

228   Hourly data for environmental correlates were retrieved from the National Oceanic and

229   Atmospheric Administration's National Data Buoy Center and a weather station at Provincetown

230   Municipal Airport (Provincetown, Massachusetts, USA). These data were used to estimate the

231   mean wind speed around the time, and immediately after, the drifters were deployed.

232   *Data Analysis*—The drifter speed was determined using the distance traveled over the

233   time interval between location points—i.e., Δdistance/Δtime = m/s. Location data were also used

234   to calculate the compass direction for the direction of travel (Table 2). We focused the analysis

235   on the trajectories on the first four hours after deployment, limited by the average time it took for

236   the mini-boat to strand.

237   **Comparing hotspots of drifter strandings to sea turtle strandings**

238   The STSSN collects data each winter on cold-stunned sea turtles, including location and

239   condition (dead/alive), as rescue teams recover stranded turtles. Data for the 2019 Cape Cod Bay

240   sea turtle stranding season were provided by the Massachusetts Audubon Society. STSSN

241   volunteers recovered a total of 299 cold-stunned sea turtles, dead and alive, from the beaches of

242   Cape Cod Bay during the 2019 stranding season—from 9 November 2019 to 3 April 2020.

243   Locations of high-density stranding locations (hotspots) were identified using a kernel

244   density analysis in ArcGIS, for both the stranded sea turtles and the drifters. Drifter stranding

245   data were grouped by deployment date and drifter type, and the deployment dates were

246   compared to the 2019 sea turtle stranding data. Since drift time varied by deployment date, sea

247   turtle stranding data were restricted to either the latest date the drifters stranded or by one

248   week—whichever was more restrictive.

249   **Results**

250   **Drifter Designs**

251   Except for one of the Davis drifters—which was swept out of the bay and lost at sea—

252   nearly all of the Davis, surface, and bottom drifters and the miniboat were recovered after

253   stranding. GPS-equipped sea turtle surface drifters were recovered by beach walkers over an 8-

254   month period but some were not found because they were not satellite-tracked. Drift time

255   differed between drifter types. We documented that, on average, drift time was 10 times longer

256   for Davis drifters than for surface drifters (Table 1). Similarly, drift time was 10 times longer for

257   bottom drifters than surface drifters (Table 1).

258   **Observed Drifter Data**

259   Three of the six deployment clusters produced sufficient data for comparison—at least

260   one of each drifter model transmitted consistently from these three clusters—because either the

261   transmitter did not communicate with the satellite or the GPS data logger was damaged and the

262   data could not be retrieved. For example, one of the bottom drifters was slightly too heavy and

263   pulled the transmitter below the surface, preventing communication with the satellites, and rough

264   seas also contributed to loss of communication at times. The waterproof housing on some of the

265   GPS data loggers also failed, causing the USB connector to rust from the saltwater, making the

266   data irretrievable. The missing data for these three deployments prevented comparisons between

267   the surface and bottom drifters.

268   Although the effects of currents varied by wind conditions (Table 2), there were marked

269   differences in the trajectories of the traditionally used Davis drifters, surface drifters, and bottom

270   drifters. The sea turtle surface and bottom drifters moved in distinctly different patterns

271   throughout the duration of drift from deployment to stranding. Despite a greater difference in

272   depth between the two sea turtle-shaped drifters (surface and bottom), we observed more

273   separation between the Davis drifter and the sea turtle surface drifter than between the two

274   different sea turtle drifter models (Fig. 5). The degree of divergence between the tracks varied

275   under different wind conditions, but, regardless of date of deployment, the data exhibited

276   noticeable differences in the trajectories of the four drifter models. Hotspots for the strandings of

277   the bottom drifters were south of the hotspots of the surface drifters.

278   **Comparing hotspots of drifter strandings and sea turtle strandings**

279   Several drifter sets were deployed during the week with peak stranding numbers

280   associated with cold stunning in 2019. The stranding hotspot for all drifter models (Fig. 6a) was

281   centered in Truro, Massachusetts, northeast of our deployment site. A majority of the 299 sea

282   turtles stranded during the winter of 2019 were recovered in Barnstable, Massachusetts (n=69,

283   23%) and other hotspots (Fig. 6b). The stranding hotspot for the surface drifters (Fig. 7a) was

284   also in Truro, ~12 km north of the bottom drifter hotspot (Fig. 7b) in Wellfleet, Massachusetts.

285   When comparing the sea turtle-shaped drifter strandings to the cold-stunned sea turtle

286 strandings for the season (Fig. 8) we saw an overlap in stranding locations but not necessarily the

287 hotspots. For example, the stranding locations for the drifters deployed on 14 November were

288 centered in the outer Cape (Fig. 8a), while the sea turtle strandings for the week of 14 November

289 were centered in the mid-Cape (Fig. 8b). Of the different drifter models, the bottom drifter

290 stranding hotspots were closest to the 2019 stranding hotspot for cold-stunned sea turtles.

291 **Discussion**

292   Expanding on previous research by Liu et al. (2019) and Santos et al. (2018), we

293 incorporated sea turtle-shaped surface and bottom (drogued) drifters that were more

294 representative in size and shape of individuals in the study population into our study of the

295 currents in Cape Cod Bay. We found that the sea turtle-shaped surface drifter model behaved

296 distinctly different from the Davis drifters that were previously used to study currents in Cape

297 Cod Bay and sea turtle stranding locations (see Liu et al., 2019). However, as the distance

298 between the drifters increased, so did the variability between the trajectories of the surface and

299 bottom drifters. For example, if the surface drifter entered the longshore current while others

300 were still in deeper water, we could no longer compare their paths directly since they were in

301 very different regions and water masses. This is the reason we chose to limit our analysis to

302 roughly the first four hours after deployment.

