Oceanic and Atmospheric Correlations to Cetacean Mass Stranding Events in Cape Cod Massachusetts, USA

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Abstract

Groups of pelagic dolphins and whales (order cetacea) regularly strand on beaches throughout the world and are referred to as mass stranding events (MSEs). MSEs have been observed for centuries, however the underlying causes remain unclear. We investigated possible connections between MSEs in Cape Cod Massachusetts, USA, and regional wind and ocean currents. The seasonal MSE distribution is strongly correlated to both wind and ocean current strengths, and correlation is maximized when MSEs are compared to environmental data one month in the past. Furthermore, a superposed epoch analysis (a Chree analysis) indicates significant shifts in ocean current strength for months surrounding MSEs. These results may indicate that atmospheric and oceanic effects are possible underlying factors influencing MSEs. These factors could generate environments conducive for prey assemblages that attract cetaceans, or perhaps by driving seasonal production of prey species.

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Key Points:

- Cetacean stranding events are concentrated along the SE shores of Cape Cod Bay.
- Wind speeds and ocean current speeds are strongly correlated to the seasonal number of cetacean mass stranding events in Cape Cod.
- Wind and ocean interactions may produce near-shore upwelling that contribute to cetacean mass stranding events.
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Abstract

Groups of pelagic dolphins and whales (order cetacea) regularly strand on beaches throughout the world and are referred to as mass stranding events (MSEs). MSEs have been observed for centuries, however the underlying causes remain unclear. We investigated possible connections between MSEs in Cape Cod Massachusetts, USA, and regional wind and ocean currents. The seasonal MSE distribution is strongly correlated to both wind and ocean current strengths, and correlation is maximized when MSEs are compared to environmental data one month in the past. Furthermore, a superposed epoch analysis (a Chree analysis) indicates significant shifts in ocean current strength for months surrounding MSEs. These results may indicate that atmospheric and oceanic effects are possible underlying factors influencing MSEs. These factors could generate environments conducive for prey assemblages that attract cetaceans, or perhaps by driving seasonal production of prey species.

Plain Language Summary

Dolphins and whales are regularly found stranded on the beaches of Cape Cod, Massachusetts. These events often occur with several animals stranded together and sometimes with much larger numbers. It is not clear what causes these animals to beach. We analyzed 18 years of stranding reports and found that more mass stranding events (MSEs) occur during the time of year when there are stronger winds and ocean currents. This could mean that the winds and ocean currents contribute to causing these stranding events. We conjecture that winds and ocean currents create a favorable environment for the animals these dolphins feed on, and that these offshore dolphins and whales strand while chasing this prey into shallower inshore waters.

1 Introduction

Dolphins and whales, also referred to as cetaceans, regularly strand in significant numbers on shorelines around the world (Aristotle in 350 BCE, translated in 1910; Thoreau, 1864; Geraci, 1978). A mass stranding event (MSE) occurs when two or more animals that are not mother / calf pairs are beached during an ebb tide and in relative proximity (Klinowska, 1985; Geraci and Lounsbury, 1993; Sharp et.al., 2015). Mainly offshore deep-water species strand in mass events (Reeves et al., 2002). Often, stranded animals die despite human intervention to rescue and release them.

