

Acoustical dead zones and the spatial aggregation of whale strandings

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Abstract

Cetacean strandings display a marked geographical clustering. We propose a simple, two-dimensional ray-dynamics model of cetacean echolocation to examine the role played by coastline topography in influencing the location and clustering of stranding sites. We find that a number of coastlines known to attract cetacean strandings produce acoustical “Dead Zones” where echolocation signals are severely distorted by purely geometric effects. Using available cetacean stranding data bases from four disparate areas, we show that the geographical clusters in the observations correlate strongly with the regions of distorted echolocation signals as predicted by the model.

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1. Introduction

Cetaceans have a remarkable history of stranding (Dudok van Heel, 1962, 1966; Wood, 1979; Geraci and St. Aubin, 1979; Reynolds and Odell, 1991; Geraci and Loundsbury, 1993; Simmonds, 1997). Virtually all mass strandings of cetaceans have involved species of toothed whales (*Odontoceti*). In North America, the substantial majority of these have been of the five species: sperm whale *Physeter macrocephalus*, long-finned pilot whale *Globicephala melas*, short-finned pilot whale *Globicephala macrorhynchus*, false killer whale *Pseudorca crassidens* and white-sided, *Lagenorhynchus acutus*, and white-beaked, *Lagenorhynchus albirostris*, dolphins. Some stranded whales have obviously been sick or have suffered injuries (Odell et al., 1980; Walsh et al., 1991; Bossart et al., 1991) and have probably come ashore for that reason. However, in most strandings, including all

mass strandings of *Odontoceti* of up to hundreds of individuals, the majority of animals appear to have been healthy on arrival (Geraci and Loundsbury, 1993; Reynolds and Odell, 1991). Hypotheses to account for stranding of apparently healthy cetaceans include behavioral tendencies to follow a leader (Wood, 1979; Odell et al., 1980), disorientation caused by parasites lodged in the ear canals (Geraci, 1979), disorientation caused by geographical anomalies in the earth’s magnetic field (Kirschvink et al., 1986; Klinowska, 1986; Kirschvink, 1990; Brabyn and McLean, 1992; Brabyn and Frew, 1994), failure of the animals’ echolocation system (Dudok van Heel, 1962, 1966) and even attempts to traverse historical passages that are now dry land (Wood, 1979). One of the most perplexing aspects of whale strandings is the strong geographical clustering of stranding sites. Of the many stranding hypotheses, only two, involving geomagnetic anomalies and echolocation distortion, potentially explain this geographical clustering.

Many of the cetaceans that strand, especially the mass-stranding *Odontocetes* such as sperm and pilot

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whales, typically do not forage close (< 10 km). to shore. Therefore it is particularly puzzling that these species are the ones that often strand in large numbers. Pilot whales do move inshore at certain times of the year to pursue prey such as herring and squid (Geraci and Loundsbury, 1993). Therefore it is possible that strandings are composed of two parts: (1) initial movement toward shore in pursuit of prey and (2) subsequent disorientation due to distortion of echolocation signals eventually resulting in stranding.

Many previous hypotheses for cetacean strandings are unsatisfactory. The notion that social cohesion or the tendency to follow a leader is, at best, incomplete because there are numerous records of strandings of individual, healthy cetaceans, including those of gregarious species like pilot whales. For example, of 37 strandings of long-finned pilot whales on Sable Island, Nova Scotia, 34 were of single whales (Lucas and Hooker, 2000).

While parasites are frequently found in the ear canals of cetaceans, most stranded animals lack these (Geraci and Loundsbury, 1993). For the many strandings, especially of pilot whales, that have occurred in Cape Cod Bay, it has been proposed that the animals that have stranded are trying to traverse a channel that has been closed for 400 years (Wood, 1979). It strains credibility that cetaceans lack the learning ability, or that selection has not eliminated this tendency from the population. It is possible that it would be selectively advantageous for odontocetes inhabiting the northwest Atlantic to swim east in response to trouble. This behavior would prove fatal in the peculiar bay created by the arm of Cape Cod. Nevertheless, such an explanation is not capable of explaining strandings elsewhere, such as those in New Zealand studied here. Thus the remaining hypotheses that could explain the clustering of cetaceans in specific geographical regions are disorientation due to either (1) magnetic anomalies or (2) impaired echolocation.