303   It is also important to note that the different drifter design elements could have influenced

304 the drift pattern of the sea turtle drifters. For instance, the hinged flippers on the sea turtle surface

305 drifter could have added drag, while the choice of ballast weight—although the weight was

306 comparable to the recorded weights of similarly sized cold-stunned sea turtles—could have

307   exposed more of the carapace than what may be observed in a cold-stunned sea turtle. This

308   difference in buoyancy would increase the influence of wind on the drifters and future research

309   will correct the drifter design to account for this. The weight of the ballast on the bottom drifter

310   also caused loss of data for some drifters because the buoys were pulled below the surface

311   preventing communication with the satellite. Additionally, although the weight of the buoy

312   attached to the bottom drifter was insignificant compared to the weight of the drifter, we cannot

313   rule out the possibility that the surface area of the buoy added to the effect of the wind on the

314   drifter.

315   Our analysis showed an overlap between the stranding locations of the sea turtles and

316   drifters, although the proximity of the drifter deployment location to the shore likely added to the

317   difference in stranding hotspots (i.e., drifters vs. turtles). We also noted that the stranding

318   hotspots for the bottom drifters were south of the hotspots of the surface drifters. These results

319   were consistent with what we generally know about variation in currents with depth in the

320   Northern Hemisphere—because of friction and the Coriolis effect, deeper currents flow to the

321   right of the wind direction in a process called an Ekman spiral.

322   The difference in stranding time between the surface and bottom drifters—bottom drifters

323   taking approximately ten times as long to strand—may provide clues as to the timing and

324   condition (alive or deceased) of cold-stunned sea turtles. Cold-stunned sea turtles strand in pulses

325   following cold fronts—with earlier waves arriving mostly alive and later mostly deceased—and

326   these data could suggest that the turtles that strand later could have been submerged.

327   Another important observation was that two drifters, both deployed on 31 October—one

328   during a pilot study in 2018 (see Supplemental Information) and one during this study in 2019—

329   drifted out of Cape Cod Bay and into the Atlantic Ocean. On both occasions, they were deployed

330   during the cold-stun stranding season, which begins mid-October, but before the first dramatic

331   seasonal change in weather. This could indicate that, even if cold stunning occurs early in the

332   season, some turtles may be pushed out into the open waters of the Atlantic Ocean rather than

333   becoming trapped in the bay—likely increasing their chances of survival if they reach the

334   warmer waters of the Atlantic.

335   Experiments of this sort in the future might include deployment locations throughout the

336   bay. While we do not know where in the bay sea turtles lost mobility, there were several days

337   (22%) when cold-stunned sea turtles were found near the Davis drifters and bottom and surface

338   sea turtle drifters. When team members were sent to recover the satellite-tracked drifters,

339   approximately seven cold-stunned sea turtles were found—three live turtles near a bottom drifter

340   and three (two live and one dead) near a Davis drifter. Also, while searching for stranded turtles,

341   rescue teams found four beached surface sea turtle drifters near approximately 15 live cold-

342   stunned sea turtles on one day and three more sea turtle drifters near two live cold stunned turtles

343   on another. One caveat, however, is that this may be entirely coincidental because the small

344   sample size of our drifter deployments limits the conclusions we can make about the correlation

345   between drifter stranding locations and sea turtle stranding hotspots.

346   As described by Liu et al. (2019), particle tracking can be conducted through numerical

347   ocean models to estimate the origin of cold-stunned turtles. However, more experiments need to

348   be conducted with particles in different layers of the water column. As shown in our study, water

349   parcels, and therefore free-drifting turtles, will be transported to different regions of the coast

350   depending on the depth of water at their point of origin.

Conclusion

351

352   Previous research on the relationship between drifter data and stranding locations

353   addressed several knowledge gaps but did not wholly capture the conditions experienced by

354   cold-stunned sea turtles. However, this study developed and tested drifter models—a sea turtle-

355   shaped surface drifter similar to the one used by Santos et al. (2018) and a new sea turtle-shaped

356   bottom drifter—that more closely simulate the movement of immobilized cold-stunned sea

357   turtles in Cape Cod Bay. These findings serve to advance our understanding of sea turtle drift

358   trajectories, particularly for the individuals that sink to the bottom upon stunning, a group that

359   has received little attention. This new information may help to inform conservation efforts

360   focused on the recovery of cold-stunned sea turtles in Cape Cod Bay.

361   The variability of the currents in Cape Cod Bay makes it inherently difficult to predict

362   stranding locations for turtles not floating at the surface, but the information gathered by this

363   study will help expand search efforts by demonstrating that stranding locations vary depending

364   on whether sea turtles are floating at the surface or below after cold-stunning. Also, taking into

365   consideration the differences we observed in stranding hotspots for drifters and sea turtles,

366   further research is needed to compare stranding locations to different drifter deployment

367   locations throughout the bay, ideally to simulate different cold stunning locations, including

368   where turtles are located before they cold stun. Understanding the environmental correlates

369   driving sea turtle strandings, both at the surface and bottom, will increase the likelihood of more

370   quickly recovering cold-stunned sea turtles in Cape Cod Bay, thereby increasing the chances of

371   survival.

372   While cold stunning is only one of the many threats to critically endangered Kemp's

373   ridley sea turtles, it is one of the most crucial threats to the thousands of juvenile sea turtles

374   foraging in the Northwest Atlantic region. The information gathered by this research brings us

375   closer to identifying the pathways of transport for cold-stunned turtles through both the surface

376   and bottom currents—one puzzle piece at a time.

377   **Acknowledgments**

378   We thank captain Chip Carroll and the crew of the F/V Albatross for assistance with drifter

379   deployments; Ryan Page for educational outreach collaborations and helping with drifter

380   construction; students from regional schools and non-profit organizations working with at-risk

381   youth for help building, decorating, and deploying drifters; and the Sea Turtle Stranding and

382   Salvage Network volunteers who helped recover stranded drifters. We also thank our reviewers

383   for the thoughtful and thorough feedback that helped improve this manuscript.

