Massed strandings of whales and dolphins – effects of wind, waves and tides.

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Research Article

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Abstract

We have examined125 mass-stranding events of cetaceans (> = 10 individuals) on New Zealand shores over the past 40 years, with a view to understanding the causes of this longstanding puzzling phenomenon. The wind, waves, wave refraction, shore slopes and tides at the dates and locations of these events were considered. The mass-strandings involved 10 different species, but by far the most common involved the Long-finned Pilot Whale, *Globicephala melas edwardii*. We find that the data appear to be consistent with a three-stage process. The first stage is that when an animal becomes ill, its body may become bloated and float on the surface, and the wind and waves may drive it onshore. The second stage is that pod members may accompany a dying (incapacitated) or dead body as a result of strong social bonds, in species that live in pods. The third stage involves the tides and the beach slope. If these are of sufficient amplitude, the nearby attendees will quickly become stranded in the intertidal region of a gently sloping beach, as the water level falls. We have evaluated the evidence we have available for the first and third stages, omitting strandings inside estuaries. In the overwhelming majority (91%) of these mass-strandings, the data indicate that wind and waves would have driven floating bodies toward the stranding site. Examination of the nearshore slopes and the tide ranges at the stranding sites showed that the vast majority were on slowly shelving beaches with large tidal ranges, so that the water level would retreat rapidly over 10s of metres. These 2 results are even more pronounced if only mass strandings of Long-fin Pilot Whales are considered.

Introduction

The causes of the stranding of large numbers of whales and dolphins on beaches, resulting in the deaths of most if not all individuals involved, have been an unanswered question at least since the days of Greek philosopher Aristotle (who noted this curious phenomenon in his *Historia Animalia* in 350 BCE). Various suggestions have been made to explain this, including possible disease, parasitic infection, sympathetic mass suicide, electromagnetic disorientation, and anthropogenic activity (Cordes, 1982, Sunduram et al., 2006). It is clear that in the great majority of mass-strandings, many of the animals that arrive together on a beach are not near death, as they appear to swim away competently once moved to deeper water by rescuers (though some may return to the beach). Many species mass-strand, but with rare exceptions (e.g. D'Amico *et al*. 2009) each of the mass stranding events involves only one species, and the numbers that strand together appear to reflect the size of the social groups in which these animals move around in the oceans. In the case of Long-finned Pilot Whales (*Globicephalus melas*), the strandings often involve larger numbers than those recorded at sea, but they appear to divide into widely-spaced smaller groups while foraging (Visser et al. 2017), so that average group sizes at sea may be underestimated.

Because cetaceans navigate by sound, one suggested cause has been the possible dysfunction of echo-location, due to the lack of sonic reflection from a gently sloping beach, or because of the absorption of sound by the presence of sand or microbubbles in shallow water (Dudok van Heel, 1962, Chambers and James 2005, Sundaram et al., 2006). These suggestions have yet to be thoroughly tested, but one might expect that animals approaching a beach with a gentle slope would have some warning because they could easily detect that the depth beneath them is small and decreasing.

Suggestions that geomagnetic topography may be having an effect can be discounted, at least in the New Zealand environment, as herd strandings have been shown to have no relationship to geomagnetic contours or magnetic minima (Brabyn 1991, Brabyn & Frew, 1994). The relation to geomagnetic storms is also rather weak for New Zealand (Pulkinnen et al. 2020, Vanselow 2020).

A simple explanation, one that appears most likely to us, is that one or more individuals become sick (incompetent) and drift onto the shore, and group members follow these incapacitated individuals as they drift onto the shore, due to social bonds that are not yet fully understood. Reggente et al. (2016) have described such nurturing behaviour, and Brabyn (1991) and Brabyn & McLean (1992) describe observations from data prior to mid 1989, which are indicative of the results presented here. Brabyn (1991), in particular, noted that offshore species are more prone to herd-strand than inshore species, and gave a description of these phenomena up to that date. We have gathered evidence for this hypothesis using massed stranding events in New Zealand over the past 40 years.

