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Likely locations of sea turtle stranding mortality using experimentally-calibrated, time and space-specific drift models

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ABSTRACT

Sea turtle stranding events provide an opportunity to study drivers of mortality, but causes of strandings are poorly understood. A general sea turtle carcass oceanographic drift model was developed to estimate likely mortality locations from coastal sea turtle stranding records. Key model advancements include realistic direct wind forcing on carcasses, temperature driven carcass decomposition and the development of mortality location predictions for individual strandings. We applied this model to 2009–2014 stranding events within the Chesapeake Bay, Virginia. Predicted origin of vessel strike strandings were compared to commercial vessel data, and potential hazardous turtle-vessel interactions were identified in the southeastern Bay and James River. Commercial fishing activity of gear types with known sea turtle interactions were compared to predicted mortality locations for stranded turtles with suggested fisheries-induced mortality. Probable mortality locations for these strandings varied seasonally, with two distinct areas in the southwest and southeast portions of the lower Bay. Spatial overlap was noted between potential mortality locations and gillnet, seine, pot, and pound net fisheries, providing important information for focusing future research on mitigating conflict between sea turtles and human activities. Our ability to quantitatively assess spatial and temporal overlap between sea turtle mortality and human uses of the habitat were hindered by the low resolution of human use datasets, especially those for recreational vessel and commercial fishing gear distributions. This study highlights the importance of addressing these data gaps and provides a meaningful conservation tool that can be applied to stranding data of sea turtles and other marine megafauna worldwide.

1. Introduction

Many of the world's marine megafauna are highly threatened by a mixture of anthropogenic pressures (Learmonth et al., 2006; Crain et al., 2009; Wallace et al., 2013; Lewison et al., 2014) and natural threats (George, 1997; Gulland and Hall, 2007; Heithaus et al., 2008). Among these species are marine sea turtles, of which six out of the seven species worldwide are listed on the IUCN Red List of Threatened Species (http://www.redlist.org). For sea turtles and other marine megafauna, a better understanding of the impacts of anthropogenic activities on these species is essential to assessing risk of population extinction and identifying effective conservation strategies. Sea turtle strandings provide an important opportunity to study turtle mortality and identify threats for future mitigation and conservation actions, however, identifying potential causes of mortality of stranded sea turtles can be extremely challenging due to state of carcass decomposition and the lack of physical evidence of the cause of mortality (Hart et al., 2006; Koch et al., 2013). In particular, interactions with some fishing gears often do not leave marks on turtles, due to a combination of gear type and sea turtle anatomy (i.e. hard parts), thus solely using injuries noted at time of stranding to attribute cause of death has been suggested to grossly underestimate fisheries-induced mortality (Barco et al., 2016). Fishing activity has been noted as a large driver of anthropogenic sea turtle mortality worldwide, with lethal interactions documented in gear types including longlines, trawls, gillnets, pound nets, dredges, seines and pots (Lewison et al., 2004; Zollett, 2009; Wallace et al., 2010; Finkbeiner et al., 2011). Despite the current vulnerability of sea turtle species and known interactions with recreational

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and commercial fishing gear, as well as commercial and recreational vessel traffic, management actions are still frequently hindered by lack of specific information on where and when human-turtle interactions occur.

The Chesapeake Bay (Bay) and its surrounding coastal waters are critical foraging and developmental habitats for thousands of sea turtles that use these waters seasonally (Musick and Limpus, 1997; Mansfield, 2006). However, hundreds of deceased turtles are found stranded on Virginia's coastline each year. The Virginia Sea Turtle Stranding and Salvage Network (VAQS), currently led by the Virginia Aquarium & Marine Science Center, has been responding to strandings throughout the state since the 1970s, documenting 100–300 events annually in the past decade (Swingle et al., 2016). Strandings are observed throughout the year, although the majority of annual strandings usually occur during a strong spring peak in May and June when turtles are first entering the Bay (Lutcavage and Musick, 1985; Coles, 1999). Mortality continues at a relatively high level throughout the summer, followed in some years by a small fall peak in strandings associated with turtles migrating out of the Bay to avoid cold winter temperatures (Mansfield et al., 2009). Juvenile loggerheads are the most commonly reported sea turtles found within Virginia's waters, followed by the critically endangered Kemp's ridley (http://www.redlist.org) (Lutcavage and Musick, 1985; Coles, 1999; Barco and Swingle, 2014). Importantly, Virginia's waters provide crucial habitats for loggerheads from several different western Atlantic distinct population units (Conant et al., 2009; Mansfield et al., 2009; NMFS, 2011; Ceriani et al., 2017), thus local mortality could lead to detrimental impacts among multiple loggerhead subpopulations (Mansfield et al., 2009). Strandings likely represent a minimal measure of actual at-sea mortality, with some studies in open ocean environments estimating stranding events to represent only 10–20% of total deaths (Epperly et al., 1996, Hart et al., 2006; note, however, that these stranding percentages may be higher in the semi-enclosed Bay). Given the important role the Bay plays in regional sea turtle life cycles, detailed information on the times, places and causes of mortality are essential to maintaining and increasing these populations.