384   **References**

385   **Avens L, Ramirez MD, Hall AG, Snover ML, Haas HL, Godfrey MH, Goshe LR, Cook M,**

386   **Heppell SS. 2020.** Regional differences in Kemp's ridley sea turtle growth trajectories

387   and expected age at maturation. *Marine Ecology Progress Series* **654**:143–161.

388   https://doi.org/10.3354/meps13507.

389   **Bouchard SS, Bjorndal KA. 2000**. Sea Turtles as biological transporters of nutrients and

390   energy from marine to terrestrial ecosystems. *Ecology* **81**: 2305-2313.

391   https://doi.org/10.1890/0012-9658(2000)081[2305:STABTO]2.0.CO;2

392   **Beşiktepe ST, Lermusiaux PFJ, Robinson AR. 2003.** Coupled physical and biochemical data-

393   driven simulations of Massachusetts Bay in late summer: real-time and postcruise data

394   assimilation. *Journal of Marine Systems* **40–41**: 171–212 https://doi.org/10.1016/S0924-

395   7963(03)00018-6.

396   **Bevan E, Wibbles T, Najera BMZ, Sarti L, Martinez FI, Cuevas JM, Gallaway BJ, Pena**

397   **LJ, Burchfield PM. 2016.** Estimating the historic size and current status of the Kemp's

398   ridley sea turtle (*Lepidochelys kempii*) population. *Ecosphere* **7**:

399   https://doi.org/10.1002/ecs2.1244.

400   **Burke VJ, Standora EA, Morreale SJ. 1991.** Factors affecting strandings of cold-stunned

401   juvenile Kemp's ridley and loggerhead sea turtles in Long Island, New York. *Copeia* **4**:

402   1136–1138 https://doi.org/10.2307/1446115.

403   **Caillouet CW Jr, Shaver DJ, Landry AM Jr. 2015**. Kemp's ridley sea turtle (*Lepidochelys*

404   *kempii*) head-start and reintroduction to Padre Island National Seashore, Texas.

405   *Herpetological Conservation and Biology* **10:** 309–377.

406   **Cook M, Reneker J, Nero RW, Stacy BA, Hanisko DS, Wang Z. 2021.** Use of drift studies to

407   understand seasonal variability in sea turtle stranding patterns in Mississippi. *Frontiers in*

408   *Marine Science* **8**:659536 https://doi.org/10.3389/fmars.2021.659536.

409   **Davis RE. 1985.** Drifter observations of coastal surface currents during CODE: The statistical

410   and dynamic views. *Journal of Geophysical Research* **90**: 4756–4772.

411   **Garrison T. 2013.** *Oceanography: An invitation to marine science.* Belmont: Brooks/Cole-

412   Cengage Learning.

413   **Griffin LP, Griffin CR, Finn JT, Prescott RL, Faherty M, Still BM, Danylchuk AJ. 2019.**

414   Warming seas increase cold-stunning events for Kemp's ridley sea turtles in the

415   Northwest Atlantic. *PLoS ONE* **14**: e0211503

416   https://doi.org/10.1371/journal.pone.0211503.

417   **Haza AC, D'Asaro E, Chang H, Curcic M, Guigand C, Huntley HS, Jacobs G, Novelli G,**

418   **Özgökmen TM, Poje AC, Ryan E, Shcherbina A. 2018**. Drogue-loss detection for

419   surface drifters during the Lagrangian Submesoscale Experiment (LASER). *Journal of*

420   *Atmospheric and Oceanic Technology* **35**: 705–725 https://doi.org/10.1175/JTECH-D-17-

421   0143.1.

422   **IUCN (International Union for Conservation of Nature). 2020.** The IUCN Red List of

423   Threatened Species. Available at https://www.iucnredlist.org.

424   **Johnson SA, Bass AL, Libert B, Marshall M, Fulk D. 1999.** Kemp's ridley (*Lepidochelys*

425   *kempi*) nesting in Florida. *Florida Scientist* **62**: 194–204.

426   **Lazell JD Jr. 1980**. New England: Critical habitat for marine turtles. *Copeia* **1980**: 290–295

427   https://doi.org/10.2307/1444006.

428   **Liu X, Manning JP, Prescott R, Page F, Faherty M, Zou H. 2019**. On simulating cold-

429   stunned turtle strandings on Cape Cod, Massachusetts. *PLoS ONE* **14**: e0204717

430   https://doi.org/10.1371/journal.pone.0204717.

431   **Milton SL, Lutz PL. 2003**. Physiological and genetic responses to environmental stress. In: PL

432   Lutz PL, Musick JA, & Wyneken J, eds. *The biology of sea turtles II*. Boca Raton: CRC

433   Press, 163–187.

434   **Moise M. 2021.** Sea turtle cold stunning report 2020. National Oceanic and Atmospheric

435   Administration, Greater Atlantic Regional Fisheries Office, National Marine Fisheries

436   Service, Gloucester, Massachusetts.

437   **Morreale SJ, Meylan AB, Sadove SS, Standora EA. 1992.** Annual occurrence and winter

438   mortality of marine turtles in New York waters. *Journal of Herpetology* **26**: 301–308

439   https://doi.org/10.2307/1564885.

440 **Morreale SJ, Standora EA. 2005.** Western North Atlantic waters: Crucial development habitat

441   for Kemp's ridley and loggerhead sea turtles. *Chelonian Conservation and Biology* **4**:

442   872–882.

443 **National Park Service. 2018, October 1.** Rarest sea turtle nests on Queens Beach [Press

444   Release]. Available at https://www.nps.gov/gate/learn/news/rarest-sea-turtle-nests-on-

445   queens-beach.htm

446 **National Research Council. 1990.** *Decline of the sea turtles: Causes and prevention*.

447   Washington, D.C.: National Academy Press.

448 **Nero RW, Cook M, Coleman AT, Solangi M, Hardy R. 2013**. Using an ocean model to

449   predict likely drift tracks of sea turtle carcasses in the north central Gulf of Mexico.

450   *Endangered Species Research* **21**:191-203 https://doi.org/10.3354/esr00516.

