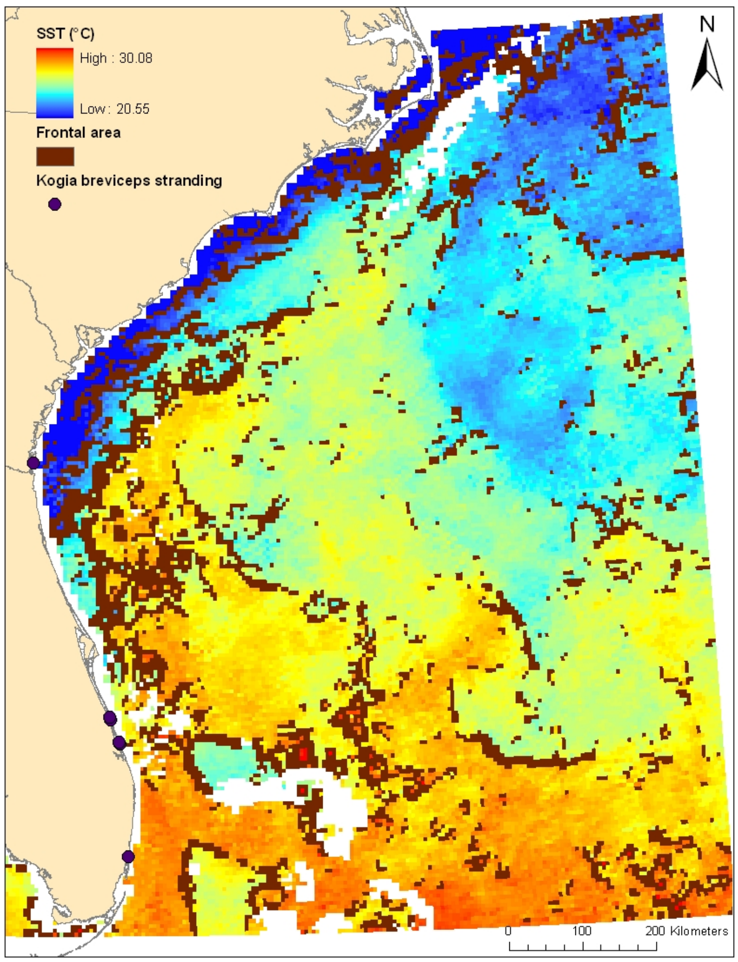
Modeling pygmy sperm whale (*Kogia breviceps*, De Blainville 1838) strandings along the southeast coast of the United States from 1992 to 2006 in relation to environmental factors



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Modeling pygmy sperm whale (*Kogia breviceps*, De Blainville 1838) strandings along the southeast coast of the United States from 1992 to 2006 in relation to environmental factors

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ABSTRACT

Pygmy sperm whales are the second most commonly stranded marine mammal in the Southeastern Unites States (SEUS). They most often strand alive and the causes of these events remain largely unknown. Generalized linear models were built to identify potential relationships among environmental factors and the occurrence of pygmy sperm whale strandings in the SEUS. Two methods were used to model environmental parameters depending on the nature of the data. One method used data from NOAA buoys compiled over a week before a stranding event. Predictor variables included hourly wind direction and speed, wave height, average wave period, barometric pressure, and water temperature. The other method used Sea Surface Temperature data from satellite images compiled monthly, monthly Multivariate El Niño Southern Oscillation Index (MEI), and bathymetric data. Frontal features were extracted from the images using ArcMap Geographic Information System and landscape metrics were computed on these images in FRAGSTATS. The model compiled from buoy data was relatively stronger (AIC = 497.5) at predicting strandings. It indicated that more strandings occurred when there were sustained high wind speeds, low barometric pressures, and swell waves in the week before stranding events. While the other model was relatively weaker (AIC = 718.7), it showed that less numerous fronts and high MEI index were generally associated with a higher number of strandings. This study is a step toward appreciating which environmental factors may contribute to the observed marine mammal stranding patterns as well as the distribution of pygmy sperm whales. It is an attempt at building predictive statistical models that could be useful for the management of cetaceans.

