6-2-2008

An Analysis of Dwarf and Pygmy Sperm Whale (Kogia sp.) Stranding Data in the Southeast United States

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By

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Submitted to the Faculty of
Nova Southeastern University Oceanographic Center
in partial fulfillment of the requirements
for the degree of Master of Science with a specialty in:

Marine Biology

Nova Southeastern University

June 2, 2008

Masters of Science:

Marine Biology

Thesis of

Nicole M. O'Brien

Submitted in Partial Fulfillment of the Requirements for the Degree of

Nova Southeastern University
Oceanographic Center

June 2008

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Abstract

Pygmy sperm whales (*Kogia breviceps*) and dwarf sperm whales (*Kogia sima*) strand frequently in the southeastern United States (SEUS). To detect seasonal trends in *Kogia* sp. strandings across the SEUS, all 979 stranding events from 1977 through 2005 were segregated by month. A peak in strandings occurred in the late summer and early fall (July – October). The entire SEUS was divided into segments of similar coastline orientation, 1) North and South Carolina, 2) Georgia and the east coast of Florida, 3) Florida Keys, 4) west coast of Florida, 5) Florida panhandle, Alabama and Mississippi, 6) Louisiana and 6) Texas. Most areas displayed a significant peak in strandings in summer and a smaller significant peak in winter. A seasonal index analysis of the strandings revealed the same pattern as the general seasonal analysis. Analysis of wind direction changes preceding stranding events revealed six patterns. The most common pattern was when winds shifted from downwelling-favorable to upwelling-favorable during the week prior to a stranding. Analysis of sea level confirmed that when wind was upwelling-favorable, sea level decreased and when wind was downwelling-favorable, sea level increased.

Seasonal upwelling along central Florida's Atlantic coast observed in the summer correlates with upwelling-favorable wind patterns during summer months, and increased *Kogia* sp. strandings. A smaller peak in strandings that occurs in the winter months appears to occur when there is a shift from the 'normal' downwelling-favorable conditions into a brief period of upwelling-favorable conditions. Along Florida's Atlantic coast, distances to isobaths from stranding sites were not significantly different from distances of randomly selected sites to isobaths; however, there is a tendency

towards shorter distances to isobaths. Along the Georgia, South Carolina and North Carolina coast, distances to isobaths from strandings sites are significantly different from distances of randomly selected sites to isobaths. The distinctive bathymetry of the SEUS Atlantic coast may contribute to strandings across the entire SEUS Atlantic coast. Analysis of the frequency of *Kogia* sp. strandings during the lunar cycle revealed no significant correlation between strandings and lunar day. Both wind direction and bathymetry may influence frontal structures and water movements, and thus abiotic environmental factors may be significant factors in determining the locations and timing of *Kogia* sp. stranding events.

Acknowledgements

I would like to thank my committee, Dr. Edward O. Keith, Dr. Daniel Odell, and Dr. Sean Kennan. Chiefly, thank you Dr. K. for giving me the opportunity to do this research and for believing that I was the right person to carry out the work. Your patience and diligence in assisting me is greatly appreciated. Thank you, Dr. Odell, for providing the verified stranding data that made all of this possible and for your helpful revisions and suggestions. And, thank you Dr. Kennan for your thoroughness in helping me to understand the physical oceanographic concepts that were central to my work. I would also like to thank a previous graduate student of the OC, Rebekah Walker Szivak for providing me with invaluable guidance in conducting my analyses. Financial support for this project came from the John H. Prescott Marine Mammal Rescue Assistance Program, Grant Number NA06NMF4391055, and from Nova Southeastern University.

I would like to thank the volunteers of the Southeast United States (SEUS) Marine Mammal Stranding Network for their time and invaluable data collection. I would also like to thank the coordinators who gave me permission to use the data. The groups who collected stranding data in the SEUS include: National Oceanic and Atmospheric Administration – National Marine Fisheries Service, Hubbs-SeaWorld Research Institute, Rosenstiel School of Marine and Atmospheric Sciences of the University of Miami, Florida Keys Marine Mammal Rescue Team, Marine Mammal Conservancy, Florida Fish and Wildlife Conservation Commission - Marine Mammal Pathobiology Laboratory, Institute for Marine Mammal Studies, Harbor Branch Oceanographic Institute, Clearwater Marine Aquarium, Dolphin Research Center, Marine Animal Rescue Society, Mote Marine Laboratory, Cape Hatteras National Seashore, The Charleston Museum, Cumberland Island Museum, Cape Lookout National Seashore, Padre Island National Seashore, Texas Parks and Wildlife Department, Louisiana Department of Wildlife & Fisheries, North Carolina Aquarium, Canaveral National Seashore, North Carolina Maritime Museum, Emerald Coast Wildlife Refuge, Virginia Aquarium & Marine Science Center, Collier County Natural Resources Department, University of North Carolina Wilmington, Wild Dolphin Project, Georgia Department of Natural Resources, Marine Animal Productions, Florida Department of Environmental Protection, Florida Marine Patrol, Florida Marine Mammal Stranding Network – Southwest Region, Florida's Gulfarium, The University of Texas at Austin, Marine Science Institute, Texas Marine Mammal Stranding Network, South Carolina Department of Natural Resources, Georgia Conservancy, National Museum of Natural History, Marineland Florida, South Carolina Marine Mammal Stranding Network, Louisiana Marine Mammal Stranding Network, and New England Aquarium.

Finally, I would like to thank my family and friends for supporting and encouraging me throughout this whole process. Especially my husband, Kevin, for endlessly motivating me when I was not on task. Despite his own tremendous workload in medical school, he always listened to my complaints and found ways to convince me it could be worse. Thank you Mom and Dad for your continued support and enthusiasm for my studies. I would not have made it this far without your encouragement.

This research is dedicated to Kokomo, the first stranded cetacean with whom I volunteered, who happened to be a pygmy sperm whale, and who sparked my interest in researching the possible contributory factors of cetacean strandings.

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1.1. Strandings

1.1.1. General Cetacean Strandings

Cetacean stranding events, including live and dead, mass or single, have been documented for over two millennia (Thompson 1910, Bryden 1999). Many theories have been proposed regarding the causes of cetacean strandings. Stranding behavior is thought to be related to acoustic interference, parasitic infections of the inner ear which prevent sonar location, anthropogenic noise, pollution, attempts to follow ancient migratory pathways which are now closed, disorientation due to complex bathymetry, wind driven on-shore currents, and even variations of the geomagnetic field (Bryden 1999). Geraci and Lounsbury (2005) suggest more possible causes for cetacean strandings – complex topographic and oceanographic conditions, contaminants, weather conditions, predators, natural toxins, following prey inshore, disease, social cohesion, human-related injuries. It may be that cetaceans follow their prey too close to the shore, and become beached. Pilot whales (*Globicephala* sp.) are a good example of this because they pursue squid inshore along Cape Cod, MA, and frequently strand there (Thurston 1995). Unfortunately, stomach content analysis often indicates that animals had not been eating before they strand. The causes of mass strandings are uncertain and controversial (Walker *et al.* 2005). Cetacean strandings can occur as either single animals, usually dead, or in groups, with both live and dead animals.

Location also seems to play a role in many instances of strandings. Areas such as Cape Cod, MA, and Sable Island and the Bay of Fundy, Nova Scotia, are known as "whale traps" (Thurston 1995). Tides in such places recede quickly and can strand animals on to the long, gentle slope of the beach. Additionally, changes in the circulation of Cape Cod Bay, driven by significant interannular variation in wind-forcing, affect cetacean zooplankton prey and thus cetacean distribution (Costa *et al.* 2006).

Toothed cetaceans use echolocation to identify objects in their path and likely use echolocation as a navigation tool. Sundaram *et al.* (2006) examined Cape Cod Bay and three bays in New Zealand, and using a simple two-dimensional ray-dynamics model of cetacean echolocation and found acoustical "dead zones" in all four areas examined. Interestingly, many of these predicted "dead zones" were highly correlated with observed stranding locations and also a gently sloping bathymetry. Other areas that the model predicted would be "dead zones" did not have any strandings, and Sundaram *et al.* (2006) suggest that this is because these areas are located near abrupt continental slopes and lack gently sloping bathymetry.

An analysis of strandings in Australia (1920-2002) found a clear 11-13 year periodicity in the number of events through time (Evans *et al.* 2005). These events were positively correlated with the regional persistence of both westerly and southerly winds, reflecting long-term and large-scale shifts in sea-level pressure gradients. Periods of sustained westerly and southerly winds in southern Australia result in colder and presumably nutrient-rich waters being driven closer to southern Australia, resulting in increased biological productivity during the spring. This study suggests that large-scale climatic events can provide a powerful distal influence on the tendency of whales to strand (Evans *et al.* 2005).

Wind stress on the surface of the ocean can force the movement of water masses in the upper hundred meters of the water column. The net direction of transport is 90 degrees to the right (left) of the wind in the northern (southern) hemisphere due to the effect of the Coriolis force. This transport of water is termed the Ekman Transport. Along-shore winds produce Ekman Transport since the mass of water moves perpendicular to the coast (Barber and Smith 1981). When the surface Ekman transport diverges from the coast, upwelling occurs, and when the surface Ekman transport converges with the coast, downwelling occurs (Brink 1991). During upwelling, nutrient rich subsurface water is brought to the surface and then flows horizontally away in a coherent surface flow.

Coastal upwelling is time carrying in that transport occurs after the wind has been blowing for a specific time and is space varying in that transport occurs at a specific place (Barber and Smith 1981). Conditions are either upwelling-favorable or downwelling-favorable depending on the direction of wind on the coast (Brink 1991). Major coastal upwelling occurs on the eastern boundary of oceans, where the wind is persistently favorable for continued coastal upwelling (Barber and Smith 1981). The southeast United States coast is on the western boundary of the Atlantic Ocean, and therefore is not dominated by coastal upwelling. However, isolated or seasonal upwelling events can occur dependng on the direction of wind forcing.

The Atlantic coast of central Florida is a region that has well-defined summer upwelling (Pitts and Smith 1997). When wind stress is from the southeast in this region, Ekman Transport in surface layers is seaward, favoring wind-forced upwelling in the mid-shelf. Upwelling-favorable winds may induce upwelling conditions offshore. Shanks *et al*. (2000) found that as the wind forcing relaxes following an upwelling event, the upwelling front moved inshore. This could be caused by either relaxed upwelling-favorable winds or a switch to downwelling-favorable winds. The Gulf Stream, the western boundary current in the Atlantic Ocean, begins with the Florida Current, which stretches from the Florida Straits up through Cape Hatteras (Gyory *et al.* 2001). When seasonal meanders of the Florida Current combine with seasonal shifts in wind forcing, upwelled water is forced to the inner shelf. Small-scale winter upwelling is driven by frontal eddies rather than upwelling-favorable winds and shifts in the Florida Current (Pitts and Smith 1997).

Cetacean strandings in the northwest United States may be highly dependent on physical oceanographic features that bring the carcass to shore (Norman *et al.* 2004). Currents and wind affect when and where an animal strands and animals may strand hundreds of kilometers from their normal range. Cetacean carcass distribution may be affected by upwelling and downwelling of water masses (Norman *et al.* 2004). Upwelling, nutrient rich waters are predicted to draw higher numbers of cetacean prey, and so the probability of cetaceans to strand during times of upwelling should increase (Bradshaw *et al*. 2006). Fronts, vertical circulation patterns, and eddy-like motions can be due to wind stress applied unevenly in space and time (Own 1981). In areas of wind-driven upwelling, phytoplankton form dense concentrations (Franks 1992), leading to higher fish and squid aggregation in these areas (Owen 1981; Mann and Lazier 2006). Prey abundance may explain the variation in cetacean sightings. The largest oceanographic fronts are associated with western boundary currents, such as the Gulf Stream. Shelf break fronts form due to upward mixing of cool, nutrient-rich water over the shelf, which can be caused by estuarine circulation, Gulf Stream meanders, and wind (Mann and Lazier 2006).

Coastal geometry and bottom topography may significantly affect the properties of the coastal water column. In west Florida, these factors force southward flow and a coastal jet (Yang *et al*. 1999). Bathymetry of an area may affect the incidence of cetacean strandings. Many strandings are associated with gently sloping beaches where the bottom topography may not reflect the approaching landmass (Mazzuca *et al*. 1999). Cetacean distributions were highly correlated with bottom depth and bathymetric depth gradient in the northeast Gulf of Mexico (Biggs *et al*. 2000). Strandings may occur if animals accidentally get trapped and subsequently grounded by the outgoing tide. Incidents like these occur frequently in areas with long meandering channels, broad tidal flats, strong or unusual currents, or extreme tidal flow or volume (Geraci and Lounsbury 2005). Given that many strandings occur where the bottom topography may not reflect the approaching landmass, it is evident that bathymetry may play an important role during a stranding.

Walker (2003) investigated seasonal factors affecting each reported mass stranding in Florida (76 events) from 1977 through 2001. The analysis found that there were peaks in strandings during the winter and spring on the east coast of Florida, and peaks during the summer and fall on the west coast of Florida and in the Florida Keys. Each peak correlates with upwelling favorable wind conditions on the respective coasts. Walker (2003) also suggested that seasonal variations in wind speed and direction may create frontal convergences in the ocean that are followed by cetaceans. A switch from upwelling- to downwelling-favorable winds may draw the prey, and the cetaceans, close to shore. Then, as the front dissipates in the shallow water, subsequent lack of food, heavy physiologic parasite loads, and/or other factors then may debilitate the animals, leaving them at the mercy of the tides and water movements (Walker 2003, Walker *et al.* 2005). Walker (2003) suggested that strong social cohesion is important, such that when a single animal comes ashore, others in the group are likely to follow (Perrin and Geraci 2002) and also suggested that prevailing winds and deep water close to shore are important factors in the initial stages of a stranding.

1.1.2. Kogia sp. Strandings

Pygmy sperm whales (*Kogia breviceps*) are the second most frequently stranded cetacean in the southeast United States, the fourth most frequently stranded in the Hawaiian Islands, the third most commonly recorded stranded cetacean in the southwest Gulf of Mexico and are also the most frequently recorded stranded cetacean in New Zealand (Baird *et al.* 1996, Ortega-Argueta *et al.* 2005). Historical stranding records (1883-1988) of *Kogia* sp. in the southeastern United States, and subsequent records from 1988-1997, indicate that pygmy sperm whales account for about 83% of the *Kogia* sp. strandings, while dwarf sperm whales (*K. sima* or *simus*) account for the remaining 17% (Waring *et al.* 2005). Males outnumbered females for *K. breviceps*, whereas there were twice as many female *K. sima* as males (Odell *et al.* 2004). Mass strandings of *Kogia* sp. are rare; nearly all recorded *Kogia* sp. strandings are of single animals or of cow/calf pairs, which are typically counted as one stranding (Baird *et al.* 1996). Free-ranging pygmy sperm whales occur individually or in groups of up to six and dwarf sperm whales occur in groups of up to ten animals (Caldwell and Caldwell 1989). Social groupings are typically small and thus social cohesion may not be an important factor in *Kogia* sp. strandings. Winds, currents, tides, magnetic fields, and lunar cycles may differentially influence the probability of Kogia strandings. A large dataset of strandings maintained by the Marine Mammal Health and Stranding Response Program and long-term physical oceanographic data provide a unique opportunity to examine the correlations of *Kogia* sp. strandings with physical oceanographic parameters.

1.2. The Genus Kogia

The pygmy sperm whale and the dwarf sperm whale are distributed worldwide in temperate to tropical waters (Caldwell and Caldwell 1989, McApline 2002, Bloodworth and Odell in press). These closely related and morphologically similar species are commonly confused by scientists and wildlife officers because they live in deep water usually far from shore, may dive for long periods, typically show a low profile at the surface, rarely engage in aerial or surface-active behavior, and tend to avoid vessels (Baird 2005).

Prior to 1966, most scientists only recognized one species within the genus *Kogia* (Handley 1966). This makes it difficult to distinguish which species is actually referred to in early publications. Both species are small (< 3.8 m), and have a small, underslung lower jaw (Baird *et al.* 1996). Comparatively, *K. breviceps* is larger in both total body length and weight, has a smaller caudally located dorsal fin, maxillary teeth are rare, and more mandibular teeth than *K. sima* (Chivers *et al.* 2005). Barros and Duffield (2003) present a dichotomous key for the identification of the two species from the morphometrics of stranded adult animals and Baird *et al.* (1996) present a table of distinguishing characteristics.

Electrospray Ionization Mass Spectrometry (ESI MS), a technique used to obtain the molecular weight of intact biological molecules, has been successfully used to differentiate between the *Kogia* species. Duffield *et al.* (2003) distinguished the two species using ESI MS for myoglobin and hemoglobin alpha-chain. The results did not vary with geographical source of the tissue. This process is proposed as a revolutionary technique to rapidly and effortlessly identify *Kogia* sp., in contrast to using external morphology, which can be extremely subjective. High-quality tissue must be obtained from specimens for this type of identification, and a laboratory with proper equipment is necessary, so in some cases where tissue quality has been compromised or a laboratory is not available, visual identification using morphology is used.

1.2.1. Distribution and Abundance

Although *Kogia* sp. are among the most commonly stranded cetaceans in some parts of the world, both species are considered rare, primarily due to their offshore distribution (Cardona-Maldonado and Mignucci-Giannoni 1999). In addition to being morphologically distinctive, biological data indicate that the two *Kogia* species occupy different ecological niches. Patterns of distribution inferred from stranding records and at-sea sightings suggest that both species occupy all ocean basins, with *K. sima* found predominantly in tropical waters, and *K. breviceps* inhabiting both tropical and temperate waters (Chivers *et al.* 2005). Barros *et al.* (1998) speculated that dwarf sperm whales may have a more pelagic distribution than pygmy sperm whales, and/or dive deeper during feeding bouts. In the western North Atlantic and the Gulf of Mexico dwarf and pygmy sperm whales occur primarily along the continental shelf edge and over deeper waters off the shelf (Hansen *et al.*1994, Mullin *et al.* 1991). In the Gulf of Mexico *Kogia* sp. were sighted more frequently in waters 400-600 m in depth (Mullin *et al.* 1994) over the upper continental slope with high zooplankton biomass (Baumgartner *et al.* 2001).

Both species are also known from the Caribbean Sea, and occur throughout the year (Cardona-Maldonado and Mignucci-Giannoni 1999).

The best available abundance estimate for *Kogia* sp. is 395 (CV = 0.40) in the western North Atlantic (Waring *et al.* 2007) and 453 (CV = 0.35) for 2003 – 2004 in the northern Gulf of Mexico (Waring *et al.* 2007). The minimum population estimate for *Kogia* sp. is 285 in the western North Atlantic and 340 in the northern Gulf of Mexico (Waring *et al.* 2007). Potential Biological Removal (PBR) is calculated as the product of minimum population size, one-half the maximum productivity rate, and a "recovery" factor (Wade and Angliss 1997). The PBR for *Kogia* sp. in the western North Atlantic is 2.0 and 3.4 in the northern Gulf of Mexico (Waring *et al*. 2007).

1.2.2. Dietary Habits

In common with the other member of the superfamily Physeteroidea, dwarf and pygmy sperm whales consume primarily oceanic cephalopods, with fish and other organisms such as crustaceans being represented infrequently (Table 1) (Santos *et al.* 2006). Due to the difficulties in studying the diets of cephalopod-eating whales, virtually all that is known about the diet of *Kogia* sp. is gathered from stranded individuals (Beaston 2007). Epi-, meso- and bathypelagic prey have been identified from the stomach contents of stranded individuals from both species, and differences in prey composition suggest partitioning of their preferred habitats at sea (Chivers *et al.* 2005).

In 13/14 specimens of *K. breviceps* stranded in the northeast Atlantic, food remains in the stomach consisted almost entirely of cephalopod beaks, with some crustacean and fish remains being present (Santos *et al.* 2006). In an analysis of the stomach contents of 27 *K. breviceps* that stranded in New Zealand, cephalopod beaks from 23 species in 13 families were recorded (Beatson 2007). Cephalopods constituted 94% of the prey remains, while crustaceans and fish each constituted 3% (Beatson 2007). Pygmy and dwarf sperm whales stranded in Brazil had both consumed offshore cephalopods, with no particular differences in the family composition of cephalopods found in the stomachs of the two specimens (Augiar dos Santos and Haimovici 2001).

Based on bathymetric distribution of critical prey species, *K. breviceps* is thought to feed as a juvenile to at least 500 m and as an adult from 650-1100 m (Beaston 2007). The small underslung lower jaw and the flattened snout suggest that *Kogia* may feed at or near the bottom at least some of the time (Caldwell and Caldwell 1989). However, the majority of species recorded from the diet are vertical migrators, and *K. breviceps* may feed primarily at night when prey are closest to the surface (Beaston 2007).

Stranded *Kogia* sp. have also been found to have consumed oceanic debris, especially plastics, and this may occasionally contribute to mortality and strandings. A young male *K. breviceps* stranded alive on Galveston Island, TX, and was transported to a rehabilitation facility where he subsequently died. Upon necropsy the first two stomach compartments (forestomach and fundic chamber) were completely occluded by a plastic garbage can liner, a bread wrapper, a corn chip bag, and two pieces of plastic sheeting (Tarpley and Marwitz 1993). Stranded *Kogia* sp. in Florida have likewise been found to have ingested plastic debris (Barros *et al.* 1989) and the seaweed *Sargassum* (Raun *et al.* 1970).

1.3. Lunar Cycles and Cetaceans

Published literature addressing the influence of lunar cycles on cetacean strandings is lacking. One paper suggesting a link between cetacean strandings and the moon deals with a mass stranding of sperm whales in Mexico in 1978 (Anon. 1979). This article suggested that the cause of the stranding was related to the whales following squid, which are known to come into shallow waters in the dark of the moon. This could be significant because *Kogia* sp. are known to consume squid as prey (Barros and Duffield 2003, Cardona-Maldonado and Mignucci-Giannoni 1999). Another study of sperm whales (Whitehead 1996) examined the effect of lunar cycles on feeding success, as defined by defecation rate, for three environmental cycles: lunar, diurnal and tidal. Whitehead determined that there was no significant variation in the defecation rate during the lunar cycle. The only study documenting the lunar cycle having a direct effect on marine mammals does not involve cetaceans, but Galapagos fur seals (*Arctocephalus galapagoensis*) (Trillmich and Mohren 1981). This study showed that nocturnal hauling out behavior by these seals peaked around the time of the full moon.

Other marine animals such as zooplankton are known to have abundance patterns influenced by lunar cycles (Gliwicz 1986). For reasons that are not clear, *Kogia* sp. have been found to congregate in regions of high zooplankton biomass over the upper continental slope in the Gulf of Mexico (Baumgarter *et al*. 2001). In addition, some marine species, including certain reef fish, have reproductive cycles linked to the moon (Robertson *et al*. 1990). The occurrence of invertebrates displayed synchrony with tidal and lunar cycles in Japan (Saigusa *et al*. 2003), and the faunal assemblage of an intertidal salt marsh creek in the Netherlands also displayed tidal, diel, and semi-lunar cycles (Hampel *et al*. 2003). If the prey of *Kogia* sp. are affected by lunar cycles, it may be that *Kogia* strandings are linked to lunar cycles.

Cephalopods	**Fish**	**Crustaceans**
Abralia sp.	*Chauliodus sloani*	*Aristaemorpha folicea*
Abraliopsis sp.	*Lampanyctus* sp.	*Carcinides maenas*
Ancistrocheirus sp.	*Maurolicus muelleri*	*Gnathophausia ingens*
Brachioteuthis riseii	*Photichthys argenteus*	*Gnathophausia* sp.
Chiroteuthis veranii	*Pyrosoma* sp.	*Goneplex angulata*
Galiteuthis sp.	*Rexea solandri*	*Hymenodora* sp.
Histioteuthis reversa	*Scopelopsis multipunctatus*	*Pandalopsis* sp.
H. bonnelli	*Symbolophorus* sp.	*Pandalus* sp.
H. miranda	Triglidae	*Pasiphaea pacifica*
H. sp.		*Penaeus californiensis*
Loligo forbesi		*Polybius henslowi*
L. vulgaris		
Lycoteuthis diadema		
Moroteuthis sp.		
Octopoteuthis sp.		
Ommastrephes sp.		
Onychoteuthis boreali-japonicus		
Phasmatopsis sp.		
Pygrpsis sp.		
Pyroteuthis sp.		
Rossia macrosoma		
Sepioteuthis australis		
Taningia sp.		
Taomius pavo		
Teuthowenia pellucida		
Todarodes sagittatus		
Todarodes sp.		
Vampyroteuthis sp.		