Anomalies in the earth's magnetic field might cause confusion in animals using magnetic fields as an orientational cue (Kirschvink et al., 1986; Klinowska, 1986; Kirschvink, 1990; Brabyn and McLean, 1992; Brabyn and Frew, 1994), and the distribution of such anomalies could explain geographical clustering. While the distribution of strandings in Britain and the United States has been correlated with the distribution of magnetic anomalies (Kirschvink et al., 1986; Klinowska, 1986; Kirschvink, 1990), such correlation was not found for stranding data from New Zealand (Brabyn and McLean, 1992; Brabyn and Frew, 1994).

The second possibility is that strandings are a consequence of distorted echolocation signals due to local coastline topography and bathymetry. Indeed, Brabyn and McLean (1992) and Dudok van Heel (1966) list a number of local shoreline factors present in a majority of single and mass strandings. These include

sandy bottoms, gently sloping beaches and the presence of nearby coastal headlands. As illustrated by Dudok van Heel (1962), simple ray dynamics acoustic arguments show why echolocation signals may be seriously degraded on gently sloping beaches.

Odontocetes use echolocation both for the detection of prey and for navigation (Dudok van Heel, 1962; Wood, 1979; Geraci and St. Aubin, 1979; Reynolds and Odell, 1991). Cetaceans are thought to use high frequency (50–200 kHz) pulses for detecting prey and lower frequency (down to 20 Hz) pulses for communication and navigation. Compared to its use for prey detection, the use of echo-sounding by cetaceans for navigational purposes has received relatively little attention. Nevertheless, it is accepted that cetaceans do use echolocation for navigation and that the emitted sounds are of sufficient intensity to serve this purpose. For example, killer whales (*Orcinus orca*) produce echolocation clicks in a frequency range of 1–18 kHz that can be heard from a distance of at least 3 km (Barrett-Lennard et al., 1996). Also, *Globicephala* certainly emit sounds at low enough frequencies (1–11 kHz) to be useful in the detection of the sea floor (Wartzok and Ketten, 1999).

In order to test the premise that multiple stranding sites are determined by particular coastline topography, we draw an analogy to an open acoustical chamber. We consider a two-dimensional model, corresponding to extended shallows, and acoustic ray dynamics within which acoustic “Dead Zones” are determined by the geometry of the chamber. On an actual coastline, these locations appear where the acoustical echo is weak. When echoes are used to determine distance to the coastline, weaker signals can lead to a gross miscalculation in direction-to-shore and distance-to-shore results. “Dead Zones” can be spatially extensive (approximately tens of kilometers across) so the whale's likelihood of escaping the “Dead Zone” is small, thus enhancing the probability of stranding.

Of course, bottom topography, sea floor composition, baroclinic density inhomogeneities and a host of complications inherent in shallow water acoustics will additionally affect sound propagation. While we restrict the present analysis for simplicity to a two-dimensional ray dynamics model, we do not mean to imply that these other considerations are unimportant. Our goal is to determine whether the simplest, zeroth-order echolocation model might explain the high degree of spatial clustering in observed cetacean stranding sites.

2. Model

In recent years, ray-dynamical models have enjoyed renewed interest and success in the analysis of ocean-acoustic propagation data. In that context, the variation

of sound–speed with depth is a crucial component in “channeling” sound, in analogy to a waveguide (Smirnov et al., 2001). However, this picture is modified when considering propagation in a shallow-water, coastal situation. Here, sound–speed variation is not an issue, rather reflection of sound occurs due to the water surface, bottom and gradients in the bathymetry. With the inclusion of such coastal features as tides and surf, a mathematical model can rapidly become quite complex. In order to establish that particular coastline topographies might prejudice cetacean stranding to particular geographic locations, we consider here a simple model that nevertheless captures an essential element of echolocation signal distortion.