INTRODUCTION

Marine mammal strandings occur when dead or alive individual(s) end up on the beach, out of their natural habitat. These events have been reported since antiquity, affecting the vast majority of known species, and occurring worldwide (Odell, 1987). However, the causes of many strandings still are not fully understood (Walker *et al*., 2005). Among numerous hypotheses, adverse meteorological conditions have been linked to strandings (Geraci and St. Aubin, 1979). For example, rising barometric pressure has been correlated to strandings because it indicated that low pressures, which mean inclement weather conditions, occurred recently before a stranding event (Brabyn, 1991). It is possible that storms disorient offshore species leading animals to stray far inshore compared to their usual habitat range (Mignucci-Giannoni *et al*., 1999) where they might forage less effectively. In such cases it is likely that weakened animals might be left at the mercy of inshore currents (Lopez *et al*., 2002). Oceanographic characteristics such as upwelling, downwelling and other wind-driven currents also seem to be associated with stranding of marine mammals (Brabyn and McLean, 1992; Norman *et al*., 2004). Walker *et al*. (2005) observed a shift in wind, which corresponds to a switch from upwelling to downwelling conditions, in the week preceding mass strandings of cetaceans on the east coast of Florida. Oceanographic conditions may cause a shift in prey distribution such that pelagic predators venture inshore outside of their natural habitat, exposing the whales to unfamiliar currents and topography. Also, it is possible that carcasses that are close to the shore are more influenced by coastal currents, which may bring them to the beach (Lopez *et al*., 2002; Norman *et al*., 2004).

Kogiidae are distributed in tropical and temperate water in all three oceans. Pygmy (*Kogia breviceps*) and dwarf (*K.* sima) sperm whales are offshore species that can dive deep, around 500 m to 1000 m, and for extended periods of time (Mullin *et al*., 2004; Baird, 2005). They seem to live independently or in small groups (Caldwell and Caldwell, 1989). They tend to shy away from vessels and only rarely display active behavior at the surface (Baird, 2005). This makes them hard to study at sea and therefore *Kogia* spp. are known mostly through the study of stranded specimens, so that their basic biology is still largely not understood (Manire *et al*., 2004, Braid 2005). Even though pygmy sperm whales are considered a relatively rare species, they strand in high numbers compared to other species and in many cases they strand alive with unclear causes for the event. Two regions of the world seem to have especially high number of pygmy and dwarf sperm whale strandings: around the coasts of South Africa and along the Southeast coast of the United States (SEUS) (Best, 1982; Sylvestre, 1983; McAlpine, 2002). In the SEUS pygmy sperm whales are the second most commonly stranded cetacean (Odell, 1991). Both regions mentioned above are characterized by strong oceanic boundary currents. Along the Atlantic coast of the SEUS, the Gulf Stream is particularly close to the continental shelf. As a result, the water from the Gulf Stream interacts directly with surrounding waters above the continental slope, through meandering and formation of eddies (Haney, 1986; Miller and Lee, 1995). Frontal zones occur when different water masses come into contact. The rapidly changing conditions of temperature, salinity, nutrients, and dissolved gases along a front create a zone where organisms concentrate. Predators are known to follow these areas of enhanced productivity (Brandt and Wadley, 1981; Baumgartner *et al.*, 2000). Frontal zones in the study region occur over the upper continental slope where cooler waters along the continental shelf meet the warm, saline waters of the Gulf Stream (Bane and Brooks, 1979; Lee *et al*., 1991). Similar types of fronts and eddies can be found along other western boundary currents such as the Agulhas Current along the eastern coast of South Africa (Owen, 1981).

Oceanographic conditions and large scale fronts are linked to weather and connected to large scale climatic phenomenon such as the El Niño Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) (Almarez and Almat, 2004). ENSO and NAO are known to have worldwide effects on atmospheric and oceanic conditions (Stenseth *et al.*, 2003). For instance, both climatic anomalies have been shown to alter the path of the Gulf Stream and affect shelf water north of Cape Hatteras (Taylor *et al.*, 1998). Such changes in oceanic conditions can have strong effects on primary productivity, which can be reflected in the distribution of species at higher trophic levels (Planque and Taylor, 1998).