The causes for this phenomenon are poorly understood and likely involve multiple factors (Perrin and Geraci, 2002; Domingo et al., 2002; Robson, 1984; Cordes, 1982; Geraci and Loundsbury, 1993). The hypotheses for the causes of mass stranding events include (1) oceanographic conditions such as unusual tides, sea state, bathymetry and coastal topography (Brabyn and McLean, 1992; Nicol, 1985; Warneke, 1983; Sergeant, 1982; Stephenson, 1975; McCann, 1964; Dudok van Heel, 1962; Gilmore, 1957; A.G.Tomilin, in lit. Warneke, 1983); (2) meteorological events such as electrical storms (Warneke, 1983); (3) disturbance of echolocation in shallow waters (associated with sediment size and bottom contour/slope) (Dudok van Heel, 1962; 1966; Sundaram et al., 2006); (4) changes in the physical and biogeochemical characteristics of water masses (Mann and Lazier, 1991); (5) environmental forcing (wind) and its effects on water masses and prey assemblages (Walker et al., 2005; Evans et al., 2005; Brabyn and McLean, 1992); (6) prey behavior or escape from predators; (7) social cohesive behavior (the group follows a disoriented or sick member, the 'key whale') (Wood, 1979; Odell et al., 1980); (8) regression to ancient instinctive behaviors (Wood, 1979), and (9) navigational errors due to space weather and geomagnetic storm disturbances (Klinowska, 1985; 1986a; 1986b; 1988; Kirschvink et al., 1986; Kirschvink, 1990; Rogan et al., 1997; Vanselow and Ricklefs, 2005; Vanselow, 2020; Granger et al., 2020; Pulkkinen et al., 2020).

Cape Cod Massachusetts, USA, (the Cape) is considered a stranding “hot spot” along with Golden Bay, New Zealand, Ocean Beach, Tasmania and Geographe Bay, Western Australia (Hamilton, 2018). Cape Cod is a hook-shaped peninsula projecting into the Atlantic Ocean forming Cape Cod Bay (see Figure 1). We are motivated to investigate the causes of MSEs in Cape Cod not only to gain insight about this phenomenon at this location, but also as a means of possibly understanding the causes of stranding events elsewhere.

2 Data and Methods

2.1 Data

Three datasets (Mass stranding reports, wind data, and ocean current data) were used in our analysis and are described below.

2.1.1 Mass Stranding Data

The International Fund for Animal Welfare (IFAW) has coordinated a comprehensive marine mammal stranding response program along the shorelines of the Cape since 1998. The IFAW provided their stranding records after filtering to remove human-induced strandings and unusual mortality events (UMEs). They identified MSEs using a standard rubric that considers timing within the tidal cycle, location and species. The records delivered for analysis spans March 1999 to December 2017 and have one record for each stranded animal that includes: a unique MSE identifier (MSID), date, position (latitude and longitude), species and animal condition (live, fresh dead, decomposed, etc.). Note the MSID was repeated in multiple records to indicate which animals were part of the same MSE.

2.1.2 Wind Data

Hourly wind direction (degrees from north) and strength (m/s) were collected from the National Oceanographic and Atmospheric Administration (NOAA) National Data Buoy Center (NDBC). While other stations were closer to stranding sites, buoy station 44013 provided the most complete, long-term and continuous data set nearest to Cape Cod Bay. Station 44013 is located approximately 16 nautical miles east of Boston Harbor (Figure 1). The data spanned January 1998 through December 2018.

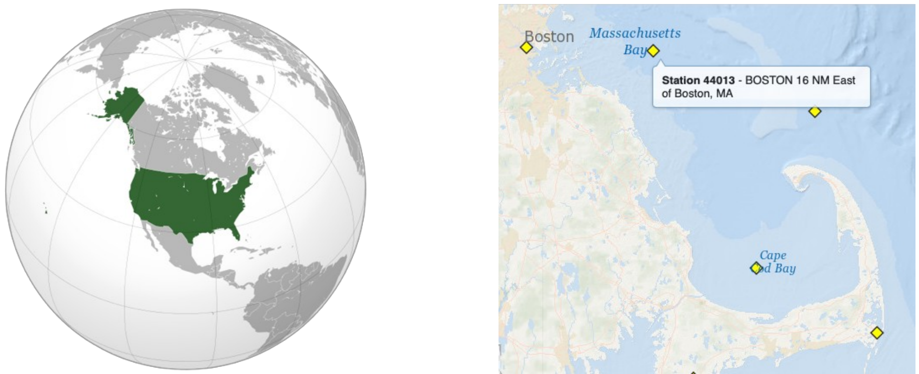

Figure 1: *The Location of Cape Cod Bay and Buoy Station 44013*. Cape Cod is on the NE coast of The USA, shown in green. Buoy Station 44013 is located at 42.346 N 70.651W. (Image credit: Addicted04, 2020)