451 **Nero RW, Cook M**, **Reneker JL, Wang Z, Schultz EA, Stacy B. 2022.** Decomposition of

452   Kemp's ridley (Lepidochelys kempii) and green (Chelonia mydas) sea turtle carcasses

453   and its application to backtrack modeling of beach strandings. Endangered Species

454   Research. *Endangered Species Research* 47:29-47 https://doi.org/10.3354/esr01164.

455 **Novelli G, Guigand CM, Cousin C, Ryan EH, Laxague NJM, Dia H, Haus BK, Özgökmen**

456   **TM. 2017.** A biodegradable surface drifter for ocean sampling on a massive scale.

457   *Journal of Atmospheric and Oceanic Technology* **34**: 2509–2532.

458 **Poulain P. 1999.** Drifter observations of surface circulation in the Adriatic Sea between

459   December 1994 and March 1996. *Journal of Marine Systems* **20**: 231–253.

460 **Putman NF, Hawkins J, Gallaway BJ. 2020**. Managing fisheries in a world with more sea

461   turtles. *Proceedings of the Royal Society B* **287**: https://doi.org/10.1098/rspb.2020.0220.

462 **Reneker JL., Cook M, Nero RW. 2018.** Preparation of fresh dead sea turtle carcasses for at-sea

463   drift experiments. NOAA Technical Memorandum NMFS-SEFSC-731. 14 pp.

464   https://doi.org/10.25923/9hgx-fn38.

465 **Santos B, Kaplan DM, Friedrichs MAM, Barco SG, Mansfield KL, Manning JP.** 2018.

466   Consequences of drift and carcass decomposition for estimating sea turtle mortality

467   hotspots. *Ecological Indicators* 84: 319-336

468   https://doi.org/10.1016/j.ecolind.2017.08.064.

469 **Shaver DJ. 2005.** Analysis of the Kemp's ridley imprinting and headstart project at Padre Island

470   National Seashore, Texas 1978-1988, with subsequent nesting and stranding records on

471   the Texas coast. *Chelonian Conservation and Biology* **4**: 846–859.

472 **Shaver DJ, Schroeder BA, Byles RA, Burchfield PM, Peña J, Márquez R, Martinez HJ.**

473   **2005.** Movement and home range of adult male Kemp's ridley sea turtles (*Lepidochelys*

474   *kempii*) in the Gulf of Mexico investigated by satellite telemetry. *Chelonian Conservation*

475   *Biology* **4**: 817–827.

476 **Shaver DJ, Tissot PE, Streich MM, Walker JS, Rubio C, Amos AF, George JA, Pasawicz**

477   **MR. 2017.** Hypothermic stunning of green sea turtles in a western Gulf of Mexico

478   foraging habitat. *PLoS ONE* **12**: e0173920 https://doi.org/10.1371/journal. pone.0173920.

479 **Signell RP, List JH. 1997.** Effect of wave-enhanced bottom fraction on storm-driven circulation

480   in Massachusetts Bay. *Journal of Waterway, Port, Coastal, and Ocean Engineering* **123**:

481   233–239.

482 **Spotila JR, O'Connor MP, Paladino FV. 1997.** Thermal biology. In: Lutz PL, Musick JA, eds.

483   *The biology of sea turtles*. Boca Raton: CRC Press, 297–314.

484 **Spotila JR. 2004**. *Sea turtles: a complete guide to their biology, behavior, and conservation*.

485   Baltimore: The Johns Hopkins University Press.

486 **Still BM, Griffin CR, Prescott R. 2005.** Climatic and oceanographic factors effecting daily

487   patterns of juvenile sea turtle cold-stunning in Cape Cod Bay, Massachusetts. *Chelonian*

488   *Conservation and Biology* **4**: 883–890.

489 **Warner JC, Butman B, Dalyander PS. 2008.** Storm-driven sediment transport in

490   Massachusetts Bay. *Continental Shelf Research* **28**: 257–282

491   https://doi.org/10.1016/j.csr.2007.08.008.

492 **Wibbels T, Bevan E. 2019.** *Lepidochelys kempii.* The IUCN Red List of Threatened Species.

493   e.T11533A155057916. Available at https://dx.doi.org/10.2305/IUCN.UK.2019-

494   2.RLTS.T11533A155057916.en.

495 **Witherington BE, Ehrhart LM. 1989.** Hypothermic stunning and mortality of marine turtles in

496   the Indian River Lagoon System, Florida, U.S.A. *Copeia* **1989**: 696–703

497   https://doi.org/10.2307/1445497.

Dimensions and mean drift times 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 (hrs)		
					Mean	Range	SD
Mini-boat	1.36	1.52	0.91	5	5	3–6	±1.30
Davis-style	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 Bottom	0.13	0.36	-11.5	4	160	44–371	±150.34

Table 1: Dimensions and mean drift times 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.

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

The estimated speed is the average of the first four hourly readings for the period after the drifters were deployed.

Date	Drifter	Compass direction	Direction (degrees)	Estimated speed (m/s)
11/14/2019	WIND	NNE	18	4.41
11/14/2019	Mini-boat	N	4	0.83
11/14/2019	Sea Turtle Surface	NWN	326	0.11
11/14/2019	Davis-style	NW	312	0.11
11/14/2019	Sea Turtle Bottom	NWW	306	0.07
11/19/2019	WIND	ENE	66	2.62
11/19/2019	Mini-boat	E	87	0.37
11/19/2019	Sea Turtle Surface	ES	104	0.15
11/19/2019	Davis-style	SEE	119	0.14
11/19/2019	Sea Turtle Bottom	ESE	114	0.15
11/26/2019	WIND	NNE	27	8.94
11/26/2019	Mini-boat	NEN	37	1.01
11/26/2019	Sea Turtle Surface	NE	44	0.20
11/26/2019	Davis-style	NEE	35	0.22
11/26/2019	Sea Turtle Bottom	NE	47	0.18

Table 2: Initial direction of travel and speed of drifters and the corresponding wind variables.