Finally, strandings seem to occur most often at specific sites (Gearci and St. Aubin, 1979; Best, 1982). Bathymetric features could be linked to increased frequency of strandings at specific sites directly by disrupting echolocation signals that affect the navigation ability of certain species (Kirschvnik, 1990; Sundaram *et al.*, 2006) or indirectly by creating currents that carry sick animals or carcasses toward the coast.

The main objectives of this study were to investigate a potential correlation between the number of pygmy sperm whale strandings along the Atlantic coast of the SEUS and environmental factors, as well as compare the power of models built from two different sources of data and on different time scales. One model tested the hypothesis that along the SEUS changes in wind speed and direction, barometric pressure, as well as oceanographic conditions (wave height, average wave period and sea surface temperature) are associated with strandings in the following week. The other model tested a three-fold hypothesis. First, strandings occur predominantly where the shelf is narrow and the slope is steep (as defined by the distance of the 50 m contour line to the coast). Second, high (positive or negative) climatic indices for ENSO and NAO are associated with higher number of strandings. Finally, the configuration of surface frontal features (considered areas of high productivity) has an effect on the distribution and abundance of prey such that prey aggregate along well defined fronts and contribute to the stranding of pygmy sperm whales when fronts are closer to shore.

METHODS

Stranding Data

Location and date of pygmy sperm whale strandings from 1992 to 2006, inclusive, were obtained upon request through the National Oceanic and Atmospheric Administration, National Marine Mammal Stranding Network database. Missing geographic coordinates were estimated using Google Earth™ mapping service, based on descriptions in the stranding record.

Age classes were defined according to length as follows. In the case of females, any individual less than 150 cm in length was considered a calf, individuals between 150 cm and 190 cm were considered juveniles, individuals between 190 cm and 260 cm were considered sub-adults, and individuals above 260 cm in length were considered adults. In the case of males, any individual less than 170 cm in length was considered a calf, individuals between 170 cm and 200 cm were considered juveniles, individuals between 200 cm and 270 cm were considered sub-adults, and individuals above 270 cm in length were considered adults.

Months were grouped to reflect seasons in the studied regions: January to March (winter), April to June (spring), July to September (summer), and October to December (fall). Cross tabulation analysis in SPSS 16.0 for windows (SPPSS Inc., IBM Corporation, Armonk, NY) was used in order to determine if the number of strandings varied significantly according to season. Kruskall-Wallis tests and Tukey's HSD were performed in R 2.8.1 (Free Software Foundation. Inc., Boston, MA) and used to test for the effect of season on the length of stranded animals.

Strandings were plotted in ArcGIS 9.2 on a map of the United States provided by ESRI (Redlands, CA) and projected into UTM coordinate system (NAD_1983_UTM_Zone_17N). The density tool was used to analyze the distribution of strandings along the coast (Figure 1).

Buoy Data

Hourly wind direction and speed, wave height, average wave period, barometric pressure, and water temperature were obtained from NOAA's National Data Buoy Center (http://www.ndbc.noaa.gov/). Nine buoys were chosen to cover the study area and dates corresponding to stranding records: 41001 (east of Cape Hatteras, NC, 34.68°N, 72.66°W), 41002 (East of Charleston, SC, 32.32°N, 75.36°W) 41004 (southeast of Charleston, SC, 32.50°N, 79.10°W), 41008 (Gray's Reef, southeast of Savannah, GA, 31.40°N, 80.87°W) 41009 (east of Cape Canaveral, FL, 28.50°N, 80.16°W), 41010 (east of Cape Canaveral, FL, 28.95°N, 78.48°W), 41022 (Olympic Southwest, 31.89°N, 80.86°W), FPSN7 (Frying Pan Shoals, NC, 33.48°N, 77.59°W), and FWYF1 (Fowey Rock, FL, 25.59°N, 81.1°W) (Figure 2).

Each stranding was paired with the closest buoy that had available data for the week before the stranding date (stranding event). In order to account for months with no strandings recorded in the studied region, a random date was generated in SPSS for each of these months. These dates were randomly assigned a buoy (no stranding event). A program written in R 2.8.1 was used to decompose the wind vector into two orthogonal components, so as to determine wind magnitude and direction. The mean, minimum, maximum and range of each variable retrieved from the buoys were calculated over an eight-day period including a week prior to the stranding/no stranding events.