The New Zealand data set

Stranding events have been recorded in New Zealand dating back to the1840's, and the record-keeping has been a legal requirement since 1978. They cover a large number of the species that have been recorded to strand both individually and in large groups. Brabyn & McLean (1992), and more recently Betty et al. (2020), have provided detailed descriptions of the spatial and temporal distribution of these stranding events, identifying "hot spots" and temporal records, and focussing on the Long-finned Pilot Whale (LFPW), which is by far the most significant species for strandings in large numbers in New Zealand waters. The database used here was provided by the New Zealand Department of Conservation, via Mr. Mike Ogle, Hannah Hendricks and *Project Jonah* (projectjonah.org.nz). The data contain some 3782 stranding events, dating from 1980 to the end of 2019. The great majority of these recorded events involve single animals, spread over the whole range of species in New Zealand waters, as described by Betty et al. (2020).

While mass strandings are often defined as involving 3 or more animals, we focus our analysis on events that involve 10 or more stranded animals, dated from 1980 onwards, as such numbers are unlikely to involve chance simultaneous strandings of individual animals or mother-calf pairs, and wind and wave data were available from 1980. This gives a data set of 125 massed stranding events, each involving one species, with numbers of animals in each event ranging from 10 to 616. All mass strandings appear to involve both young and older individuals. During the 1980-2019 period there were 24 events with 100 or more stranded animals, with the largest number of stranded animals in a single event being 616 in the Farewell Spit region. All of these large events involved pilot whales.

The social cultures of cetaceans

Species of whales and dolphins vary in their social structures, many of which are not fully understood. Pilot whales represent the majority of the massed strandings considered here, so some details of their life-style are relevant. These animals are born in pods that may number up to several hundred animals. Long-fin Pilot Whales found in New Zealand take 11 to 15 years to mature to adulthood (Betty et al. 2019). In the North Atlantic sub-species, both the males and females in the pod are born in the pod, but none of the male members are fathers (Amos et al., 1991, 1993). As the culture of the *Globicephala melas* subspecies appear to be very similar, we assume that the same applies for the South Pacific subspecies. Males must leave the pod to breed with females in other pods. Females born in the pod remain there, and males may or may not return to their home pod.

Members of the pod, most prominently females, generally help younger pod members, even though they may not be the parent (Amos et al.,1991; Oremus et al., 2013; Augusto et al., 2017). Thus although Oremus et al. (2013) have shown that mass strandings in New Zealand and Tasmania involve multiple matrilineal lineages, and mothers and calves are not stranded close to each other, large groups of pilot whales might well stay with a dying senior pod member due to a strong cultural relationship between young and older pod members.

Species other than pilot whales that mass strand in New Zealand may also live for decades in pods, so that it seems possible that when senior members eventually become incapacitated, if they have been prominent in pod social structure, younger pod members might accompany the sick or dying pod member as it drifts, due to social bonds. The cetacean subfamily Globicephalinae includes killer whales, false killer whales and pygmy killer whales as well as the pilot whales. Each of these species mass strands and exhibits strong social structure (Martien et al. 2017). Kinship groups also occur in sperm whales (Richard et al. 1996). In some mass stranding species, the groups that swim together are not all closely related individuals, so that kin selection alone does not explain the social bonds (Ball et al., 2017; Martien et al., 2014, Kobayashi et al.,2020; Patel et al., 2017; Westbury et al., 2021). But Norris and Schilt (1988) and Moller (2012) discuss how cooperative and altruistic patterns in cetaceans could evolve to extend beyond familial units.

It is indisputable that groups of competent individuals of these species do become stranded, and we are interested in determining whether this may be because they accompany one or more dying and bloated individuals. We note the increasing number of impressive studies of the genetic and the social structure of cetacean species, and this field is still developing (Moller, 2012, Reeves et al. 2022).

