Massed Strandings of Whales and Dolphins – Effects of Wind, Waves and Tides.

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Research Article

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Abstract

We examined 125 mass-stranding events of cetaceans (≥ 10 individuals) on New Zealand shores over the past 40 years. 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*. Our hypothesis is that mass-stranding is a three-stage process. The first stage is when an animal becomes ill, its body may become bloated and float on the surface, and the wind and waves may drive it ashore. We assume the second stage is that the dying or dead body may be accompanied by pod members as a result of strong social bonds. 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 of a gently sloping beach as the water level falls. We have evaluated evidence for the first and third stages. In the overwhelming majority (91%) of the mass-strandings (omitting events inside estuaries), the available data showed that wind and waves would drive floating objects (bodies) toward the stranding site. Examination of the nearshore slopes and the tide ranges showed that the vast majority of the stranding sites were slowly shelving beaches where the tides would retreat rapidly over 10s of metres. These 2 results are even more pronounced if only Pilot Whale mass strandings 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, Sundaram et al., 2006). It is clear that 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. Many species mass-strand, but each of these mass strandings 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. We have gathered evidence to evaluate what seems a likely cause of this behaviour - that they follow one or more dying or dead individuals that drift onto the shore.

These cetaceans navigate by sound, and another suggestion has been the possible disfunction of echolocation, due to the lack of sonic reflection from a gently sloping beach (Dudok van Heel, 1962, Sundaram et al., 2006), or because of the absorption of sound by the presence of microbubbles in shallow water (Chambers & James, 2005). 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 (Brabin & Frew, 1994). Thus the most reasonable explanation appears to be that some individuals become sick and drift onto the shore and others in the group follow them, probably due to social bonds that are not yet fully understood.

Here we address this question by an examination of observations of massed stranding events in New Zealand over the past 40 years. Such events have been recorded in New Zealand dating back to the 1840'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 in large groups. These data were provided by the New Zealand Bureau of Meteorology, via Ms. Hannah Hendricks and *Project Jonah* (projectionah.org.nz).

Brabin & 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 New Zealand data set

The data set as used here contains 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). We focus our analysis on events that involve 10 or more stranded animals, dated from 1980 onwards. This gives a data set of 125 massed stranding events, with numbers of animals in each event ranging from 10 to 616. 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 Short-finned Pilot Whales (*Globicephala macrorhynchus*) instead, or may not, due to uncertainty in identifying them at the time, but the distinction is not significant here (Short-finned Pilot Whales prefer warmer waters, and are rarely found near New Zealand, but have a similar social structure. The uncertain cases are denoted *Globicephala sp* in Table 1).

The main data set for analysis 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 (*Tursiops aduncus*) (5), Sperm Whale (*Physeter macrocephalus*) (3), Gray's Beaked Whale (*Mesoplodon grayi*) (2), Killer Whale (*Orcinus orca*) (1), Pygmy Killer Whale (*Feresa attenuata*) (1), False Killer Whale (*Pseudorca crassidens*) (1), and the Southern Right Whale Dolphin (*Lissodelphis peronii*) (1).

Common locations of the stranding events have been described by Brabyn & McLean (1992), and updated in more detail by Betty et al. (2020). For the period under consideration here (1980-2019), 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. As Pilot whales are much over-represented in these massed strandings, some details of their life-style are relevant. These animals are born in pods that may number up to several hundred animals. They take 5 years to mature to adulthood. All the animals in the pod, both male and female, are born in the pod, but none of the male members are fathers (Amos et al., 1991, 1993). Males must leave the pod to breed, apparently, 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, these large groups of pilot whales might stay with a dying senior pod member due to a strong cultural relationship between young and older pod members.

Species considered here other than Pilot whales may also live for decades in pods, so that when senior members eventually die, if they have been prominent in pod social structure, younger pod members might accompany a sick or dead pod member as it drifts, due to these social bonds. In many of these other species, the groups that swim together are not closely related individuals, so that kin selection is not involved (Ball et al., 2017; Martien et al., 2014, Kobayashi et al., 2020; Patel et al., 2017; Westbury et al., 2021). But it is indisputable that 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). We expect that more evidence on this aspect will be available soon.

For all cetacean species, when the animals die it is not uncommon for their floating corpses 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 (Amos et al., 1993) that, as a species, 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.

Nor are Pilot whales over-represented in stranded groups containing 3 to 9 animals. In a total of 115 events in this range over 40 years, 16 of these events are Pilot whales, which is a number comparable with those of other species. This pattern suggests that Pilot whales strand together in the groups that live together.

The stranding process- stage 1: a floating body

We decided to examine 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.

The stranding process- stage 2: wind and waves on a floating body

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)

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

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.