Table 1. Prey items found in stomachs of stranded *Kogia* sp. Table compiled from Cardona-Maldonado and Mignucci-Giannoni 1999, Santos *et al*. 2006, Augiar dos Santos and Haimovici 2001, Beatson 2007, Hale 1947, Raun *et al*. 1970, Ross 1979, Eliason and Houck 1986, Klages *et al*. 1989, Allen 1941, Scheffer and Slipp 1948, Vidal *et al*. 1987.

2. Methods

2.1. Stranding Data

Data from each reported *Kogia* sp. stranding along the SEUS coastline from 1977 through 2005 were collected by employees and volunteers from the SEUS Marine

Mammal Stranding Network. The SEUS coastline includes North Carolina, South Carolina, Georgia, Florida, Alabama, Mississippi, Louisiana, Texas, Puerto Rico and the U.S. Virgin Islands. All events were verified prior to this analysis under a previous John H. Prescott Grant to Daniel K. Odell, Grant # NA1FX2006. Visual representation of the stranding data using ESRI© ArcView (ESRI, Redlands, CA, USA) was also provided. All investigators and/or agencies responsible for collecting the data were contacted and permission received to use all information contained in the SEUS database. The nine strandings reported from Puerto Rico and the U.S. Virgin Islands were excluded from all analyses.

2.2. Seasonal Analysis

Stranding events were analyzed for seasonal trends. The stranding events were divided into months and seasons to explore related trends. Three month moving averages were used to smooth the data and facilitate the analysis (Spiegel and Stephens 1999). Single sample t-tests were conducted on each month to determine whether any month significantly differed from the mean of all months in the year. Significance for the t-tests was set at the alpha < 0.05 level. Due to the physical and oceanographic natures of the coastline within the Southeast Region, the Region was divided into segments of similar coastline orientation, for example 1) the Carolina coast, 2) the Georgia and eastern Florida coast, 3) the Florida Keys, 4) The west coast of Florida, 5) the panhandle of Florida and the southern coasts of Alabama and Mississippi, 6) The Louisiana coast, and 7) the coast of Texas. Single sample t-tests and an ANOVA were then run on each location to determine whether certain months at a location differed from the monthly average for that location. Significance was set at the alpha < 0.05 level.

A seasonal index was calculated for each separate analysis of the data. A seasonal index estimates how the data vary from month to month throughout a typical year (Spiegel and Stephens 1999). Each season was analyzed for each year through the entire dataset and then averaged for all years (1977-2005 inclusive). The average-percentage method was used, by which the data for each season are expressed as a percentage of the average for the year (Spiegel and Stephen 1999). The percentages for corresponding seasons of each year were then averaged to give the seasonal index number. An ANOVA was run on the index, as well as single sample t-tests for each season versus an expected value of 100. Significance for the t-tests and ANOVA was set at the alpha < 0.05 level.

2.3. Wind Analysis

When coastlines are straight, across-shelf transport caused by alongshore winds can cause upwelling- or downwelling-favorable conditions (Brooks and Mooers 1977, Lentz 2001). However, complex coastlines do not necessarily respond to wind forcing in a two-dimensional way. Because a majority of the *Kogia* sp. strandings occur where coastlines typically are oriented in a north-south direction (Figure 1), analysis of the influences of wind were focused on this area within the Southeast Region – North Carolina, South Carolina, Georgia, and eastern Florida. North Carolina and South Carolina strandings were grouped together, and Georgia and eastern Florida strandings were grouped together. Stranding events were analyzed for wind trends. Hourly wind data – direction and speed – were obtained from NOAA National Data Buoy Center (NDBC) buoys (http://www.ndbc.noaa.gov/hmd.shtml) and analyzed relative to the *Kogia* sp. strandings.

Upon recovery, a stranded cetacean is examined and the body condition is given a code on a scale of 1 to 5, where Code 1 is alive, Code 2 is fresh dead, Code 3 is moderate decomposition, Code 4 is advanced decomposition, and Code 5 is mummified/skeletal. Strandings that were classified as Code 4 or higher, or that were not given a code, were excluded from analysis as they had been dead for an unknown period of time and thus may have drifted from other locations. Strandings were further chosen for analysis if they were in proximity (< 50 km) of a buoy that transmitted wind data during the month prior to the stranding. Strandings were eliminated from analysis if the corresponding buoy received more than six hours of error readings in any 24-hour period during the month prior to the stranding. Wind patterns were analyzed for 151 strandings.

The wind intensity in a North-South and East-West direction for each day during the month prior to each stranding was determined. The wind direction (A, in degrees clockwise from North) and wind speed (S, in m/s) were averaged for each day in the month prior to the stranding event. Average daily wind direction, was converted to a right handed coordinate system (that is, clockwise from due east) (Arfken 1985). Wind intensity in a North-South and East-West direction for each day was calculated as follows:

$$u = S\cos(A')$$
$$v = S\sin(A')$$

where A' is A in radians, u is the wind intensity in a North-South direction, and v is the wind intensity in a East-West direction.

The orientation of the coastline was measured in degrees for each buoy location, using a Cartesian coordinate system (that is, counterclockwise from due east). The wind vectors were then transformed into the rotated coordinate system orientated with the coastline – i.e. a local coordinate system with the x-axis in the alongshore direction, and the y-axis across shore:

$$u' = u \cos(\theta) + v \sin(\theta)$$
$$v' = -u \sin(\theta) + v \cos(\theta)$$

where (u,v) are the east and north wind components, u',v' are the alongshore and cross-shore wind components, and theta is the angle of the coastline. Note that $u' > 0$ ($u' < 0$) means the alongshore wind component is to the right (left) facing the shore, and $v' > 0$ ($v' < 0$) means the cross-shore component is onshore (offshore). Thus, a perfectly north-south coastline with land to the west and ocean to the east has easterlies $u' > 0$ and southerlies $v' > 0$.

The averaged daily wind speed alongshore and across-shore were plotted for the fourteen days preceding each stranding event and analyzed for common wind situations. Winds were categorized as either upwelling-favorable or downwelling-favorable, with upwelling-favorable representing wind direction that could potentially cause movement of water away from the coast, and upwelling-favorable representing wind direction that could potentially cause movement of water towards the coast. For the wind patterns that emerged, one-sample Chi-Square (χ^2) analyses were conducted. A χ^2 was conducted for each region (North Carolina – South Carolina and Georgia – eastern Florida) and for both regions combined. To determine the upwelling and downwelling season along the SEUS Atlantic coast, alongshore and across shore wind velocities were computed for each buoy analyzed. Averages for each month during the entire time the buoy was collecting data were calculated and plotted using Excel.

Sea level data were also examined to determine whether the coastal waters were responding to the wind conditions. The sea level data must be correlated with local winds to determine which fluctuations were due to wind driven circulation and which were due to coastal trapped waves (Brink 1991). Daily sea level data (in millimeters, pre-corrected for tidal fluctuations) were obtained from NOAA's National Oceanographic Data Center (NODC) and analyzed (http://www.nodc.noaa.gov/General /sealevel.html). Hourly atmospheric pressure data were also collected from the NDBC to correct the sea level for atmospheric pressure changes. The atmospheric correction was applied to the sea level, and the sea level was subsequently plotted for the fourteen days prior to each stranding event. The wind intensity plots were compared with the sea level plots to determine if and how the sea level was responding to the wind forcing. Correlation between wind intensity and sea level was calculated by combining all the pairs of wind and sea level data for each wind buoy and sea level station. Mean sea level at each station was subtracted out and all wind/sea level pairs were combined into one correlation. Regression analyses were conducted on each wind buoy/sea level station and on all combined. Significance for the regression was set at alpha < 0.05.

2.4. Bathymetry Analysis

The distance from each *Kogia* sp. stranding site to the 10 m, 20 m, and 50 m isobath for each stranding event was determined. For stranding sites located on islands or keys, a straight-line distance from the site to each isobath was measured, bisecting the island if necessary, to obtain the shortest distance to a set isobath.. The measurements were made using MapTech® Chart Navigator and Contour Professional and Maptech® Chart Navigator Professional (MapTech Inc., Amesbury, MA, USA). The overall slope of the sea floor from the stranding site to each isobath was also calculated using the isobath depth and the distance to shore. This analysis was divided into two regions –

Chart Navigator and Contour Pro was used for the analysis of the Atlantic coast of Florida, and Chart Navigator Professional was used for the analysis of Georgia, South Carolina and North Carolina. Results are reported for each grouping individually and for all areas combined. Frequency distributions were graphed for each region for the distance from the strandings sites to each isobath and for the slope from the stranding sites to each isobath, and a normal curve was added to each distribution. The normal curve was generated by calculating the mean and standard deviation of the data, and is symmetric about the mean using standard deviations to generate the curve.

The null hypothesis for this analysis is that if the bathymetry or slope of sea floor were unimportant, the distances from each stranding site to set isobaths would show a normal distribution. If, however, there is a tendency towards either longer distances or shorter distances to isobaths, the bathymetry of an area can be assumed to be important. The data were tested for normality, and a test for skewness was performed. Each isobath was tested separately, once as a measured distance to the isobath and a second time as the calculated slope of the sea floor. To ensure that Southeast Region coastlines themselves are not skewed, a number of random points were chosen along the coast and measured to the 10 m, 20 m and 50 m isobath to compare with stranding data. After these isobath measurements were made, a Wilcox signed rank test (non-parametric equivalent of paired t-test) was performed on each set of isobath data (Green and Salkind 2005).

2.5. Lunar Cycle Analysis

If the presence of *Kogia* sp. prey in Florida and the southeastern United States cycles with the phase of the moon, it may be that some species of prey are abundant during a new moon, while other species may be abundant during a full moon. *Kogia* sp.

specializing on these different prey assemblages would be more likely to strand during phases of the moon corresponding to the abundance of their preferred prey items. In this analysis, the original dataset of strandings was utilized. Strandings were excluded if the body condition was Code 3 or higher or unreported because of the uncertainty of the time of death and strandings reported as cow/calf pairs were treated as one stranding to eliminate bias, leaving 568 strandings for this analysis. The lunar day was determined for each stranding, with day 0 being the new moon and day 14.75 being full moon. Spearman rank tests were conducted to examine the correlation between lunar cycles and *Kogia* sp. stranding events during the lunar cycle.

3. Results

Figure 1 shows the distribution of all 979 *Kogia* sp. strandings in the SEUS (excluding Puerto Rico and the U.S. Virgin Islands) between 1977 and 2005. Most strandings occurred along the coasts of North and South Carolina, Georgia, and the east coast of Florida. Figure 2 shows the number of strandings each year in the SEUS from 1977 through 2005. A mean of 33.8 animals stranded each year (SD = 13.27). More animals stranded along the Atlantic coast (n = 812) than the Gulf Coast (n = 167). Forty-nine percent (n = 477) of the animals were male, thirty-six percent (n = 357) were female, and the remaining fifteen percent (n = 145) were not sexed. Seventy-five percent (n = 731) of the total strandings were *K. breviceps*, while eighteen percent (n = 180) were *K. sima*, and the remaining seven percent (n = 68) were not identified to species level. For the purposes of this analysis, all three designations are included as one taxon. Fifty-five percent (n = 583) of the stranded *Kogia* sp. were first observed alive. Eighty-four percent (n = 823) of the *Kogia* sp. stranded alone, and of the remaining sixteen percent, most were mother-calf pairs. For the purposes of this analysis, mother-calf pairs were considered as one stranding event.

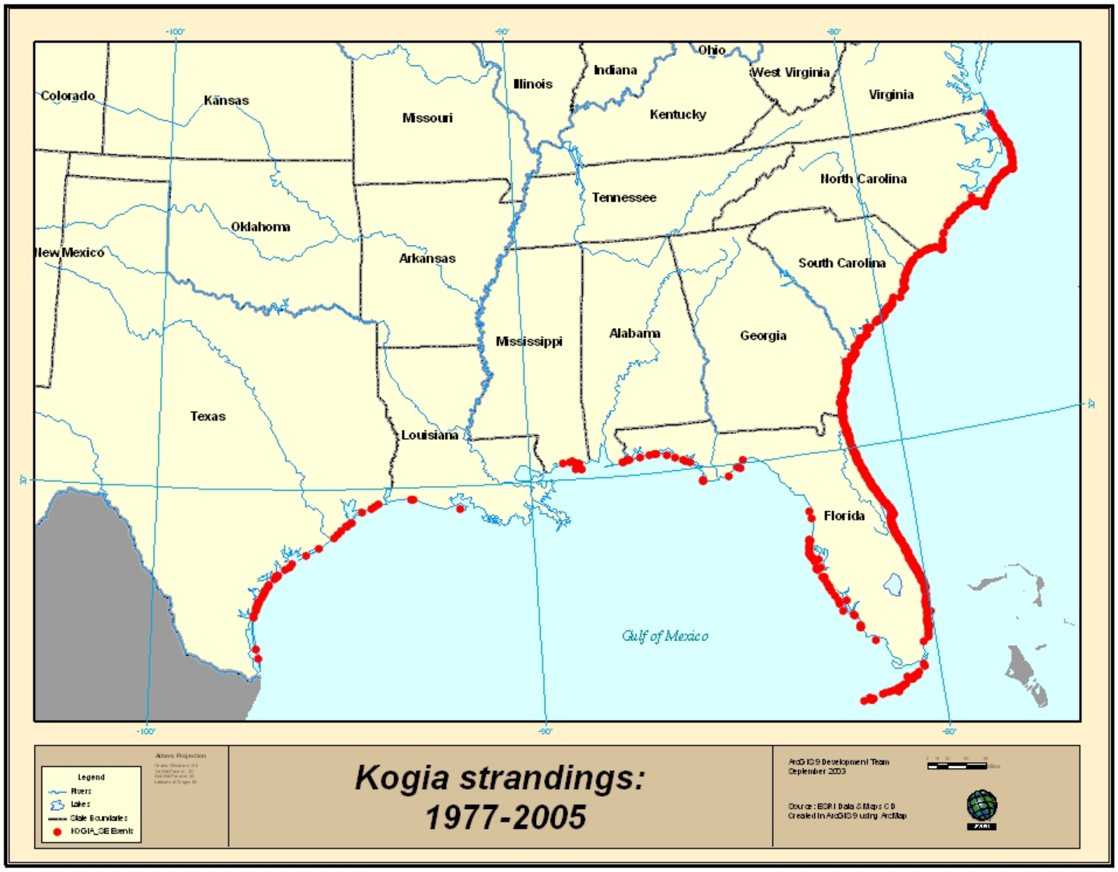


Figure 1: Distribution of *Kogia* sp. stranding events in the SEUS from 1977-2005. Most strandings occurred on the east coast of Florida, Georgia, and the Carolinas. Map courtesy of Daniel K. Odell.

3.1. Seasonal Analysis

In an attempt to detect seasonal trends in *Kogia* sp. strandings across the entire southeast region, all stranding events were segregated by month and plotted (Figure 3). This analysis suggested that there is a peak in *Kogia* sp. strandings across the region in the late summer and early fall (Jul – Oct). The winter month of March, and summer months of July, August, and September were significantly higher than the mean for all months. The spring months of May and June and fall months of November and

December were significantly low. Segregating the entire data set by season, where Winter is the months of January through March, Spring is April through June, Summer is July through September, and Fall is October through December, Figure 4 shows a peak in strandings in the summer, and another smaller peak in the winter.

In an attempt to determine if this seasonal trend would vary by state within the southeast region, the strandings were segregated by state and then plotted versus month (Figure 5). As is evident, the majority of the *Kogia* sp. strandings occurred in Florida, and there does appear to be a similar peak in *Kogia* sp strandings in Florida during the late summer and fall. However, North Carolina does not appear to conform to this trend, with a peak in strandings in April and May.

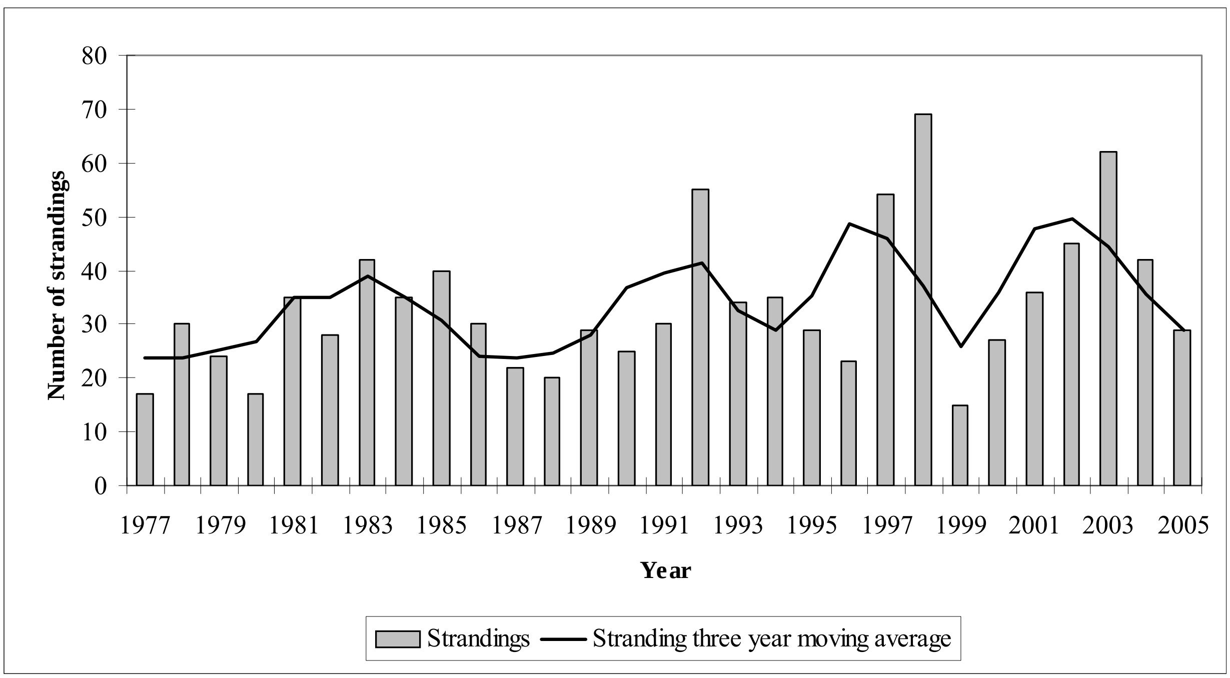


Figure 2: Frequency of dwarf and pygmy sperm whale strandings in the SEUS each year with three year moving average, from 1977 – 2005 inclusive.

Due to the physical and oceanographic natures of the coastline, the Southeast Region was divided into segments of similar coastline orientation as described above.

Figure 6 displays the seasonal breakdown of *Kogia* sp. strandings by region. Most segments maintained the pattern seen across the region, with a peak in strandings in the winter and summer, with the exception of Texas, with a peak in the fall. In most regions with the winter and summer peaks, the summer peak is greater than the winter peak, e.g. Georgia and Eastern Florida and the Carolinas. In contrast, the winter peak in strandings in the Florida Keys was greater than the summer peak.

An ANOVA test did not show significance between the locations as separate samples; however, once again single sample t-tests of each region showed differences between certain months and the mean of all the months. A summer peak in strandings was indicated in most regions. The Carolinas had a significantly higher number of strandings in February, August and September, and a significantly lower number in May, June and October. Georgia and east Florida had a significantly higher number of strandings in March, August, July, September, and October and a significantly lower number in February, April, November and December. The Florida Keys had a significantly higher number of strandings in February, March, July and September, and a significantly lower number in January, May, August, November, and December. The west coast of Florida had a significantly higher number of strandings in January, August, and September, but the months of April, May, June, July, October, and November were all lower. The Florida panhandle and Mississippi had a significantly higher number of strandings in August, September and December, but the months of April, June, July, October, and November were lower. The Texas coast had a significantly higher number of strandings in October and November only, with January, April, and May being lower.

The fall peak in Texas is illustrated by the significance of the t-test during the months of October and November in that region.

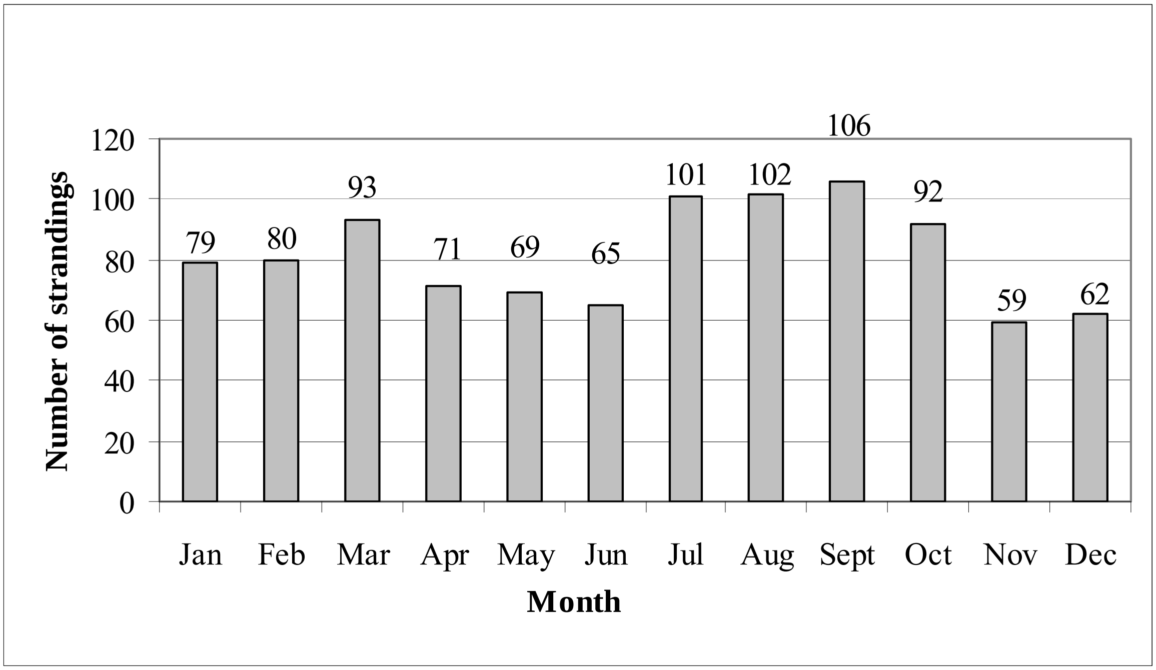


Figure 3: Total *Kogia* sp. strandings during each month for the SEUS, from 1977 – 2005.

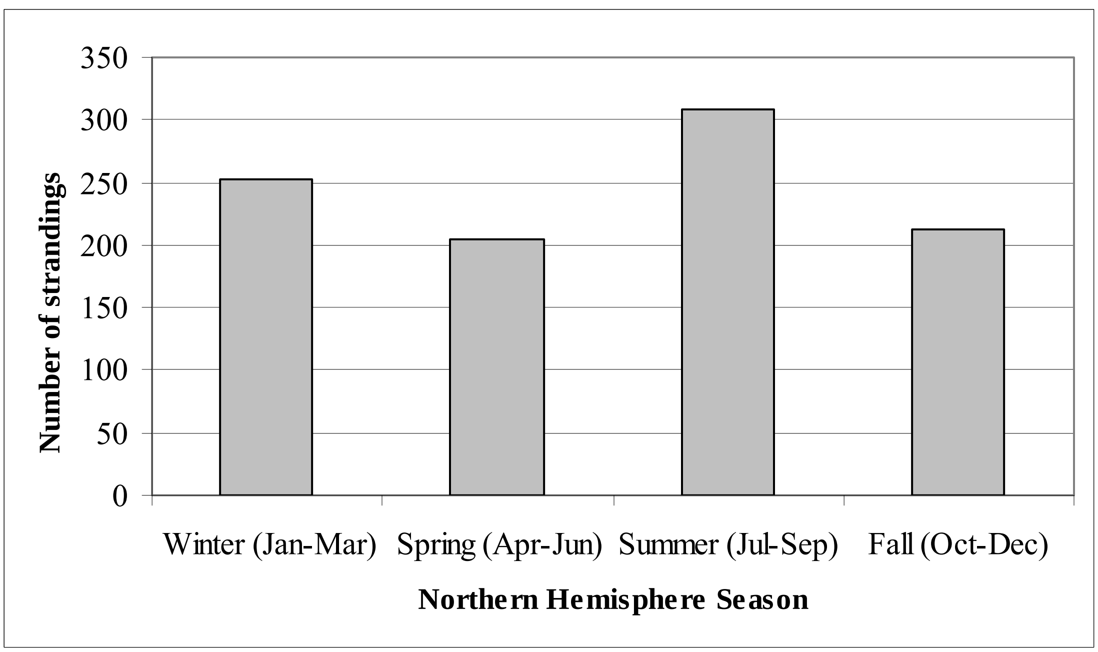


Figure 4: Histogram of all *Kogia* sp. strandings from 1977 – 2005 showing peaks in the summer and winter.

