

Article

Dead on the Beach? Predicting the Drift of Whale Remains Improves Management for Offshore Disposal

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Abstract: Whale mortality and strandings have increased in recent years, with deceased whales often brought to landfill. However, the disposal of whale remains offshore holds significant ecological importance and can be a culturally and ethically sensitive approach. Moreover, offshore disposal mitigates potential risks associated with onshore whale remains disposal, such as the spread of diseases and the logistical challenges of managing large carcasses. A challenge with offshore disposal is defining the best release location to avoid the remains drifting ashore or into shipping channels. Here we compared the drift model outputs using a drift forecast model (SARMAP) for a 14 m whale carcass that was moved offshore in southeast Queensland, Australia, and fitted with a satellite tracker over an observation period of 150 h until positioning signal ceased. The modelling was conducted using different ocean products (BLUElink, HYCOM, and Copernicus), which showed a good agreement with the tracked whale carcass, albeit with changing wind conditions and contrasting currents flowing northward along the coast and, further offshore, flowing south. This case study illustrated that wind was the foremost driver of carcass drift due to the surface area above the water surface. The drift forecast simulations allowed for a reliable prediction of the floating whale drift that can assist authorities with decision making. Offshore disposal of whale carcasses is a sustainable practice but requires good planning and scientific assessment.

Keywords: modelling; whale disposal; sharks; predation; drift



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1. Introduction

Whales have started to recover from commercial whaling in the past century, resulting in positive population trends for some species such as humpback whales (*Megaptera novaeangliae*). However, increasing anthropogenic impacts from pollution, boating, fishing, climate change, and offshore development have caused an increase in whale mortality and, consequently, strandings [1–3]. On the east coast of the USA, 37 humpback whale strandings were reported in 2023 (NOAA, <https://www.fisheries.noaa.gov/national/marine-life-distress/2016-2024-humpback-whale-unusual-mortality-event-along-atlantic-coast>, accessed on 10 January 2024) and similar numbers were seen for the Australian east coast (pers. communication). Large whales either perish offshore, with most cetaceans sinking at the time of death [4] or float for some time, die at depth, or wash up and perish on shore [5].

While the majority of deceased whales never reach the shoreline, those that do can become a hazard. The removal of deceased whales that wash up or float near populated coastal areas can be a logistical challenge and receives attention from the public. In some

instances, costly exhumation of beached, buried whales was required after public concerns were expressed that a carcass might attract sharks to the area (ABC News, <https://www.abc.net.au/news/2017-10-24/whale-exhumed-sunshine-coast/9080632>, accessed on 25 January 2024).

Complexity arises from the considerable size of the deceased whales, the diverse potential locations for strandings or floating whales, and challenges associated with accessing certain beaches. There are also technical, social, economic, and environmental factors to consider [6].

There are currently seven different disposal strategies recognized as possible management responses regarding deceased whales (Appendix A Table A1). In populated areas, whale remains may be transported to landfill (1). This requires adequate transportation and use of an excavator. It is most feasible when beaches are accessible and have a landfill or holding facility in proximity. The disposal of whale remains in landfills can be culturally controversial and raises ethical questions. There are also concerns due to the potential for disease transmission during handling. Decomposition of organic matter in landfills produces gases such as methane and carbon dioxide. In some cases, the deceased whale may be transported to a rendering facility (2), where it is processed and turned into products such as biodiesel. Composting is another option, wherein the deceased whale is placed in a controlled environment to decompose naturally, and the resulting compost can be used as fertilizer [7]. The burial of deceased whales (3) on or near the beach is frequently employed as a management strategy, particularly with smaller whale species. This involves digging a trench and burying the carcass in the sand. While burying whale carcasses can contribute to nutrient cycling and enhance coastal ecosystems, influencing soil composition and fostering local flora, it also presents challenges. This includes the potential spread of diseases, groundwater contamination, and the attraction of scavengers, which may impact local fauna and give rise to public health concerns [8,9].

Allowing natural decomposition (4) to occur is a strategy often employed in remote locations or with smaller whale species. Over time, the carcass breaks down through biological processes and the remains are dispersed by ocean currents. This method is not feasible on frequently visited public beaches due to unpleasant smell, sight, and associated health risks.

In cases where the carcass is large and close to shore or partially stranded, one strategy is to tow it (5) out to deeper waters. By releasing the carcass away from the coastline, it allows natural processes, such as decomposition and scavenging by marine organisms, to occur without affecting coastal ecosystems. This strategy can be regarded as the most ethical and culturally sensitive form of dealing with deceased whales. However, there are challenges associated with offshore disposal, such as the need for the whale to be repositioned in offshore regions that represent the least possibility for a return to shore, while also not posing a navigational hazard. Furthermore, repositioning deceased whales offshore also requires expertise, suitable weather conditions, and appropriate vessels and crew for towing and release operations.

In some instances, attempts have been made to sink deceased whales (6) to the ocean floor. This can be achieved by attaching weights or other materials to a floating carcass or a whale towed offshore. The idea is to reduce the risk of whale remains floating ashore as well as reducing any navigational hazards. This method has been deployed in the past to study decomposition rates of whale carcasses in various oceans [10]. Explosives (7) have been used historically to break down large deceased whales into smaller, more manageable pieces [6]. This method is less common today due to obvious safety and environmental concerns. Generally, the scientific community recognizes that the disposal of whales demands careful planning and execution to mitigate potential adverse effects. Whether offshore disposal is suitable depends on a number of factors, including external factors such as weather conditions, size of whale, and the type and number of scavengers influencing decomposition rates.

1.1. Large Whale Offshore Disposal and Decomposition

Following death, baleen whales (Mysteceti) can significantly expand, causing them to float until forces of wind and waves, degradation from sunlight, and damage from scavengers reduces buoyancy (Figure 1). If there is sufficient buoyancy retained in fatty tissues, whale remains may linger at, or close, to the water's surface while denser tissues, like bones, are shed. Different whale species also have different density and buoyancy characteristics. For instance, Right whales (*Eubalaena glacialis*, *E. australia*) are more buoyant on the surface than humpback whales (*Megaptera novaeangliae*) [11]. During a mortality event with 14 humpback whales over a 5-week period in 1987 at Cape Cod Bay, USA, all whales (except one that was towed immediately after death) sank then re-floated due to gas produced during decomposition [5,12].