For all cetacean species, when the animals die it is not uncommon for their floating cadavers to be deposited on nearby coasts. This is reflected by the large number of single strandings, over all relevant species in the New Zealand records. Over the 40-year period considered, there are 3063 recorded single strandings, including 180 cases of single stranded pilot whales.

The next most common stranding number is two animals. In contrast with some other species, stranding events consisting of two pilot whales alone are relatively rare – over the 40-year period there are 8 recorded stranded-pairs of pilot whales out of a total of 196. This is consistent with evidence for the northern sub-species that they tend not to form strong pair-bond relationships (as other species may do), but the males (in particular) can exist as individuals outside a pod, or have a close relationship within a large pod community (Amos et al., 1993). Nor are pilot whales over-represented in stranded groups containing 3 to 9 animals. In a total of 115 stranding events in this range over 40 years, 16 of these events involve pilot whales, which is a number comparable with those of other species.

The stranding process- Stage 1: wind and waves on a floating body

We have examined the fit of the data (particularly the pilot whale data) to the hypothesis that the massed strandings are due to the beaching of one or more pod members who have become ill (for whatever reason), and whose body has become buoyant (for example due to bloating of the gut), and floats on the surface. The motion of such a floating object will be subject to the effects of both the wind and waves at the surface. If a coastline is nearby, the direction of the wind and waves will largely determine whether the floating animal is driven towards the shoreline.

In deep water, where waves are present but not breaking, the main effect of waves on the mean motion of floating bodies is via Stokes drift. This is a mean motion of particles on the surface of the water due to the nonlinear dynamics of sufficiently large waves, which is given by (Craik, 2005)

$$u_s = \frac{4(\pi a)^2}{\lambda T} \quad . \qquad (1)$$

Here u_s is the resultant mean speed of the floating object/body in the direction of the waves, a is the wave amplitude, λ the wavelength and T the wave period. Realistically, this gives speeds of magnitude 2 cm/s, which is approaching 2 km/day.

The above gives mean surface speeds due to non-breaking waves, but if the waves are breaking, the speed of the floating object will be much larger. This would be the case when the object reaches the wave surf zone.

The effect of the wind on floating object movement can be estimated as the drag, and this can be somewhat larger than the wave effect in the deep sea. To some extent these two factors (wind and waves) tend to be aligned, as the wind generates the waves. The wind direction can change more quickly, but there is a tendency for the two factors to be aligned, given sufficient steady wind. This consideration of the effects of wind and waves suggests that floating animals may be driven ashore from nearby seas over a period of about a day, but strandings may be noticed only after some time, so that the wind and waves over the two days prior to a stranding must be considered.

The stranding process- stage 2: pod members accompany the floating animal

Our hypothesis assumes that pod members would accompany a senior pod member who is incapacitated and floating. This would depend on the existence of strong social bonds in the group, and we note that many authors have described such social bonds, due to kinship in various cetaceansin the sub-family Globicephalinae (Augusto et al., 2017, Martien et al. 2017), or more complex relations in sperm whales (Whitehead 1996, Richard et al. 1996) and dolphins (Moller 2012) but we have no direct evidence that such bonds result in pod members of each species following incapacitated animals.

The stranding process- stage 3: the beach slope and the tides

Where the coastline consists of steep cliffs or rocky environments, the floating body may remain in the water, or be thrown up by heavy wave action, and the associated pod would presumably keep it's distance, and there would be no subsequent record of a mass stranding event. But if it is a gently sloping beach, the body of the injured animal would be gradually pushed into very shallow water.

This third part of the massed stranding process also concerns the tides. If the tidal range is significant, and the tide is fairly high as a dead or incapacitated animal arrives, it will be driven to a high level on the beach. If the tide is ebbing, both the dying individual and the accompanying pod members will rapidly become stranded on the beach. The offshore species such as pilot whales will have no significant familiarity with tides, and hence not be aware that the sea level may change by as much as several metres. On a gently sloping beach, a tidal range of even a metre may cause the local shoreline to retreat laterally by several metres in a matter of minutes.