Environmental variables were aggregated monthly in SPSS 16.0. The variables included the median of the mean and range of the variables, the minimum of each variable minimum, and the maximum of each variable maximum. Some variables were expected to be correlated, so a correlation matrix was performed in SPSS 16.0 to insure that no highly correlated variables (coefficient equal to or more than 0.9) were included in the models. The sum of strandings per month over the study region was the dependent variable.

Satellite Data and GIS

Satellite images provide a way to study the landscape of the ocean surface (or seascape) and gain perspective on the dynamic environment in which marine animals live (Steele, 1989). Horizontal gradient in sea surface temperature (SST) is indicative of location and strength of oceanic fronts. Therefore, SST can be used to identify frontal features (Cayula and Cornillon, 1992). SST data derived from satellite imagery (Advanced Very High Resolution Radiometer Pathfinder 5) were obtained online with NASA's physical oceanography Distributive Active Archive Center's Ocean Earth Science Information Partner Tool (POET) (http://poet.jpl.nasa.gov) which provides 4 km resolution monthly averages. The geographical extent of the data was from 25 to 36 degrees of latitude north and 72 to 82 degrees of longitude west.

The SST images were used to identify the edges of surface fontal and mesoscale features in the Gulf Stream region. For this purpose, the images were projected into the UTM coordinate system (NAD_1983_UTM_Zone_17N) and clipped to within 400 km of the coast. The largest warm water feature was defined by reclassifying the surface layer to isolate temperatures falling above one standard deviation of the entire image (Figure 3). The distance from this feature to stranding locations was calculated using the "near" tool. For each month that had zero strandings, one hundred random points were generated along the coast and the distance from each point to the feature was averaged.

SST values were also plotted in GIS ArcMap 9.2 (ESRI, Redwood, CA) as rasters with cell size of 0.05 degrees and projected into the UTM coordinate system

(NAD_1983_UTM_Zone_17N) to identify fronts. The “slope” tool in the Spatial Analyst toolbox was used to identify zones where horizontal temperature gradients were high. The slope layer was then reclassified into two groups using the natural breaks method in order to isolate cells of strongest slope from the rest of the image. This method was chosen as the most effective in highlighting frontal zones where temperature changed rapidly (Figure 3). These frontal zones or patches formed the basis for applying landscape metrics. In addition, the “near tool” was used to calculate the distance from each stranding to the closest frontal zone. For each month that had zero strandings, one hundred random points were generated along the coast and the distance from each point to the nearest frontal zone was averaged.

Metrics used to describe how the structure of the environment reflects underlying biological processes in terrestrial landscape ecology can be applied to aquatic environments (Steele, 1989; Kracker, 1999; Turner, 2005). Landscape metrics were applied to the frontal seascape using Fragstats 3.3 (McGarigal *et al.*, 2002). For the purpose of this study, five different metrics were calculated on each monthly image. These metrics were chosen to maximize ways to quantify the sea surface features and capture information on the spatial configuration of the ocean “landscape”. Total number of patches (TNP) and largest patch index (LPI) were calculated in order to represent how many fronts were identified for that month and what percentage of the landscape was occupied by the largest front. The radius of gyration (Gyrate) measures patch extent and was used to represent overall size and shape of the fronts. A higher radius of gyration implies that patches are more elongated in shape as opposed to compact. Patch fractal dimension (Frac) is a measure of shape complexity of the fronts in the landscape. It is approximated by: 2*[log(perimeter)/log(area)]. It approaches 1 for simple geometric shapes and approaches 2 for convoluted shapes. Contiguity index (Contig) indicated the adjacency of fronts to each other. For both Frac and Contig the area-weighted mean (AM), coefficient of variation (CV), and range

(RA) were calculated. In the case of Gyrate, only the area-weighted mean and range were calculated; the coefficient of variation was not included because it was correlated with the area-weighted mean. Taken together, these landscape metrics provide information about the configuration of fronts as a feature across the sea surface and could be interpreted in term of organisms' distribution, movements, and predator-prey relationships (Table 1).