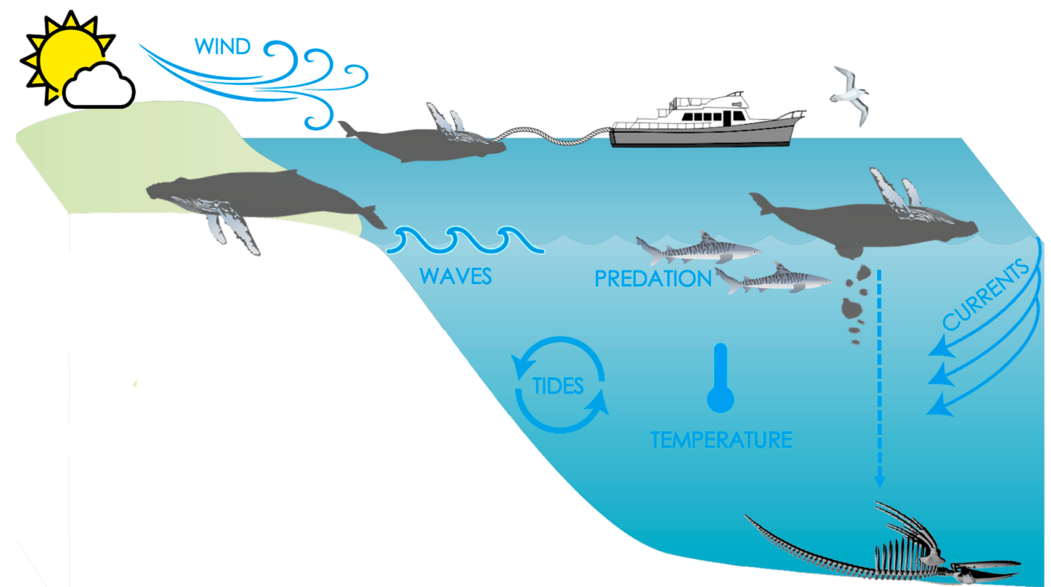


Figure 1. Illustration of removal of deceased whales offshore and relevant factors influencing the drift of floating whale remains. Sun exposure, water temperature, and scavengers contribute to decomposition rates with wind, waves, tides, and currents, as well as rate of decomposition, determining the drift.

Water temperature plays a key role in gas production from gut bacteria. It can be estimated that it takes about 24 h at 30 °C and 3–5 days at 20 °C for a baleen whale to refloat (pers. communication). Warmer sea temperatures will enhance bacterial growth resulting in faster heat development inside the deceased whale body [13]. A sperm whale (*Physeter macrocephalus*) (10 m) in the Seychelles, which presented a water temperature of 29 °C, was floating at first sight and then anchored with 5–6 tiger (*Galeocerdo cuvier*) and bull sharks (*Carcharhinus leucas*) feeding at any one time. After 5 days, the whale remains were consumed and sank [14]. Scavengers such as tiger sharks play a crucial role in reducing the time a deceased whale stays afloat (Video S1). Tiger sharks actively target the blubber and avoid muscle tissue [10,15], thereby reducing the buoyancy of a deceased whale. Further reports and studies from large deceased whales (10 m and more) from South Africa (water temperature of 14 °C) suggest a longer decomposition time at the surface (>7 days), even in the presence of sharks [16]. The duration of sharks lingering at the site where whale remains occurred or are buried was observed to be 7 days, with duration of stay decreasing daily due to a reduction in scavenging success [17].

1.2. Modelling Drift

Whale remains have been towed out to sea for offshore disposal in a number of countries, including Australia, South Africa, and the USA [6]. However, not all of these offshore disposals were successful. For example, a humpback whale washed ashore again after being

towed out to sea near Los Angeles, USA, underlining the importance of estimating drift and the best disposal locations (The Guardian, <https://www.theguardian.com/environment/2016/jul/17/dead-whale-wally-california-beach-los-angeles-county>, accessed on 25 January 2024).

Predictions regarding the movement of deceased whales adrift at sea can be useful in supporting the comprehension of likely stranding sites along coastlines, in concert with an understanding of the potential for the presence of whale remains in shipping lanes or coastal waters frequented by the public for activities such as swimming, fishing, and other recreational activities. Safety considerations for coastal water community users should encompass the potential for the deceased whale to draw predatory sharks, in addition to posing a hazard to boating.

Drift of whale remains, or any objects, is predominantly influenced by wind and current forcing. Buoyancy influences the drift speed, with whale remains being more driven by wind the more buoyant they are and the more inflated they are above the water surface. There are several models that allow for object drift tracking at sea that consider factors such as wind and currents. A study on deceased floating common dolphins (*Delphinus delphis*) near the French Atlantic coast was performed using the drift prediction model MOTHY (Modèle Océanique de Transport d'HYdrocarbures). Originally devised by Météo-France for forecasting the movement of oil slicks, MOTHY was subsequently modified to accommodate solid objects such as cargo containers [18]. The MOTHY model forecasts the trajectories of floating objects by computing the vertical profile of currents and assessing the impact of wind on the exposed portion of the object [19]. Hydrodynamic models such as the America SEAS (AMSEAS) model were applied to deceased floating turtles in the Gulf of Mexico [20]. Another software package is the Search and Rescue Model and Planning (SARMAP) model that is capable of predicting the movement of various floating objects (e.g., person in the water, rafts or capsized boats on the sea surface) in compressed time mode for search and rescue missions [21]. To achieve this, SARMAP uses inputs such as spatially and time-varying winds and currents, along with the drift characteristics specific to the floating object.

Here, we investigate and validate the projected drift trajectories of a deceased whale at sea that required consideration of various factors such as environmental conditions, ocean currents, and the size of the carcass to enhance our understanding of its movement patterns. We further discuss the implications of the case study's findings for the potential improvement of offshore disposal practices and their relevance in comparison to other existing management strategies for stranded whale carcasses.

2. Materials and Methods

The study area is located in the waters of the Sunshine and Fraser Coast in southeast Queensland, Australia (Figure 2). Specifically, the location is between Noosa Headlands in the south (26.378° S, 153.119° E) and Double Island Point in the north (28.168° S, 153.558° E) and further north to Fraser Island (25.793° S, 153.077° E), with a mean water depth ranging from 10 m nearshore to 60 m approximately 30 km offshore. The region is part of the fast-growing south-east Queensland region [22]. The coastal area is dominated by sandy beaches and an open embayment facing towards the Coral Sea. Regional climate conditions are characterized by a sub-tropical hot and humid wet season (November–April) and a mild dry season (May–October) with mostly easterly to south-easterly trade winds all year. The sea surface temperature (SST) ranges from 20 °C to 28 °C between the wet and dry seasons, respectively [23]. The East Australian Current (EAC) brings warm, tropical water from the north and a coastal, northward current generally brings cooler waters. The strength of these currents varies with the seasons, with the EAC weakening during the Austral winter months between May to November [24]. During the autumn and winter months, the wind-driven Fraser Island Gyre develops between southern Fraser Island (25° S) and Moreton Bay (27° S), creating a near-coast northern flow and cross-shelf transport [25]. Mean significant wave height of the region is around 1 m [26], and there is a

predominance of south-easterly waves. A semidiurnal tide with a 1–2 m range creates tidal flows nearshore.