We consider an echolocation model based entirely on ray dynamics. The applicability of ray dynamics is validated by the size of the sound source (the whale) relative to the propagation distance (on the order of kilometers) and is further reinforced by considering the ratio of typical wavelengths associated with echolocation signals and the scale of the reflecting coastlines features. As noted earlier, while cetaceans produce sound in a large frequency range, typical echolocation signals occur in the .5–10 kHz range corresponding to wavelengths of 0.1–3 m. Contrasting these scales with typical coastline lengths and our kilometer resolution validates the ray approximation.

The use of a planar or two-dimensional geometry, as described above, implies simplification to the idealized case of gently sloping bathymetry, which has some observational support in the stranding literature (Dudok van Heel, 1966), and a homogeneous shallow water medium. With this view, the coastline acts as the boundary of an open acoustical cavity, where *open* refers to the fact that there is an outlet to the sea.

2.1. Implementation

A schematic of the model is shown in Fig. 1. For each coastline considered, we construct a grid of off-shore whale locations, shown by crosses, which act as point sources for the acoustic signals. For the results shown in Fig. 2 and discussed below, the grid spacings are in the range $\Delta x = 0.010^\circ\text{--}0.015^\circ$ in latitude and longitude. The coastline data is obtained from the NOAA data-base (NOAA, Data Center) at a resolution of approximately 2–3 points per kilometer at the latitudes we consider. The coastline “polygon” is then used as a reflecting surface for the two-dimensional ray dynamics in order to compute signal return times as a function of source location.

For each source location, the initial direction of the emitted ray bundle is assigned as follows. By determining the center of the angle subtended by the two rays from the source location to extreme points on the coastline, a *mean direction angle* to the shore (denoted

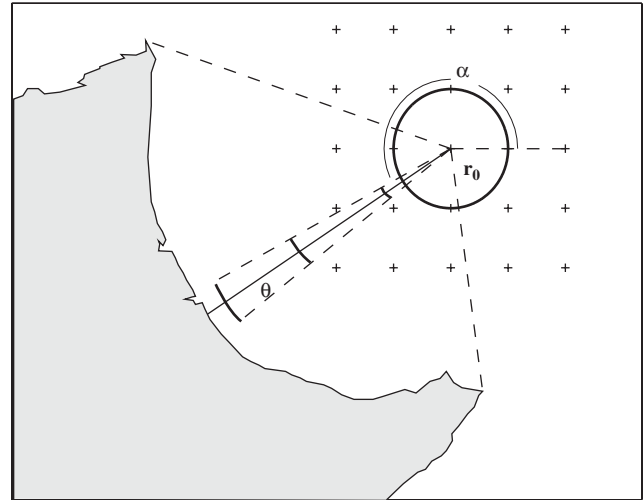


Fig. 1. Schematic of the model where the crosses denote the grid of acoustical point source locations; r_0 denotes the radius of area used for estimating the return time; α is the mean direction of the acoustical rays and θ is the angle of the cone of rays.

by α) is computed for each location on the grid. Given the *mean direction angle*, the dynamics of $n = 60$ rays launched in a $\theta = 20^\circ$ cone centered on α are computed assuming Snell’s law for reflection from the coastline. Comparison of model results for values of n ranging from 40 to 100 indicates that the model is relatively insensitive to the number of rays. Similarly, results obtained by varying the mean direction angle $10^\circ\text{--}20^\circ$ in either direction produce quantitatively similar locations of decreased return signal fidelity. The choice of $\theta = 20^\circ$ is within the range of an emitted acoustical cone for cetaceans (Thomas and Kastelein, 1990).

In order to determine how specific coastline topographies might directly degrade echolocation signals, we define a fidelity measure based on the length of the signal return path. The signal return time, T_r , is defined by the time required for any ray to return to any point within a radius r_0 of the initial source. The size of r_0 is given by the density of the grid of source locations. To compute signal fidelity, the return time is compared to the time, t_s , required for a ray to traverse twice the distance from the coast to the source location along the mean angle θ . The ratio $R = T_R/t_s$ of return times is thus a measure of the distance of signal propagation, and, assuming homogeneous signal attenuation along the path, provides a measure of returned signal strength. A ratio of $R = 1$ implies the most accurate echolocation assessment of distance of shore.