2.1.3 Ocean Current Data

The MERRA (Modern-Era Retrospective analysis for Research and Applications) Ocean reanalysis project was used to generate the ocean current data as an east-west and north-south current strength (m/s) and at a 1-degree spatial resolution for the period from June 2012 through June 2019. This reanalysis is produced within the climate model framework that has been used in support of the decadal prediction activities under the Coupled Model Intercomparison Project Phase 5 (CMIP5, Ham & Kug, 2014) and the GMAO (Global Modeling and Assimilation Office) seasonal forecast system (GEOS-S2S-1, Borovikov et al., 2019). The coupled model integrates the Fortuna version of the GEOS-5 AGCM (Goddard Earth Observing System, Version 5 Atmospheric General Circulation Model, Molod et al., 2012) with a Catchment land surface model (Koster et al., 2000), the Modular Ocean Model version 4 (MOM4, Griffies et al., 2004) and the “CICE” sea ice model (Hunke & Lipscomb 2008). All components are coupled together using the Earth System Modeling Framework (ESMF).

The atmospheric model uses a Cartesian grid with a 1° × 1.25° horizontal resolution and 72 hybrid vertical levels with the upper most level at 0.01hPa. The nominal resolution of the ocean grid is ½°, with a meridional equatorial refinement to ¼°. The ocean data assimilation procedure uses an Ensemble OI method (GEOS-iODAS, Vernieres, 2012), and the observations suite of the ocean and sea ice components includes in-situ temperature and salinity profiles, analyzed sea surface temperature, sea level anomalies from altimetry and sea-ice concentration. Sea surface salinity climatology is used to constrain the model in the early data sparse (pre-Argo) years. To couple the ocean and sea ice component of GEOS-5 with a realistic AGCM, a replay method in which the AGCM is constrained to GMAO’s MERRA is used (Rienecker et al., 2011). Since MERRA was completed in 2016, GEOS Forward Processing Near-Real Time (FP NRT) atmospheric analysis has been used.

2.2 Methods

Summary statistics for the MSE data were produced and animal locations were mapped. Stranding events (MSIDs) were aggregated by the month of the year to produce a seasonal distribution. Since the majority of species involved in these MSEs are sympatric, we did not differentiate based on species.

In a similar manner, the wind data were aggregated by month of the year and vector-averaged to determine seasonal distributions of average monthly wind speeds and directions.

The ocean current data were also aggregated by month of the year, then vector-averaged and regionally averaged to determine the seasonal variation of monthly ocean current magnitudes and directions. Three nested regions of decreasing size were investigated, all of which encompassed the Cape and Cape Cod Bay (Figure 2). Boundaries for the largest region (Region 1) were chosen to consider the broader ocean current characteristics near the Cape. The smallest region (Region 3) was chosen to examine the currents in the immediate vicinity of the Cape and Cape Cod Bay. A mid-sized area (Region 2) was selected between the other two regions.

a)

Region	Boundaries
Region 1	44.1N and 39.9N 73.1W and 65.9W
Region 2	43.1N and 40.9N 71.1W and 68.9W
Region 3	42.3N and 41.5N 71.1W and 69.7W

b)

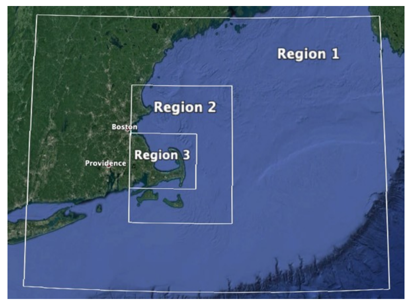

Figure 2: *Region Boundaries*. a) Boundaries for the regions considered with the ocean current analysis. Borders were chosen to ensure inclusion of data falling directly on boundaries. b) Google Earth image of the regions.

Pearson correlation coefficients were computed between the MSE seasonal distribution and the environmental seasonal distributions with varying monthly time offsets (a time-lagged correlation analysis).