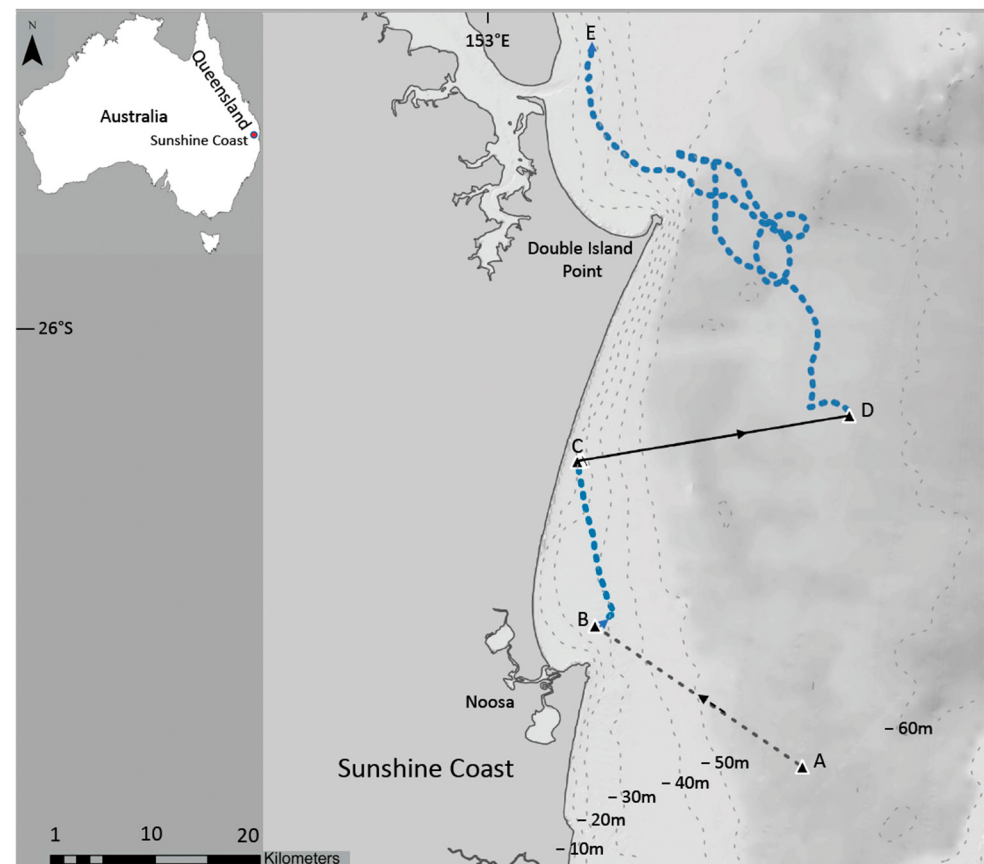


Figure 2. Study location and track of whale remains. First sighted on the 16 July 2023 at 4:00 p.m. (A), resighted on the 17 July 2023 at 1:26 p.m. and a satellite tracker deployed (B), intercepted on the 18 July 2023 at 7:00 a.m. and towed offshore (C), released with satellite tracker at 1.40 p.m. (D) and last signal from satellite tracker received on the 25 July 2023 at 3:00 a.m. (E).

2.1. Whale Remains and Position Tracking

In the afternoon (4:00 p.m.) of the 16 July 2023, a floating whale was reported by Australian Volunteers Coastguard south of Noosa Heads (Figure 2; 26.481° S, 153.334° E) with a northwest drift. It was then resighted approximately 4 km northwest from Noosa Heads the next day. The whale remains were identified as a female humpback whale with an estimated size of 14 m total length, an approximate body width of 5 m, pectoral fins each 4–5 m in length, and a total weight between 20–25 t. The height of the animal exposed above the water surface was estimated at 1.5 m. As the head of the whale was missing, it is assumed the whale was likely killed by a ship strike in previous days. Decomposition of the whale had begun, with multiple shark bite marks visible and an inflated body indicating gas development from the intestines (Figure 3).

A fully charged DAF SPOT Trace satellite tag (<https://www.tracertrak.com.au/> accessed on 3 March 2024) fixed in a watertight housing was attached to the floating whale on the 17 July 2023, at 1.45 p.m. (26.340° S, 153.124° E) (Figure 3). The satellite tag was set to transmit its location at 5-min intervals and its updated position was accessed online via a portal from which the location data were also downloaded. The whale drifted in a north-westerly direction until the morning of the 18 July, when it was intercepted before reaching the shoreline and repositioned (towed) offshore to avoid it being stranded on a public beach. The deceased whale was released approximately 30 km offshore (26.128° S, 153.381° E) and a recharged SPOT tag redeployed using a rope fitted around the whale

body and the pectoral fins (Figure 3). The drift of the whale remains was monitored using an online portal receiving the satellite tag data feed until the last signal was received on the 25 July, when it was assumed that the whale remains sank or batteries of the satellite tracker failed. Weather and wave conditions were monitored from nearby publicly accessible weather stations maintained by the Bureau of Meteorology and wave rider buoys operated by the Queensland Department of Environment, Science and Innovation (Appendix A Figure A1).

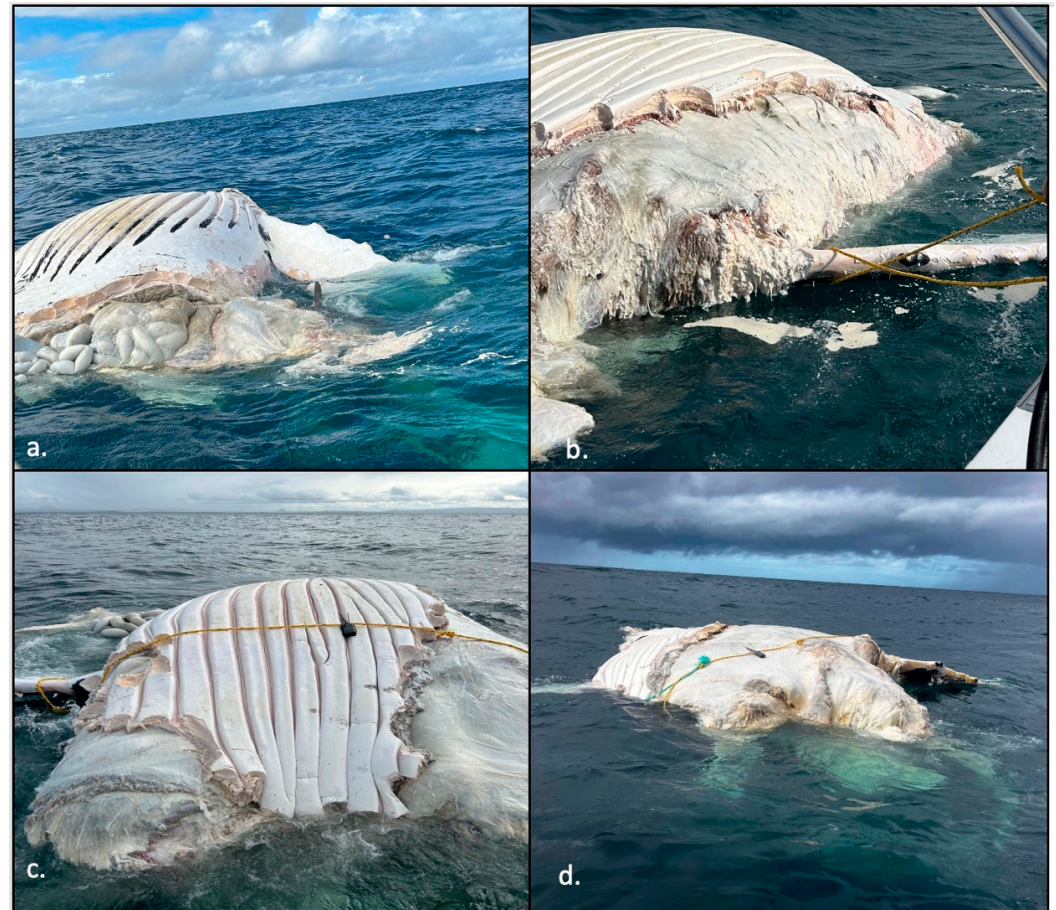


Figure 3. (a) Inflated deceased whale and tiger sharks (*Galeocerdo cuvier*) sighted on 17 July 2023, (b) clearly visible bite marks from tiger sharks, (c) side view of deceased whale with deployed satellite tracker on the 17 July 2023, (d) deceased whale with redeployed satellite tracker on the 18 July, 2023 (Images credit Paddy Marine).