The seasonal index run on the data illustrate the same patterns found in the general seasonal analysis (Figures 7 and 8). If no seasonality existed, the index for each season should be 100. The Carolinas, Georgia & eastern Florida, and western Florida all have bimodal peaks with an index of over 100 – winter and summer. The bimodal peak in strandings in most regions is seen with winter having the smaller peak and summer having the larger peak. Interestingly, the Florida Keys show a relatively even distribution around the expected value of 100, with values of just over 100 occurring during the summer and fall. This contradicts the peak in strandings seen in the Keys during the winter but supports the smaller peak in strandings seen in the summer. The Florida panhandle and Texas have a seasonal index of over 100 only during the summer and fall, respectively.

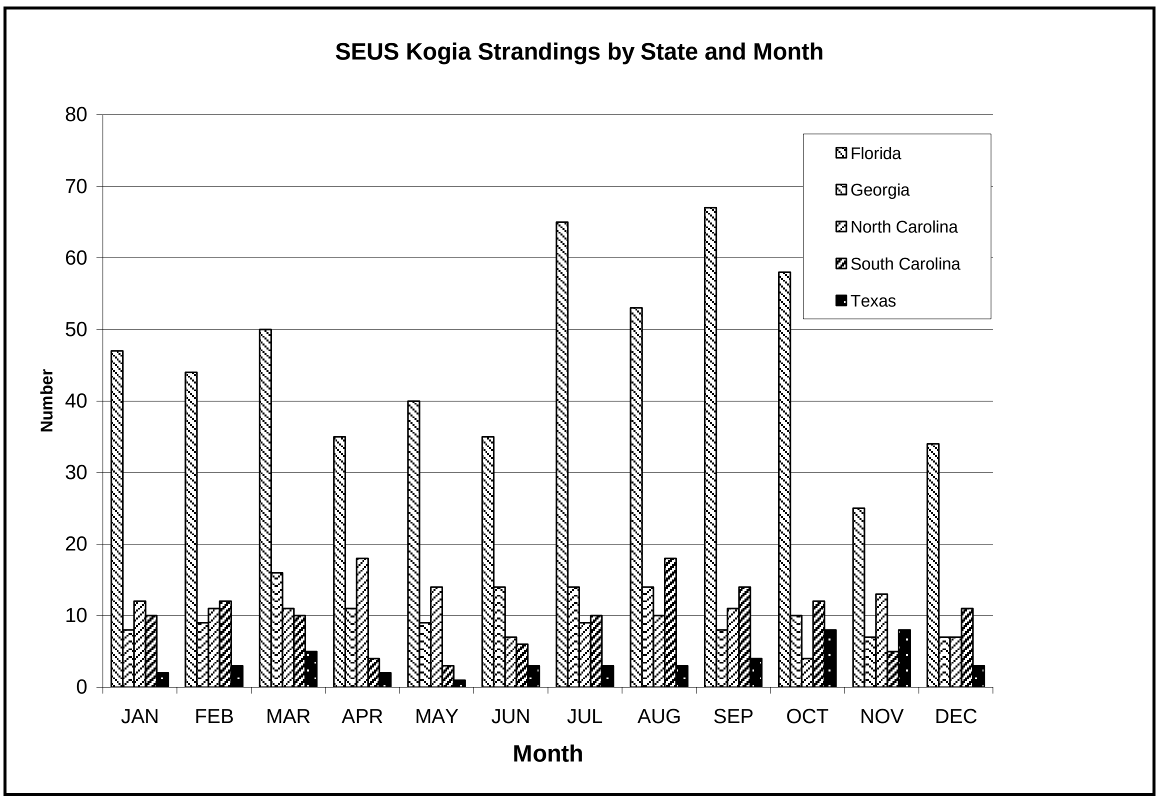


Figure 5: Frequency of *Kogia* sp. strandings during a calendar year, for 1977 – 2005 inclusive.

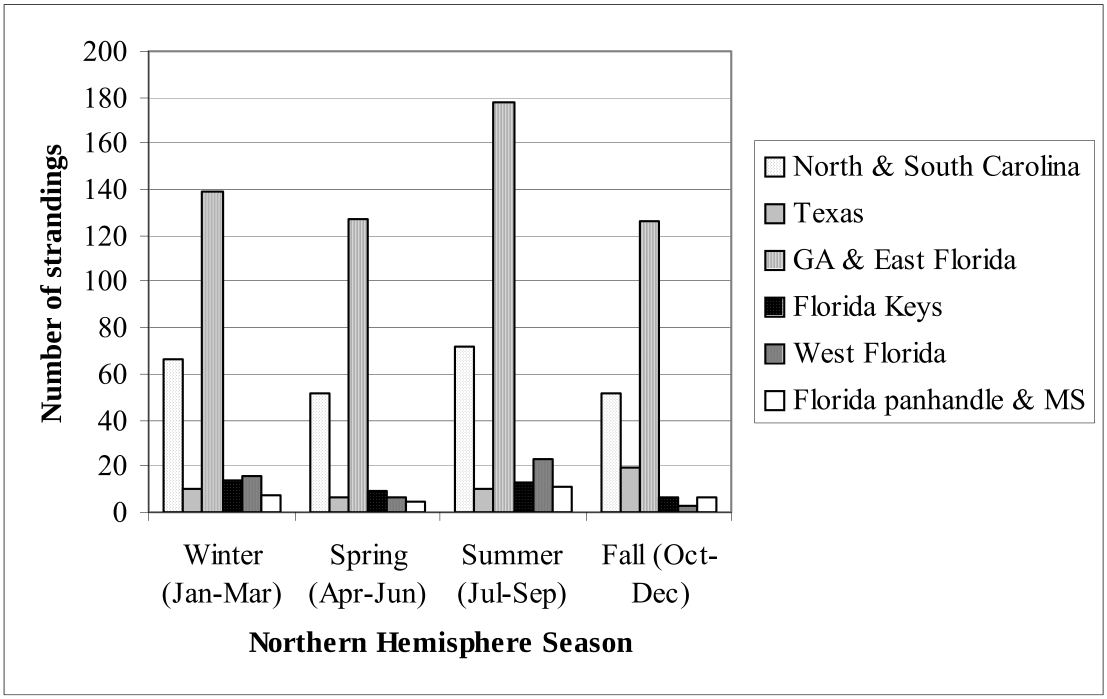


Figure 6: Frequency of *Kogia* sp. strandings from 1977 – 2005 segregated by region and season. Most regions had peaks in strandings in the winter and summer, with the summer peak being greater than the winter peak. Exceptions to this trend included the Florida Keys, with the winter peak being greater than the summer peak, and Texas, where the peak in strandings occurred in the fall.

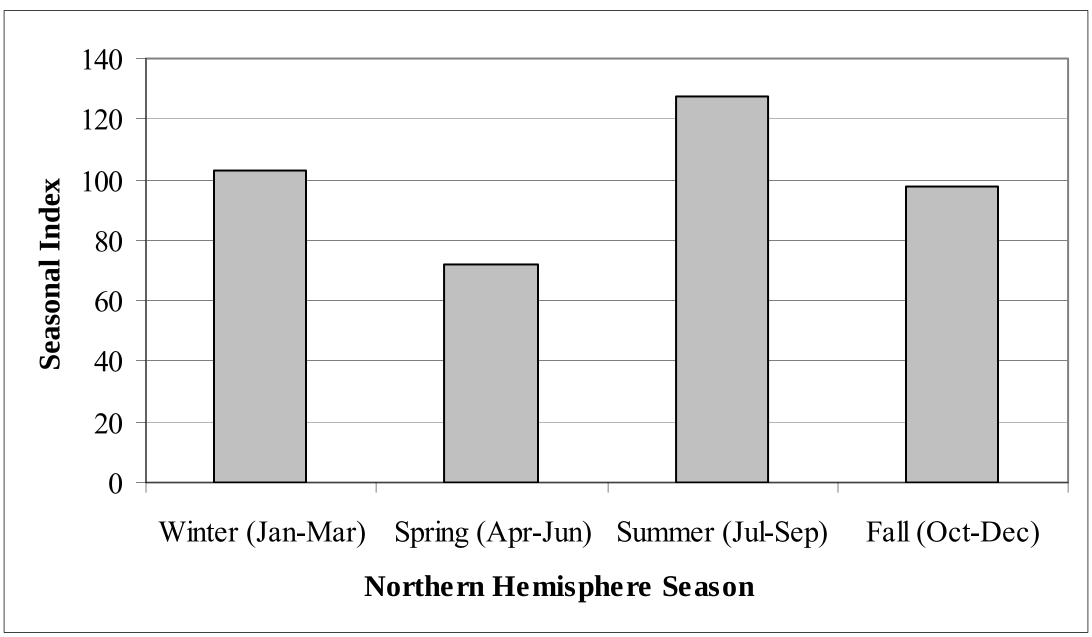


Figure 7: Seasonal index for *Kogia* sp. strandings from 1977 – 2005. Even distribution would show a frequency of 100 for each season.

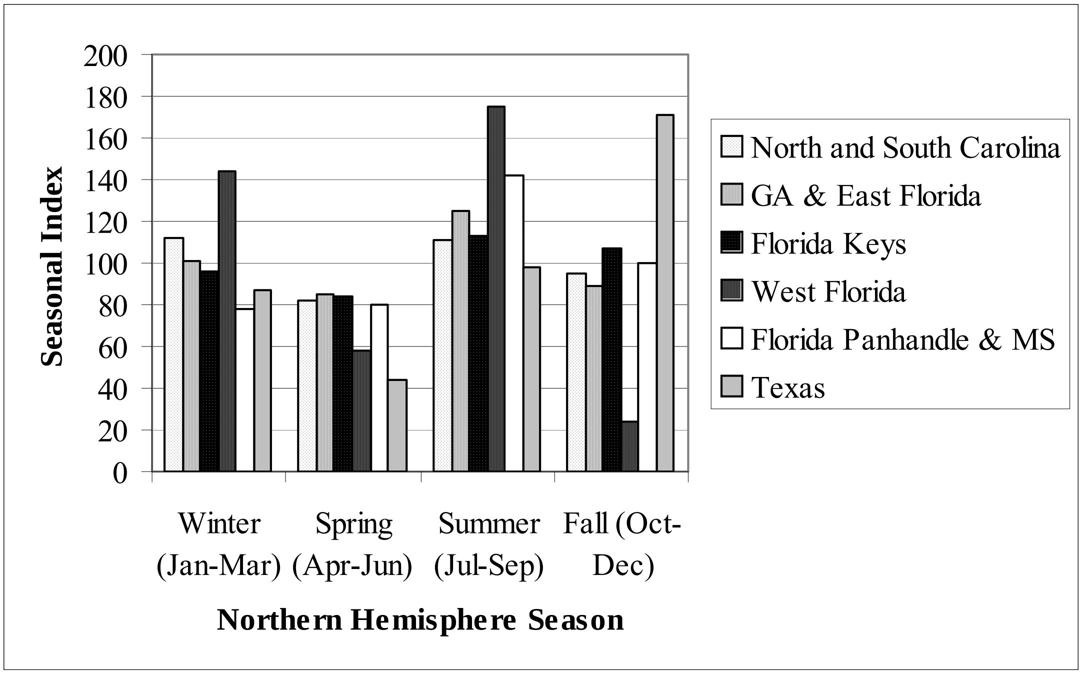


Figure 8: Seasonal index for *Kogia* sp. strandings from 1977 – 2005 separated by region. Even distribution would show a frequency of 100 for each season.

An ANOVA run on the seasonal index did not show significance. However, single-sample t-tests showed differences between certain seasons and the expected value of 100. When all regions were combined, spring was significantly lower. Single sample t-tests were then run on each region and season. The Carolinas had a significantly higher seasonal index in the winter, while Georgia and east Florida had a significantly higher seasonal index in the summer. West Florida had a significantly lower seasonal index in the fall, while Texas had significantly less in the spring. The Florida Keys and Panhandle showed no significant difference between the seasonal index for any season.

3.2. Wind Analysis

The majority (83%) of the strandings in the SEUS occurred along the eastern coasts of Florida, Georgia, North Carolina and South Carolina, and the analysis of the influence of wind on *Kogia* sp. strandings focused in these areas (Figure 9).

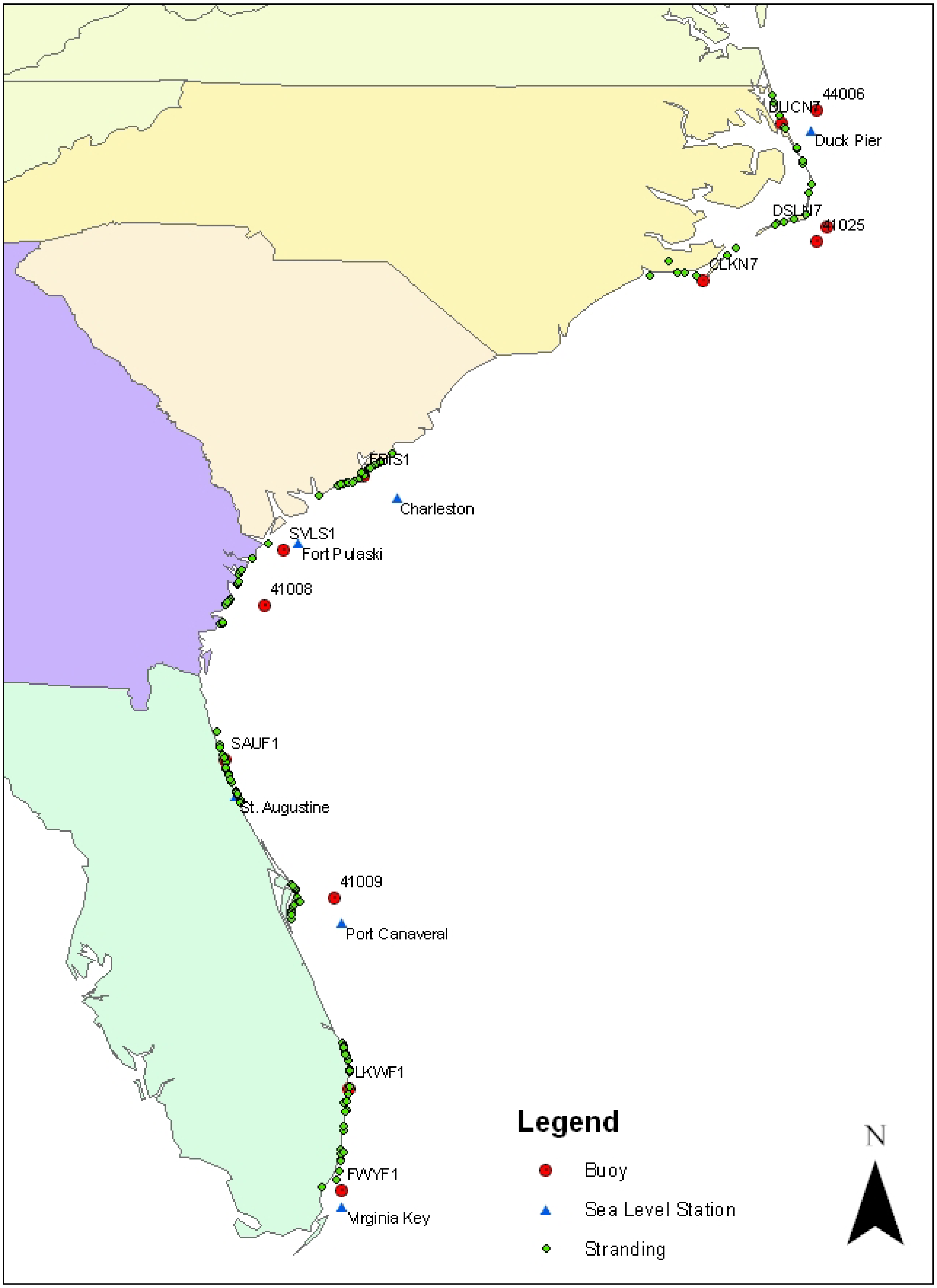


Figure 9: Map of the *Kogia* sp. stranding events analyzed for wind patterns and the corresponding stations where wind and sea level data were gathered.

Generally speaking, six different patterns emerged: 1) a change from downwelling- to upwelling-favorable winds within seven days prior to a stranding, 2) upwelling-favorable winds all fourteen days prior to a stranding, 3) major switches between upwelling- and downwelling-favorable winds during the fourteen days prior to a stranding, 4) a change from upwelling- to downwelling-favorable winds within seven days prior to a stranding, 5) a change from downwelling- to upwelling-favorable winds within the fourteen days prior to the stranding, and 6) a change from upwelling- to downwelling-favorable winds within the fourteen days prior to the stranding.

Sea level essentially mirrored the changes in wind direction and intensity at most stations. This is observed across all sixty-five strandings that were analyzed against both wind and sea level. When the wind changes direction from downwelling-favorable to upwelling-favorable winds, the sea level subsequently decreases as is expected. When the wind changes from upwelling-favorable to downwelling-favorable winds, the sea level subsequently increases as is expected. Correlations between wind intensity and sea level at each station are shown in Table 2. Subtracting mean sea level at each station allowed for combining of all wind/sea level pairs into one correlation (Figure 10). The regression was significant. When divided into locations, the r^2 value varied widely between locations and the regression was only significant at FBIS1/Charleston (r^2 = 0.2681) (Figure 11) and SVLS1/Fort Pulaski (r^2 = 0.2902) (Figure 12).

Pattern 1 was the dominant pattern, representing 32.3 percent of the strandings. The different patterns are enumerated and described in Table 3, and Figure 13 displays a frequency histogram of the different patterns for the entire east coast of Florida, Georgia South Carolina and North Carolina. Table 4 presents the breakdown of the frequencies of the different patterns in Georgia & eastern Florida and the Carolinas, respectively, and Figures 14-19 (a) are examples of each of the six patterns revealed in the wind analysis and Figures 14-18 (b) are the corresponding sea level graphs.

Wind Buoy/Sea Level Station	N	r^2
41009/Port Canaveral	10	9.30E-03
44006/Duck Pier	1	4.79E-02
DUCN7/Duck Pier	9	1.63E-02
FBIS1/Charleston	29	2.68E-01
FWYF1/Virginia Key	5	3.14E-02
SAUF1/Saint Augustine	8	1.74E-02
SVLS1/Fort Pulaski	3	2.90E-01

Table 2: Correlation (r^2) between wind intensity and sea level at all locations.

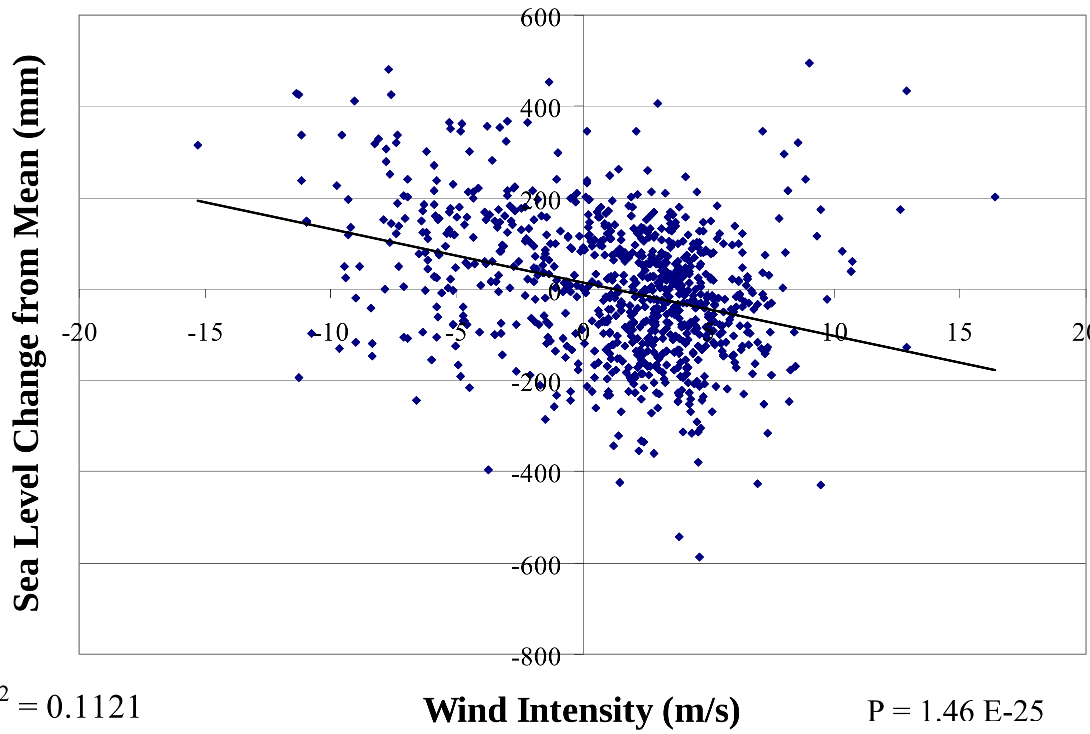


Figure 10: Correlation (r^2) between wind intensity and sea level change from mean for all wind and sea level pairs. Negative wind intensity values indicate downwelling-favorable winds while positive wind intensity values indicate upwelling-favorable winds.

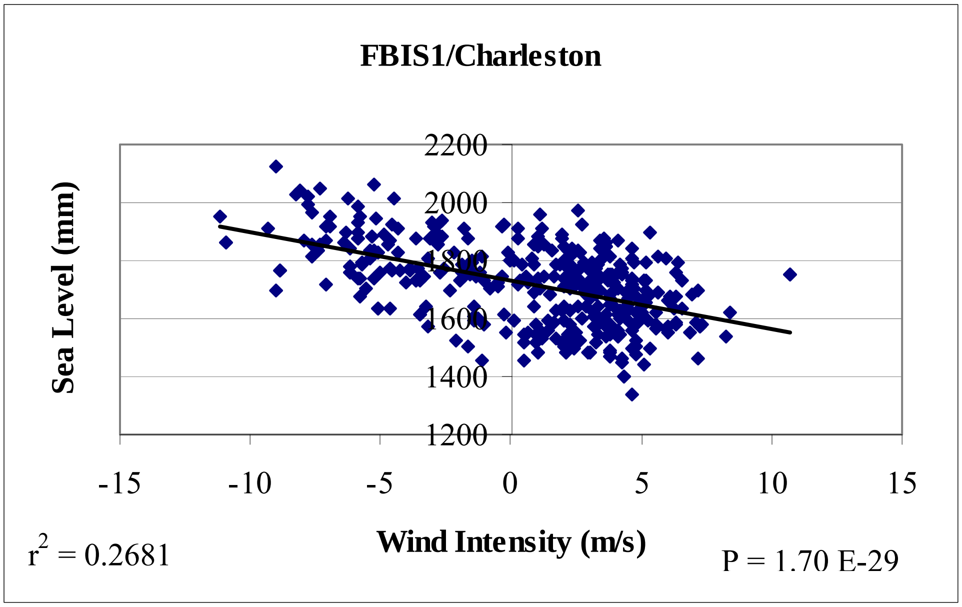


Figure 11: Correlation (r^2) between wind intensity and sea level for the wind buoy FBIS1 and the sea level station Charleston. Negative wind intensity values indicate downwelling-favorable winds while positive wind intensity values indicate upwelling-favorable winds.

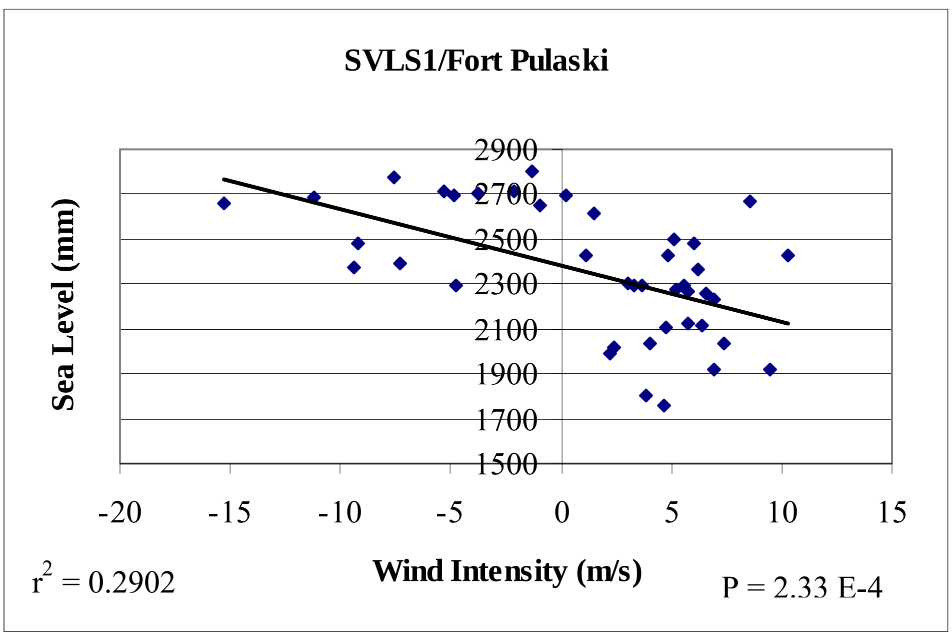


Figure 12: Correlation (r^2) between wind intensity and sea level for the wind buoy SVLS1 and the sea level station Fort Pulaski. Negative wind intensity values indicate downwelling-favorable winds while positive wind intensity values indicate upwelling-favorable winds.