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).
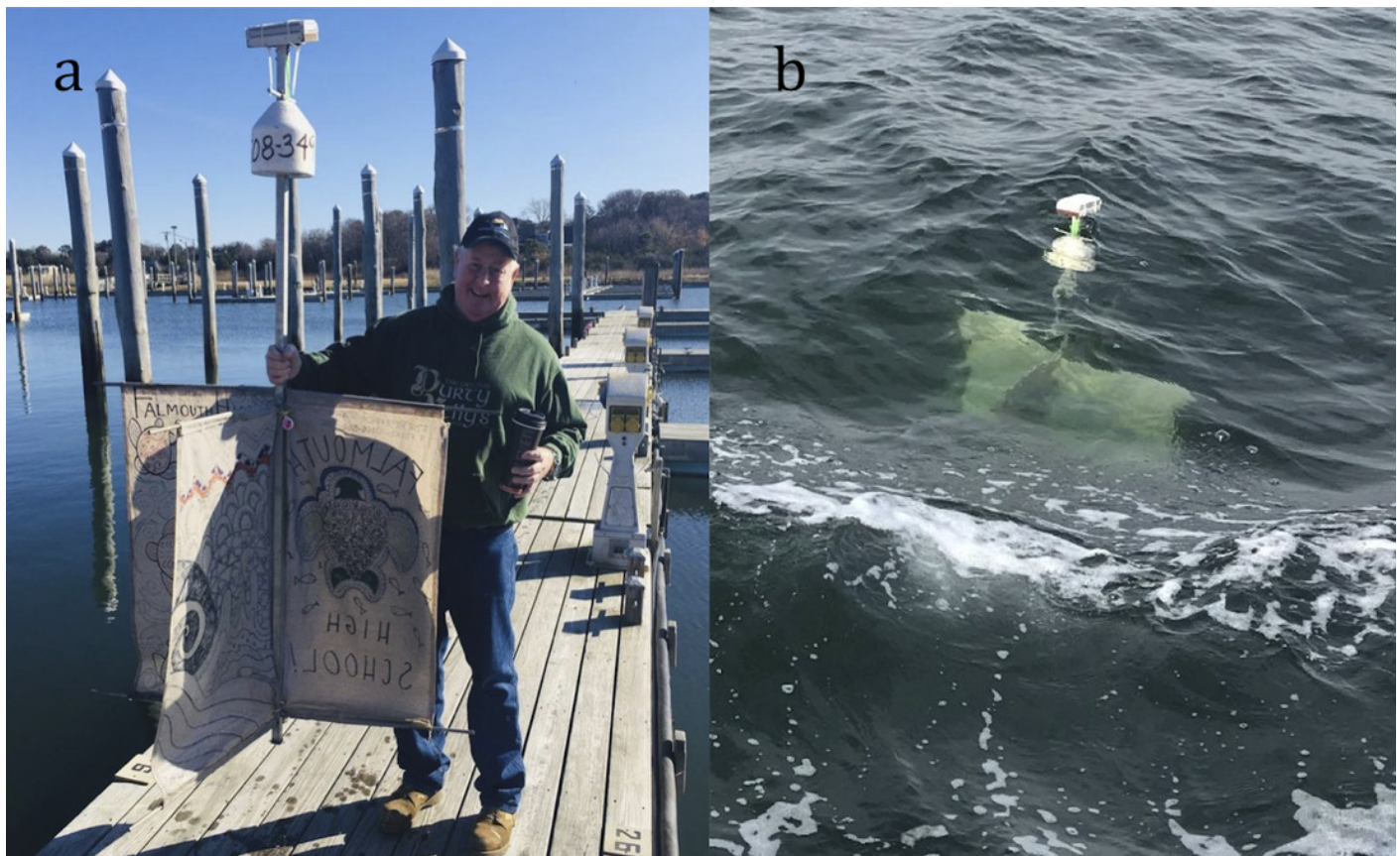
Figure 2

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) Beached sea turtle surface drifters. Photo credit: Felicia Page.
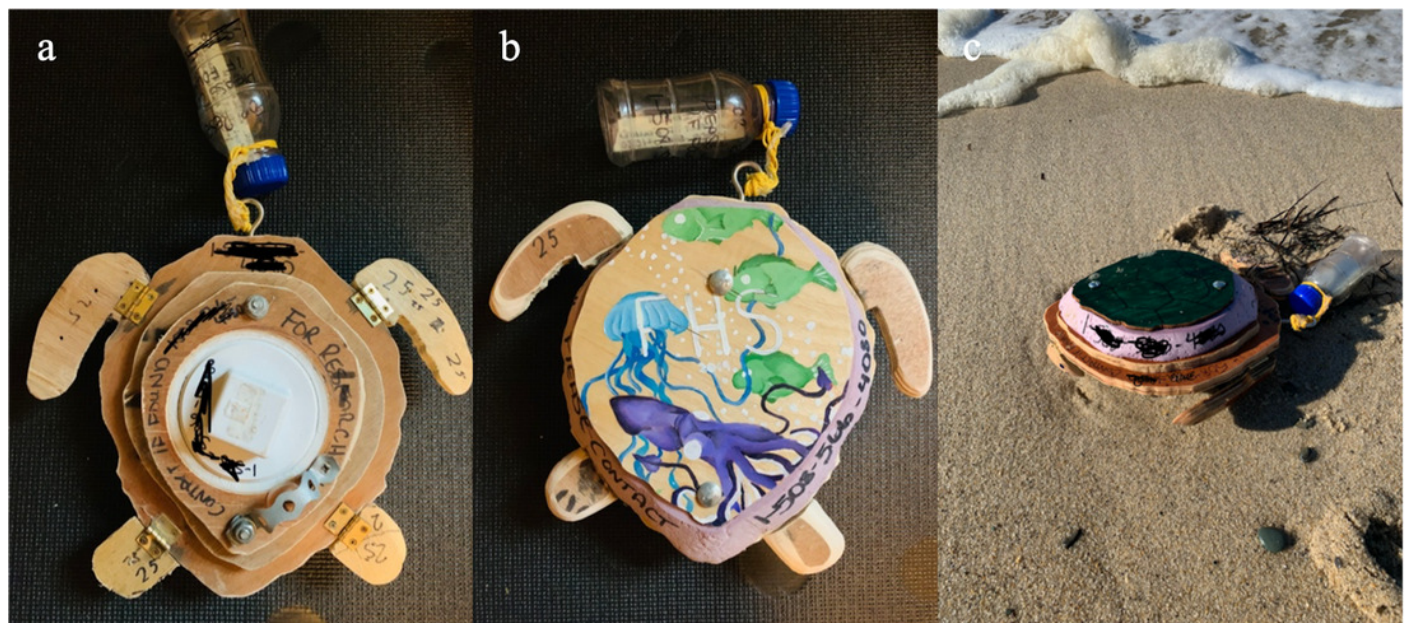
Figure 3