2.2. Drift Trajectory Modelling

The SARMAP (RPS, Version 7.1.1.11) drift modelling software, developed by Applied Science Associates, Inc. [27], was employed in this study to forecast the drift of the whale remains. SARMAP has undergone validation through numerous global studies [28–31]. SARMAP operates as a Lagrangian particle tracking model, designed to predict the movement of various floating objects on the sea surface [32,33]. In this study, SARMAP utilized the Monte Carlo method to compute the drift of the carcass, whereby 1000 particles were released to forecast the movement of the modelled whale remains. The model calculates the spatial and temporal variations of each particle based on the drift or leeway characteristics of the selected object and metocean conditions. The results derived from the simulation are presented as a time-varying spatial density map, offering insights into the potential drift path of the target over time.

2.3. Search Object Database

The combined effect upon the drift of an object due to wind and waves is described as the “leeway”. The leeway of an object varies from object to object and therefore a set of measured leeway coefficients is specified for each drift object to accurately determine their drift characteristics. Without the correct leeway coefficients, it is impossible to accurately forecast how that object may drift. Leeway field tests are currently the most common and most accurate method for determining the leeway coefficients of a drift object [33,34]. This process entails measuring how an object drifts in response to surface currents, influenced by wind and wave action. The latest definition, proposed by Breivik et al. [35], describes leeway as the motion induced by wind (at 10 m reference height) and waves relative to the ambient current (between 0.3 and 1.0 m depth).

In SARMAP, users have access to a database containing drift behavior for 101 objects, which is based on established U.S. Coast Guard datasets. This database enables users to select the most suitable object for their situation. However, no leeway data were available, at the time of this study, for whale remains, and the influence of the winds blowing against the exposed surfaces of the whale is not well understood. An assessment of the SARMAP object database was undertaken to select objects that could potentially best represent a deceased floating whale. As such, individual modelling simulations were initially conducted using both a (i) life raft equipped with a deep ballast system and canopy with a windage of 0.9% and a (ii) skiff in a swamped or capsized condition with a windage of 1.7%, in order to gauge the different drift behavior.

2.4. Environmental Data

In SARMAP, the simulated drift of an object is divided into two primary velocity components. The first velocity component represents the drift of the object caused by the mean flow field, typically obtained from current and wind forecast models. The second velocity component accounts for the drift due to turbulence also known as horizontal dispersion, which encompasses sub-grid scale processes that may not be accurately replicated in current and wind models. By treating these two velocity components separately, SARMAP can effectively account for the contributions from both large-scale circulation and smaller-scale turbulent motion, enabling a more comprehensive understanding of the object’s drift behavior.

The currents within the study area are influenced by tidal flows and large-scale drift currents, which are driven by factors such as wind shear on the water surface and the presence of the EAC, which impinges close to the coast. To accurately characterize the “total current”, the influence of tidal and ocean current data was included as input into SARMAP.

Tidal current data were generated using RPS’ advanced ocean/coastal model, HYDROMAP. This model simulates tides resulting from astronomical tides, wind stress, and bottom friction [36]. Employing a sophisticated dynamically nested-gridding strategy, the tidal model domain for this study was sub-gridded to a maximum resolution of 500 m along the coastline, starting from an offshore resolution of 8 km.

Data from three global ocean current models were sourced for individual comparison as part of the consensus forecasting approach (Table 1). These models included BLUElink, Hybrid Coordinate Ocean Model (HYCOM), and Copernicus Global Operational Forecast (Copernicus). There was consensus among the three ocean current models, although the Copernicus model product (Copernicus, <https://marine.copernicus.eu/> accessed on 15 April 2024) proved to be more accurate when compared against the measured whale track and was chosen for our presented modelling output.

Given that the atmospheric fields driving the Copernicus ocean model originate from the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecast System, we utilized the same wind data to incorporate wind forcing affecting the carcass. A more detailed presentation of the model can be found in Lellouche et al. [37].

Table 1. Ocean model product parameters. BOM (Bureau of Meteorology), NOAA (National Oceanic and Atmospheric Administration—National Centers for Environmental Prediction), ECMWF (European Centre for Medium-Range Weather Forecasts), and CMEMS (Copernicus Marine Environment Monitoring Service).

Model	Provider	Horizontal Resolution	Vertical Coordinates	Forecast Length (h)	Time Step (h)	Wind Forcing	Grid Limits
Blue Link	BOM	0.1° × 0.1° (10 km × 10 km)	51 z layers	96	3	ACCESS-G	Global [−74.90 to 75.00]° N, [−180 to 180]° E
HYCOM	NOAA	1/12° (~9 km)	32 hybrid layers	144	3	NOAA	Global
Copernicus	CMEMS	0.083° × 0.083° (~9 km × ~9 km)	75 layers	240	1	ECMWF	Global

2.5. Dispersion Parameters

The horizontal dispersion coefficient serves two primary purposes within drift models: (i) compensating for drift associated with sub-grid scale turbulent processes not accounted for by ocean forecast models and (ii) addressing uncertainties within environmental forcing data, including waves, winds, and currents. The values of horizontal dispersion vary across regions and over time, depending on the amount of horizontal current shear or turbulence present. Using too large a value can cause particles to separate, leading to a larger predicted area; while this increases the likelihood of containing the object, it compromises the accuracy of predicting whether the whale remain would strand on a public access (recreational) beach. During this study, sensitivity testing was conducted using varying literature-based horizontal diffusion parameters for nearshore coastal and ocean waters, ranging from 5 m²/s and 10 m²/s.

2.6. Comparison of Simulated Trajectory and Satellite Track

For a measure of the quality of fit, we used the average track error calculated as the mean distance between hourly model predictions and corresponding positions of the tracked whale remains based on time. Additionally, the hourly measured drift speed and direction of the whale remains were compared with modeled hourly wind speeds and directions to assess the drift characteristics over time.

Pearson correlations were used to explore data and identify relationships between whale remains drift speed with wind speed. A criterion of $p < 0.01$ was used to determine significant differences using SPSS for Windows (SPSS Inc., Chicago, IL, USA, version 20). No data transformations were performed.