Pattern Number	Description of Pattern
1	Downwelling favorable to upwelling favorable within 7 days prior to stranding
2	Upwelling favorable 14 days prior to stranding
3	Major switches from upwelling to downwelling favorable in 14 days prior
4	Upwelling favorable to downwelling favorable within 7 days prior to stranding
5	Downwelling favorable to upwelling favorable in 14 days prior
6	Upwelling favorable to downwelling favorable in 14 days prior

Table 3: Results of the wind analysis found six patterns listed here in order of decreasing frequency.

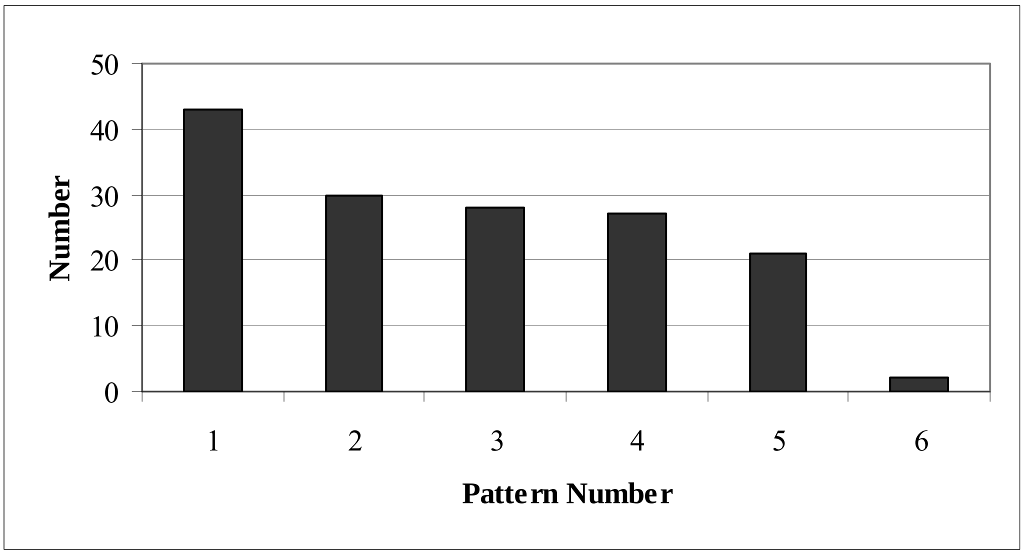


Figure 13: Frequency of the six different wind patterns found in the wind analysis.

Pattern Number	Georgia & eastern Florida	North Carolina & South Carolina	Total
1	21	22	43
2	25	5	30
3	18	10	28
4	16	11	27
5	13	8	21
6	2	0	2

Table 4: Frequency distribution of the six wind patterns found in the wind analysis.

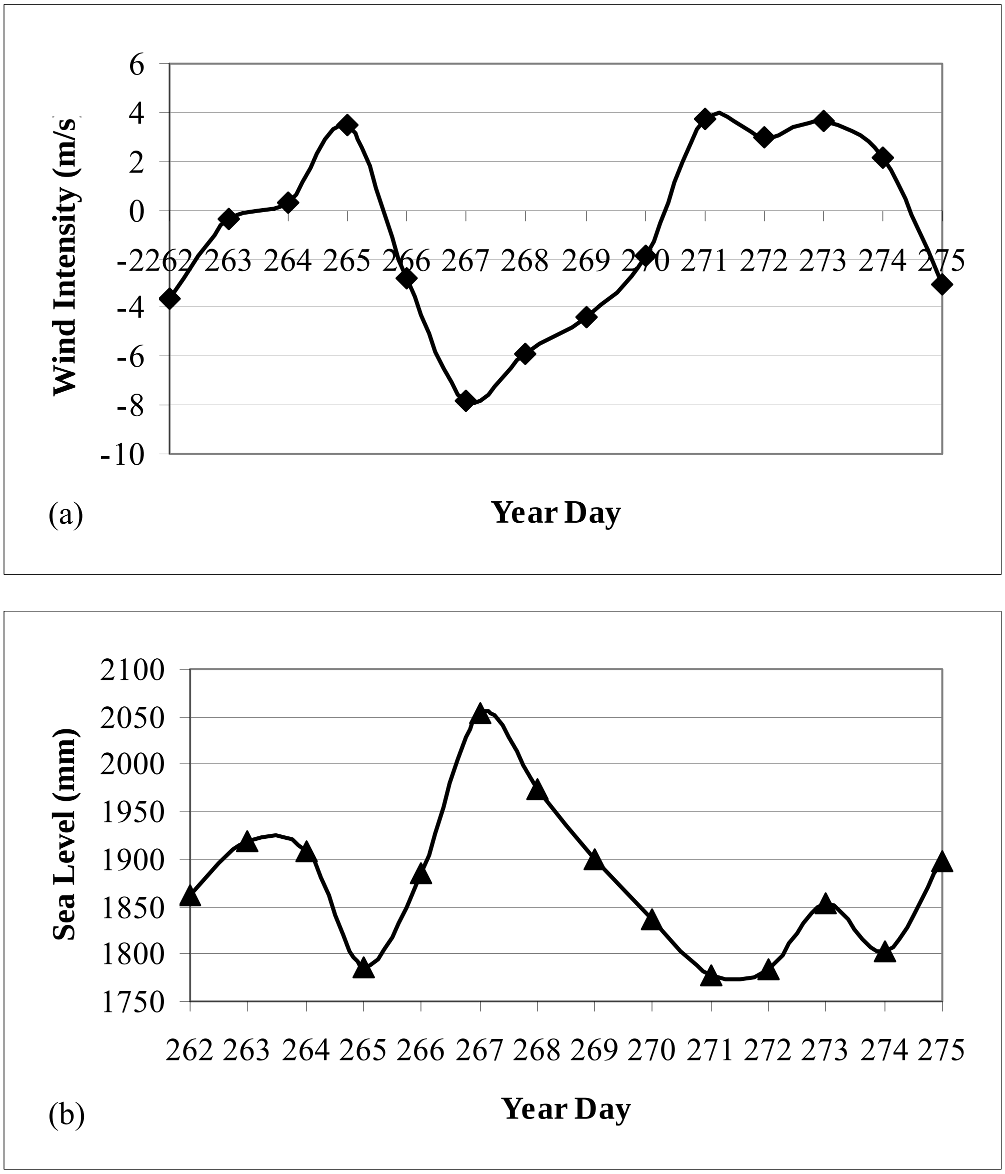
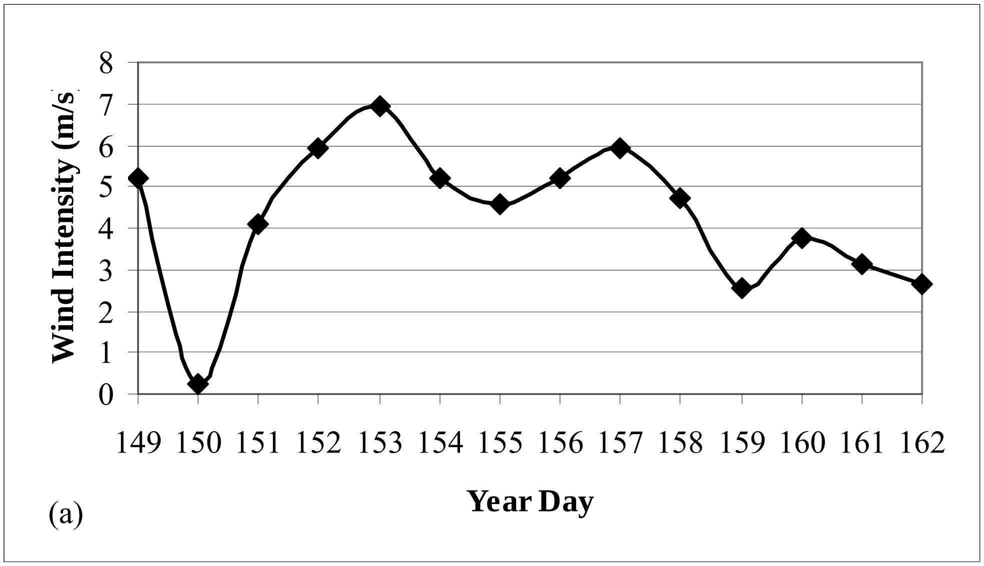


Figure 14: (a) Wind pattern 1 demonstrating a change from downwelling- to upwelling-favorable winds within seven days prior to the stranding event. The last day is the day of the stranding event. Positive y-axis values reflect upwelling-favorable winds and negative y-axis values reflect downwelling-favorable winds. (b) Corresponding change in sea level. A rise in sea level indicates a downwelling of water and a drop in sea level indicates upwelling of water. When there was a shift from downwelling favorable wind to upwelling favorable wind at year day 270, there was a subsequent upwelling of water indicated by the lower sea level.



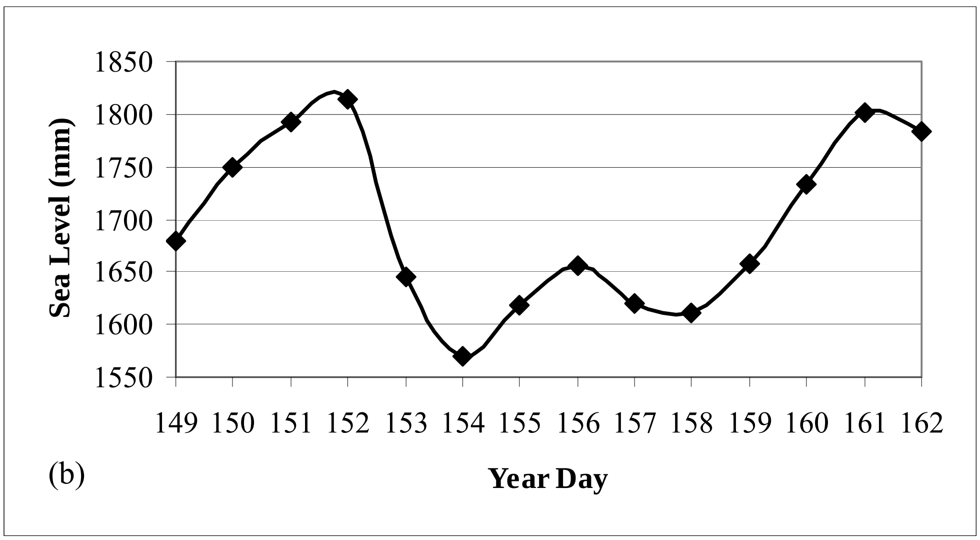
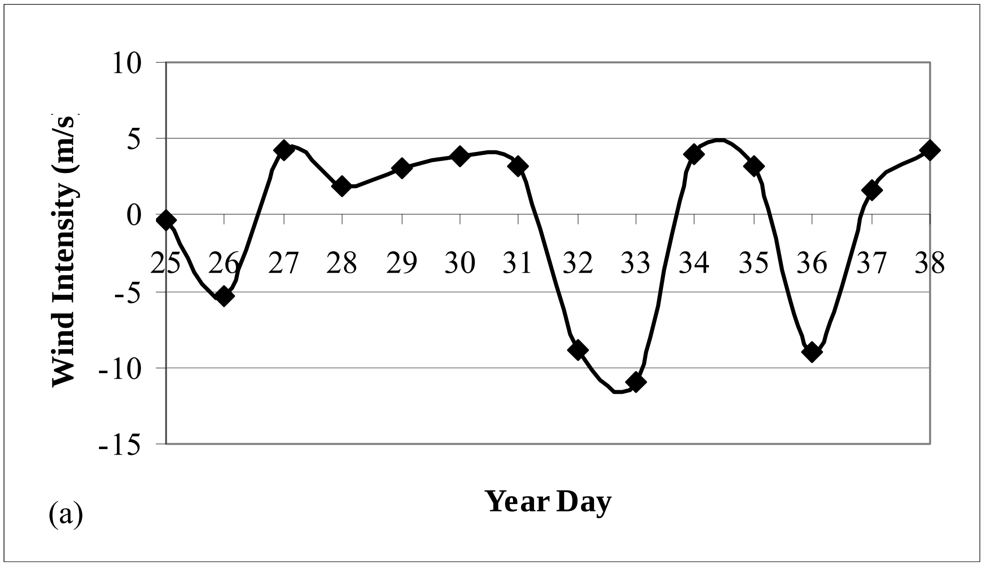


Figure 15: (a) Wind pattern 2 demonstrating a upwelling favorable winds all 14 days prior to a stranding event. The last day is the day of the stranding event. Positive y-axis values reflect upwelling-favorable winds and negative y-axis values reflect downwelling-favorable winds. (b) Corresponding change in sea level. A rise in sea level indicates a downwelling of water and a drop in sea level indicates upwelling of water.



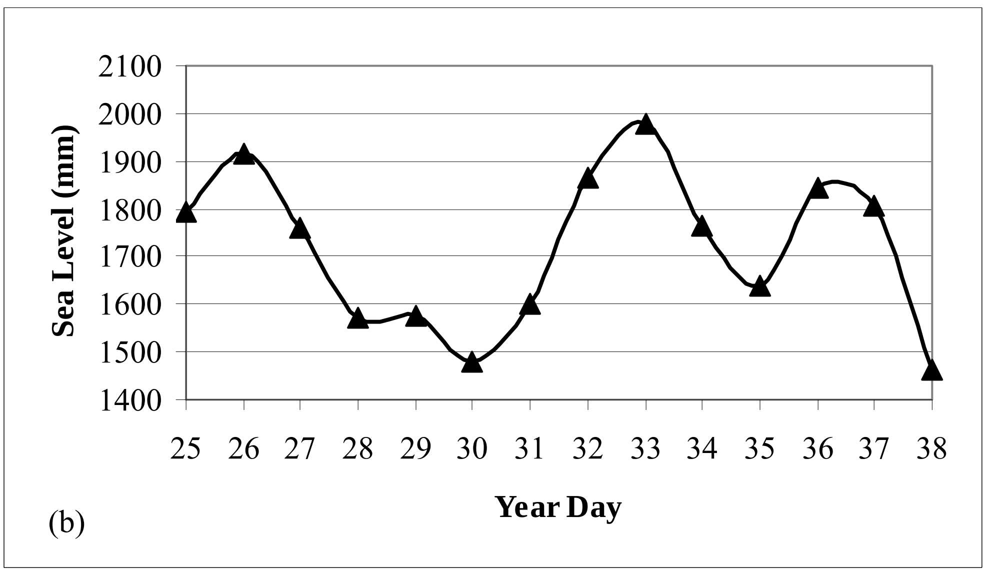
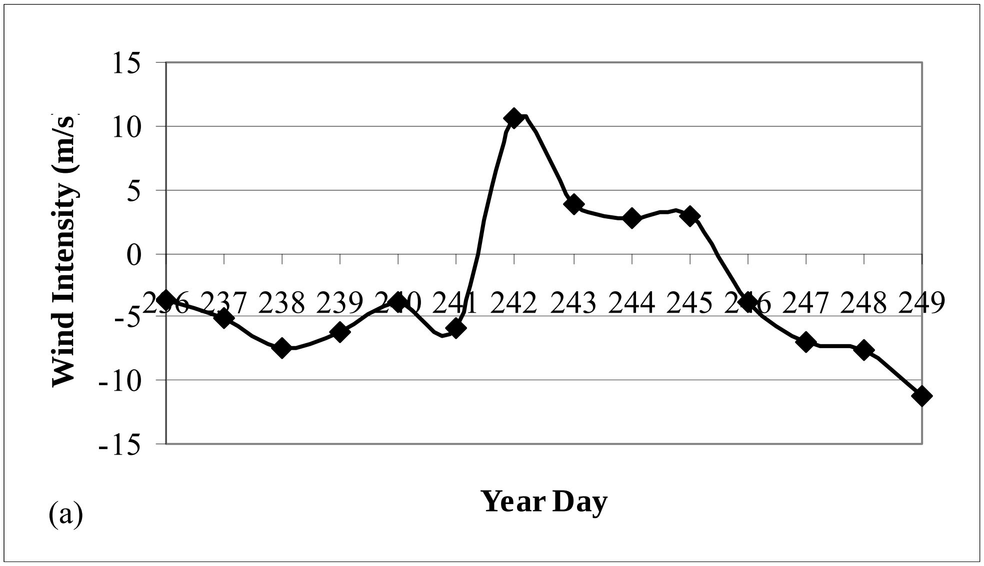


Figure 16: (a) Wind pattern 3 demonstrating major changes from upwelling- to downwelling-favorable winds in the 14 days prior to the stranding event. The last day is the day of the stranding event. Positive y-axis values reflect upwelling-favorable winds and negative y-axis values reflect downwelling-favorable winds. (b) Corresponding change in sea level. A rise in sea level indicates a downwelling of water and a drop in sea level indicates upwelling of water.



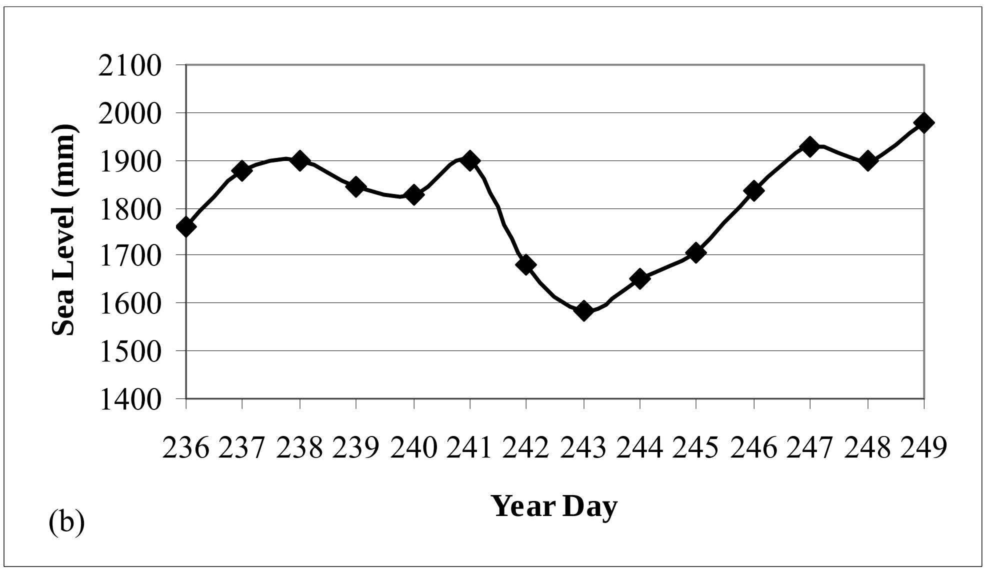


Figure 17: (a) Wind pattern 4 demonstrating a change from upwelling- to downwelling-favorable winds within 7 days prior to the stranding event. The last day is the day of the stranding event. Positive y-axis values reflect upwelling-favorable winds and negative y-axis values reflect downwelling-favorable winds. (b) Corresponding change in sea level. A rise in sea level indicates a downwelling of water and a drop in sea level indicates upwelling of water.

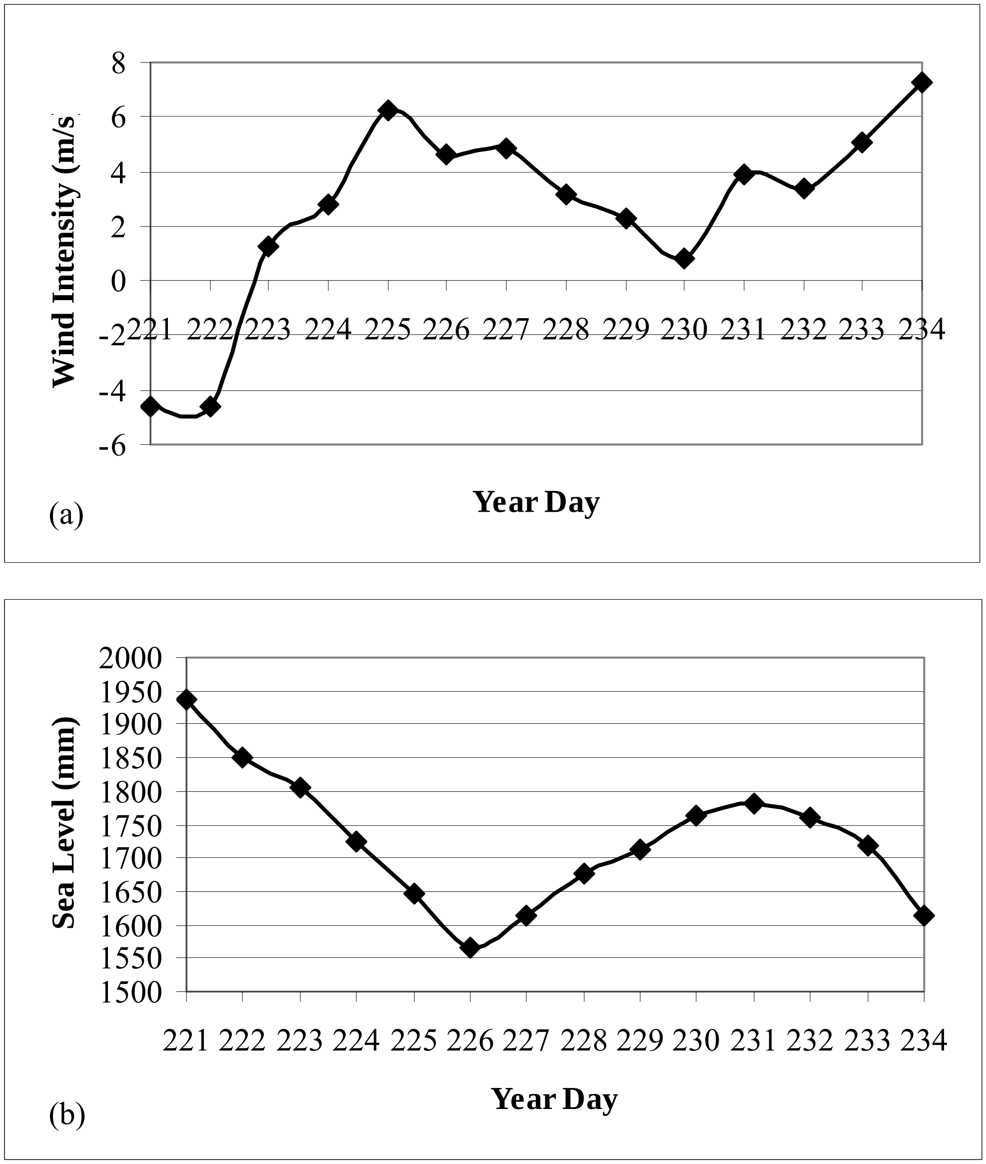


Figure 18: (a) Wind pattern 5 demonstrating a change from downwelling- to upwelling-favorable winds in the 14 days prior to the stranding event. The last day is the day of the stranding event. Positive y-axis values reflect upwelling-favorable winds and negative y-axis values reflect downwelling-favorable winds. (b) Corresponding change in sea level. A rise in sea level indicates a downwelling of water and a drop in sea level indicates upwelling of water.