Finally, superposed epoch analyses, also called Chree analyses, were conducted for the monthly wind and ocean current data using MSEs as the basis. The average wind strength and ocean current magnitudes were computed for offsets up to 12 months before and after MSEs.

3 Results

3.1 Cape Cod MSEs Overview

Summary statistics and species proportions are listed in Table 1. The largest MSE was recorded on 29 July 2002 where 56 long-finned pilot whales (*Globicephala melas*) were stranded on Chapin Beach in Dennis, Massachusetts. Most MSEs are recorded as involving two animals. The majority of MSEs involved *Delphinus delphis* and *Lagenorhynchus acutus*, pelagic odontocetes.

Table 1: *Summary of MSEs in Cape Cod 1999 - 2017*

Number of MSEs	209
Num. of animals	1117
Mean Animals / MSE	5.3
Mean MSEs / year	11.1
Mean Animals / year	59.3
Species:	%
Delphinus delphis (Dd)	61.6
Lagenorhynchus ac. (La)	29.2
Globicephala melas (Gm)	6.9
Grampus griseus (Gg)	2.0
Stenella coeruleoalba (Sc)	0.2
Tursiops truncatus (Tt)	0.2

3.2 Stranding Map and Seasonal MSE Distribution

A map of animal stranding locations and a graph of the number of MSEs aggregated by the month of the year are shown in Figure 3. Stranding events with more than one species identified were categorized as “mixed”. The majority of the mixed MSEs contained only common dolphins (*Delphinus delphis*) and Atlantic white sided dolphins (*Lagenorhynchus acutus*).

a)

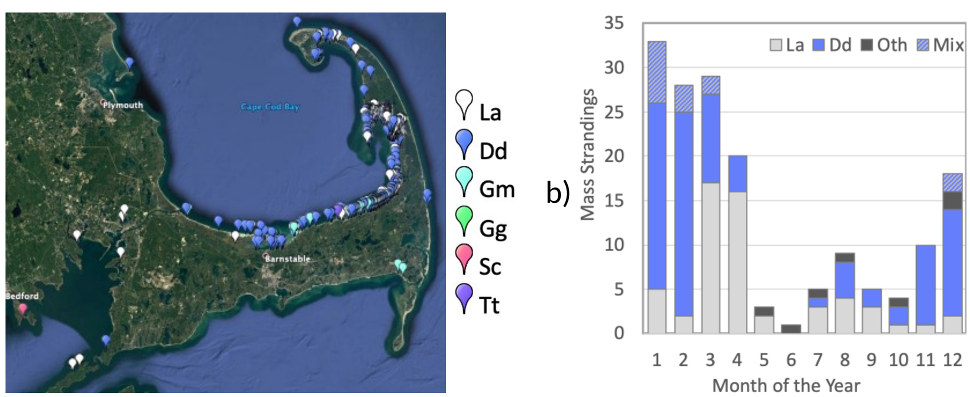

Figure 3: *Map of Stranded Animals and Seasonal MSEs.* a) Map of the Cape. Markers identify the locations of animals involved in MSEs from March 1999 – Dec 2017. b) The number of MSEs that occurred in each month of the year. Blue indicates *Delphinus delphis* (Dd) MSEs; grey are *Lagenorhynchus acutus* (La) MSEs; blue/white hash are MSEs with mixed species (Mix) and black (Oth) are MSEs consisting of *Globicephala melas* (Gm), *Grampus griseus* (Gg), *Stenella coeruleoalba* (Sc) or *Tursiops truncatus* (Tt) species.

3.3 Seasonal Wind Distribution and Comparison to MSEs

Wind analysis results are shown in Figure 4. Wind strength is lowest mid-year and predominantly blows from south to north during this period (Figures 4a and 4b). In the autumn and winter, the wind strength is much stronger and predominantly blows toward the ESE. Correlation of the seasonal wind distribution to the seasonal MSE distribution reaches a maximum (0.97) when the wind data is shifted forward in time by one month (Figure 4c). The wind epoch analysis indicates that the average monthly winds are weaker in the months preceding and following a stranding event (Figure 4d).