3. Results

During the observation period, the sea surface water temperature was 21 °C, the maximum wave height was 4 m, and the average wave height 1.5 m (based on local wave rider buoys from Wide Bay and Mooloolaba, Figure A1). The main wind direction until the 19 July 2023, was southeast to south with a maximum wind speed at sea of approximately 30 km/h. The wind direction changed to northeast for several days and then, on the 22 July 2023, to southeast with 40–50 km/h. These highly variable wind directions and wind speeds influenced the drift of the whale remains.

The observation period of the whale remains spanned 16 July 4:00 p.m. until 25 July 3:00 a.m. (179 h), of which 150 h were covered with a satellite tracker with 5 min interval location recordings (data telemetered). When first sighted, the deceased whale drifted 26.2 km within 22 h towards the Sunshine Coast with an average speed of 1.2 km/h. Thereafter the deceased whale was resighted the next day at approximately 12:00 p.m. and had drifted another 17.5 km at 1.1 km/h before it was relocated offshore on the 18 July 2023 from where it drifted at an average speed of 0.7 km/h for over 171 km until the satellite tag signal was lost. A gradual decline of drift speed and the effect of wind on drift speed

(Table 2), even under increased wind speed conditions, was apparent (Figure A2). The drift of the deceased whale significantly correlated with wind speed, in particular within the first days of observation between 18th and 20th July, 2023 ($r^2 = 0.38$, $p < 0.01$), though the correlation between whale remains drift speed with wind speed declined between 21 and 25 July 2023 ($r^2 = 0.24$, $p < 0.01$) (Figures 4 and A3a,b). The drift speed and modelled wind direction was more correlated in the first days and modelled current speed became more correlated to the drift speed of the whale remains in the last days of observation.

Table 2. Outline of events and average drift speed of whale remains.

Date	Time	Location of Whale Remains	Lat/Long	Distance Drifted (km)	Average Speed (km/h)	Activity on Whale Remains
16 July 2023	4:00 p.m.	South of Noosa Heads	−26.48183 153.33417	-	-	First sighted by Coastguard
17 July 2023	1:45 p.m.	North of Noosa Heads	−26.3402 153.12417	26.2	1.2	Sighted and fitted with tracker
18 July 2023	7:09 a.m.	East of Cooloola beach	−26.17422 153.10828	17.5	1.1	Sighted and towed offshore
18 July 2023	1:40 p.m.	Offshore of Coloola beach	−26.12883 153.11145	27.5	4.1	Repositioned offshore
20 July 2023	1:04 p.m.	East of Double Island Point	−25.87401 153.2444	37.3	0.8	Loss of satellite tag signal for 11 h
25 July 2023	3:00 a.m.	South of Fraser Island	−25.76318 153.12045	114	0.7	Loss of satellite tag signal

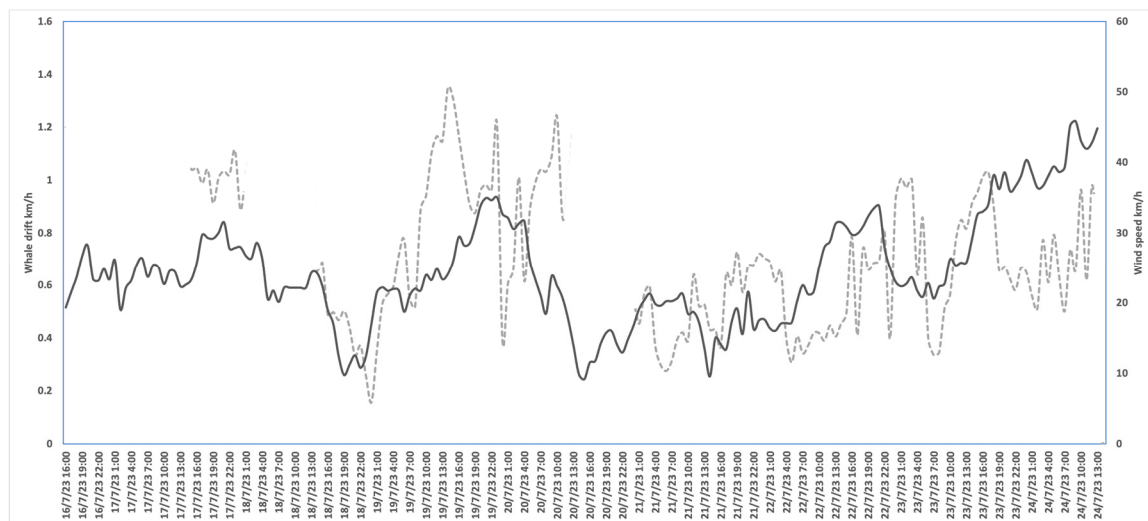


Figure 4. Hourly drift of the deceased whale (dashed line) for available observation times in relation to hourly modelled wind speed (grey line).

Due to the sequence in the availability of data, we initially simulated the drift of the deceased whale for the 18–25 July 2023 (Figure 5a) and then 16–18 July 2023 (Figure 5b).

The initial forecast modelling involved simulating the drift of the deceased whale immediately following the time after it was taken offshore and released on 18 July 2023, at approximately 2:00 p.m. The coordinates, date/time, and description of the whale state (Figure 3), which suggested advanced decomposition with parts of the whale body missing, were available. Inputs into the SARMAP model included ocean current data (plus HYDROMAP tides) and ECMWF winds. Upon assessment of the ocean current data, it was found that the deceased whale was released in a transition zone between coastal northward currents and the offshore southward EAC. Due to the advanced decomposition of the whale and the unknown influence of the winds, we selected two objects within SARMAP (a life raft and a skiff) with different windage factors to assess their drift behavior. The skiff, having double the windage, travelled further north than the life raft. The drift of each

object type was very similar across all three ocean current models. Once the corresponding positions of the tracked whale remains were available, it was found that the drift of the skiff matched most accurately, while the model predicted life raft drift was too slow. This trend was consistent across all three ocean current products, with the Copernicus global ocean data (plus HYDROMAP tides) and ECMWF winds providing the best simulation output, matching the same distance and direction as the tracked deceased whale between the 18–25 July 2023.