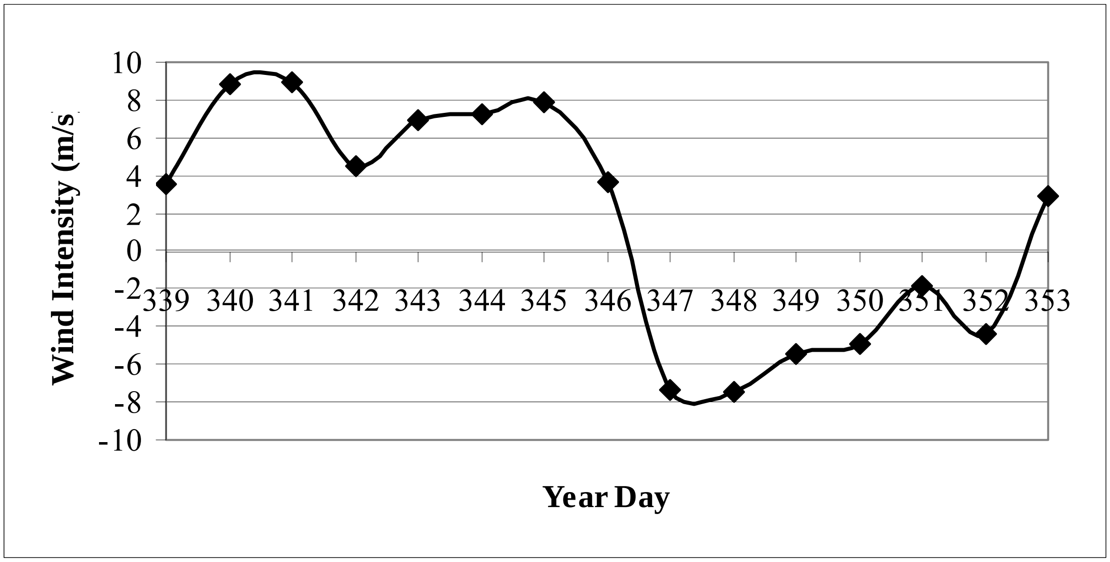


Figure 19: Wind pattern 6 demonstrating a change from upwelling- to downwelling-favorable winds in the 14 days prior to the stranding event. The last day is the day of the stranding event. Positive y-axis values reflect upwelling-favorable winds and negative y-axis values reflect downwelling-favorable winds. Sea level data were not available for this pattern.

If the wind patterns preceding stranding events do not correspond to the strandings, there would be an even proportion of patterns revealed. Chi-Square (χ^2) analysis of the frequency distribution of the six wind patterns for the entire east coast of Florida, Georgia and the Carolinas found a significant deviation from the predicted even proportions of patterns ($\chi^2 = 36.033$, $p < 0.001$). Splitting the region into sections of similar coastline, the distribution of the patterns in Georgia and eastern Florida was significantly different from the predicted even proportions ($\chi^2 = 19.884$, $p = 0.001$) and the frequency distribution was again significantly different from predicted for the North and South Carolina results, ($\chi^2 = 14.893$, $p = 0.005$).

A general wind velocity pattern was observed throughout the region (Figures 20 and 21). Strong upwelling-favorable winds occur at most buoys during summer months. A switch in wind directions to downwelling-favorable winds occurs in late summer/early fall and lasts through winter. A switch back to upwelling-favorable winds in the spring was observed at all buoys. Table 5 shows the number and percentage of each wind pattern prior to a stranding that occurred in each season.

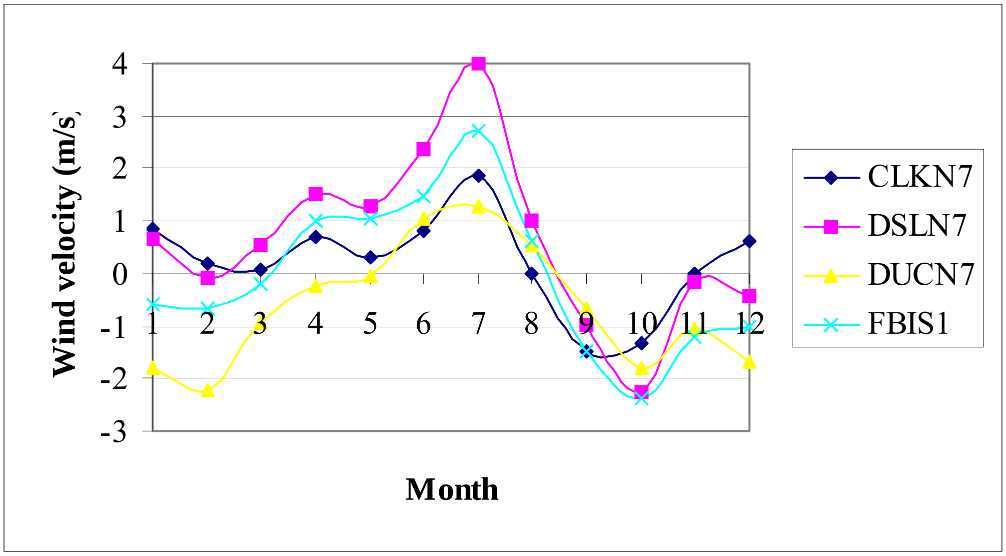


Figure 20: Wind velocity averages during the calendar year at buoys in North and South Carolina. January is month 1 and December is month 12. Positive values indicate upwelling-favorable winds and negative values indicate downwelling-favorable winds.

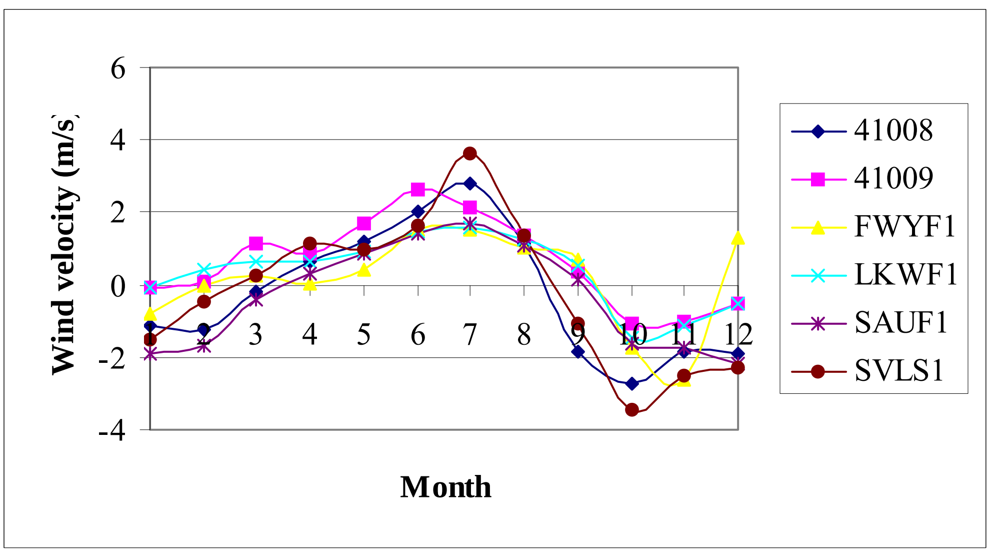


Figure 21: Wind velocity averages during the calendar year at buoys in Georgia and eastern Florida. January is month 1 and December is month 12. Positive values indicate upwelling-favorable winds and negative values indicate downwelling-favorable winds.

Pattern Number	Winter	Spring	Summer	Fall
1	13 (30.2)	6 (14)	12 (27.9)	12 (27.9)
2	3 (10)	8 (26.7)	16 (53.3)	3 (10)
3	9 (32.1)	3 (10.7)	3 (10.7)	13 (46.4)
4	7 (25.9)	5 (18.5)	8 (29.6)	7 (25.9)
5	9 (42.9)	3 (14.3)	6 (28.6)	3 (14.3)
6	0 (0)	1 (50)	0 (0)	1 (50)

Table 5: Number of each wind pattern prior to a stranding during each season. Percentages of the total in each season per pattern are in parentheses.

3.3. Bathymetry Analysis

Figures 22 through 39 are histograms for distance from stranding sites to each isobath and slope to each isobath. Tables 6 through 8 are descriptive statistics for the bathymetry analysis noting the maximum, minimum, and mean distance to and slope to each isobath from stranding sites and each set of random points. Skewness statistics are also shown in these tables. A positive statistic denotes a tendency towards the left (i.e. the lower values indicating shorter distances and smaller angles). Many of the calculations demonstrate a left skew, indicating shorter distances to isobaths. Exceptions are the distance to the 20 m and 50 m isobaths for Georgia, North Carolina and South Carolina and the distance to the 50 m isobath for all combined. These skews are demonstrated with the normal curve in the histograms.

The Wilcox-signed rank test on distances between stranding sites and isobaths in Florida showed no significance between the randomly sampled points and the stranding sites for all isobaths. The two-tailed tests have a p-value of 0.297 for comparison of the 10 m isobath data, 0.077 for comparison of the 20 m isobath data, and 0.706 for comparison of the 50 m isobath data. The Wilcox-signed rank test on slope between stranding sites and isobaths showed one significance between the randomly sampled points and the stranding sites – the slope to the 50 m isobath. The two-tailed tests have a p-value of 0.109 for comparison of the 10 m isobath data, 0.432 for comparison of the 20 m isobath data, and 0.035 for comparison of the 50 m isobath data.

The Wilcox-signed rank test on distances between stranding sites and isobaths in Georgia, North Carolina, and South Carolina was significant between the randomly sampled points and the stranding sites for all isobaths. The two-tailed tests have a p-value of less than 0.001 for comparison of the 10 m isobath data, less than 0.001 for comparison of the 20 m isobath data, and 0.010 for comparison of the 50 m isobath data. The Wilcox-signed rank test on slope between stranding sites and isobaths was significant between the randomly sampled points and the stranding sites for all isobaths. The two-tailed tests have a p-value of less than 0.001 for comparison of the 10 m isobath data, 0.001 for comparison of the 20 m isobath data, and 0.025 for comparison of the 50 m isobath data.

The Florida data were combined with the Georgia, North Carolina, and South Carolina data to determine the significance of bathymetry on *Kogia* sp. strandings for the entire the SEUS Atlantic region. The Wilcox-signed rank test on distances between stranding sites and isobaths showed significance between the randomly sampled points and the stranding sites only for the distance to the 10 m isobath. The two-tailed tests have a p-value of 0.015 for comparison of the 10 m isobath data, 0.192 for comparison of the 20 m isobath data, and 0.846 for comparison of the 50 m isobath data. The Wilcox-signed rank test on slope between stranding sites and isobaths showed significance between the randomly sampled points and the stranding sites only for the slope to the 10m isobath. The two-tailed tests have a p-value of 0.040 for comparison of the 10 m isobath data, 0.246 for comparison of the 20 m isobath data, and 0.336 for comparison of the 50 m isobath data.

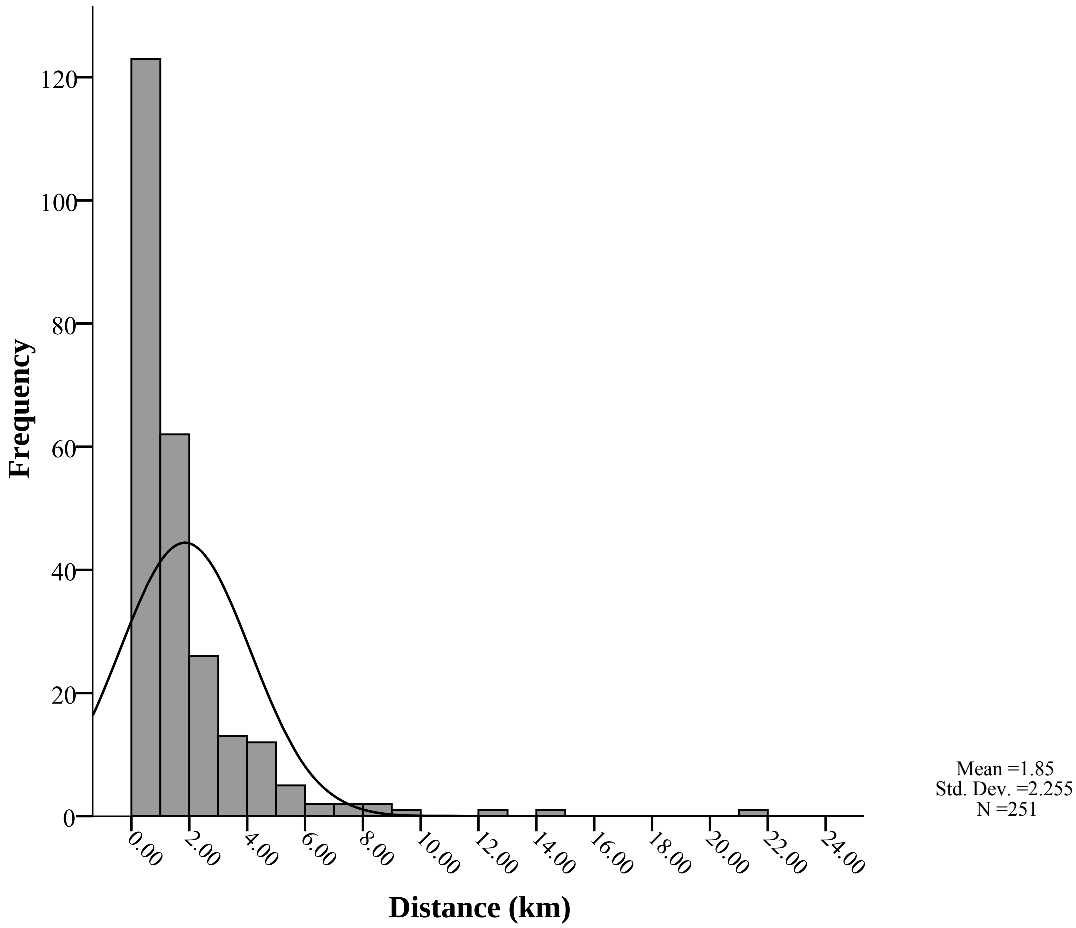


Figure 22: Histogram of distances from site of stranding event to 10 m isobath in Florida. Includes a normal distribution curve highlighting the left skew in the dataset.

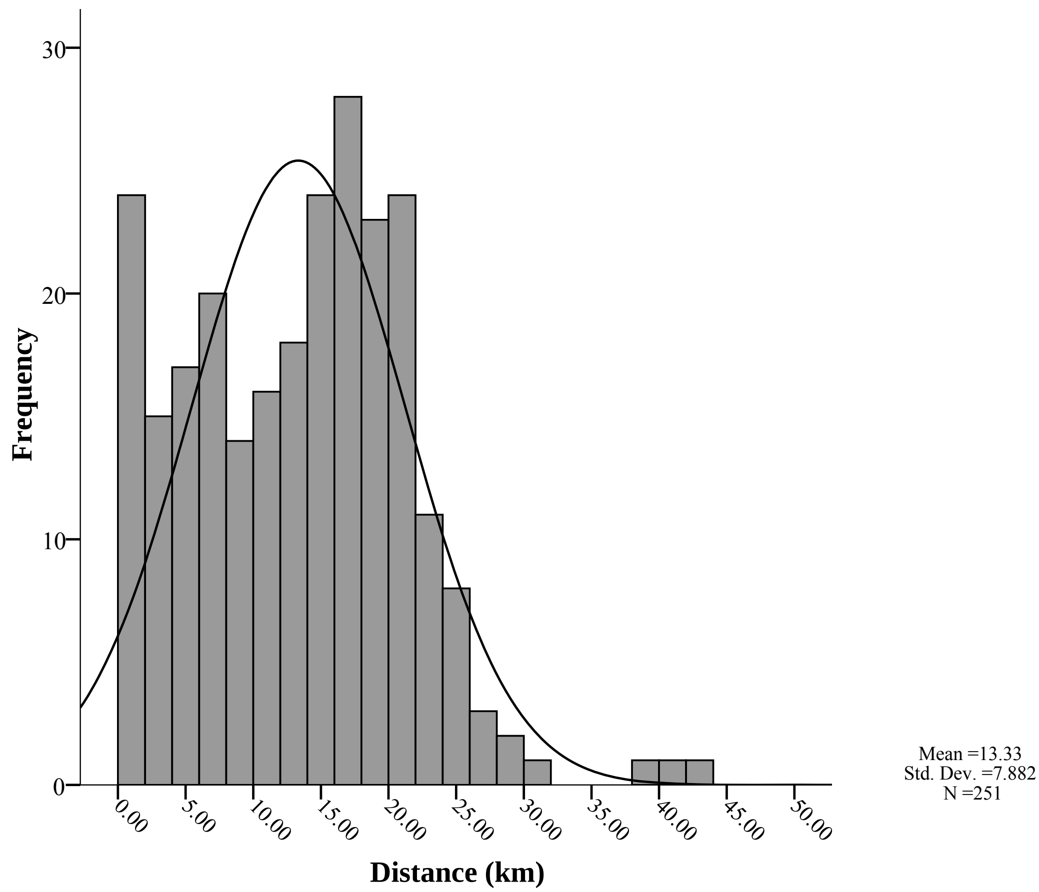


Figure 23: Histogram of distances from site of stranding event to 20 m isobath in Florida. Includes a normal distribution curve highlighting the left skew in the dataset.

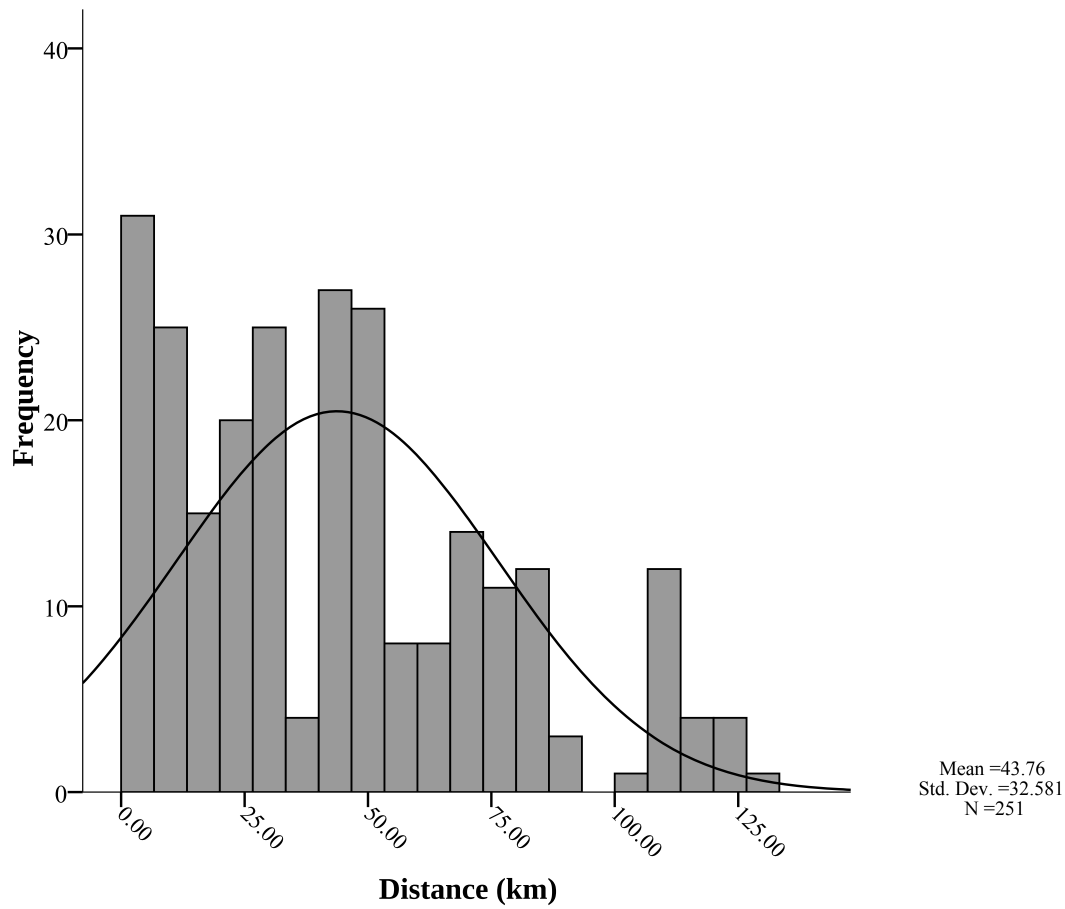


Figure 24: Histogram of distances from site of stranding event to 50 m isobath in Florida. Includes a normal distribution curve highlighting the left skew in the dataset.

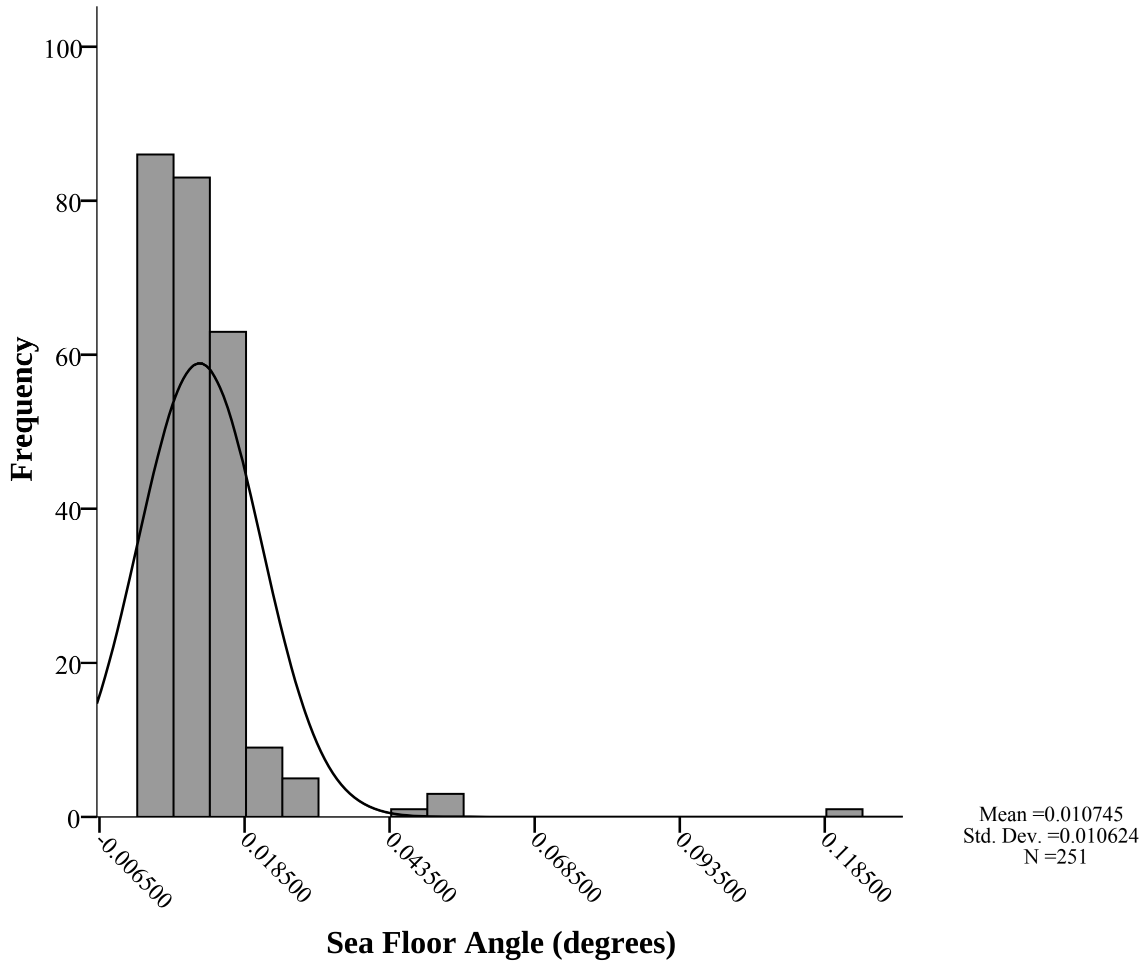


Figure 25: Histogram of bottom slope from site of stranding event to 10 m isobath in Florida. Includes a normal distribution curve highlighting the left skew in the data set.