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.*
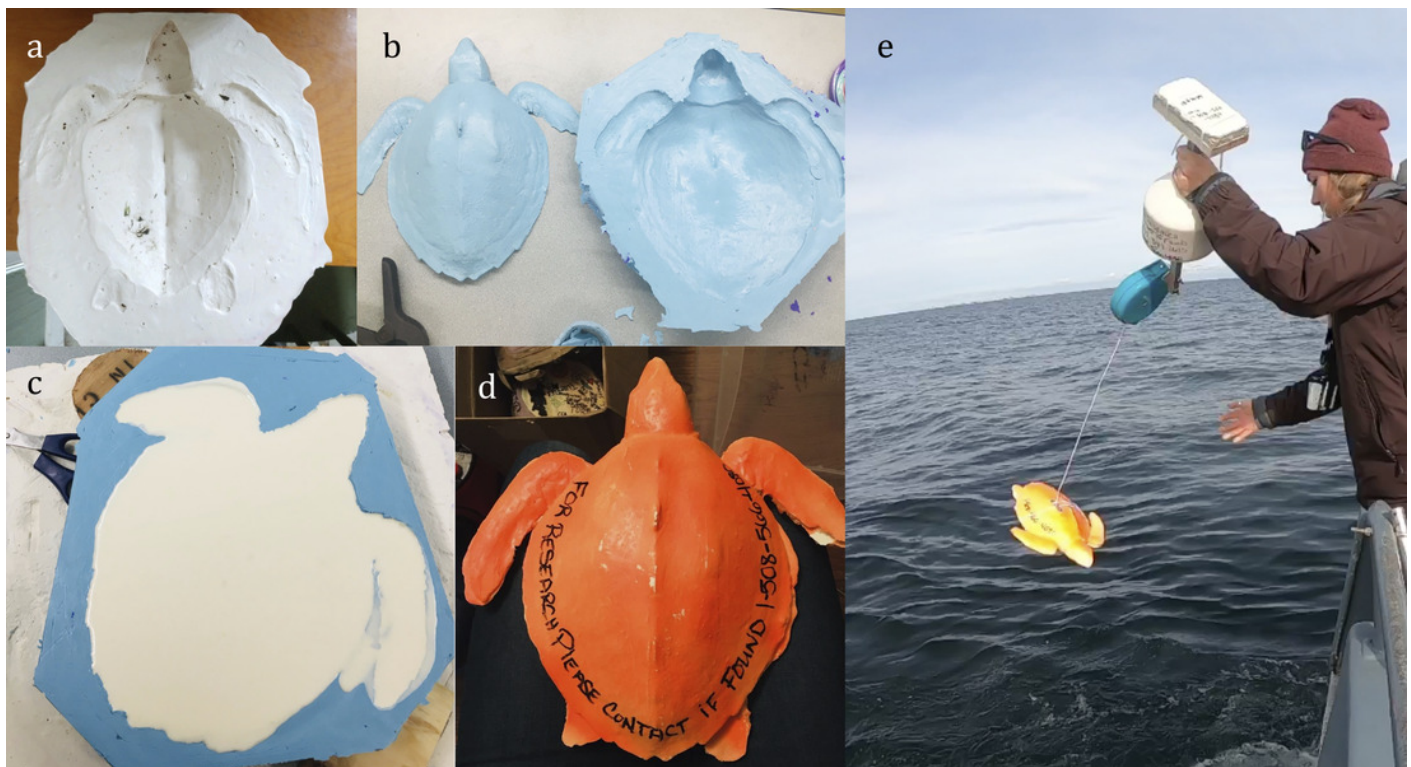
Figure 4

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.
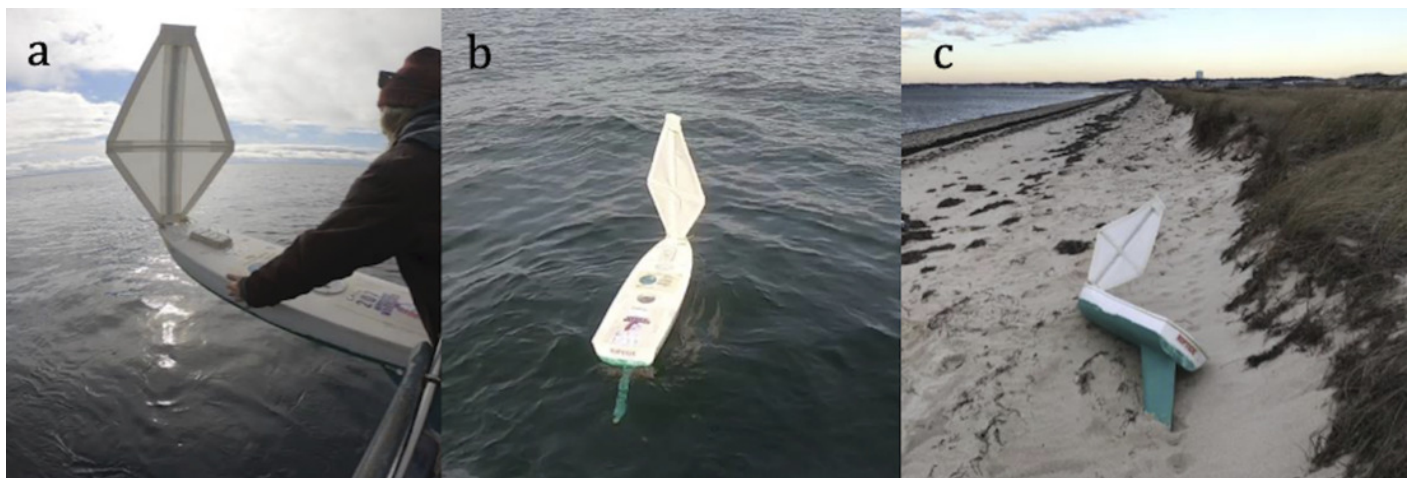
Figure 5