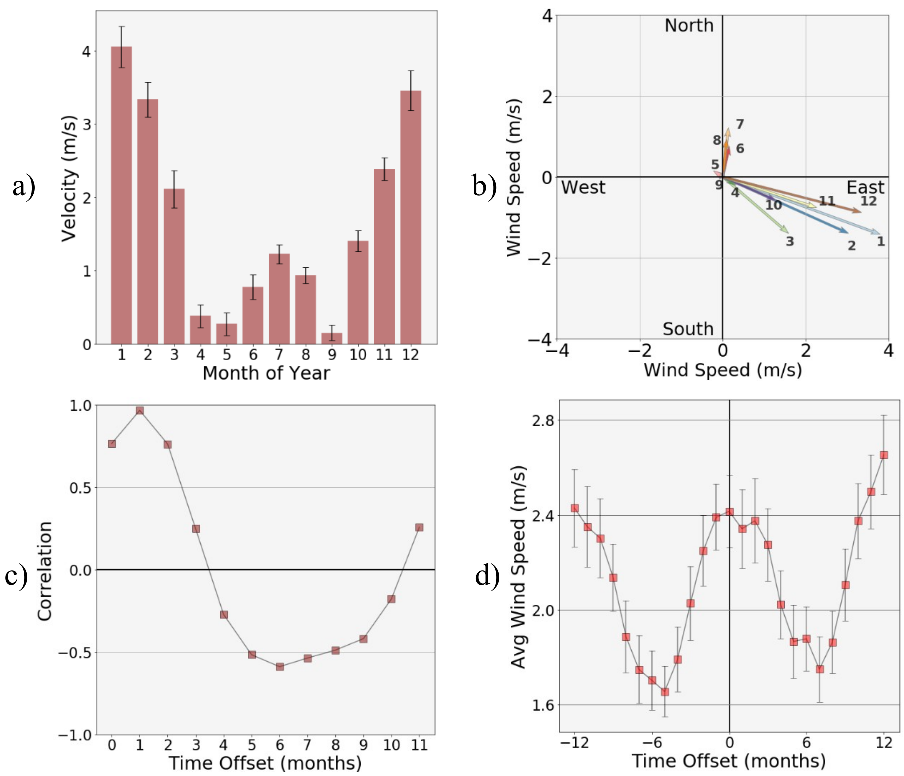

Figure 4. *Wind Analysis Results.* a) The average wind magnitudes and b) the average wind vectors aggregated by month of the year from 1998 through 2018. c) The Pearson correlation coefficients between the average wind magnitudes and the seasonal MSE distribution as the wind data is shifted forward in time. d) The average wind magnitude for the months preceding (negative offsets) and the months following (positive offsets) MSE events. The error bars in panel a) and d) represent the standard error of the mean.

3.4 Ocean Current Analysis Results

Figure 5 shows the average seasonal ocean current magnitudes, correlations and epoch analyses for each of the three regions indicated in Figure 2. In all regions, ocean currents are weaker in the summer and stronger in the autumn and winter. Also, the currents flow toward the NE during all months of the year with little directional variation. (Current vectors are not shown for brevity.) In regions 1 and 2, correlations with the MSE seasonal distribution is maximal when the ocean current data is not shifted in time (Figures 5b and 5e). However, for region 3, correlation to the MSE distribution is maximized (0.79) with a one-month shift of the ocean data into the future (Figure 5h). And in all regions, the epoch analyses show that the ocean currents are weaker in the months preceding an MSE and stronger in the months following MSEs.