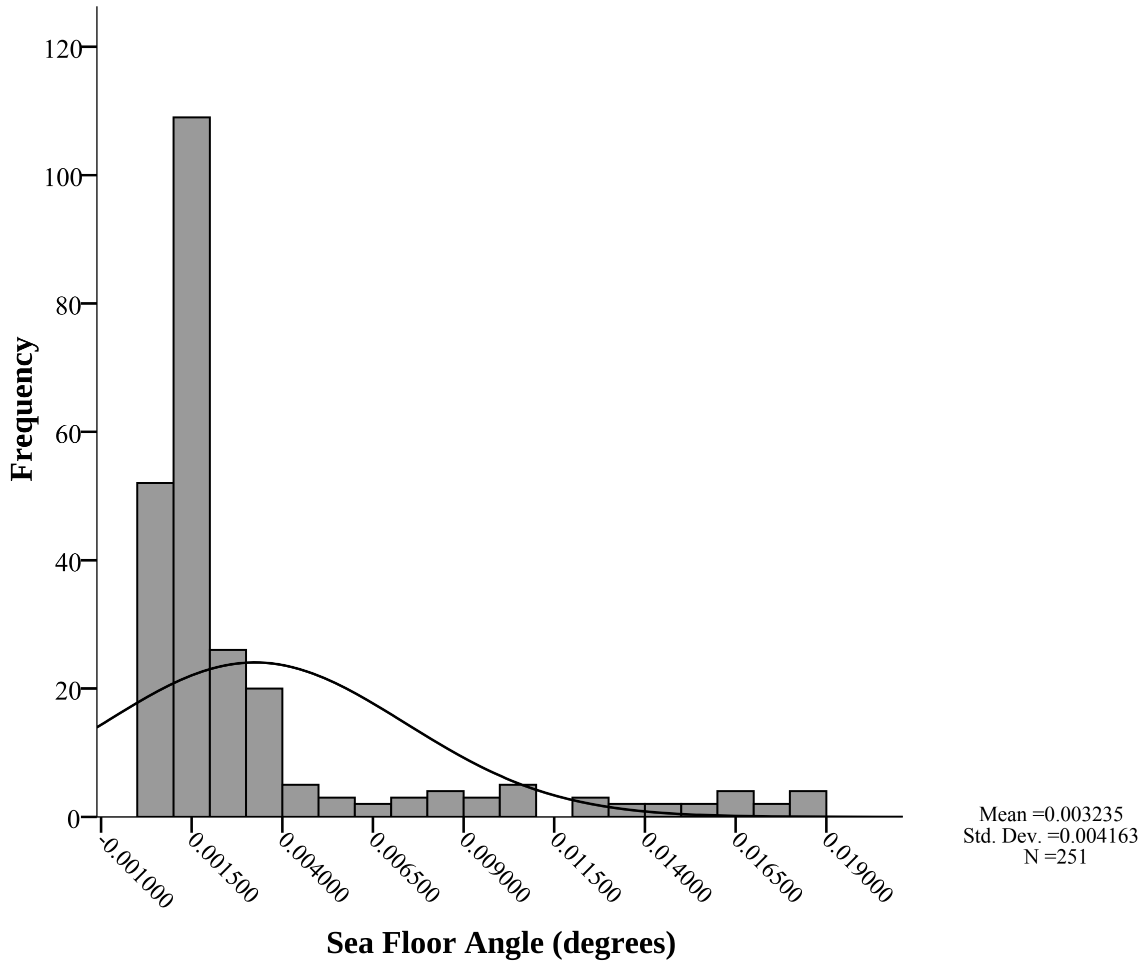


Figure 26: Histogram of bottom slope from site of stranding event to 20 m isobath in Florida. Includes a normal distribution curve highlighting the left skew in the data set.

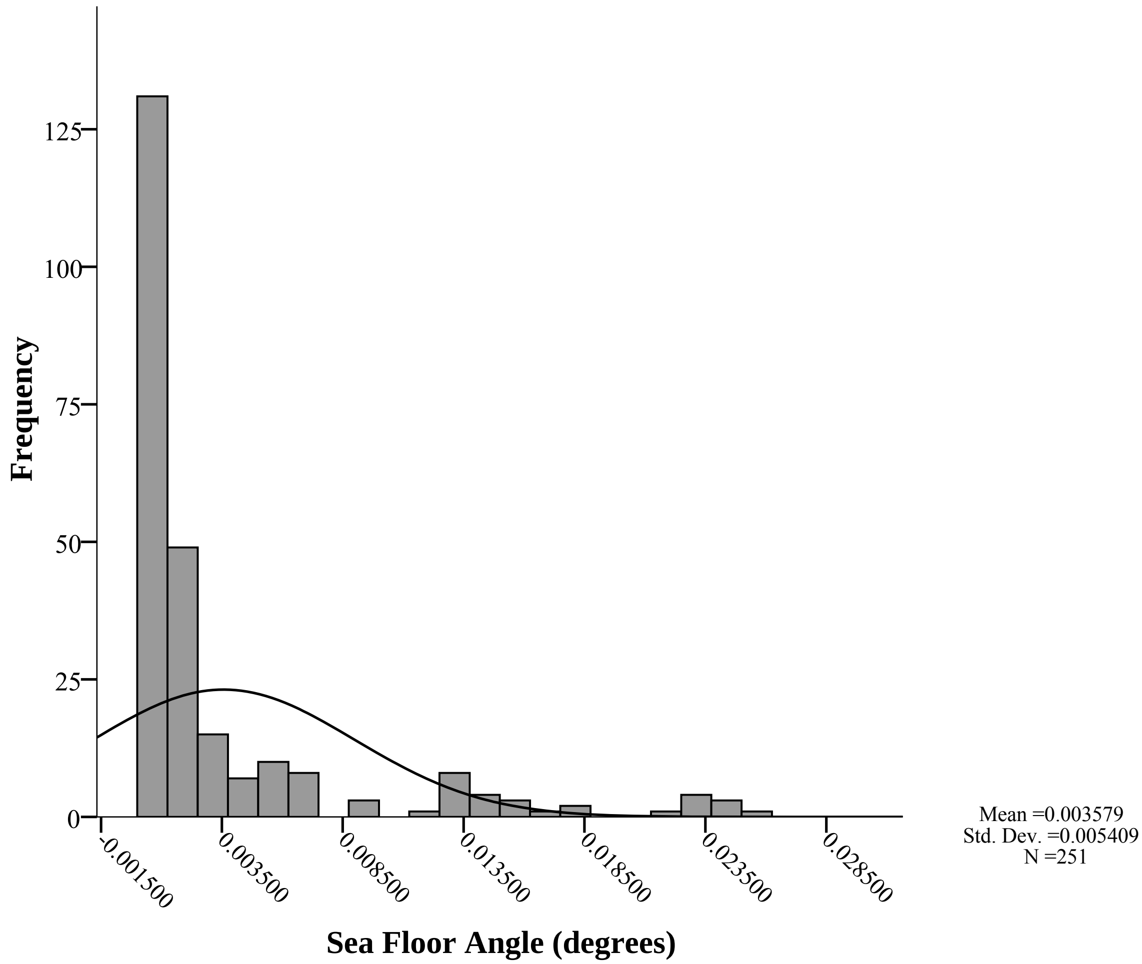


Figure 27: Histogram of bottom slope from site of stranding event to 50 m isobath in Florida. Includes a normal distribution curve highlighting the left skew in the data set.

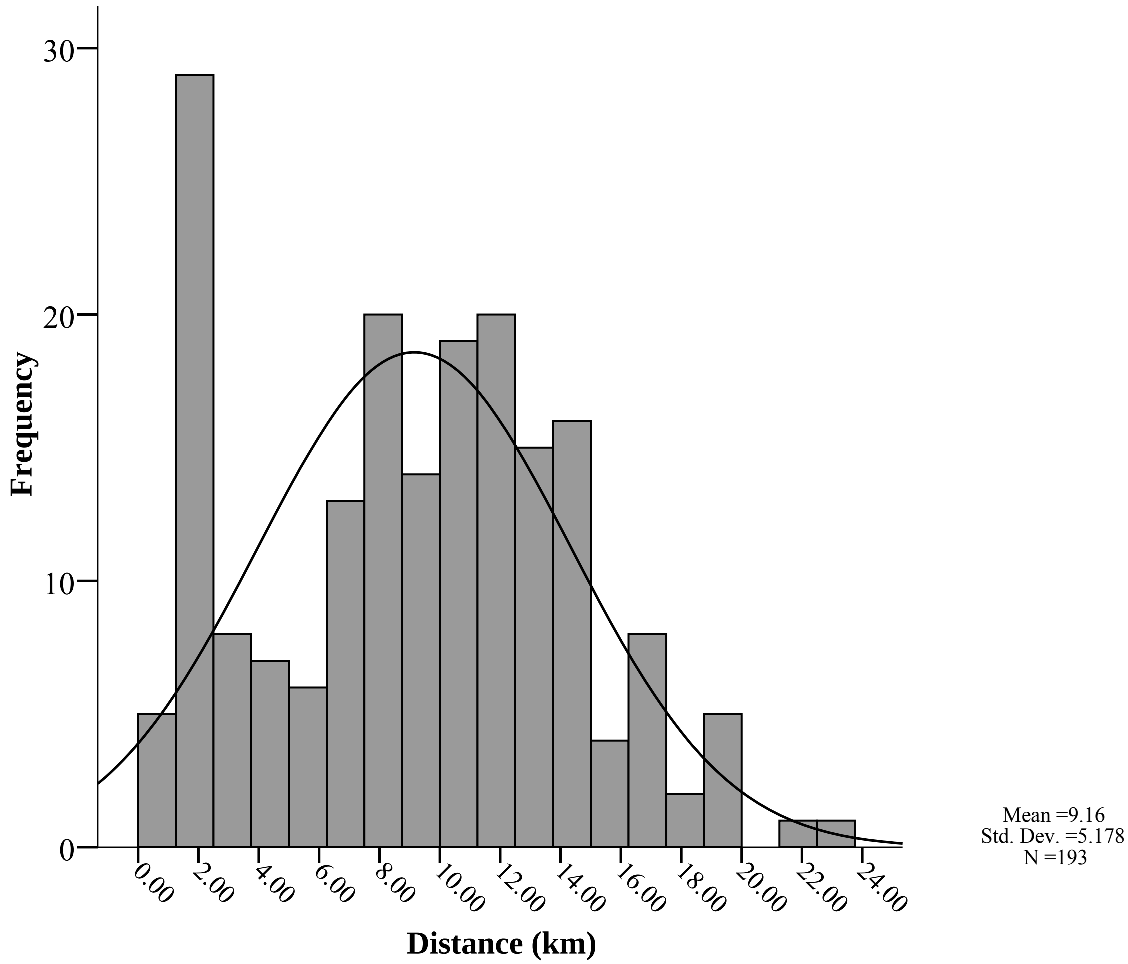


Figure 28: Histogram of distances from site of stranding event to 10 m isobath in Georgia, South Carolina and North Carolina. Includes a normal distribution curve highlighting the left skew in the dataset.

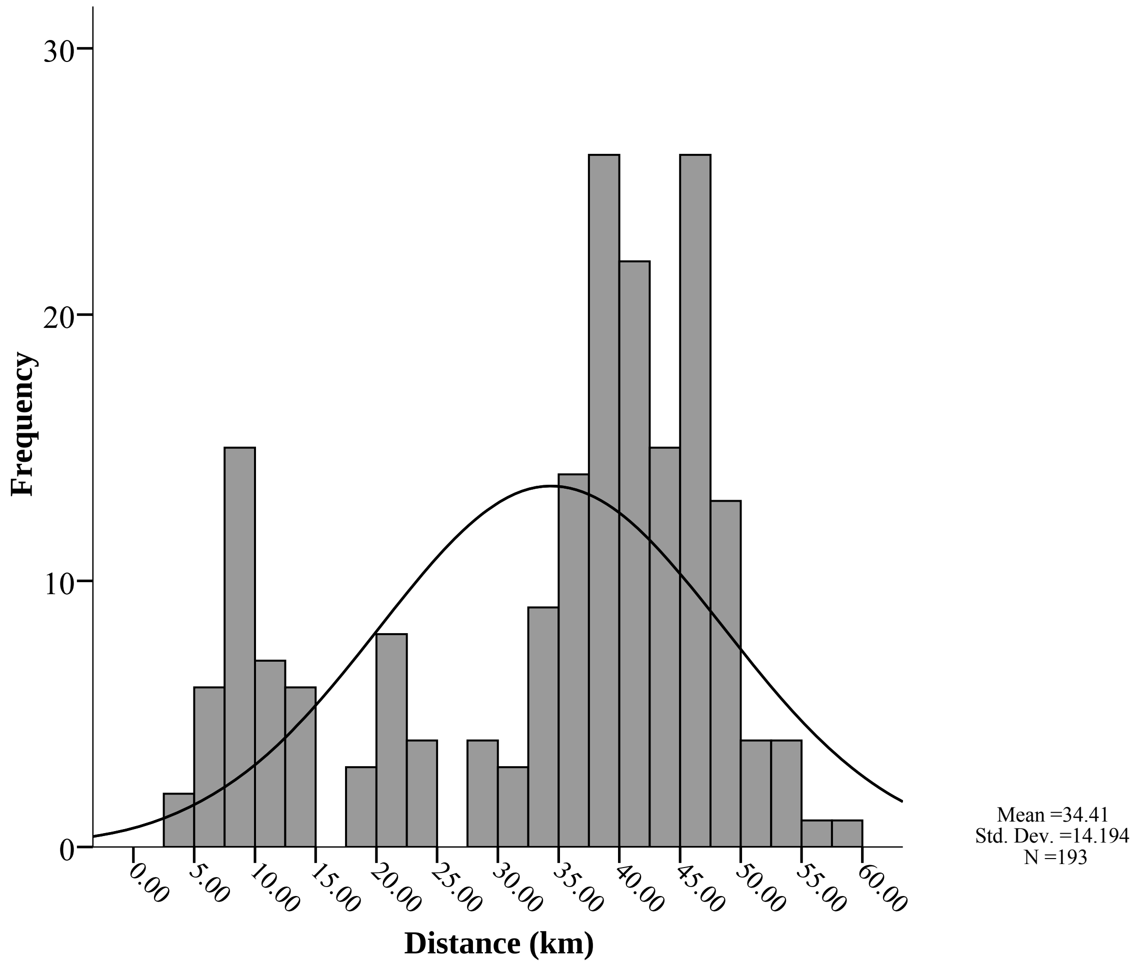


Figure 29: Histogram of distances from site of stranding event to 20 m isobath in Georgia, South Carolina and North Carolina. Includes a normal distribution curve highlighting the right skew in the dataset.

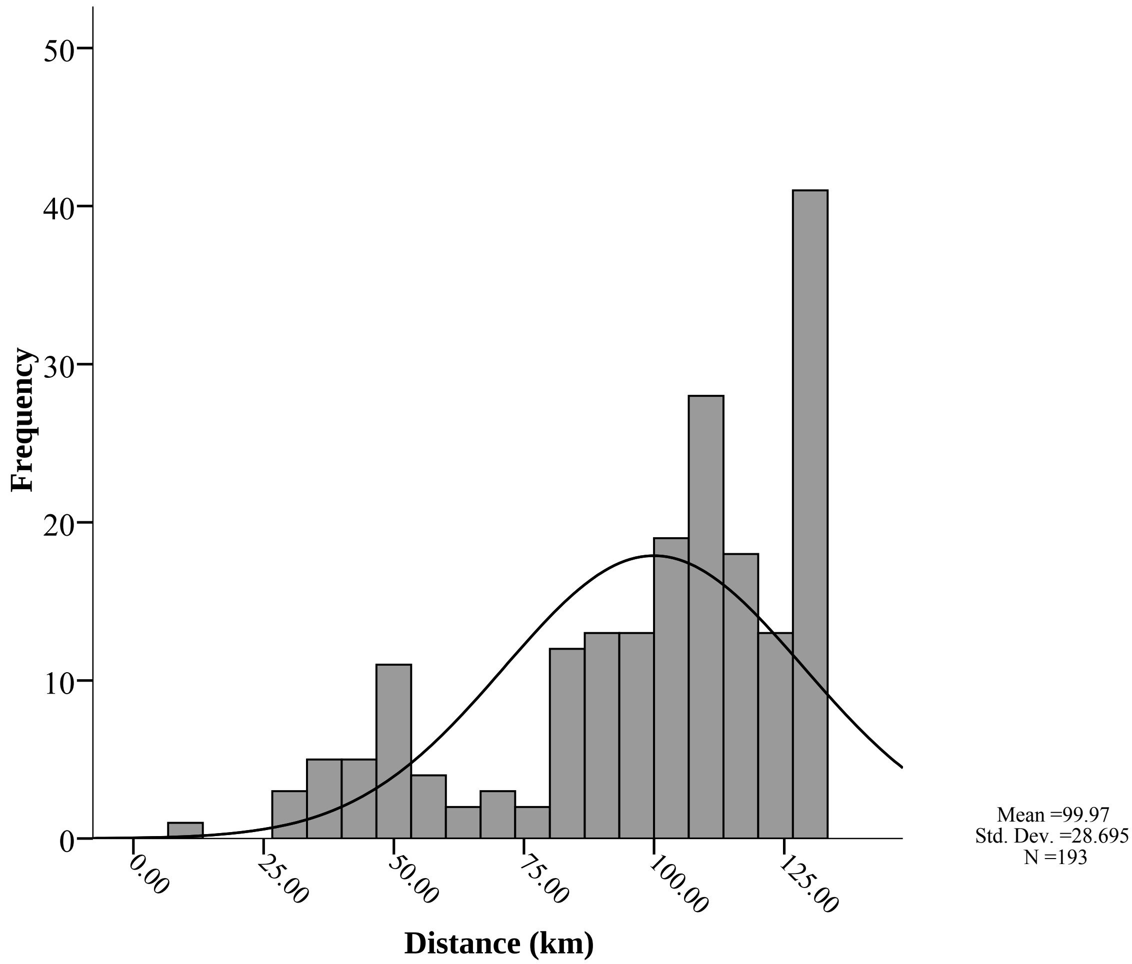


Figure 30: Histogram of distances from site of stranding event to 50 m isobath in Georgia, South Carolina and North Carolina. Includes a normal distribution curve highlighting the right skew in the dataset.

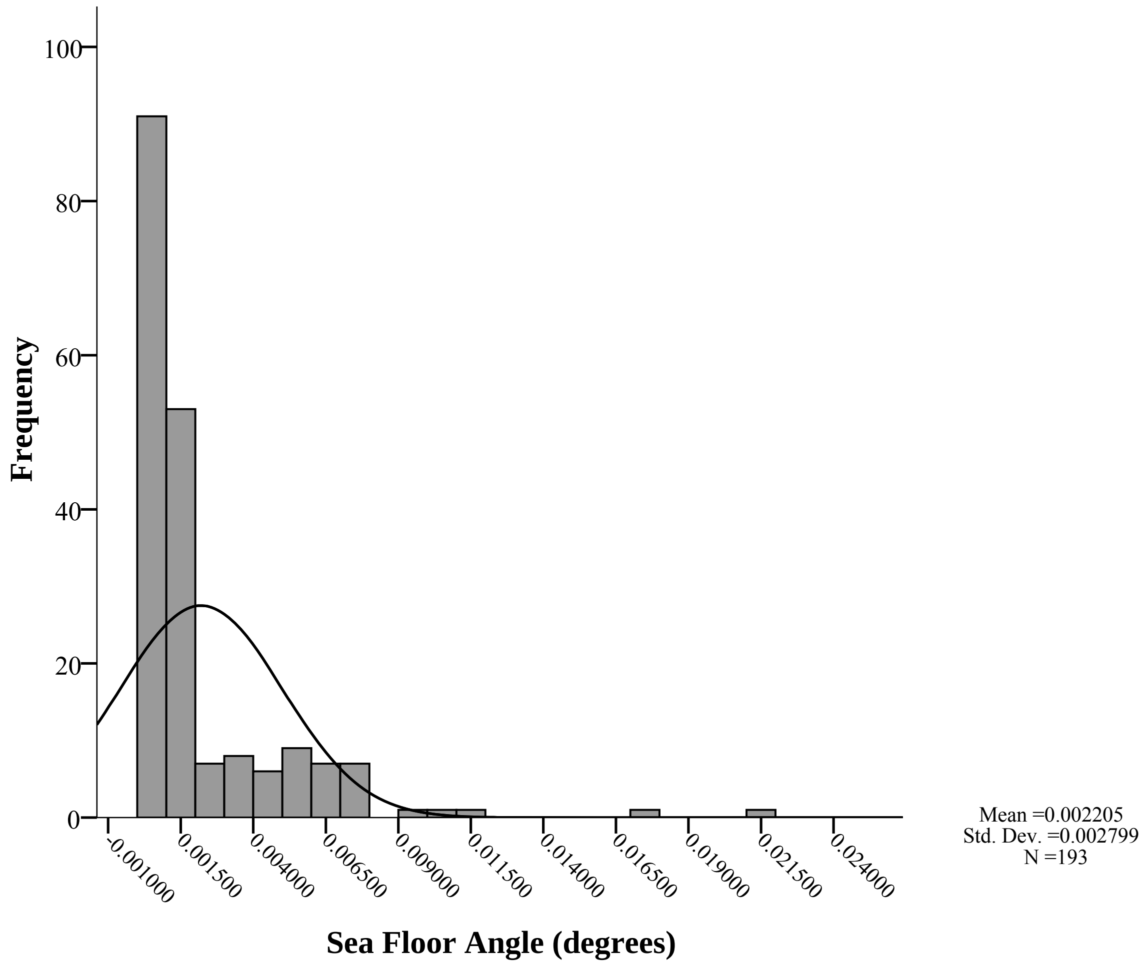


Figure 31: Histogram of bottom slope from site of stranding event to 10 m isobath in Georgia, North Carolina and South Carolina. Includes a normal distribution curve highlighting the left skew in the data set.

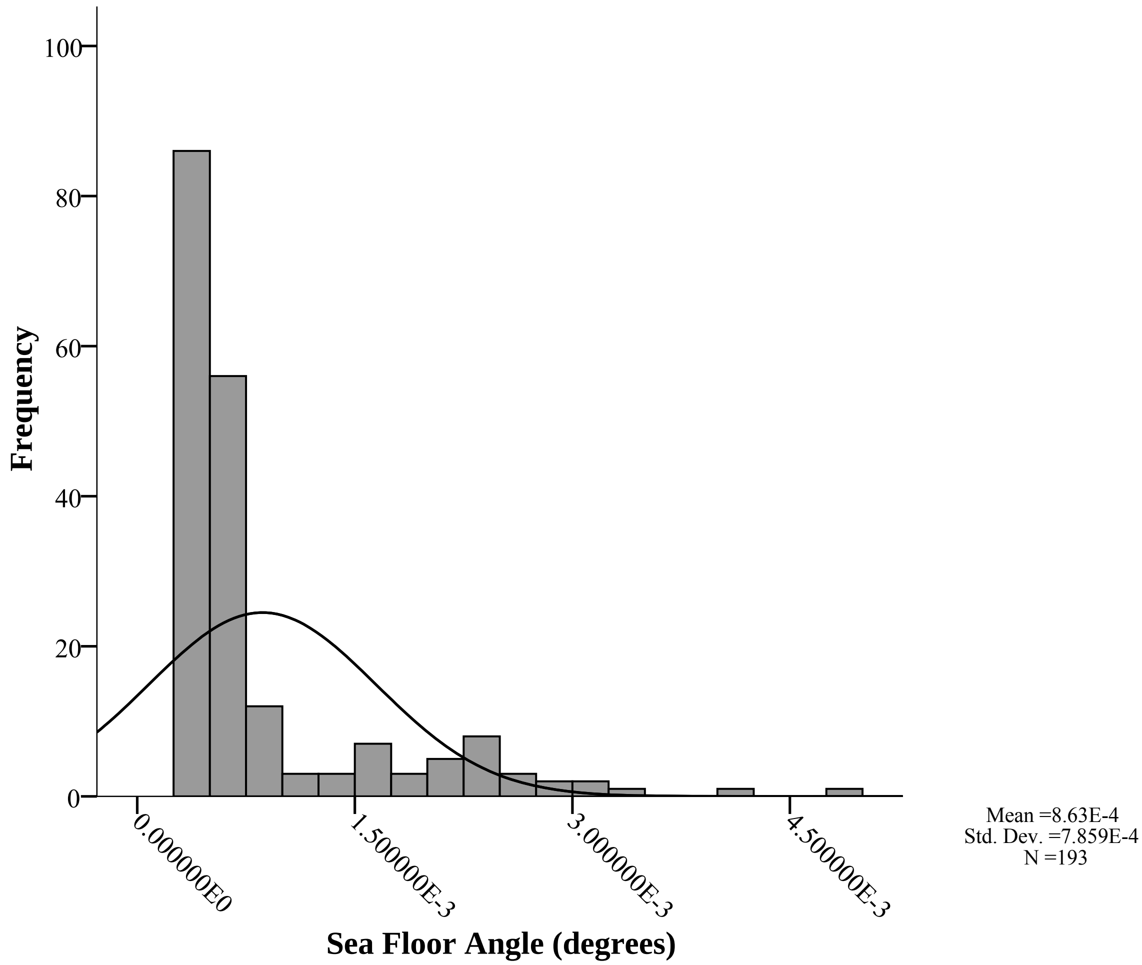


Figure 32: Histogram of bottom slope from site of stranding event to 20 m isobath in Georgia, North Carolina and South Carolina. Includes a normal distribution curve highlighting the left skew in the data set.