In summary, our hypothesis for the massed stranding phenomenon is a three-stage process: (1) that the wind and waves in the days before the stranding would drive a floating body ashore at the stranding site; (2) that the dying or incapacitated animal would be accompanied closely by many others from the group associated with it; and (3) that the beach at the time when the body arrives would be gently sloping, with the tide at least moderately high at the time, and the tide range sufficient so that the water level retreats quickly.

Methods

In order to test stages 1 and 3 of our hypothesis against available data, we have examined the 125 mass strandings of cetaceans with 10 or more animals in New Zealand waters over the 40 years 1980–2019. To evaluate stage 1 we ask whether a floating body could be driven onto the relevant beach by wind and waves on the recorded day, or the day before, as the stranding may not have been noted on the day that it occurred, particularly if this were the previous evening, and a floating body may have drifted fairly slowly for some time, as our discussion of Stokes drift makes clear. We obtained data from the European Centre for Medium-Range Weather Forecasting (ECMWF) ERA5 global reanalysis data set (Hersbach et al., 2020), to provide the amplitude and direction of both winds and waves. As used here, these data sets have a resolution of 0.5 degrees in both latitude and longitude, with one observation per day at mid-day, centred as near as possible to the site of the observed stranding event.

The ERA5 wind fields were used to drive the WAM (Wave Model) with Source Term 3 (ST3) physics (Bauer et al., 1988). The model also assimilated large amounts of altimeter data into the wave hindcast (Lionello et al., 1992). The ERA5 values of significant wave height were downloaded on a 0.50 x 0.50 degree global grid for the 40-year period from 1 January 1980 to 31 December 2019. ERA5 has been extensively adopted as a global dataset for wind, wave and other conditions.

Although the 0.50 grid resolution for the wind and wave data is generally adequate in deep water conditions, and the ERA5 dataset has been validated in a range of studies (Hersbach et al., 2020), the data are clearly limited in coastal regions. In the present application, however, the output is used to provide large-scale synoptic estimates of wind and wave conditions, for which it is well suited. ERA5 data is available at 6-hourly intervals. As the exact time of the strandings on a given day is not recorded (and generally not known), we take wind and wave conditions at midday as representative of the conditions on that day. For each stranding event, data of winds and waves were recorded and examined for the day that the stranding was recorded, and also for the day before the observed stranding.

The question addressed via these data is: whether a floating object (such as a whale body) could be driven onto the relevant beach by the wind and waves on either day. We assume that the whale pod was in the neighbourhood early on that day, or on the day before. We suppose that pods of whales are primarily interested in searching for food, which in the Long-finned Pilot Whale case is squid. Squid is fished commercially in New Zealand, for two species named *Nototodarus gouldii* and *Nototodarus sloanii*, at various locations around both North and South Islands. These squid are found in waters of depth less than 500 metres, and most commonly in waters of depth less than 300 m. This implies that the pilot whale pods spend some time reasonably close (within 10–20 km or less) to shore. This applies particularly in the regions where most of the stranding events occur, such as the Chatham Islands, Stewart Island and the Collingwood/Farewell Spit region, where the depth is less than 100 m for a considerable distance offshore.

Stage 2 of our hypothesis appears to be a reasonable assumption for the pilot whales, but the New Zealand observations also include mass strandings of 8 other species. As noted above, some live in groups of close kin, but for some of these, the individuals in social groups are not related, so that if others accompany a sick individual this is not based on kin selection. We include these events to evaluate whether the data support stages 1 and 3 of our hypothesis. If so, this suggests that a social bonding mechanism is nevertheless present, such as discussed in delphinids by Moller (2012), that results in competent cetaceans arriving on the shore together with the dying individuals.

To evaluate whether stage 3 of our hypothesis fits the stranding observations, we measured the distance from the shoreline to the 5 m depth contour at the location of each mass stranding, as a measure of the slope of the beach. To do this, we first found the precise location by latitude and longitude on Google Earth, and then located that position in Navionics charts (https://webapp.navionics.com/#boating). This allowed us to measure the distance from the shore to the nearest section of the 5 m depth contour. In addition, we have obtained the spring and neap tidal ranges for the areas involved.