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

With the exception of the mini-boat, which stranded after 4 hours, the drifter tracks shown here are limited to the first 24 hours after the deployment to provide a simplified visualization of the degree of separation between the different drifter models.

Drifter Model

- —□— Miniboat
- —+— Surface turtle drifter
- ▪▪▪▪▪ Davis-style drifter
- ▬▬▬ Bottom turtle drifter
- —► Wind
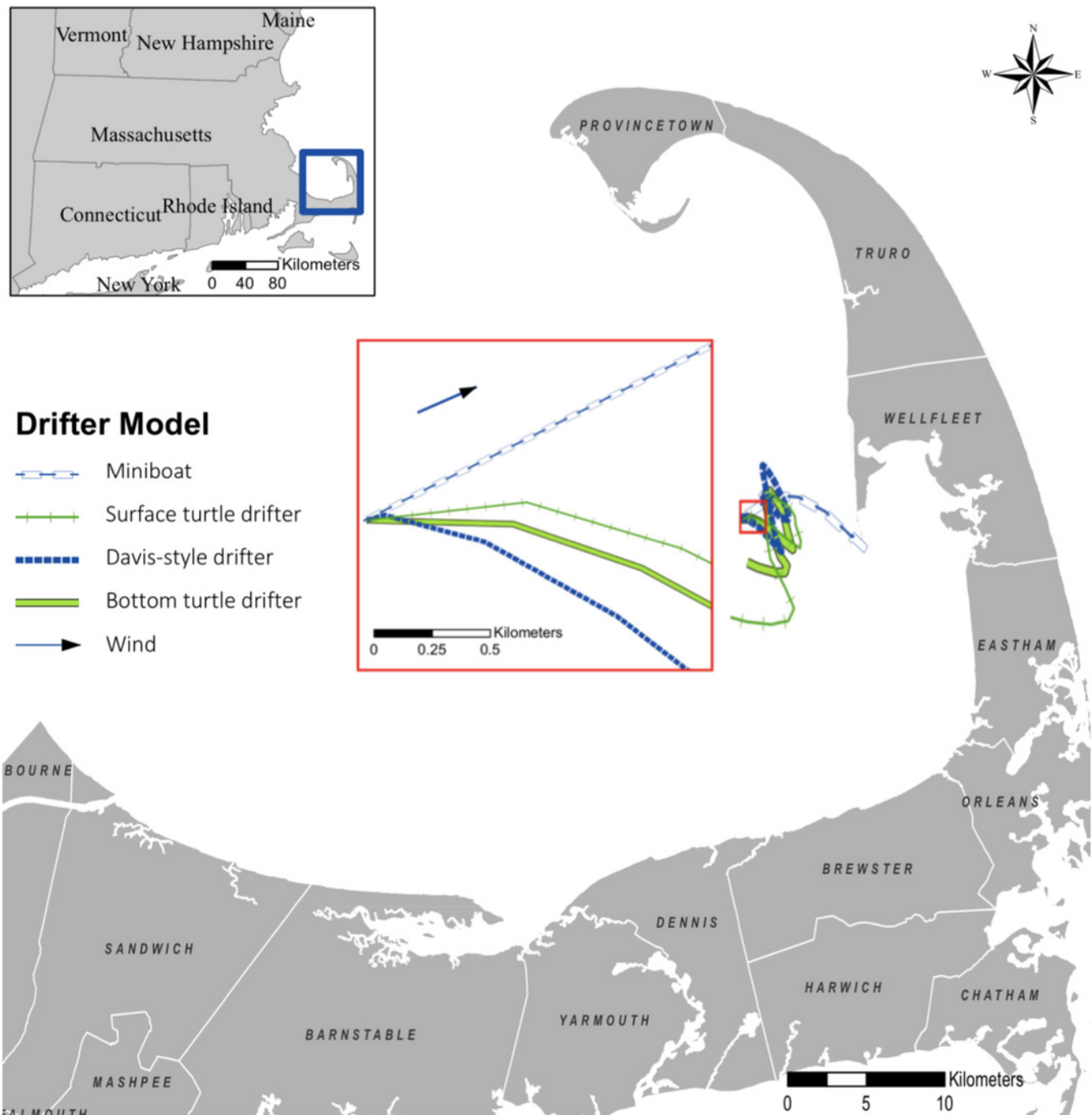
Figure 6