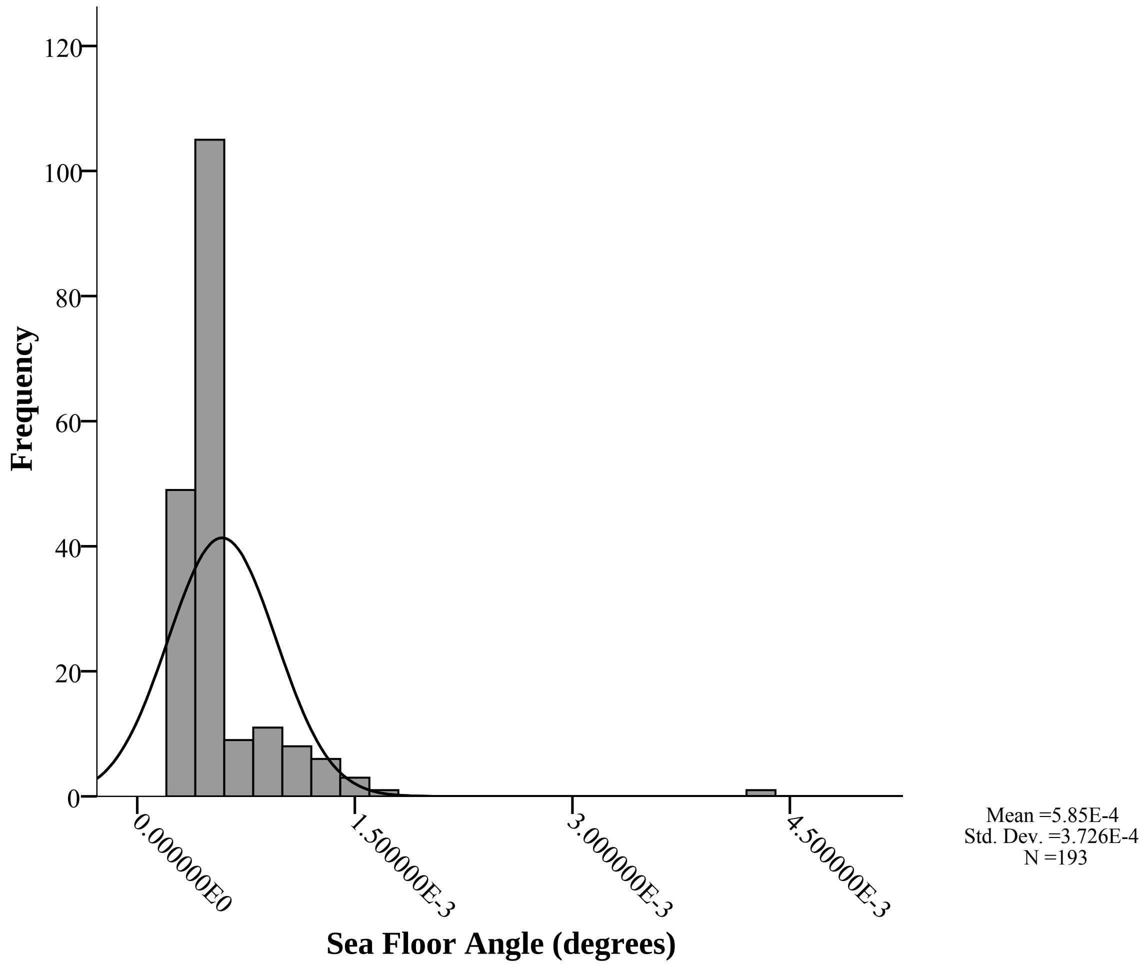


Figure 33: Histogram of bottom slope from site of stranding event to 50 m isobath in Georgia, North Carolina and South Carolina. Includes a normal distribution curve highlighting the left skew in the data set.

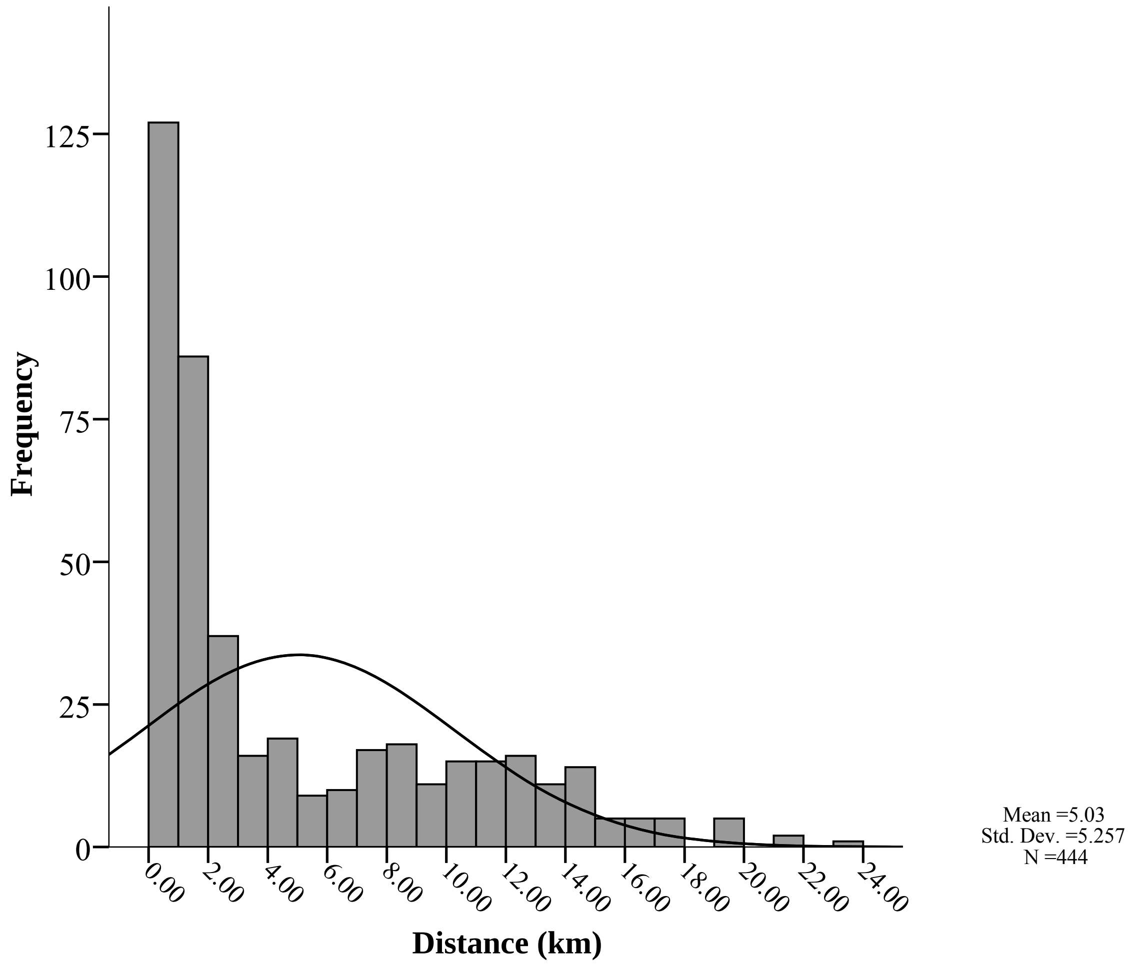


Figure 34: Histogram of distances from site of stranding event to 10 m isobath for all combined. Includes a normal distribution curve highlighting the left skew in the dataset.

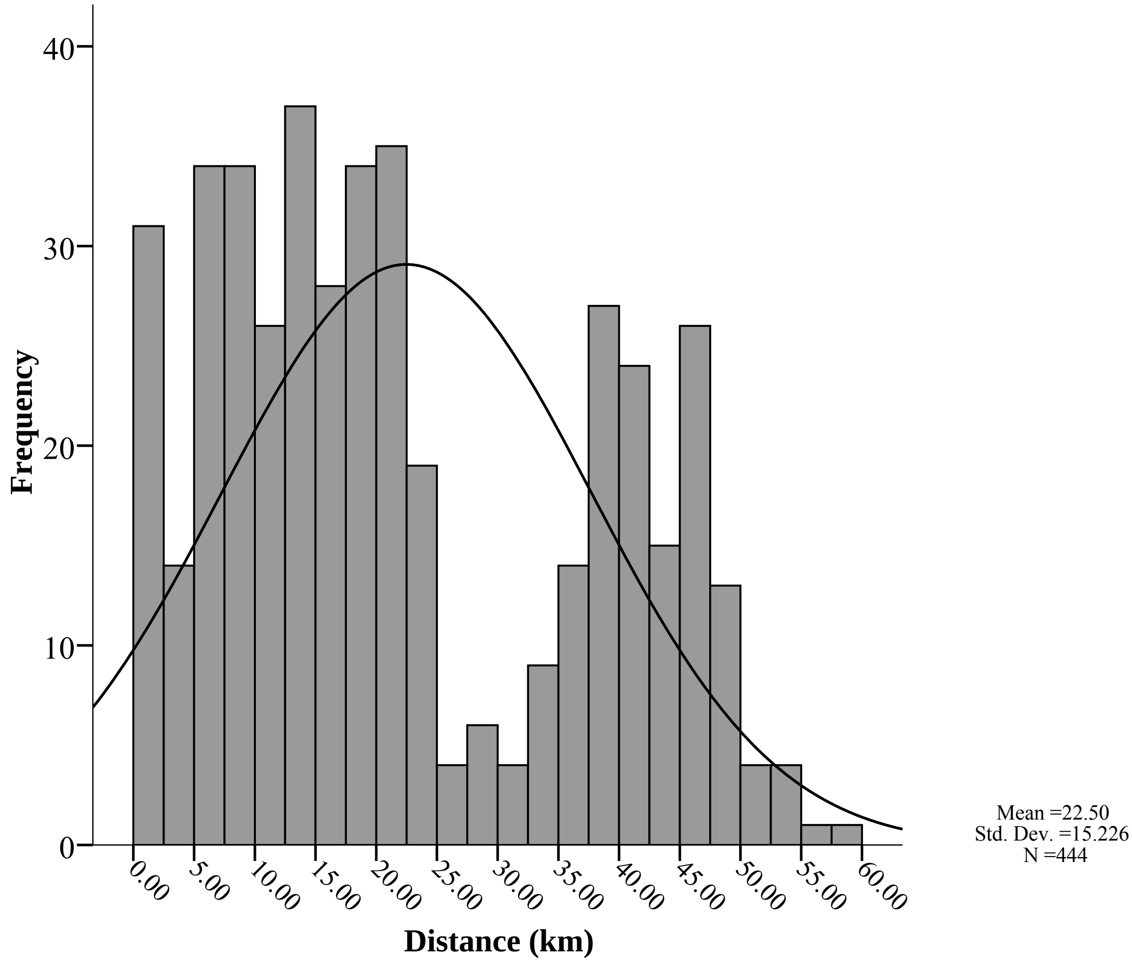


Figure 35: Histogram of distances from site of stranding event to 20 m isobath for all combined. Includes a normal distribution curve highlighting the left skew in the dataset.

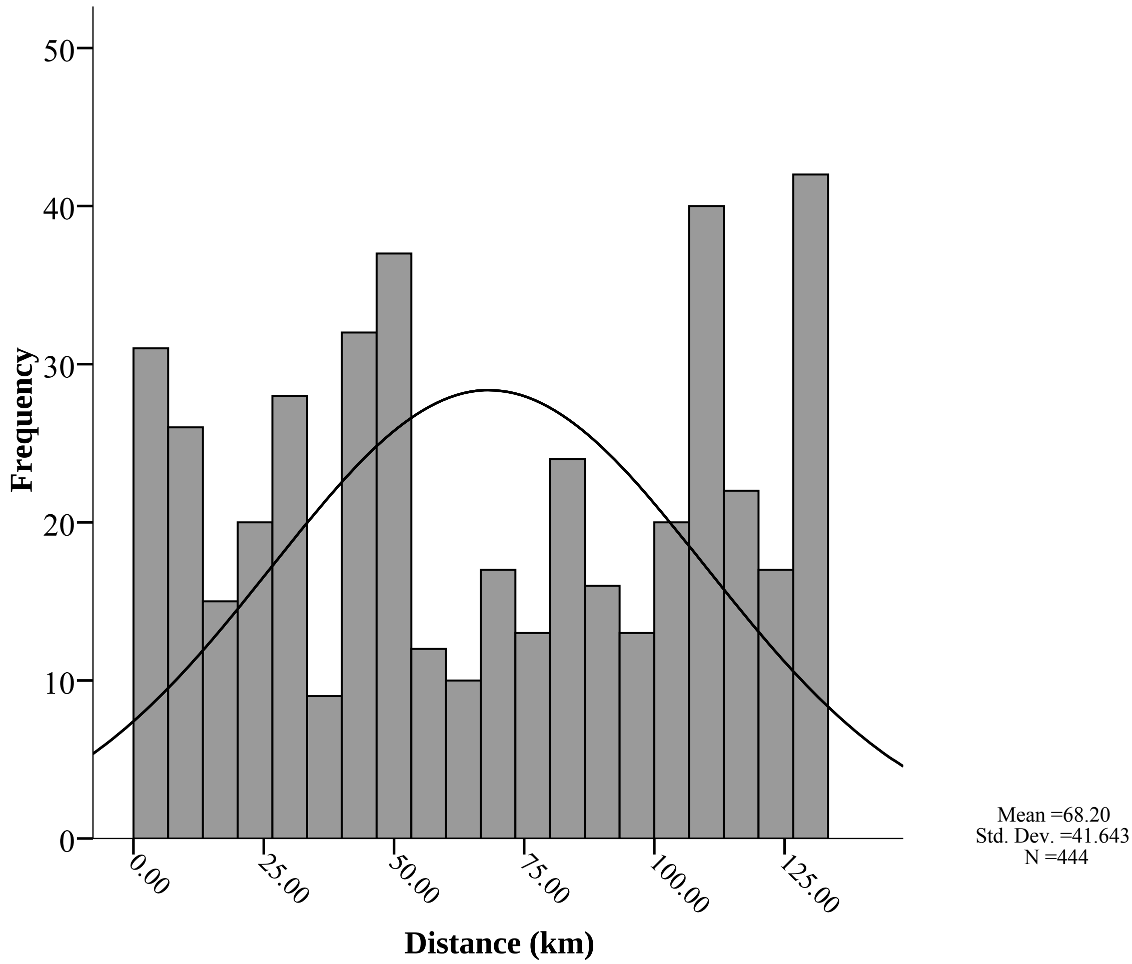


Figure 36: Histogram of distances from site of stranding event to 50 m isobath for all combined. Includes a normal distribution curve.

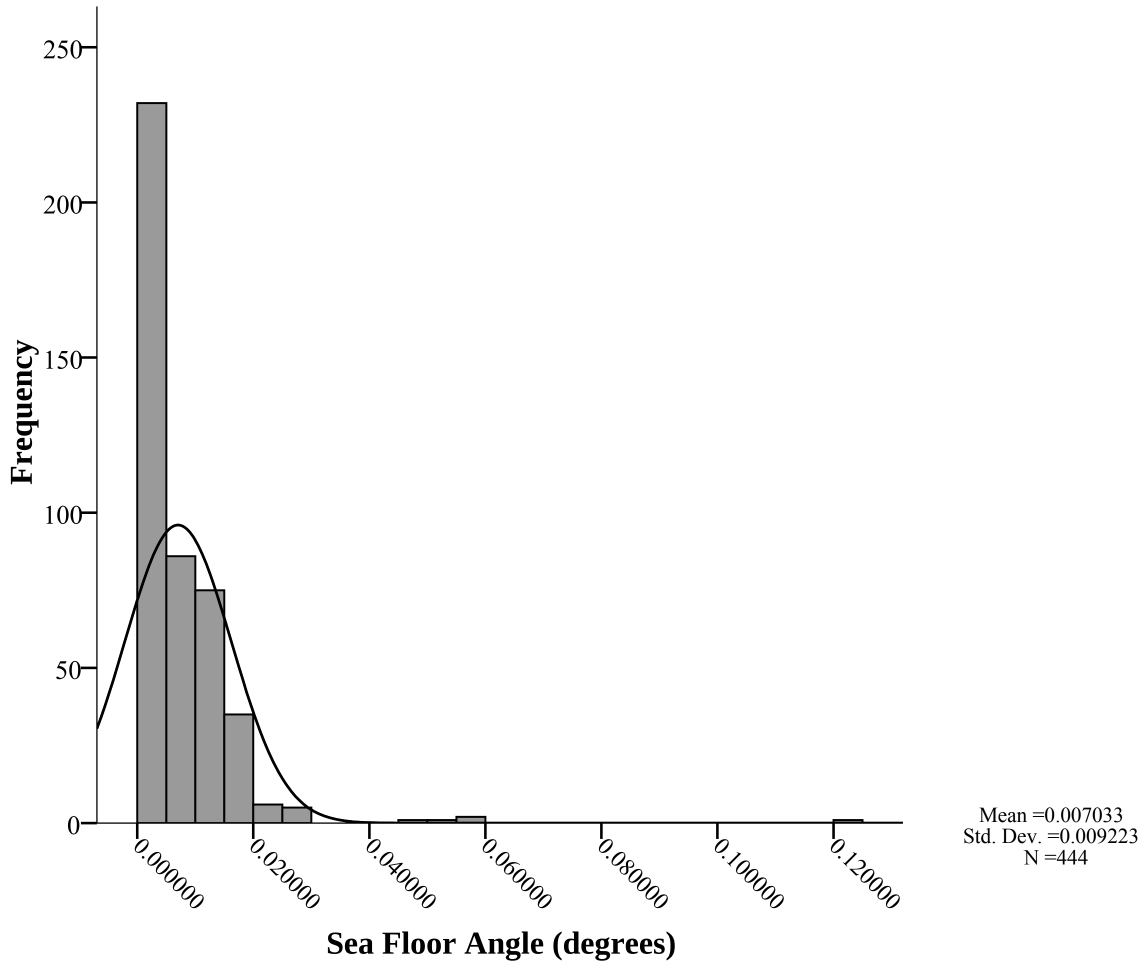


Figure 37: Histogram of bottom slope from site of stranding event to 10 m isobath for all combined. Includes a normal distribution curve highlighting the left skew in the data set.

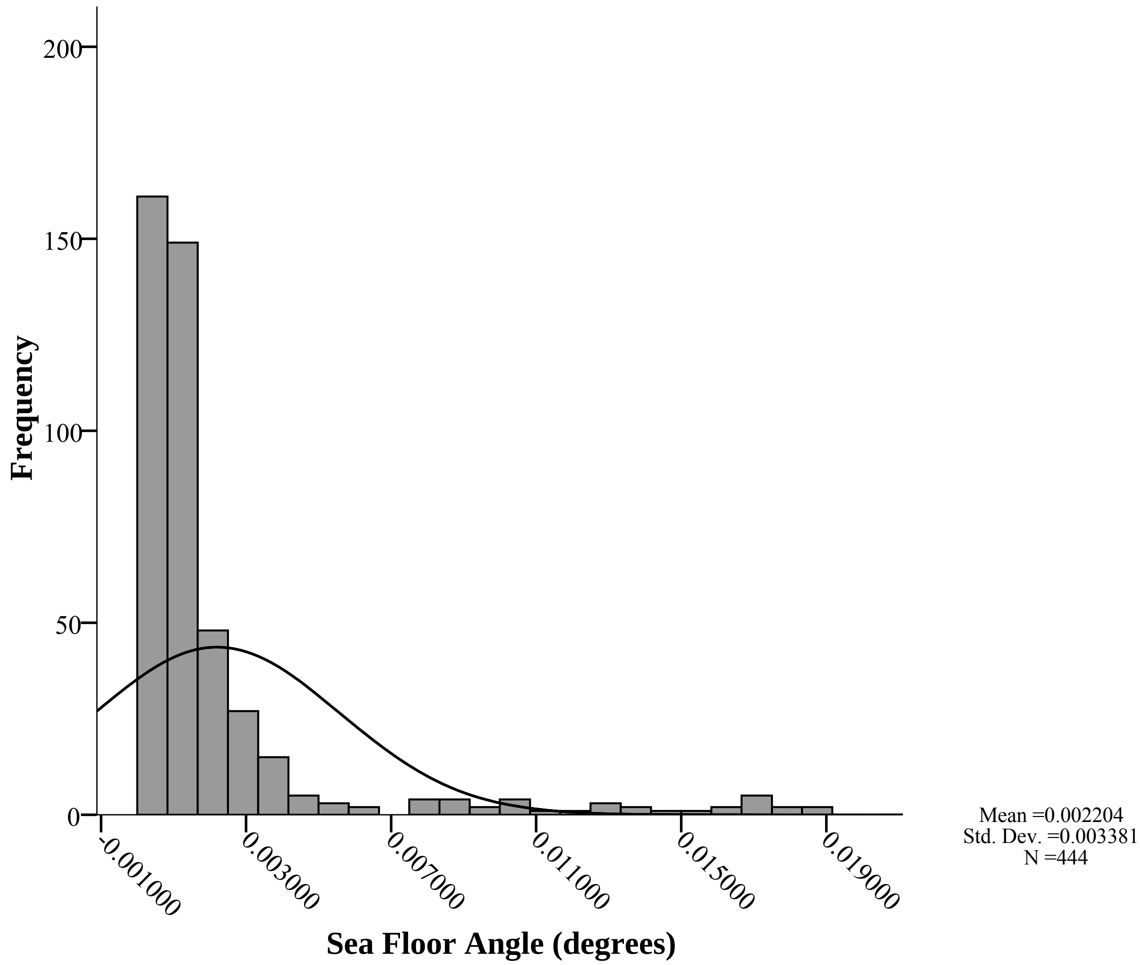


Figure 38: Histogram of bottom slope from site of stranding event to 20 m isobath for all combined. Includes a normal distribution curve highlighting the left skew in the data set.

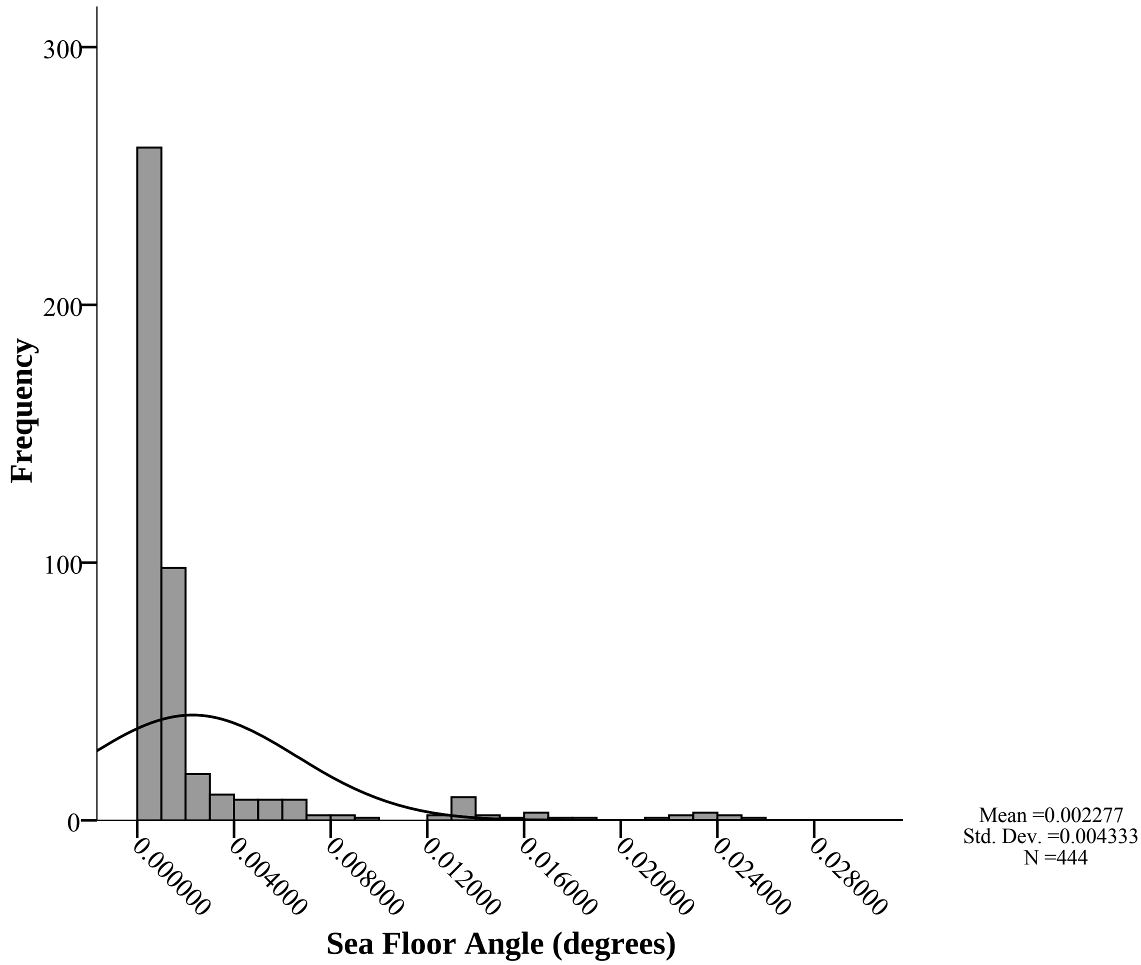


Figure 39: Histogram of bottom slope from site of stranding event to 50 m isobath for all combined. Includes a normal distribution curve highlighting the left skew in the data set.