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 its 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 pushed close to the waterline.

The stranding process- stage 3: tides

The third part of the massed stranding process concerns the tides. If the tidal range is significant and high as a dead animal arrives, it will be driven to a level above the mean tide level on the beach. Then as the tide ebbs, it will rapidly become stranded on the beach. If the associated pod is following close behind, and spread laterally to be as close as possible, they would also be rapidly stranded by a falling tide. These animals will have no significant familiarity with tides as they usually live further offshore, 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 at the time of the stranding would drive a floating body ashore at the stranding site; (2) that the dying or dead 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 associated animals would be rapidly stranded.

Methods

In order to test stages 1 and 3 of our hypothesis against available data, we have examined the 125 massed 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. 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 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 reanalysis 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 reanalysis 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 the day the event was recorded. 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 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 Island. 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 9 other species. As noted above, for some of these, the social structure is well enough understood to conclude that 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 some other social bonding mechanism may be present, 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.

Table 1. Summary of New Zealand cetacean mass strandings (≥ 10) from 1980-2020. Those strandings in estuaries are not counted for an explanation by winds, waves etc. The numbers explained by wave direction overlap with those explained by wind direction. The extras explained by wave diffraction are in addition to those explained by wave direction.

Species	# obs	Range of numbers stranded	# In an estuary/ harbour	# with wind onto that shore	# with waves onto that shore	# extras wave refraction explains	# extras if previous day also considered	# explained by wind /waves /refraction	# not explained	Distance (km) to 5 m depth		Tide range (m)	
										Mean	Range	Mean Spring	Mean Neap
<i>Delphinus delphis</i>	10	10 - 44	3	2+?1	2	3+?1	1	6+?1	?1	0.38	0.08-1.3	1.77	0.96
<i>Feresa attenuata</i>	1	11	0	0	1	0	0	1	0	0.69	0.69	2.1	1.5
<i>Globicephala macrorhynchus</i>	1	12	0	1	1	0	0	1	0	0.48	0.48	2.1	1.4
<i>Globicephala melas</i>	90	10-616	3	24	28	49	4	82	5	1.54	0.12-8.3	2.54	1.59
<i>Globicephala</i> sp.	10	10-155	0	5	7	1	0	8	2	0.85	0.23-4.3	2.07	1.12
<i>Lissodelphis peronii</i>	1	77	0	0	0	1	0	1	0	1.1	1.1	0.9	0.4
<i>Mesoplodon grayi</i>	2	10-15	0	0	1	?1	0	1+?1	?1	0.86	0.43-1.3	1.85	0.8
<i>Orcinus orca</i>	1	12	0	1	1	0	0	1	0	0.3	0.3	0.9	0.4
<i>Physeter macrocephalus</i>	3	12-20	0	3	3	0	0	3	0	0.43	0.15-0.65	2.03	1.17
<i>Pseudorca crassidens</i>	1	52	0	0	0	?1	0	?1	?1	0.43	0.43	0.9	0.4
<i>Tursiops aduncus</i>	5	11-49	2	1	0	2+?1	0	2+?1	?1	0.48	0.27-0.79	1.83	0.87
Total	125	-	8	37+?1	44	56+?4	5	106+?4	7+?4	1.3	0.08-8.3	2.36	1.44

Results

In the 125 mass stranding events, 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 and waves.

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 (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, refraction of the waves so as to drive a body ashore was not obvious but 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 assume that for the pilot whales – by far the most common strandings – the social bonds cause other pod members to stay close as the dead or dying individuals arrive on the beach.

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. Even the neap tides would lead to rapid stranding in many locations, such as Golden Bay where the 5 m depth contour is 4.3 km from the shore. Here the 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 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 supplementary 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.

Similarly for the bottlenose dolphins (*Tursiops aduncus*), we have 3 beach strandings and 2 in estuaries, and 2 or possibly all 3 of the 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.

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 at least, the assumption that fellow pod members may accompany this body due to social bonds seems reasonable, and for others it suggests that social bonds may be involved.

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 the tidal range in the Mediterranean is negligible (2-3 cm).

This may be contrasted with tides 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.

It seems likely however, that some other explanation than accompanying a dying associate is needed for the coastal dolphins and 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

Animals that are stranded in pairs may indicate that they are both dead or ill, or that they are a social couple 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, 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.

Conclusions

we have demonstrated that the majority of massed strandings of whales conforms to 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 towards a beach. The second stage is, we assume, that due to social bonds, other members of the social group would accompany the body to the level of very shallow water. At least for the cases with Long-finned Pilot Whales, this assumption seems reasonable. The third stage depends on the tides and on the beach slope. A large pod will be spread along the beach, centred on the floating body, and 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 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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