The output of the model is a map, for a given coastline, of return time ratios as a function of source location, $R(x, y)$. Extended regions of low R indicate initial positions where echolocation of the shore-line maybe severely impeded by purely geometric effects.

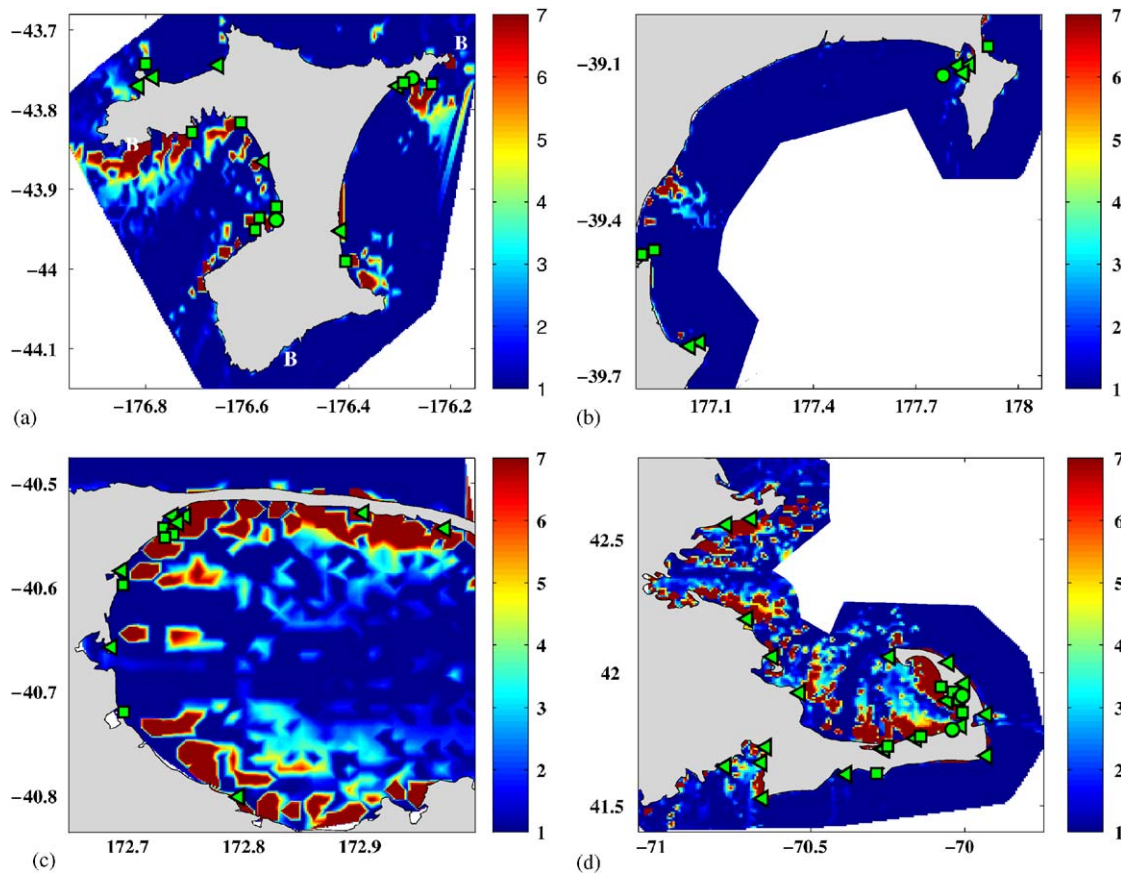


Fig. 2. Results of the acoustical analysis for four coastlines. In each case, the false color image shows the distribution of the ratio of the actual return time to the shortest possible return time. As indicated by the color-bar, blue regions allow for the most accurate assessment of distance while the red regions are the acoustical “Dead Zones”. Also shown for each coastline is the whale stranding data (green symbols) where circles, triangles and squares denote locations of single, 5 and 10 strandings, respectively. It should be noted that some of these involved large numbers of whales. In the case of Chatham Island, some of the locations where sharp changes in bathymetry occur are indicated by the symbol **B**. The implications for our model are discussed in the text.