	Isobath	N	Minimum	Maximum	Mean	Std.	Skewness
Strandings	10 m	251	8.00E-02	2.11E+01	1.85E+00	2.25E+00	4.27E+00
	20 m	251	1.07E+00	4.20E+01	3.33E+00	7.88E+00	3.47E-01
	50 m	251	1.97E+00	1.29E+02	4.38E+01	3.26E+01	6.90E-01
	10 m slope	251	8.00E-05	1.25E-01	1.07E-02	1.06E-02	5.95E+00
	20 m slope	251	4.76E-04	1.87E-02	3.24E-03	4.16E-03	2.34E+00
	50 m slope	251	3.87E-04	2.54E-02	3.58E-03	5.41E-03	2.46E+00
Random	10 m	251	5.00E-02	1.63E+01	2.41E+00	3.14E+00	2.32E+00
	20 m	251	6.00E-01	5.33E+01	1.55E+01	1.20E+01	8.25E-01
	50 m	251	1.35E+00	1.39E+02	4.72E+01	4.09E+01	6.35E-01
	10 m slope	251	6.14E-04	2.00E-01	1.16E-02	1.44E-02	9.10E+00
	20 m slope	251	3.76E-04	3.33E-02	4.38E-03	6.13E-03	1.94E+00
	50 m slope	251	3.59E-04	3.70E-02	5.56E-03	8.02E-03	1.69E+00

Table 6: Descriptive statistics for the eastern Florida bathymetry analysis.

	Isobath	N	Minimum	Maximum	Mean	Std.	Skewness
Strandings	10 m	193	4.70E-01	2.34E+01	9.16E+00	5.18E+00	8.30E-02
	20 m	193	4.01E+00	5.84E+01	3.44E+01	1.42E+01	-8.00E-01
	50 m	193	1.19E+01	1.33E+02	1.00E+02	2.87E+01	-9.69E-01
	10 m slope	193	4.27E-04	2.11E-02	2.20E-03	2.80E-03	3.32E+00
	20 m slope	193	3.43E-04	4.98E-03	8.63E-04	7.86E-04	2.36E+00
	50 m slope	193	3.75E-04	4.21E-03	5.85E-04	3.73E-04	5.57E+00
Random	10 m	193	1.09E+00	2.12E+01	6.50E+00	4.98E+00	6.12E-01
	20 m	193	2.55E+00	6.16E+01	2.83E+01	1.54E+01	7.20E-02
	50 m	193	2.98E+01	1.38E+02	9.30E+01	2.74E+01	-4.96E-01
	10 m slope	193	4.72E-04	9.17E-03	3.24E-03	2.63E-03	6.49E-01
	20 m slope	193	3.25E-04	7.81E-03	1.12E-03	9.51E-04	2.64E+00
	50 m slope	193	3.62E-04	1.68E-03	6.08E-04	2.60E-04	1.88E+00

Table 7: Descriptive statistics for the Georgia, North Carolina and South Carolina bathymetry analysis.

3.4. Lunar Cycle Analysis

While some days during the lunar month have a higher frequency of strandings than others (Figure 40), there is no significant correlation between lunar day and frequency of stranding. Spearman's rank correlation coefficient returned a value of rho = 0.006, with a significance of $p = 0.892$.

	Isobath	N	Minimum	Maximum	Mean	Std.	Skewness
Strandings	10 m	444	8.00E-02	2.34E+01	5.03E+00	5.26E+00	1.12E+00
	20 m	444	1.07E+00	5.84E+01	2.25E+01	1.52E+01	4.88E-01
	50 m	444	1.97E+00	1.33E+02	6.82E+01	4.16E+01	-9.00E-03
	10 m slope	444	8.00E-05	1.25E+02	7.03E-03	9.22E-03	5.97E+00
	20 m slope	444	3.43E-04	1.87E-02	2.20E-03	3.38E-03	3.21E+00
	50 m slope	444	3.75E-04	2.54E-02	2.28E-03	4.33E-03	3.47E+00
Random	10 m	444	5.00E-02	2.12E+01	4.19E+00	4.52E+00	1.30E+00
	20 m	444	6.00E-01	6.13E+01	2.11E+01	1.50E+01	5.53E-01
	50 m	444	1.35E+00	1.39E+02	6.71E+01	4.23E+01	-1.07E-01
	10 m slope	444	4.72E-04	2.00E-01	7.95E-03	1.17E-02	1.03E+01
	20 m slope	444	3.25E-04	3.33E-02	2.96E-03	4.92E-03	2.85E+00
	50 m slope	444	3.59E-04	3.70E-02	3.41E-03	6.51E-03	2.62E+00

Table 8: Descriptive statistics for the bathymetry analysis of the entire Atlantic coast – North Carolina, South Carolina, Georgia and eastern Florida combined.

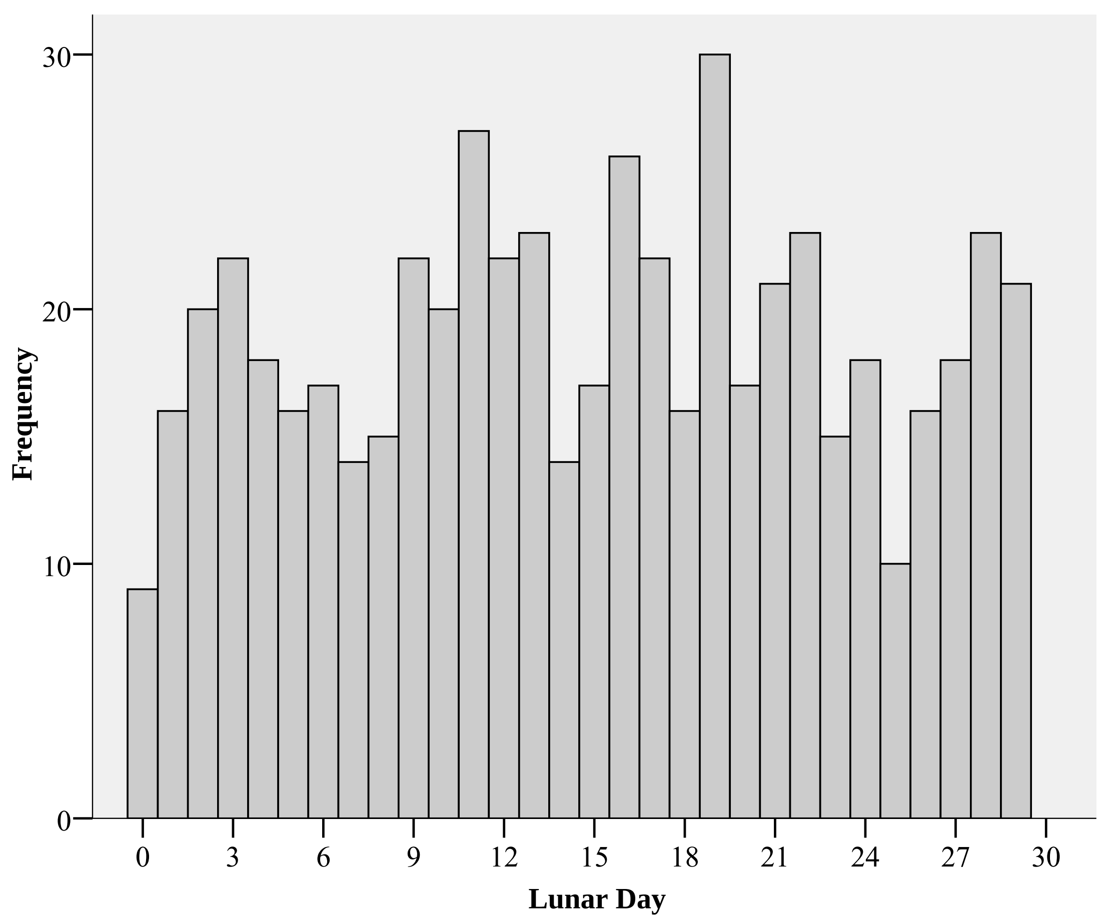


Figure 40: Histogram of *Kogia* sp. strandings during the lunar month. New moon begins at day 0 and full moon occurs at day 14.75.

4. Discussion

4.1. Seasonality and Wind Forcing

Stranding rates may fluctuate seasonally according to the prevailing weather conditions as distressed animals may be more prone to strand during irregular weather. A definite seasonal trend was observed in the *Kogia* sp. strandings, with summer and winter having a higher prevalence of strandings than spring and fall. A similar pattern was also observed in a study of mass strandings in Florida (Walker 2003, Walker *et al*. 2005). The bimodal pattern revealed here is in contrast to a unimodal pattern of stranding seasonality found in the northwest United States (Norman *et al*. 2004). In a study of stranded pygmy sperm whales in New Zealand, Beaston (2007) found that the majority of strandings occurred during late summer and early fall, corresponding with the results presented here. The stronger peak of *Kogia* sp. strandings in this analysis in summer found in the Carolinas, Georgia & east Florida, western Florida, and the Florida Panhandle & Mississippi is in contrast to the stronger winter peak found in the Florida Keys and the fall peak in Texas. This suggests that the factors that affect strandings differ based on the season and the location.

Almost all of the pygmy sperm whale strandings in the northeast Atlantic analyzed by Santos *et al*. (2006) occurred in the first and last quarter of the year, winter and fall, respectively. The authors suspect this could reflect the seasonal appearance of the species in the northeast Atlantic. Many of these strandings take place during fall months where the coastline is oriented to the North. In South Africa, pygmy sperm whales stranded more frequently in winter and spring, while dwarf sperm whales stranded more frequently in late summer and winter (Plön 2004). It is apparent in Figures

5 and 6 that pygmy and dwarf sperm whales are present off the coast of the SEUS year-round and increases in strandings typically occur during summer months. Over half of the cetacean strandings in the southwest Gulf of Mexico in 1993 and 1994 occurred during later winter and spring (Ortega-Argueta *et al*. 2005). It is obvious that there is differing seasonality in strandings depending on location, and environmental factors such as local winds and bathymetry may affect the locality and timing of *Kogia* sp. strandings.

Seasonal changes in wind forcing have been distinguished as an important aspect of the ocean environment (Fiedler 2002). These physical events may induce biological changes, or biological changes may intensify due to the environmental conditions. Major coastal upwelling regions are on the eastern boundaries of oceans. The SEUS is on a western boundary and does not experience winds persistently favorable for continued coastal upwelling (Barber and Smith 1981). However, wind stress does cause the movement of water (Figures 10 through 12, 14 through 18) and well-defined summer upwelling has been documented along the Atlantic coast of Central Florida (Pitts and Smith 1997). Upwelling and downwelling along the North Carolina shelf are confined to the coast during stratified conditions in the summer, and at the shelfbreak during unstratified conditions in the fall (Lentz 2001). The coastal location of upwelling and downwelling activity in the summer in North Carolina corresponds to the increase in *Kogia* sp. strandings seen in summer months. Sea level and wind correlations revealed in this analysis are consistent with the ocean response being the Ekman transport giving upwelling when wind is alongshore and positive (to the right when facing the beach), and giving downwelling when wind is alongshore and negative (to the left when facing the beach).

While the wind conditions in winter months may not be ideal for upwelling conditions, upwelling does occur due to the eddies of the Florida Current. The smaller peak of *Kogia* sp. strandings in the winter months correlate to the season that frontal eddies of the Florida Current tend to create upwelling conditions (Pitts and Smith 1997). Times of peak strandings coincide with both the summer wind-induced upwelling and the winter eddy-induced upwelling. Upwelling has not been indicated during spring or fall months, and this corresponds to the lower number of total strandings observed during spring and fall months. Nearshore upwelling may draw prey and thus *Kogia* sp. into the area, and when the conditions cause a relaxation of upwelling or a change to downwelling-favorable conditions (Shanks *et al*. 2000), bulk movement of water onshore may draw *Kogia* sp. even closer to shore. Although it is unlikely that wind forcing alone will cause an individual *Kogia* sp. to strand, the direction and speed of wind affects the movement of water. If the animals are ill or otherwise compromised, certain navigation methods may become more important and the animal may follow certain water properties into an atypical environment, thus stranding.

According to Walker *et al.* (2005), the prevailing winds in the summer on the east coast of Florida are from the south, which generally force water away from the coast. The upwelling-favorable winds during summer months at each buoy in Florida agree with this, as do wind trends for buoys in Georgia, South Carolina, and North Carolina (Figures 20 and 21). In contrast, the prevailing winds on the east coast of Florida during winter months are from the north, causing bulk water movement towards the shore, and this may contribute to the peak of strandings in the winter along the east coast of Florida and Georgia by moving animals closer to shore. In this analysis, downwelling-favorable winds were observed on the east coast of Florida during the fall and winter, and upwelling-favorable winds were observed during the summer. This is in agreement with the upwelling seen in the summer by Pitts and Smith (1997) along the central Florida east coast. It is interesting that the seasons with the peaks in strandings, winter and summer, have very different wind patterns. This suggests that wind forcing alone does not alter the frequency of *Kogia* sp. strandings. Water does not respond to wind-forcing one-dimensionally, and the wind velocities observed may not reflect the true properties of the water movement.

On the west coast of Florida, the prevailing winds and water movements are the opposite of those on the east coast of Florida. This suggests that it is the wind driven movement of the water and/or frontal eddies that is important, and not the season itself. Interestingly, the differential between the seasons of peak strandings (winter and summer) and the seasons of few strandings (spring and fall) is greater in this region than on the east coast of Florida. This suggests that the two factors potentially influencing *Kogia* sp. movements, i.e. the movement of prey driven by water, and bulk water movement, have a greater influence on *Kogia* sp. movements along the west coast of Florida than they do on the east coast of Florida. In Texas, the prevailing winds in the fall are also from the north or northeast (Ward 1916, McGowen *et al*. 1977). Due to Ekman Transport, winds from these directions would likely cause onshore movement of water and prey (Barber and Smith 1981), possibly drawing animals closer to the shoreline, increasing their risk of stranding. In the summer, the prevailing winds in Texas are from the south and southeast, causing water movements parallel to the coastline. This may explain why Texas has a peak of *Kogia* sp. strandings in the fall, with fewer strandings in the winter and summer.

In a study of *Kogia* sp. strandings in South Africa, Plön (2004) reported that during easterly winds, a localized upwelling cell forms, and is especially conspicuous at headlands. This wind-induced upwelling occurs yearly during the summer months of February and/or March, the same time-frame as the peak in dwarf sperm whale strandings. It may be that the prevailing winds and unique bathymetry at the headlands are both factors in dwarf sperm whale strandings.

Note that wind intensity patterns 1 and 4 were identified by Walker *et al.* (2005) as preceding 15/16 mass strandings that occurred on the east coast of Florida between 1977 and 2002. Walker *et al*. (2005) identified pattern 4 as the most frequent while in the current analysis pattern 1 was the most common. An important distinction is that Walker looked at mass strandings of various species, with a focus on pilot whales, while this analysis covered *Kogia* sp. only, and *Kogia* sp. rarely mass strand. However, *Kogia* sp. are characterized as offshore animals and like pilot whales are squid feeders (Santos *et al*. 2006; Thurston 1995). This analysis also covered a larger and more complex geographic range than Walker *et al*. (2005). The greatest percentage of strandings (28.5%) occurred within a week after a change from downwelling-favorable to upwelling-favorable winds. Of these, the greatest percentage (30.2%) occurred during the winter downwelling favorable season, as well as an additional 27.9% during the fall downwelling season. It appears that a change from the ‘normal’ downwelling conditions may affect strandings in the winter months. Of the twenty-seven strandings that occurred within a week after a change from upwelling-favorable conditions to downwelling-favorable conditions, 29.6%

occurred during summer upwelling favorable months. Again, it appears that a change from the 'normal' conditions of summer may affect strandings. However, of the thirty strandings with the second most common wind pattern – upwelling favorable conditions for the entire two weeks prior to stranding – 53.3% occurred during the summer upwelling favorable months. It appears here that prolonged conditions, not a change from the normal conditions of the season may affect strandings.

4.2. Bathymetric Effects on Strandings

Cetacean distribution is highly affected by bathymetry and topography. In a study of beaked whales off the northeastern coast of the United States, Waring *et al*. (2001) found that whales were associated with two features: (1) the cool, shelf-edge water between the 200 m and 2000 m isobaths and (2) submarine canyons. Many studies have concluded that gradually sloping beaches may be a factor in cetacean strandings (Mazzuca *et al*. 1999). Coasts with gentle slopes with a rapid drop in depth close to shore may create an environment favorable to cetacean strandings (Walker *et al*. 2005). It has been suggested that a gradually sloping beach may disrupt sonar reflection, causing confusion and subsequent stranding in areas that may be acoustic 'dead zones' (Sundaram *et al*. 2006).

In a study of mass strandings in Florida, Walker *et al*. (2005) found that the mean distance from shore to all isobaths was shorter for stranding sites than for randomly selected sites. However, using the same methods as Walker *et al*. (2005), the results presented here provide clear evidence that measurements of distances from *Kogia* sp. strandings to isobaths in Florida were not different from random points. This difference in results may be attributed to the differences in sample size for the two analyses or it may be an aspect of the differences between mass and single strandings. In this analysis, similar to Walker *et al*. (2005), the skewness statistics for distance to stranding sites and bottom slope are all positive in Florida, indicating a nonsignificant tendency towards shorter distances and smaller angles – a gentle sloping to each isobath.

Interestingly, measurements of distances from *Kogia* sp. strandings to isobaths in Georgia, North Carolina and South Carolina are different from distances of random points to isobaths. Distances to isobaths are shorter at sites of strandings than at randomly selected sites. Skewness statistics for this northern region of the SEUS Atlantic coast indicate longer distances from stranding sites to the 20 m and 50 m isobaths and from random points to 50 m isobaths. Strandings are grouped into certain areas and not randomly distributed across the coast. This indicates that this part of the SEUS Atlantic coast behaves differently from the Florida Atlantic coast. In fact, the coast off North and South Carolina has a much wider continental shelf than Florida's Atlantic coast. It indeed has a gently sloping coast like Florida, but the deeper depths are farther from the coast. Local currents may behave differently in this region than off of Florida and the placement of carcasses may be affected by these currents. Another confounding factor is that in more remote areas such as the Georgia outer islands, stranding effort is limited and perhaps strandings are not reported.

If the SEUS Atlantic coast is examined as a whole, the picture changes slightly. Measurements of distances from *Kogia* sp. strandings to the 10 m isobath and the slope of the seafloor from strandings to the 10 m isobath are significantly different from randomly selected points. In addition, distance from stranding sites and random points to the 50 m isobath tend to be longer. This occurs because the northern and southern areas of the

SEUS Atlantic coast have differing widths of the continental shelf. Caution should be taken when comparing the northern region with Florida and when combining the data into one set as Maptech® Chart Navigator and Contour Professional was used to analyze Florida strandings while MapTech® Chart Navigator Professional was used to analyze Georgia, South Carolina, and North Carolina strandings. The two software sets were produced by the same company; Chart Navigator Professional replaced Chart Navigator and Contour Professional, but it did not have as great of functionality for the purposes of this analysis, and the resolution of the analysis was not as high.

Walker (2003) proposed that the change from high to low sea floor relief in Florida may be important in mass cetacean stranding events. This may be the case for single strandings of pygmy and dwarf sperm whales, however, these strandings are distributed over the entire Florida Atlantic coast. Pygmy and dwarf sperm whales are most often found in deep waters (Davis *et al*. 1998). The unique bathymetry of Florida – gradually sloping coasts with a drop close to shore, allowing a closer deep isobath – may contribute to strandings across the entire Florida Atlantic coast. This may be why no difference was found between stranding sites and random points. It was also found that the coasts of Georgia, South Carolina and North Carolina had gently sloping topography with the deeper waters further from the shore. These results suggest that a gently sloping coast, whether situated on a wide or thin shelf, may correlate with *Kogia* sp. strandings.

4.3. Lunar Cycle Effects on Strandings

Many marine organisms, including various zooplankton and reef fishes, have been found to have varying behavior according to lunar cycles (Gliwicz 1986, Robertson *et al*. 1990). The only previous study linking cetacean strandings to the lunar cycle involved sperm whales (Anon. 1979). The predicted cause of this stranding was that the whales were following squid, their prey, which are known to enter shallow water during periods when the moon is dark, around the new moon. This was the assumption for the present analysis because *Kogia* sp. consume squid as the bulk of their diet. However, *Kogia* sp. in the SEUS are not more likely to strand during any particular phase of the moon. Some potential explanations include: 1) their prey do not follow a lunar cycle, 2) the animals that stranded were not closely following their prey, 3) prey may follow lunar cycle but different species of prey are available at all times and *Kogia* sp. are opportunistic predators, expressing no preference in prey. In order to test this further, one would need to determine the abundance of *Kogia* sp. prey in the SEUS and determine whether those prey follow the lunar cycle.

5. Conclusion

Some scientists believe that single animal strandings are a consequence of disease and animals are brought to shore passively, while mass strandings occur actively. However, I present evidence here that this may not always be the case for pygmy and dwarf sperm whales. *Kogia* sp. are often 'lone' travelers, so whether they come to shore actively or passively, they will likely be single animals. Pygmy sperm whales occur individually or in groups of up to six and dwarf sperm whales occur in groups of up to ten animals (Caldwell and Caldwell 1989). It is clear that summer is the time of year when pygmy and dwarf sperm whales strand more frequently. Many factors may affect this higher likelihood: temperature, availability of prey, and wind patterns. The forced movement of water due to wind changes may affect where prey is located as well as the location and movement frontal convergences. Bulk movement of water may actually help to pull animals into shore (i.e. passive movement). However, the location of frontal convergences may dictate where *Kogia* sp. are when they feed, and subsequent environmental changes may affect strandings (i.e. a combination of active and passive movement).

The bathymetry of a coastline and how the water moves due to the bathymetry could have an effect on where cetaceans strand. Florida's Atlantic coastline is generally gradually sloping with deep water nearer to the shoreline. This deep water close to shore is likely a major habitat for deep diving cetacean species such as dwarf and pygmy sperm whales, and having a deep water area close to the coastline may be the reason numerous *Kogia* sp. are stranded along the whole of Florida's east coast. The rest of the SEUS Atlantic coast from Georgia northwards through North Carolina has a different morphology from the Florida Atlantic coast. The deep water areas are further from shore, and the bathymetry is generally very gently sloping. Physical, abiotic factors are important in determining the location and timing of future stranding events.

Two scenarios present themselves here. During the summer upwelling season, a wind-induced oceanic front may develop offshore in deeper waters off central Florida and in the shallow, stratified waters of North Carolina. A shift in wind direction and intensity may cause a weakening of this upwelling or a shift to downwelling conditions. The upwelling front may move inshore, drawing prey and subsequently *Kogia* sp. closer to shore. A further change in winds from downwelling-favorable back to the seasonal upwelling-favorable may cause the front to develop again further from shore. This could cause confusion in the animals and they may consequently strand.

The second scenario is almost opposite of the summer upwelling season scenario. During the winter downwelling season, no wind-induced oceanic front will be located near the coast. A change in winds to upwelling-favorable may induce upwelling and a front may develop, concentrating prey and therefore *Kogia* sp. A shift back to the seasonal downwelling conditions may cause the front to dissipate. The whales, especially if compromised by illness, may become confused by the shallow sloping bathymetry, and consequently strand. The second scenario presented may also be more affected by frontal eddies of the Florida Current. While wind-driven water movement would produce downwelling if the intensity was strong enough, upwelling may actually occur as eddies move along the coast. This would actually cause events as described in the first scenario, with the difference being that the eddy causes the upwelling instead of the wind.

These scenarios may not occur exactly as described, but it is obvious that for a stranding to occur, several factors must coexist. This analysis of the SEUS Atlantic coast found wind induced water movement and bathymetry to be important in the timing and location of *Kogia* sp. stranding events. It is important to note that physical abiotic factors may not be the initial cause of the stranding, but they may affect the movements of the whales. Biological issues, such as illness, likely compromise the animals, and the physical factors affect movement towards the coast and where and when the whale will strand.

Clearly, dwarf and pygmy sperm whale strandings remain a mystery. This study has not taken into consideration any pathology of the stranded animals, but it has provided evidence of correlations of strandings and environmental factors such as wind direction and speed, and bathymetry of a coastline. Further studies should focus on the pathology of the animals to determine illness or injury patterns. In situ research of the preferred prey items of dwarf and pygmy sperm whales may also provide answers. Research should focus on whether prey follow a lunar/tidal pattern, and how wind intensity and bathymetry may affect concentration of prey species.

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