In order to monitor El Niño and La Niña phases, the monthly Multivariate El Niño Southern Oscillation Index (MEI) was used because it compiles six different variables (sea-level pressure, zonal and meridional components of surface wind, sea surface temperature, air temperature, and cloudiness), and therefore is best suited to represent worldwide ocean-atmosphere coupling (Wolter and Timlin, 1993). Monthly MEI was downloaded from NOAA's Earth System Research Laboratory web site (http://www.cdc.noaa.gov/people/klaus.wolter/MEI/table.html). Monthly North Atlantic Oscillation (NAO) indices were downloaded from NOAA's National Weather Service climate prediction center web site (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/norm.nao.monthly.b5001.current.ascii.table).

Gridded bathymetric data for the SEUS were derived from the NGDS 3 Arc-Second Coastal Relief Model available from NOAA's Geophysical Data Center (http://www.ngdc.noaa.gov/mgg/coastal/). Fifty meter contours were created using the "surface analyst contour tool" in ESRI ArcGIS 9.2. Contours were projected into the UTM coordinate system (NAD_1983_UTM_Zone_17N). The distance from each stranding point to the 50 m isobath was measured in GIS ArcMap 9.2 using the "near tool". For each month that had zero strandings, one hundred random points were generated along the coast and the distance from each point to the 50 m isobath was averaged.

Meteorological indices, seascape metrics and bathymetry data were aggregated monthly in SPSS 16.0. The variables included year, month, average and standard deviation of sea surface temperature, mean distance of each stranding edge of the largest warm water front (GS_near_dist), location of the closest front (Near_dist), and the 50 m isobath (Bathy) as well as the seascape metrics, El Niño and NAO indices. Some variable were expected to be correlated, so a correlation matrix was performed in SPSS 16.0 to insure that no highly correlated variables (coefficient equal to or more than 0.9) were included in the models. The sum of strandings per month over the study region was the dependent variable.

Generalized Linear Models for Both Data Sets

Analysis of large data sets that include variables spatially and temporally dependent make the use of classic multivariate methods problematic (Chandler, 2005). Generalized Linear Models (GLZ) have the advantage of allowing the distribution of the response to be chosen, and the relation with the predictor to be defined through a monotonic link function. Inferences are based on maximum likelihood (Bradshaw *et al.*, 2004; Chandler, 2005). Poisson distribution is appropriate to fit count data (Lindsey, 1997) and fit the distribution of the pygmy sperm whale strandings analyzed here (Figure 5).

Stepwise regression on a GLZ using Poisson distribution and log link function was performed in R 2.8.1 to determine which of the environmental variables were better predictors of the number of pygmy sperm whales stranded. The best model was chosen as the one with the lowest Akaike Information Criterion (AIC). The AIC is an index of model fit defined as: -2 * (maximized log-likelihood) + 2 * (number of variables). A lower AIC indicates a better fit (Fox, 2002). The model variation from the null was calculated as 100*((Null Deviance – Residual Deviance) / Null Deviance). An analysis of deviance with a χ^2-test was performed on the best model to test the significance of the variables included in the model. Visual inspection of the partial residual plots was used to identify trends.

RESULTS

Stranding Data

A total of 360 pygmy sperm whales were reported stranded on the Atlantic coast of the southern United States between 1992 and 2006. Sixty three percent of the individuals were still alive. The majority of the stranded animals were classified as adults, comprising 75% of the strandings. Otherwise, 8% were sub-adults, 3% were juveniles, and 9% were calves (Figure 6). The number of pygmy sperm whale strandings did not vary significantly according to season ($\chi^2_{(24,N=180)} = 29.04$, $p = 0.219$) (Figure 7). However, the length of the individuals stranded varied according to season ($\chi^2_{(3,N=343)}$, $p < 0.001$), with significantly larger individuals stranding during the first six months of the year (Figure 8). Four counties showed high densities of strandings from the cluster analysis in GIS: Charleston County, SC (n= 35), Brevard County, FL (n= 32), Chatham County, GA (n= 25), and Dare County, NC (n= 25) (Figure 1).