These acoustic “Dead Zones” mark locations where distance-to-shore estimates based on echolocation would be grossly over-estimated.

2.2. Cetacean data

There is substantial data on whale strandings from various parts of the world involving a multitude of species and, for the purposes of quantitative comparison of the model with observations, choices both in terms of coastlines as well as the specifics of the stranding data are required. For the coastlines, geographical areas are selected based on (i) the availability of large numbers of well-documented *Odontocete* strandings and (ii) varied shapes of coastlines, providing both dead zones and regions with no acoustical degradation. In particular, we look for coastlines containing segments which, on a large scale, are topographically similar but distinguished by vastly different numbers of strandings. Two datasets that meet these criteria are the Marine Mammal Stranding database for North America maintained by

the Smithsonian Institution (Mead, personal communication), and the New Zealand Whale Stranding database (Brabyn, 1991). The latter dataset is made more attractive by the fact that geomagnetic anomalies were not seen to correlate well with the stranding data (Brabyn and Frew, 1994).

For species selection, in Massachusetts we study only strandings of long-finned pilot whales (*Globicephala melas*) while, for New Zealand, we consider strandings of pilot whales, false killer whales (*Pseudorca crassidens*) and sperm whales (*Physeter macrocephalus*). This particular selection of species is based on (i) the availability of uninterrupted time series extending back in time more than a hundred years suggesting a prominent history of stranding of all these species; (ii) strong evidence that the stranding species use echolocation for prey detection and to navigate; (iii) similarity of habitat selection and diet of species. Certainly many other species of cetaceans have stranded (Aurioles-Gamboa, 1992; Hersh and Odell, 1986; Jefferson et al., 1995; Mead et al., 1980) but the subset considered is, by

a wide margin, the most common stranders worldwide. Furthermore, the resolution at which coastline polygons are available sets a frequency cutoff in the model. For consistency, the acoustical analysis is restricted to species which echolocate at frequencies lower than this cutoff. Finally, we reiterate that our goal is not to explain every stranding that has occurred, but rather to provide a quantitative basis for one factor very likely influencing stranding behavior.

We begin by examining the North American database on whale strandings available from the Smithsonian Institution (Mead, personal communication). This database contains all whale strandings reported to government or other authorities in North America, beginning about 1850. The Massachusetts data is supplemented with data from New Zealand contained in a paper by Brabyn and McLean (1992). The data is based on 1140 records of strandings involving 8287 individuals and is described as “one of the largest records of strandings, in particular herd strandings, in the world”. Brabyn and McLean (1992) extracted from the data set records of pilot whales, false killer whales and sperm whales. Thus our selection of locations and datasets is consistent with the criteria stated earlier.

3. Results

“Dead Zones” were found on each of the four coastlines considered (Fig. 2). False color imagery shows the distribution of return time ratios, R . The reddest patches denote the strongest acoustical degradation while bluer areas show weaker degradation resulting in a more accurate acoustical assessment of the distance to shore. Whale strandings are indicated by green symbols where the shape distinguishes single from multiple strandings at the same location. There is a clear correlation between the observational data with the predictions of our model.

To assess the statistical significance of this correlation between our model predictions and stranding data, we first divide each coastline into a linear array of spatially contiguous bins. We arbitrarily aimed to have N (approximately 200) bins for each location, and thus each bin corresponds to about 1.4 km of coastline. We then assign to each bin values for both predicted and observed numbers of cetacean strandings. The predicted value is based on a normalization of the strength of echo-sounding distortion scaled linearly on values from 0–5. The observed value was the number of strandings that had occurred within that 1.4 km of coastline. Ranked correlation is used to test for positive association between predicted and observed values. The correlations between observed and predicted values are shown in Table 1 (all tests one-tailed). Data for all New Zealand sites are from Brabyn and McLean (1992); data

Table 1

Correlation estimates for predicted stranding locations based on acoustical “Dead Zones” and observed cetacean stranding data

Location	r_s	p	N
Chatham Island	0.23	0.001	206
Hawke’s Bay	0.31	0.00013	135
Golden Bay	0.09	0.15	130
Massachusetts	0.41	10^{-7}	235

for Massachusetts contain all records of stranded *Globicephala melaena* from the Smithsonian Institutions Database on Cetacean Strandings (55 strandings; those without position data were excluded).