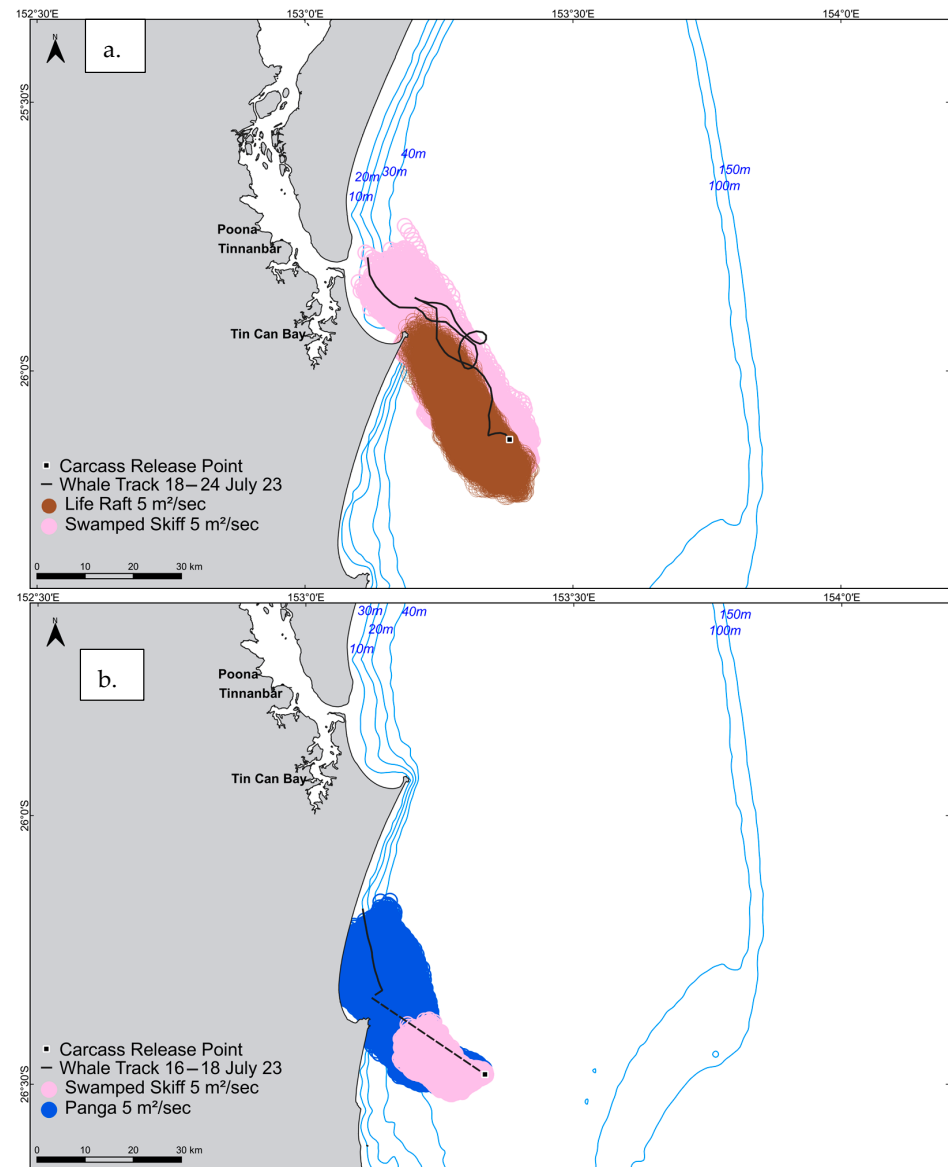


Figure 5. (a) Predicted track of the whale remains from the observation point 18–25 July 2023, based on a life raft and a swamped skiff and (b) predicted track of the whale remains from the observation point 16–18 July 2023, based on a simulated swamped skiff and Panga skiff. Overlaid is the actual track of the whale remains for the same period.

Subsequently, the effect of the swamped skiff potential drift based on horizontal dispersion coefficient values of 5 m²/s and 10 m²/s was assessed. While the larger value of 10 m²/s increased the likelihood of containing the drifting deceased whale, we opted to use 5 m²/s as the results were similar (Figure 6) and reduced the likelihood of overstating that the whale remains would wash ashore.

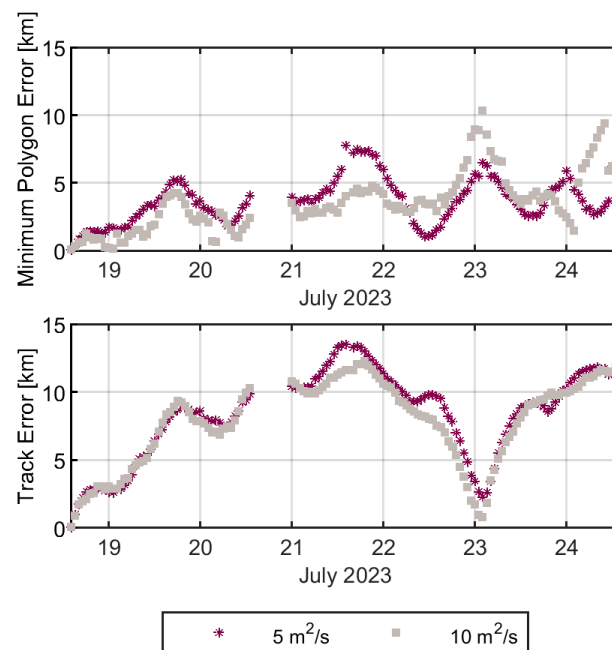


Figure 6. Minimum distance of observed whale carcass to modelled potential drift path of the whale carcass based on horizontal dispersion coefficients of 5 m²/s and 10 m²/s for the modelled swamped skiff object 18–25 July 2023.

Next, modelling of the deceased whale for the 16–18 July 2023, was initially based on the same settings as the first simulation: a swamped skiff, Copernicus global ocean data (plus HYDROMAP tides), ECMWF winds, and a 5 m²/s horizontal dispersion coefficient. Upon comparison with the actual track, the swamped skiff was found to be too slow, covering only one-third of the distance travelled by the deceased whale over the two days. As previously mentioned, the deceased whale was determined to have travelled at an average speed of at least 1.1 km/h, which interestingly was faster than was observed between 18–25 July 2023 (average speed of 0.7 km/h for over 170 km until the signal was lost), suggesting either less drag below the water surface or the whale sitting higher above the water surface. To address this, an alternative object from the SARMAP database was sought, one that would be influenced by the wind three times as much as a swamped skiff. As such, a Panga skiff POB (person on-board) 5 was selected and given a windage of 4.8%, representing 2.8 times greater wind influence compared to the swamped skiff (i.e., 4.8% compared to 1.7%). The Panga skiff's POB 5 drift from the initial observation point on 16 July provided the better simulation of the whale track until 2:00 p.m. on 17 July 2023, compared to the swamped skiff. It then followed a similar path as the whale remains for the next 17 h, concluding within the vicinity of the location as indicated by the GPS tracker at 7:00 a.m. on 18 July 2023 (Figure 5b).

4. Discussion

In this study, we established a better understanding of the predictability of the drift speed and direction of whale remains. Using the drift model SARMAP and testing various input parameters effectively simulated the whale remains trajectory matching the SPOT tagged whale remains track. Covering more than one week of observation, the whale remains were exposed to a wide range of environmental factors. The highly variable weather and wind conditions as well as different currents and progressing decomposition provided for a unique opportunity to study the drift and test forecasting abilities. The reliable prediction of the drift of whale remains has major implications for their offshore disposal, navigation, and beach safety.

4.1. Offshore Whale Carcass Disposal Enhanced through Modelling Drift

Our case study showed that providing a reliable prediction of the drift of whale remains is achievable. Such capability would allow authorities to act when intervention is necessary. Forecasts for the drift of whale remains may be used to understand potential stranding locations along the coast as well as the potential for interaction with shipping lanes or coastal waters used by the public for swimming, fishing, and other recreation activities [38]. Safety considerations might also include the potential for the remains to attract sharks.

Additionally, it may be beneficial for forecasting the cost-effectiveness of towing whale remains to various offshore distances or directing the tow to specific locations where ocean currents and wind patterns favor keeping the remains at a safe distance from shore and/or high-density vessel use regions.