Results

The 125 massed stranding events that we have extracted from the New Zealand stranding database from 1980 to 2019 are shown in the supplementary information table. The numbers of animals in each event range from 10 to 616. This table also shows the additional data we have for each stranding - on the directions the stranding position on the beach is exposed to, the wind and wave directions and speeds on the stranding day and the previous day, and the tide ranges. The results for each species are summarised in Table 1.

For each of these massed stranding events, only one species of animal was recorded. Ninety of these strandings involved the Long-finned Pilot Whales (*Globicephala melas*). In addition, up to 11 may have been LFPWs, or may have been Short-finned Pilot Whales (*Globicephala macrorhynchus*), due to uncertainty in identifying them at the time, but the distinction is not significant here, as Short-finned Pilot Whales have a similar social structure. They are rarely found near New Zealand, as they prefer warmer waters, The uncertain cases are denoted *Globicephala sp* in the supplementary material table, and in Table 1.

The data set we have analysed thus consists of 101 mass stranding events (10 or more animals) of *Globicephala*, and 24 events of other species. These other species (and the number of events) are: Common short-beaked dolphin (*Delphinus delphis*) (10), Common Bottlenose Dolphin (*Terciops truncatus*) (5), Sperm Whale (*Physeter macrocephalus*) (3), Gray's Beaked Whale (*Mesoplodon grayi*) (2), Southern Right Whale Dolphin (*Lissodelphis peronii*) (1), and the Killer Whale (*Orcinus orca*) (1), Pygmy Killer Whale (*Feresa attenuata*) (1) and False Killer Whale (*Pseudorca crassidens*) (1). The last three species are members of the Globicephalinae subfamily.

We first separated the 8 mass strandings that are in the channels of an estuary, as offshore wind and waves are not useful predictors of how a floating body would move in this situation. Here it seems possible that the animals (dolphins in 5 cases and Long-fin Pilot Whales in 3 cases) moved into the estuary for some reason and then became stranded, possibly under the influence of local winds, waves and tides.

This leaves 117 beach strandings to be evaluated. An examination of the wind and wave data showed that for 101 (86%) of these events, the wind and waves on that day (including the refraction of waves around points onto beaches) would drive floating objects toward the beach where the stranding was observed (see Table 1, and details for each stranding in the supplementary material). In a further 4 cases, while it was not obvious that refraction of the waves would have driven a body ashore but it seemed possible. When the wind and wave data for the preceding day was considered, a further 5 events could be explained by wave direction and wave refraction. As a result, at least 91% and possibly 94% of these 117 stranding events can be attributed to the effect of wind and waves on a floating object.

If we consider only the pilot whales (both species), there are 98 mass strandings to be explained, and 91 (93%) can be explained by wind, waves and refraction over the two days.

Our data provides no evidence for why one or more dying individuals would be closely accompanied by the others in the group, but we know that for the pilot whales – by far the most common strandings – and for the three other species in the same sub-family, there are very strong social bonds (Augusto et al., 2017, Martien et al. 2017), and we consider it reasonable to assume they cause other pod members to stay close as a dead or dying individual is driven by wind and waves onto the beach. Reggente et al. (2016) have described the carrying of dead calves and juveniles in seven species of odontocetes.

Our third stage involves the tides and the slope of the beach. Tides in New Zealand waters are significant. Spring tides in most locations are in excess of two metres, and in Golden Bay where 28 mass strandings (all of pilot whales) occurred the spring tides are in excess of four metres. This is a phenomenon with which the pilot whales and other deep water species would have no familiarity or experience, as they generally live further offshore. The mean distance from shore of the 5 m depth contour, and the mean tide ranges are shown in Table 1 for the strandings of each species. For the total 117 beach strandings, the mean distance to 5 m depth is 1.3 km, and the mean tide ranges are 2.36 m for spring tides and 1.44 m for the neap tides. For the 98 pilot whale strandings, the mean distance to 5 m depth is 1.46 km, and the tide ranges are 2.49 m for springs and 1.54 m for neaps. In these conditions, even the neap tides would lead to rapid stranding in many locations. In particular, in Golden Bay where the 5 m depth contour is 4.3 km from the shore, the bottom slope is extremely small, and accompanying pod members would be very rapidly stranded, even by a neap tide of 2.6 m.