Buoy Data Model

The stepwise regression on the buoy data returned a model with an AIC of 497.48 (compared to 516.16 for the null model) (Table 2). This model explained 61.46% of the variation from the null. It should be noted that 17 events were omitted in the analysis due to gaps in the buoy data. The analysis of deviance (Dev) confirmed the significance of the minimum wind speed (Dev = 43.67, p < 0.001), maximum wind speed (Dev = 23.19, p <0.001), range of wind speed (Dev = 41.96, p < 0.001), mean wave height (Dev = 10.44, p < 0.01), maximum average wave period (Dev = 5.11, p = 0.02), range of average wave period (Dev = 39.01, p < 0.001), minimum barometric pressure (Dev = 4.98, p = 0.03), standard deviation of barometric pressure

(Dev = 26.56, $p < 0.001$) and maximum water temperature (Dev = 6.79, $p = 0.01$) (Table 3). It should be noted that the p-values given by the analysis of deviance would change slightly depending on the order in which the variables are entered in the model, but does not change the overall result. Partial residual plots showed a negative relationship between the number of strandings and minimum and range of wind speed and a positive relationship between the number of strandings and maximum wind speed (Figure 9). The plots showed a negative relationship with mean wave height (Figure 10) and the range of average wave period, but a positive relationship with maximum average wave period (Figure 11). Finally, strandings increased when barometric pressure reached extreme values as indicated by the standard deviation plot, and especially with low values, since minimum barometric pressure was significant (Figure 12). The plots also indicated a positive relationship with maximum water temperature (Figure 13).

Satellite Data and GIS Model

The stepwise regression on the generalized linear model of the distance, frontal, and meteorological indices gave a best model with an AIC of 718.73 (compared to 735.67 for the null model) (Table 4). This model explained only 8.01% of the variation from the null. The analysis of deviance confirmed the significance of the Multivariate El Niño Index (Dev = 9.81, $p < 0.002$), average SST (Dev = 4.89, $p = 0.03$) and the number of patches (Dev = 4.21, $p = 0.04$) (Table 5). It should be noted that the p-values given by the analysis of deviance would change slightly depending on the order in which the variables are entered in the model, but that the significance would not change and the overall result would be the same. The partial residual plots showed a positive relationship between the number of strandings in a month and MEI (Figure 14) as well as SST (Figure 15). The plots show a negative relationship with number of frontal features (TNP) (Figure 16).

DISCUSSION

Stranding Data

The lack of apparent seasonality in the number of strandings may indicate that there are no seasonal trends in factors associated with strandings and/or no seasonal migration of *Kogia breviceps* along the southeastern coast of the U.S. However, the difference in size of stranded individuals according to season may point towards a reproductive season. Pygmy sperm whale are thought to mate after parturition and have an 11 month gestation period, so that mating and calving occur around the same months (Plon, 2004). Significantly smaller individuals present in the stranding data from July to December could indicate that birthing and mating occurs in the summer through winter along the southeastern coast of the U.S. Considering that seasons are opposite in the northern and southern hemispheres, this seem to be in agreement with Ross (1979) and Plon (2004) who both identified calving and mating seasons to span over six to seven months from fall through spring around South Africa. Sylvestre, 1983 points to a reproductive season in winter to summer in Florida, however this estimation is based on one single cow-calf stranding.

The regions along the coast that were highlighted by the cluster analysis (Charleston, SC, Chatham, GA and Brevard, FL) correspond to two regions of even more complex oceanographic circulation than the rest of the studied area. One of these regions is situated just north of the Florida Strait, and is characterized by diverging isobaths on the outer shelf. The other region is the Charleston Gyre created because of the Charleston Bump, a singular geological element of the Blake Plateau. Both of these features influence the formation of eddies and fronts (Giovanni and Hare, 2001). Semi-permanent eddies have been shown to influence the foraging behavior of elephant seals (Simmons *et al.*, 2007). In addition, the Blake Plateau is abundant in squid (Weaver and Sedberry, 2001). Pygmy sperm whale distribution could be affected by such oceanographic features and the abundance of prey. The Atlantic coast of the Southern US is recognized as a very productive zone important for commercial fisheries (Giovanni and Hare, 2001). Therefore, these specific areas deserve specific attention in future studies investigating productivity, distribution of squid, and applicability to marine mammal strandings.