When stranded sea turtles are recovered as fresh dead carcasses, cause of death can often be determined by conducting a thorough necropsy and submitting tissues to a veterinary pathologist for histopathology. Barco et al. (2016) summarized cause of death for 70 fresh carcasses recovered in Virginia and North Carolina from 2004 to 2013. Nearly half of the turtles (n = 31; 44%) died from acute vessel (n = 15) or fishery interaction (n = 16) and most of these were apparently healthy prior to death with no significant pathology and good body condition, suggesting they were not already compromised in any way prior to mortality (Barco et al., 2016). Of those turtles that were categorized as drowning from fishery interaction, few, if any, lesions were present on the carcasses (Barco et al., 2016), which is similar to some fishery interaction cases in cetaceans (Moore et al., 2013). This lack of injuries has importance for the majority of dead stranded sea turtles observed in Virginia, which are in a moderate to advanced state of decomposition at time of discovery. Though some causes of death, such as drowning due to underwater entrapment in fishing gear, are impossible to definitively assess in these more extensively decomposed cases, they often share several of the characteristics of fishery interactions, such as a lack of lesions or obvious pathology. Collectively, these results suggest that vessel and fishery interactions are important sources of human-induced mortality in the Bay, but more information is needed on the locations of mortality to help pinpoint the gears or vessels likely responsible. Turtles in this region have been documented caught or entangled in pound net leader hedging, gillnets, trawl nets, crab pot lines and whelk pot lines (Bellmund et al., 1987; Keinath et al., 1987; Mansfield et al., 2001; Barco et al., 2016). Although there is no concrete evidence of the Chesapeake Bay's menhaden purse seine fishery causing sea turtle mortality, other purse seine fisheries in the region are known to kill turtles (Silva, 1996) and there is no state-run observer program for this and many other fisheries in the Bay (Barco et al., 2015). Narrowing down this list of potential causes for sea turtle mortality in the Bay to the most prevalent causes, locations and time periods is essential to developing targeted conservation strategies for these threatened species.

Mitigating sea turtle mortality (especially when fishery observer data are limited) requires investigation into the location of mortality in order to assess potential causal mechanisms and identify hotspots for negative human-turtle interactions. After sea turtles die, their bodies sink until decomposition gases cause the body to bloat and float to the surface (if not entangled). Partially submerged and acting as drifting objects, carcasses are transported by winds and currents. Landfall may occur if conditions are favorable to onshore transport and the turtle carcass does not decompose and sink before reaching a coastline. Santos et al. (2018) found that sea turtle carcass drift time is highly dependent on water temperature, due to decomposition rates, and that winds make an important contribution to the net transport of turtle carcasses. Oceanographic modeling and drift studies have been used in the past to understand mechanisms for larval release and dispersal (Garavelli et al., 2012), as well as to predict trajectories of drifting human bodies (Carniel et al., 2002) and cetacean carcasses (Peltier et al., 2012). A limited number of recent studies have applied this approach to sea turtle carcasses in other geographic regions (Hart et al., 2006; Nero et al., 2013; Koch et al., 2013), providing valuable insight on stranding causes and likelihood. Santos et al. (2018) conducted preliminary investigations into sea turtle carcass drift patterns within the Chesapeake Bay area specifically, however strandings were not assessed at the individual level, with potential mortality hotspots based on fairly general areas of historically high stranding rates. Furthermore, only stranding locations during June, the peak month of sea turtle strandings in Virginia, were analyzed.

In this study, we construct an oceanographic drift model for the lower Chesapeake Bay to predict the probable location of mortality for individual coastal sea turtle strandings in Virginia based on the location of stranding, state of carcass decomposition and environmental conditions. We simulated the drift patterns of dead turtles prior to stranding and identified likely locations of sea turtle mortality using the starting points of particle trajectories arriving at the stranding location at the correct time and decomposition state. Empirical results from Santos et al. (2018) were used in the drift model to parameterize the probable oceanic drift time as a function of temperature and the impact of direct wind forcing on carcass drift. We applied this adjusted model to individual sea turtle stranding observations in coastal areas of Virginia and most probable mortality locations within the region were identified for specific classes of strandings with similar characteristics (e.g., probable cause of death, state of carcass decomposition).

Overall, this study provides a basis for quantitative and qualitative comparisons with spatial distributions of potential causes of sea turtle mortality in the Bay. Our previous work parameterized the characteristics of drifting sea turtle carcasses and found general areas of likely sea turtle mortality in the Bay (Santos et al., 2018). Here, we build upon that preliminary study to predict the trajectories and mortality locations of individual strandings, aggregating results over many events and making comparisons with available information on potential causal mechanisms. The model constructed in this paper also includes a number of methodological improvements to the methods outlined in Santos et al. (2018), including the incorporation of winds, currents, temperature and carcass condition on carcass drift, that can be applied to stranding data for sea turtles and other marine megafauna around the globe to better understand and mitigate mortality events.

2. Material and methods

A model simulating the drift of dead sea turtles prior to stranding was developed using the offline Lagrangian drift simulation tool Ichthyop version 3.3 (Lett et al., 2008; Santos et al., 2018). The model was configured to release 20,000 pseudo-particles (i.e. simulated