The drift of whale remains results from the dynamic interaction of wind, waves, and current forces. This balance shifts depending on the surface areas of the whale's body exposed to wind and surface water. Variable buoyancy also plays a crucial role. A bloated deceased whale, which has increased windage, will be more affected by wind, whereas a low-lying carcass with minimal wind exposure will be more influenced by surface currents. Information about the condition of the deceased whale, including size, predation effects, loss of pectoral fins, decomposition stages, and height above the water line, is essential for accurately setting drift model parameters. Some of this information was available from photos such as the estimated height above water; however, the gradual rate of decomposition was unknown. The role of predators on the decomposition rate and therefore drift behavior can not be underestimated as our case study demonstrated [15,16].

Initially, the deceased whale was predominantly driven by wind speed, but, with continuing decomposition, this changed, resulting in a decrease in drift speed (Table 2). When modelling the drift for the first two days, simulating the drift with an object that had higher windage (Panga) was more accurate than one with lower windage (skiff). After 3 days, however, an object such as a skiff with less windage predicted the drift trajectory better (Figure 5). The deceased whale was determined to have drifted at an average speed of at least 1.1 km/h. This suggests either less drag below the water surface or the whale sitting higher above the water surface between 16th and 18th July, resulting in faster drift due to wind influence. This estimate of the whale remains drift fitted well within the overall range for other drifting objects. For example, a variety of objects windage reviewed in Breivik et al. (2011) included persons in a survival suit (2% windage); life rafts (3–6.8% windage); fishing vessels (2.7–4.2% windage); and sport boats (6–7% windage). A horizontal dispersion coefficient of 5 m²/s instead of 10 m²/s was leading to a smaller predicted area and reduced the likelihood of the whale remains becoming stranded on a public access (recreational) beach.

Based on available knowledge, we estimated the total time from death until whale fall to be between 7–10 days in subtropical waters at water temperatures around 20–21 °C with sun exposure as well as presence of scavengers [15,39]. The whale remains were first sighted on the 16th July when the whale was likely already deceased for 2 days. The signal from the GPS tracker was lost in the early morning of the 25 July, which would be in line with the estimated 10 days for a whale fall to occur. This includes an estimated 2 days for the whale to refloat shortly after it deceased [5]. The majority of whales first sink after death but resurface after a few days unless they sink below 100 m hydrostatic pressure [40]. A humpback whale in subtropical Algoa Bay, South Africa, of 13 m length was observed for 12 days [39] until it finally sank. Another example from subtropical waters was a deceased humpback whale drifting near Marin County in California, USA. The carcass was estimated to have been adrift for no more than 2 or 3 days and was observed for another 7 days [15]. Higher temperatures accelerate the rate of oil leakage, which reduces buoyancy. Elevated air temperatures and extended exposure to sunlight cause internal heat to rise to nearly 50 °C within two to three days. This heat, coupled with autolysis, breaks down the fatty acids in the blubber [13]. Examples of floating deceased whales from

tropical waters underline these observations. In New Caledonia a blue whale (*Balaenoptera musculus*) of 17.4 m length first sank after it died and resurfaced bloated after 36 hrs and sank permanently after 2 days but was subject to intensive feeding by over 40 tiger sharks, exposed to sun and warm waters [10].

This suggests that scavengers can play a major role in the decomposition in combination with warm waters ($>24\text{ }^{\circ}\text{C}$) [41] as they are targeting blubber and meat, which accounts for over 60% of the whale body mass. An adult humpback whale consists, by weight, of ~23% blubber, ~40% meat, ~15% bone, and ~15% viscera (internal organs) [42].

4.2. Study Limitations

Many factors influence an object's drift, including the speed and direction of winds and currents (large scale and tidal) and the object's dimensions including height above water surface; however, these factors also have varying effects over time with the decomposition of the whale remains. We were unable to verify the status of the whale remains after the 18 July due to weather conditions and inaccessibility of area. The GPS tracker signal was lost for 11 h, which may be due to the whale body tipping and the tracker being submerged. Given the limited knowledge on decomposition rates in different environmental conditions for floating deceased whales, the time of whale fall could also not be verified. The larger the object's surface area above the water level, the greater the influence of wind. For example, the divergence angle for a vessel is more than 45 degrees to the right and left of the average drift line. Ensuring improved reliability of forecasting the drift of whale remains requires additional observations for validation from different drifting whale remains from other locations.

To date, while models such as SARMAP are capable of simulating the drift trajectory of floating whale carcasses, they are unable to account for changes in decomposition, and global ocean models have limitations in nearshore waters [43]. This results in higher uncertainty in the prediction of the whale remains drift. In our case study, this uncertainty was in the range of 15–20 km (Figure 5). Other modelling techniques such as MOTHY, integrating hydrodynamic modelling with floating objects simulation and generally improving hydrodynamic models, could further advance the forecasting abilities. The America SEAS (AMSEAS) hydrodynamic model provides an estimate of leeway and then successfully applied modelling to the drift of deceased turtles [20]. Predictions of ocean currents are less reliable in nearshore coastal waters where the resolution of data is not sufficiently resolved. In shallow environments, drag or periods of short-term stranding on the seabed will also affect the movement of the carcass. Estimates of the draft (depth penetration) of the carcass will allow reference to the bathymetry in the area.

5. Conclusions

Offshore disposal of deceased whales requires careful consideration of various factors such as the size of the whale, its state of decomposition, proximity to human activities, and prevailing weather and sea conditions. Balancing the ecological benefits with potential risks is essential, and employing evidence-based approaches ensures responsible and sustainable management practices.

Perished whales provide a substantial nutrient source for marine ecosystems. Strategically placing whale carcasses offshore can enhance nutrient cycling and foster biodiversity contribute to carbon removal and marine floor enrichment [44] and enrich the marine floor for up to seven years [45]. Their gradual decomposition sustains scavengers and detritivores while also supporting microbial communities and deep-sea organisms. This underscores the ecological significance of offshore whale carcass disposal, advocating for sustainable practices that harmonize with natural ocean processes.

The best strategy for handling whale remains depends on multiple factors and must be decided on a case-by-case basis. Offshore disposal can be an ethical, cost-effective, and safe option if managed appropriately. Predictability of the drift of whale remains is an effective way to minimize risks. By integrating scientific research with practical management strate-