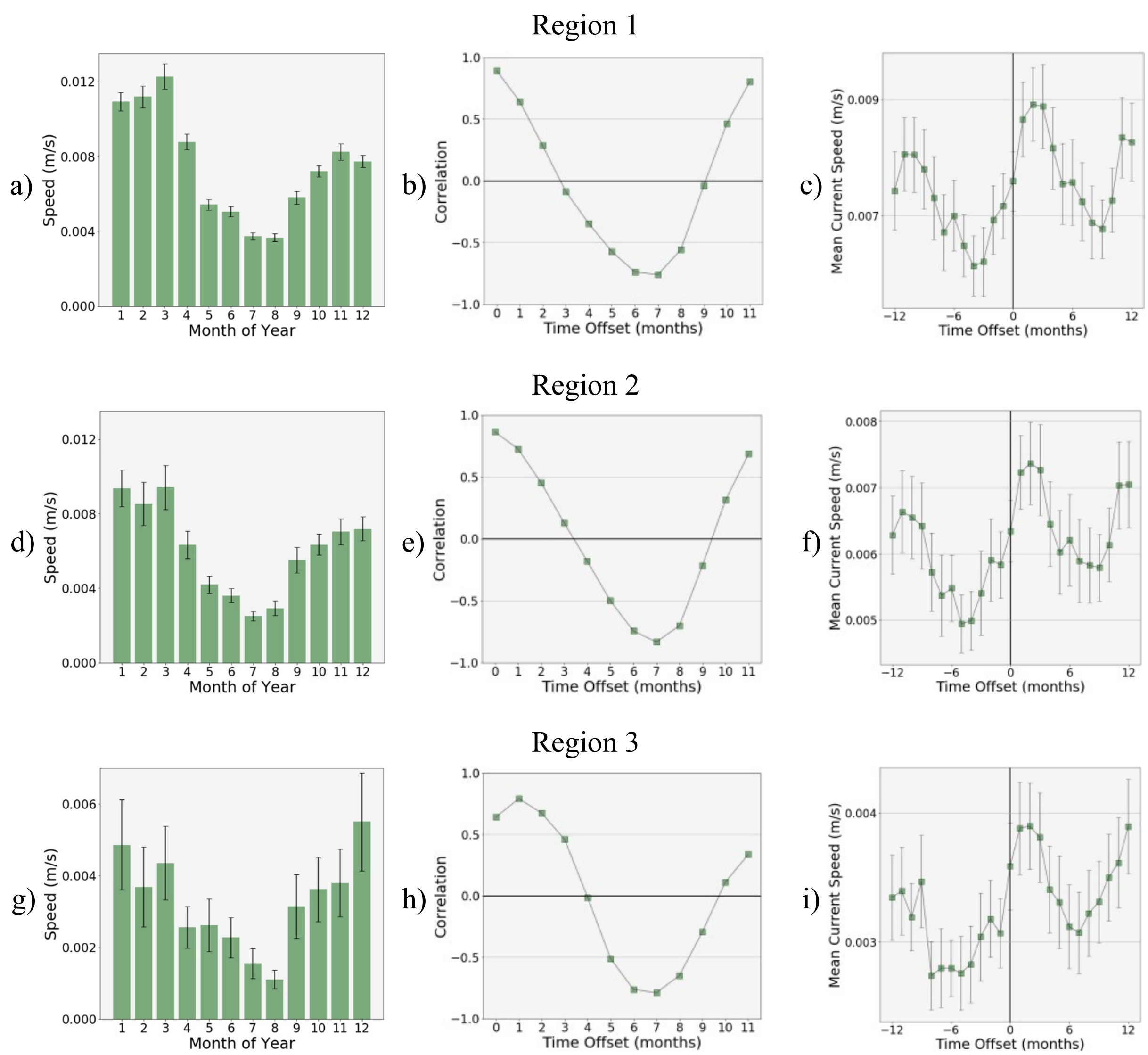

Figure 5: *Ocean Current Results*. Left column (a, d and g): the regional average ocean current magnitudes aggregated by month of the year. Center column (b, e and h): the Pearson correlation coefficients between the regional ocean current seasonal distribution and the MSE seasonal distribution as the ocean data is shifted forward in time (time-lagged correlation analysis). Right column (c, f and i): the average ocean current magnitude for the months preceding (negative offsets) and the months following (positive offsets) MSE events. All error bars represent the standard error of the mean.