Buoy Data Model

The hypothesis that pygmy sperm whale strandings along the Atlantic coast of the SEUS were influenced by meteorological changes in the week before an event was supported. The model of meteorological data indicated that more strandings occurred when there were sustained high wind speeds in the week before stranding events. Wind direction did not appear in our final model, indicating that this variable did not predict strandings, which was unexpected. Walker *et al*. (2005) identified changes in wind directions, influencing changes in water circulation patterns, as a significant factor in the week before mass stranding events. This might indicate that causes for other cetacean mass strandings are different as compared to strandings of pygmy sperm whales, which do not commonly mass strand. Also, it might reflect a difference in methodology, which does not mean that shift in wind direction should be dismissed as a factor contributing to strandings. For instance, Walker *et al*. (2005) calculated wind direction in relation to the orientation of the coastline in order to determine upwelling versus downwelling conditions, while we looked at shifts in overall wind direction, regardless of the orientation to the coast. The model indicated that more strandings occurred when waves were consistently small with long average period. This is a sign of swell with waves having traveled a certain distance from their source. Ferrero *et al*. (2002) also identified wind speed and wave height as important factors in habitat preference of small cetaceans in the north Pacific. If that is also the case for pygmy sperm whales, then it could indirectly be linked to the observed strandings by bringing the animals unusually close to shore.

The GLZ model from buoy data showed that extreme barometric pressures were linked to strandings, especially with extremely low pressures. This is consistent with Brabyn and McLean (1992) who suggested that strandings in New Zealand have been linked to rising barometric pressure, which can only occur after a low pressure. Low barometric pressures are linked to stormy conditions with high wind speed. This indicates that storms might have an influence on strandings. Further, it is consistent with the positive correlation between the number of strandings and wind speed. Newcomb *et al*. (2004) suggested that the increase in ambient noise and changes in sea state due to the passage of the storm alters the behavior of the sperm whale (*Physeter macrocephalus*), potentially driving them toward shallower waters, increasing the chance of stranding. Therefore, wind stress may have a strong indirect effect on the distribution of pygmy sperm whales.

Finally, the fact that maximum water temperature was a significant variable may simply reflect a seasonal effect, but it also might be indicative of frontal eddies spinning off from the Gulf Stream or changes in upwelling/downwelling conditions. Thorne *et al.* (2011) found depth and distance to the Gulf Stream front was a good predictor of bottlenose dolphin habitat, while SST was a good predictor of spotted dolphin habitat. If such conditions bring pygmy sperm whale unusually close to shore they could correspond to observed increase in strandings.

Satellite Data and GIS

The inclusion of month and SST in the final model might reflect some seasonality in the strandings, with higher SST corresponding to an increase in the number of strandings. Dunphy-Daly *et al*. (2008) identified an inshore movement of dwarf sperm whales in the Gulf of Mexico during winter. The two *Kogia* species may not have completely overlapping habitats. The pygmy sperm whale is found in more offshore waters and dives deeper than the dwarf sperm whale (Wang *et al.*, 2002). However, Staudinger *et al*. (2014) found both species not to be confined offshore and to have similar foraging ecologies along the coast of North Carolina and Virginia. Therefore, it could be expected that pygmy sperm whales in the northwestern Atlantic also undergo inshore movements, potentially following shifts in upwelling/downwelling conditions or eddies originating from the Gulf Stream.

Distance from the coast to the warmest water frontal feature or other fronts was not included in the final model. However, the study shows support for the effect of the number of frontal features on the occurrence of strandings. The landscape metrics in the GLZ indicated that more strandings occurred when there were fewer SST frontal features (mostly indicating larger fronts extending over the surface). For example, in August 2001 there was no strandings recorded and there were 622 frontal features. On the other hand, in October 2001 there were 8 individual pygmy sperm whales stranded and 419 frontal features identified (Figure 17). For both months MEI was close to zero. It could be that under conditions of numerous convoluted frontal features pygmy sperm whales are more evenly dispersed through their habitat. On the other hand, when foraging along large elongated frontal features, competition may increase such that some animals may venture outside of their usual habitat and might become prone to malnutrition and disease. The example given above agrees with the model, but it should be noted that this is not true in every single case. Future studies using finer time and spatial scales are encouraged.