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

Hotspots highlight areas where the largest numbers of (a) drifters or (b) cold-stunned sea turtles were recovered throughout the season. Red indicates the highest number of data points, while yellow indicates intermediate and green indicates the lowest number.
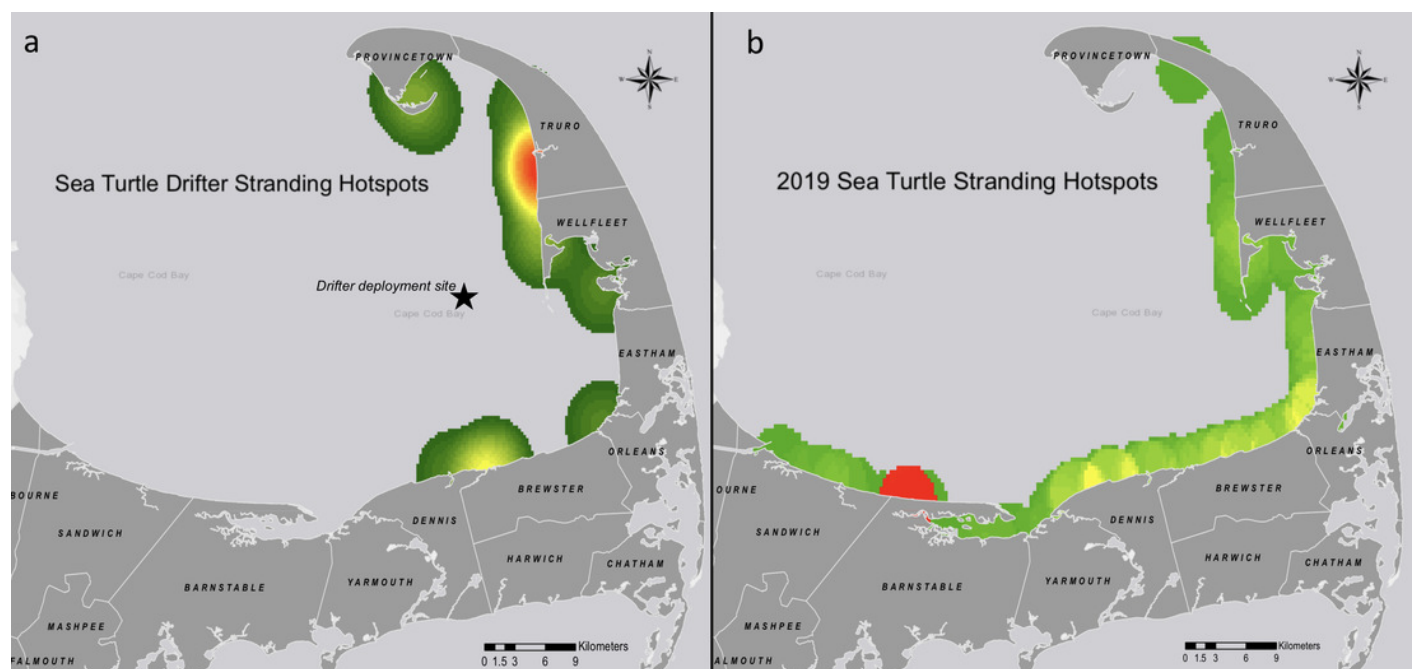
Figure 7

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. Red indicates the highest number of data points, while yellow indicates intermediate and green indicates the lowest number.
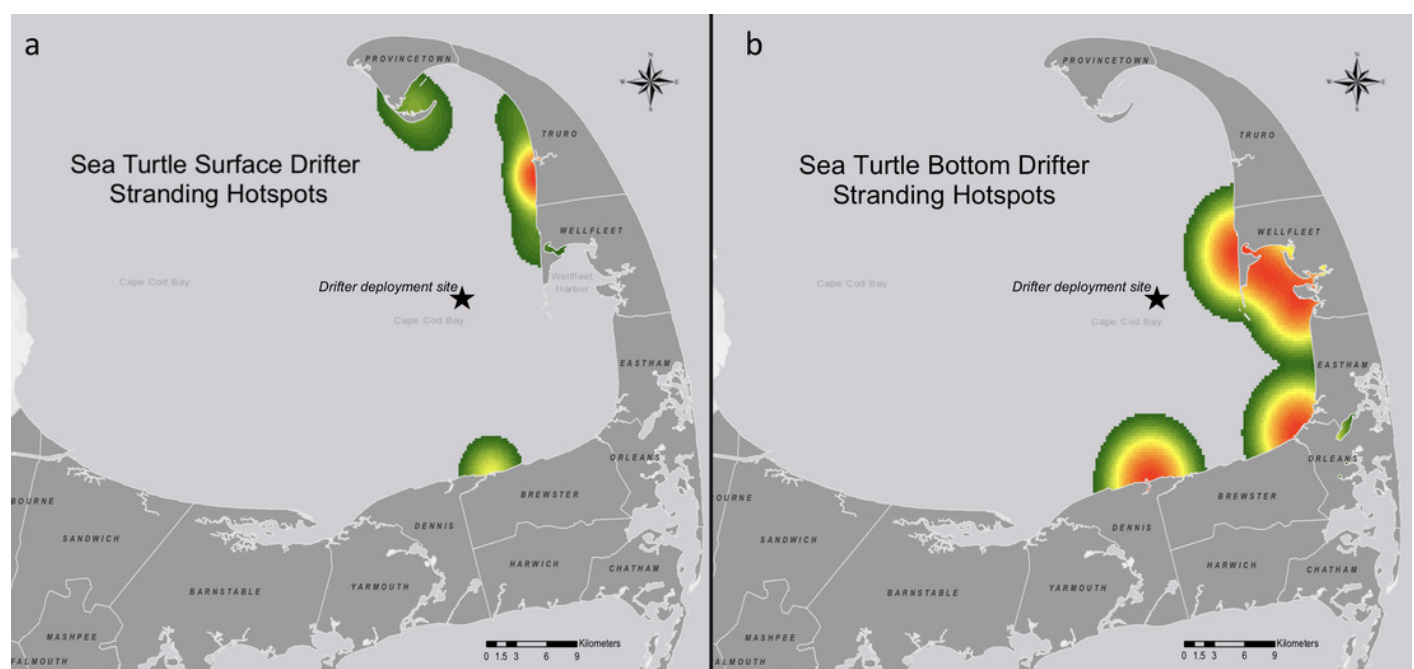
Figure 8

Comparison of sea turtle-shaped 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. This date range corresponds with the dates the drifters shown in part (a) stranded. Red indicates the highest number of data points, while yellow indicates intermediate and green indicates the lowest number.