Apart from pilot whales, there are mass strandings of 8 other cetacean species in our dataset (Table 1). Five of these are deep-water species like the pilot whales, and wind and wave directions can explain 7 of the 9 mass strandings, while in the other 2 cases this explanation seems possible. In the short-beaked dolphins *Delphinus delphis* (7 beach strandings and 3 in estuaries), 6 of the beach strandings can be explained by wind and waves driving a body onto the shore, and in the remaining case local wave refraction might possibly explain it. But here the distances to 5 m depth are 0.08–1.3 km at the stranding sites, and the tide ranges are lower – at 3 sites the spring tide range was only about 1 m (see the *supplementary material table*). Further, in this species closely related individuals are not found in the same groups (Ball et al. 2017), and this is a coastal species, that would have regular experience of the tides, although it is possible that there are separate offshore populations.

Similarly for the bottlenose dolphins (*Terciops truncatus*), we have 3 beach strandings and 2 in estuaries. 2 or possibly all 3 of these beach strandings can be explained by onshore wind and wave action, but the distances to 5 m depth are 0.27–0.79 km, and two of the tide ranges are < 1 m. This species is also coastal and would have experience with tides. The last coastal species is the killer whale (*Orcinus orca*). There is only one mass stranding of 12 individuals. In this case the wind and waves would have driven a body ashore, but the distance to 5 m depth was only 0.3 Km, and the tide ranges were < 1 m.

Discussion

We have established that for the vast majority of these events, the wind and waves would have driven a floating body onto the stranding beach. For the pilot whales and the three species in the same subfamily: *Feresa attenuata*, *Orcinus orca* and *Pseudorca crassidens*, the assumption that fellow pod members may accompany this body due to social bonds seems reasonable, and for various other species there is also evidence of kin structure of groups, social bonds, and cooperative and even nurturant behaviour (Ball et al. 2017, Jaquet and Gendron 2009, King et al. 2021, Moller 2012, Reggente et al. 2016, Richard et al. 1996, Whitehead 1996). We suggest that kin and social bonds in these species may also lead to group members accompanying disabled individuals.

For the 7–11 mass strandings where the wind and wave direction data cannot easily explain the stranding location (mostly pilot whales, and at most 9% of the total), it is plausible that the limited resolution (0.5 degrees in both latitude and longitude) is insufficient to resolve the details of the local wind and waves, or perhaps the pod was already operating very close to shore, so that the same process would still apply.

We note that no massed stranding events have been recorded in the Mediterranean Sea by *ASSOCIACIO CETACEA*, a Spanish entity founded in August 2012 with the aim of protecting, conserving and researching marine life and habitats along the Catalan coast. Long-finned Pilot Whales are known to have a presence in the western Mediterranean. These observations may or may not be confined to the Catalan coast, but the reason for the absence of stranded pilot whales may well be that, apart from the western approaches, the tidal range in the Mediterranean is negligible (2–3 cm). Large tide ranges occur in other locations where massed strandings of Long-finned Pilot Whales are significant, such as Cape Cod, Massachusetts, USA (Sundaram et al. 2006), which has gently sloping beaches, and where the tidal range of 2 metres is similar to that of New Zealand.

Observations of mass strandings that investigate the state of every stranded individual appear to be rare, so that we have not found descriptions of a bloated individual among the live whales at mass stranding events. An exception is the stranding of seven beaked whales in New Caledonia, described by Garrigue et al. (2016), where one had severe gastritis and thus may well have been floating at the surface. We are not surprised by the apparent lack of such reports, as it would be easy for an observer to miss a single bloated or incapacitated individual when a large number of live, active animals on the beach capture attention. Diligent searching for bloated bodies in mass strandings would however, be a useful test of our hypothesis.