4 Discussion

The MSE seasonal distribution and the wind distribution exhibit a bi-modal form and are remarkably similar, especially when the wind data is shifted into the future by one month. In other words, MSEs tend to occur in larger numbers one month after increased wind speeds and in smaller numbers one month after decreased wind speeds. The high correlation of wind speed and lagging MSEs naturally raises a question about a possible mechanism that may connect the two phenomena. For example, the local wind conditions could create near-shore upwelling, producing an environment that is more favorable to prey species assemblage and/or production which, in turn, attracts these pelagic odontocetes into shallow waters where they are more likely to strand (Walker et al, 2005).

Further, the region 3 ocean current analysis may indicate another contributing factor to the nutrient-stirring process. The current strength seasonal distribution is also similar to the MSE distribution and, like the wind, has a moderate correlation that increases when shifted one month into the future. The seasonal increase of currents within Cape Cod Bay might also assist in producing a beneficial environment for prey species.

When considering the wind epoch analysis (Figure 4d), we see that the mean wind strength is higher for months near MSEs, i.e., near the zero offset. While the epoch analysis for the months immediately before and after the zero offset is statistically similar (because of overlapping error bars), we can conclude that the mean monthly wind strength is lower 3 – 8 months prior to an MSE and 4 – 8 months after.

Similarly, when we consider the ocean epoch analysis in region 3 (Figure 5i), it is evident that ocean current magnitudes within the Bay are reduced 4 – 8 months before stranding events and are increasing in magnitude up to a few months after MSEs. This result appears to be contradictory to the correlation analysis (Figure 5h) which indicates ocean currents from one month earlier may be a factor in MSEs. One mitigating consideration is that the epoch analysis observations are a subset of the complete ocean current data whereas the correlation analysis uses all the data. Since the epoch analysis only uses data near the time of a MSE, it may better reflect the actual circumstances.

Another intriguing observation is that MSEs occur almost exclusively on the Bay side of Cape Cod and most are on the SE Bay shore. Very few occur on the east, south and west sides of the Cape. This might be explained, in part, by the reduced ocean currents within Cape Cod Bay. The region 3 ocean data show that currents in Cape Cod Bay are about half the strength of currents in the open ocean. Lighter ocean currents in the Bay may create a more favorable environment for prey species aggregation, production and/or cetacean predation. Or perhaps the SE Bay shores have characteristics that are more conducive to generating MSEs such as shallow-sloped underwater topography or sediment that disturbs echolocation (Sundaram et al., 2006).

Taken together these results appear to broadly align with those of Walker et al. (2005) where the authors speculated that wind-driven ocean currents (Ekman transport) produced upwelling frontal convergence zones in the near-surface water layer that could support prey assemblages. They suggested that cetaceans may track these fronts, and if the fronts move toward a shallow sloped beach, could lead to stranding events. In addition, Walker et al. (2005) conclude that stranding events occur on gently sloping beaches with a sudden increase in depth near the shore. Our approach is slightly different in that we consider seasonal trends and correlations between MSEs and environmental parameters. Furthermore, we have not yet considered shore slope characteristics near stranding sites. Continuing investigations will focus on sea-floor slopes, additional wind and ocean analysis and development of a testable stranding mechanism model that could prove beneficial to understanding the chain of events leading to MSEs and how responders might preempt these events.

5 Conclusions

The results reported here are significant and consistent with near-shore upwelling that could be a contributor to MSEs along the shores of Cape Cod and may explain why these pelagic animals enter nearshore waters where they are at greater risk of stranding. While we acknowledge that various phenomena may have significant correlations without having a causal mechanism, the capacity to explain and quantify causality is one of the critical future challenges in MSE research that could positively impact both animal welfare and conservation. Deeper insights to the causes of cetacean mass stranding will require additional types of data and alternative techniques. Certainly, further investigation is needed to examine additional factors that influence stranding events.

Acknowledgments and Data

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Datasets for this research are available via The Open Science Framework repository located online: https://osf.io/pkuqy/?view_only=90bf73fb0fb5434cbbb214f3900d205e.

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