In three out of four coastlines considered, correlation between observed and predicted stranding sites is highly significant. The correlations between observed and predicted values are as follows (all tests one-tailed): Chatham Island, $r_s = 0.23$, $p = 0.001$; Hawke’s Bay, $r_s = 0.31$, $p = 0.00013$; Golden Bay, $r_s = 0.09$, $p = 0.15$; Massachusetts, $r_s = 0.41$, $p = 10^{-7}$. For the fourth coastline, Golden Bay, the correlation is positive but not significant. Part of the discrepancy between predicted and actual stranding locations may be due to limited size of the stranding data set.

4. Discussion

Our model predicts some likely stranding sites for which there are no records of strandings. The distribution of these sites is illuminating, in that a high proportion are in areas with precipitous drops to the ocean floor, that is, areas lacking the gradually sloping beaches thought to be prerequisite to stranding (Brabyn and McLean, 1992). For the three New Zealand locations studied, there are seven sites predicted by our model to attract strandings that are more than 10 km away from any reported stranding. One of these is in Hawke Bay, four are in Golden Bay and two are at Chatham Island. Four of these seven sites are located adjacent to abrupt continental slopes, and we expect that the sites do not attract strandings because of the lack of gently sloping bathymetry at those locations. In Massachusetts, there were four under-predicted sites. Although all of Massachusetts is adjacent to fairly gentle bottom topography, three of these four sites were on the rocky north shore of Massachusetts, which is characterized by harder sea floors and more abruptly sloping bottom topography than the southeastern part of the state where the majority of strandings occurred. In sum, it seems that the predictability of our model can be improved through the inclusion of bottom topography in addition to two-dimensional aspects of the coastline.

This naturally leads to the issue of whether the planar analysis is at all justified by the stranding data. In Fig. 3, the depth variation along a section of the New England coastline is shown along with stranding data. Panel (b) is a blow-up of a section of Cape Cod where stranding data is spatially dense. Both these figures show no clear correlation between changes in depth (abrupt or gradual) and the stranding data. This weak dependence can be viewed as supporting the two-dimensional analysis. However, in terms of the model, we do expect the inclusion of the (relatively) small variations in depth to modify the extent and location of the Dead Zones but at a large computational cost. Note that our choice of