It seems likely that some other explanation than accompanying a dying associate is needed for the coastal dolphins and perhaps also the killer whales. The (single) record in the database of 41 New Zealand fur seals dead on the beach in 2018 suggests that pathogens or toxins that kill groups of marine mammals may also be involved in mass strandings, as competent seals could escape after they arrived onshore. In such cases perhaps most animals become sick and disabled at sea, and are washed up dying together on the beach or in an estuary.

Strandings in pairs

The stranding of animals in pairs may indicate that they are both dead or ill, or that they are a social or maternal dependency couple (mother and calf) where one is ill or deceased and the other accompanies the partner. For Long-finned Pilot Whales, there were only 8 stranded pair events in the 40 years of data that we have examined, indicating that social couples are not common in their culture. Of the 8 other species with significant massed strandings (10 or more animals), only two showed significant strandings in pairs: the short-beaked common dolphin (*Delphinus delphis*) with 29 events, and Grey's Beaked Whale (*Mesoplodon grayi*), with 25 events. The numbers of stranded pair events for the other 6 species are in single digit figures ranging from 0 to 7.

However, for stranded pairs, the outright winner is the Pygmy Sperm Whale (*Kogia breviceps*), with 70 paired strandings, the great majority of them in Hawkes Bay. In these records for this species, over the 40 years there is also one stranded 3-some, but no larger stranded groups. This species keeps a low profile and is not well understood, but this information implies that they spend most of their lives in pairs, rather than pods.

Conclusion

In conclusion, we have demonstrated that the majority of massed strandings of whales fit the available evidence for a three-stage process. The first stage is the death or illness of a member of the pod, whose body rises to the surface, and is then driven by wind and waves toward a beach. The vast majority of beach stranding observations appear to fit the data here. We assume the second stage is that other members of the social group accompany the body, due to social bonds, to the level of very shallow water. At least for the cases with Long-finned Pilot Whales, this assumption seems reasonable. For other species, future information on strong social bonds and nurturing of disabled individuals may support or contradict our assumption. The third stage requires substantial tides and a gradual beach slope. Again, the observations of mass strandings of offshore species appear to conform to this pattern. A group accompanying a sick individual that drifts ashore would become stranded because the locations of these strandings have gently sloping beaches and relatively large tides, so that the water would retreat laterally very rapidly as the tide falls.

The coastal species (the Short-beaked and the Bottlenose dolphins and the Killer Whales), which have experience of shallow waters and the tides, would appear to not fit this three-stage scenario, but more information is needed on their social structure and the potential for diseases and toxins to disable whole groups of cetaceans, before the question first posed by Aristotle can be fully answered.

Given the above scenario for massed stranding events, what measures could be taken to help prevent or minimise them? The answer would seem to be: “Not much”. It is possible that barriers could be erected to prevent floating objects from being blown onto appropriate beaches, but in most locations these events are too infrequent to justify such actions. A possible exception may be the Golden Bay/Farewell Spit region. Here, it would seem possible to erect a floating barrier over a length of several km, in reasonably shallow water, consisting of a series of moored buoys linked by a suitable floating material between them. If this were set up for the summer months (Dec.-Feb.) each year, and if our hypothesis for the pilot whales is correct, then most of the mass strandings at this location might be avoided.

Declarations

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Both authors contributed to the study conception and design. PGB carried out the analysis of the effects of wind and waves, RD located the positions of strandings on maps and calculated the beach slopes. Both authors contributed to the discussion of detailed implications of the results, the examination of the literature and the drafting of the paper..

The wind and wave data used are available from the first author.

There are no ethics approvals relevant in this study. We used historical data provided by the New Zealand Govt. Department, who have compiled it. We were not involved directly with the animals in any way.

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Tables

Table 1 is available in the Supplementary Files section.

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