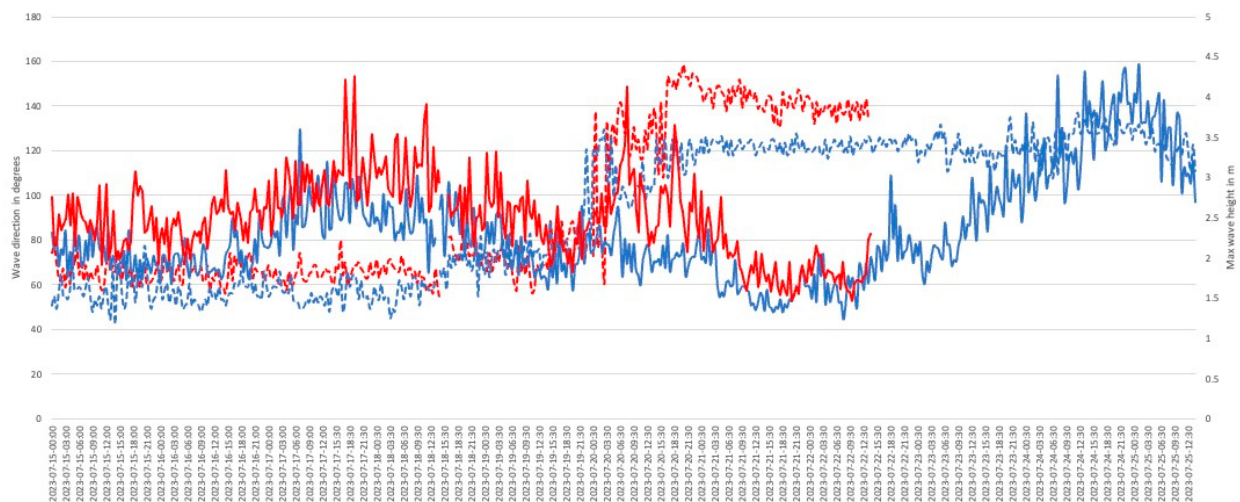


Figure A2. Mooloolaba (blue) and Wide Bay (red) wave rider buoy maximum wave height (dotted) and wave direction (line).

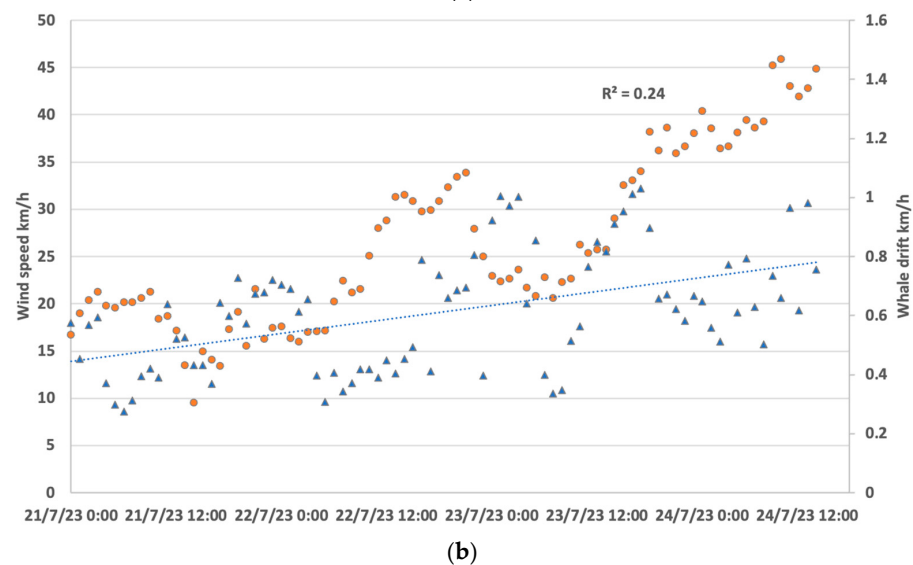
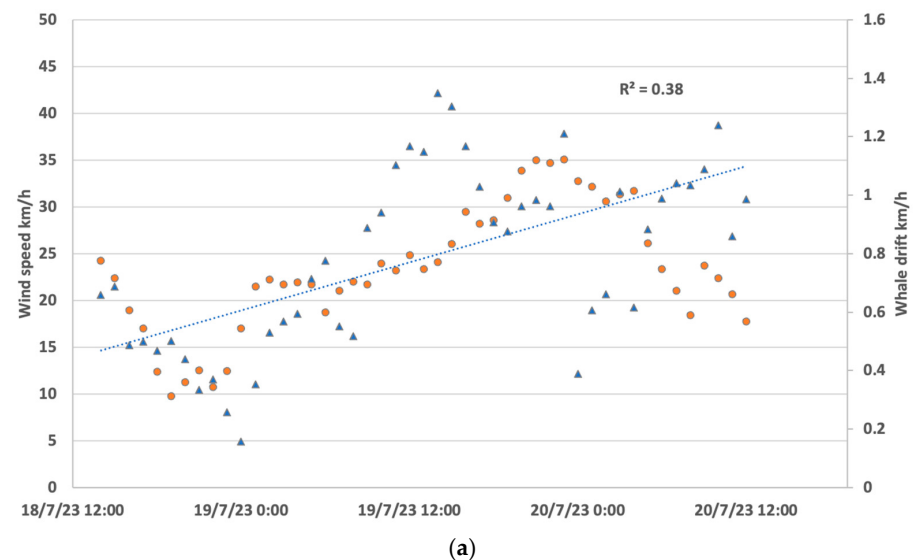


Figure A3. Relationship between wind speed (circle) and drift of whale (triangle) remains between 18–20 July 2023 (a) and 21–24 July (b).

Table A1. An overview of disposal strategies for whale carcasses.

Action	Benefits	Disadvantages/Difficulties	Most Feasible
Landfill	(1) reduced biohazard	(1) Costly (2) transportation, truck and excavator needed (3) road hazard (4) risk of handling for workers (5) unethical and culturally controversial	Public beaches that are accessible with landfill or holding facility in proximity
Rendering and composting	Turned into compost or biodiesel Reducing health hazards	(1) Costly (2) transportation, truck and excavator needed (3) road hazard (4) risk of handling for workers (5) culturally controversial	Public beaches that are accessible with landfill or holding facility in proximity
Burial on beach	(1) Nutrient enrichment for shore environment (2) reduction of biological hazard and smell	(1) Changes in groundwater quality (2) possible shark attraction to the surf zone (3) contamination from euthanasia (4) long decomposition time (5) earth moving equipment, cranes, trained operators required (6) risk for workers	Areas with foredunes, remote or less public beaches with access
Natural Decomposition	(1) Cost effective (2) decomposition through natural processes (insects, scavengers) (3) provision of food for beach organism and nutrient enrichment	(1) Changes in groundwater quality (2) unpleasant sight and smell (3) possible shark attraction to the surf zone (4) possible contamination from euthanasia (5) risk of biological contamination (6) possible refloating and washing up to a populated area	Remote areas, inaccessible locations and with smaller cetaceans
Towing out to sea	(1) Sustainable recycling nutrients at sea (2) food source for marine species in surface waters, and benthic environment (3) ethical sensible (4) potential carbon removal (5) reduced biohazard	(1) Can wash ashore again (2) expertise and knowledge required (3) suitable vessel and weather conditions needed (4) potential navigational hazard (5) unclear jurisdictional responsibilities (6) potential navigation hazard	Floating carcasses, calm weather conditions
Sinking	(1) Potential for carbon removal (2) nutrient enrichment and recycle to marine environment (3) reduced risk of navigational hazard (4) reduced biohazard	(1) Refloats (2) weights left at sea (3) expertise and knowledge required (4) less cost effective	Floating carcasses, calm weather conditions
Explosives	(1) Forced break down into smaller pieces (2) prevention of accidental, naturally occurring rupture	(1) Biohazard (2) safety hazard (3) risk of uncontrolled dispersion	Remote areas

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