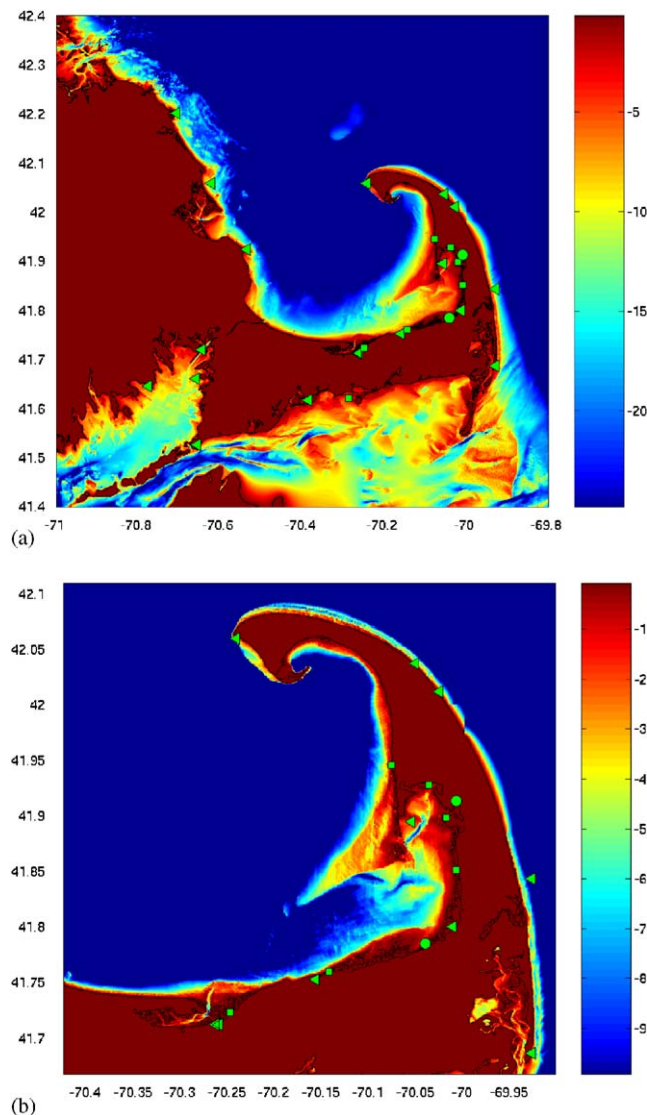


Fig. 3. Bathymetry around Cape Cod, MA, and the locations of whale strandings (green symbols). As in the earlier figure, circles, triangles and squares denote locations of single, 5 and 10 strandings, respectively. Panel (b) emphasizes the shallows over a smaller segment of the same coastline with the densest concentration of stranding data. It is clear from both panels that the correlation of strandings with bathymetric variation is not significant.

Cape Cod as an illustration was mitigated by the fact that bathymetric data was not readily available, at the appropriate resolution, for the New Zealand coastlines shown in Fig. 2.

It has been argued that acoustic distortion is unlikely to cause cetacean strandings because stranded whales that have been towed to safety often re-strand themselves right away and “echo characteristics of ‘typical’ stranding sites have yet to be mapped” (Geraci and St. Aubin, 1979). What we present here enables a re-examination of the acoustic distortion hypothesis in a way that has not previously been possible, and addresses both of the above criticisms of the theory.

First, the spatial extent of the dead zones seen in Fig. 1 suggests that, unless stranded whales are towed a considerable distance (> 20 km) from the stranding site, they are likely to encounter very nearly the same acoustic conditions that caused them to strand in the first place. In other words, they do not escape the dead zone. Alternatively, whales that have come that close to stranding might be further incapacitated due to stress. Second, it is exactly the objective of our acoustic simulations to map the acoustical properties of coastlines and to determine which locations are especially likely to cause distortion and thereby promote stranding. As shown, our simulations do indeed predict which geographical areas are most likely to contribute to acoustic disorientation in cetaceans.

The spatially extended nature of the zones of maximal distortion is also fully consistent with the following behavior reported in whales prior to stranding (Evans et al., 2002):

Its swimming action was described as frantic—it swam in a zigzag manner, churning up the water as it progressively moved inshore until it stranded on the beach.... The last two whales to strand, however, showed a different pattern in moving inshore. These were observed to swim along the shoreline, parallel with the beach in a northward direction. They then turned south, swimming back past all the other stranded whales and then turned inshore and appeared to actively strand together at a site farther south along the beach.

Such observations support our suggestion that spatially extended acoustical Dead Zones make it harder for whales to navigate their way out once trapped.

Further, the correlation between attenuation of sonar and coastline topography has been tested (Dudok van Heel, 1962, 1966) in a limited context, leading to the suggestion that this may lead a cetacean to the shallows after which “...an exit to deep water can be found only by trial and error” (Dudok van Heel, 1966).

We do not dispute the influence of magnetic anomalies upon the tendency of whales to strand themselves. However, details of our analysis constitute

especially strong support for the role played by acoustic distortion due to local topography. First, spatial association of *Globicephala* strandings with geomagnetic minima is at a scale on the order of 20–40 km, whereas correlation with acoustic dead zones that we report is on a scale of 1–5 km. Second, our probabilities of Type I error were smaller (10^{-7} in this study versus 10^{-3} for the Massachusetts coast). Third, strandings of whales in New Zealand waters do not correlate with geomagnetic anomalies (Brabyn and McLean, 1992; Brabyn and Frew, 1994). In sum, at least for Massachusetts, spatial association of *Globicephala* strandings with acoustical dead zones is substantially stronger than is their association with geomagnetic anomalies.

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