The model identified a positive influence of MEI on pygmy sperm whales strandings in the SEUS. Based on this study there is no indication whether this influence is physical or biological. For instance, MEI has been known to affect the occurrence of storms, which could affect animals directly. Also it can cause shift in prey that are reflected up the food chain, forcing predators out of their usual habitat (Wursig and Ortega-Ortiz, 1999). The lack of a significant relationship between the number of strandings and the NAO might be due to the time scale of the study. For instance, the NAO has been correlated with the Gulf Stream path when integrated over three years (Planque and Taylor, 1998). In other parts of the world cetacean strandings have been linked to climatic patterns. For example, in Australia, the number of strandings occurring through time varies in eleven to thirteen year cycles, which correlates with climate shifts that affect wind driven currents and sea surface temperatures (Evans *et al*., 2005). Even though NAO characterizes inter-annual disparities over the North Atlantic basin, climate variability over the North Atlantic Ocean possibly operates at decadal and centennial scales that are too long to be detected in this study (Black *et al.*, 1999). Nonetheless, timing of squid (primary pygmy sperm whale prey) migration around England has been linked to NAO (Sims *et al.*, 2001) and it is possible that the effects of NAO in the northeastern Atlantic are not experienced in the same way by pygmy sperm whales and their prey. More research is needed to assess the effects of the climate variability on the distribution of marine mammals and their prey in the western Atlantic.

The model did not indicate a strong relationship between the number of strandings and the distance to the 50 m isobath. More strandings were expected to occur where the 50 m isobath is closer to shore since it implies that deeper waters are closer to the coast. Walker *et al.* (2005) identified that mass stranding sites in Florida were characterized by isobaths being closer to shore. Pygmy sperm whales do not usually mass strand, so it may be that causes for these types of strandings are different. Hui (1985) found that large teuthophagous cetaceans most often associate with steep bathymetry. It may be that simple distance from the 50 m isobath to the coast is not affecting the distribution of pygmy sperm whales in the SEUS. Future studies may look into more complex features that affect the local oceanography such as diverging isobaths.

Conclusion

The model based on buoy data fit the stranding data better than the satellite and GIS model, and indicated that high winds, swell waves, extreme low barometric pressures and elevated SST were ranked as factors linked to stranding events of pygmy sperm whales in the

SEUS. Spatial and temporal scales greatly affect the predictive ability of a model. The study of strandings inherently involves spatial and temporal complexity since there is uncertainty as to when and where the animals became compromised. Nonetheless, Torres *et al.* (2008) found that fine scale models based on environmental variables performed better at predicting dolphin habitat than models including prey distribution. Satellite imagery should not be dismissed as a useful source of data to identify frontal zones, which are indicative of enhanced productivity. Further studies, refining the methods presented here, are needed to investigate the relationship between frontal configuration and marine mammal distribution.

The study of marine mammal strandings is challenging but nonetheless important. Systematically documenting strandings provides data that can be useful in conservation management of marine mammal populations (Wilkinson and Worthy, 1999). Many questions remain regarding Kogiidae biology and ecology. This study is a step toward appreciating the environmental factors that play a role in the distribution of pygmy sperm whales. It contributes to the building of a predictive model of environmental conditions that increase the likelihood of pygmy sperm whale strandings. Such model predicts that if a set of environmental conditions are met, then strandings can be expected in hot spots along the coast, which will be useful to the National Marine Fisheries Service SEUS marine mammal stranding network. Furthermore, understanding the distribution of pygmy sperm whales at sea could allow future studies to focus on specific areas to survey. Future studies examining a combination of environmental factors at different time and spatial scales are encouraged.

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Table 1: Landscape metrics used in order to analyze frontal seascape.

(http://www.umass.edu/landeco/research/fragstats/documents/Metrics.htm)

Metric	Description	Ecological Significance
Number of Patches (TNP)	Total number of patches in the landscape without including background.	Represents a measure of the heterogeneity of the landscape. It reflects the stability level of predator and prey interaction and competition.
Largest Patch Index (LPI)	Percent of landscape covered by the largest patch.	Relates to the distribution and degree of possible organisms' concentration in one area.
Radius of Gyration (Gyrate)	Measures how far across the landscape patches extend (elongated vs. compact shapes).	Represents connectivity across the landscape, reflecting organisms' possibility of movement across ecosystem.
Fractal Dimension (Frac)	Relationship between perimeter and area.	Gives an index of patches compactness, which affects organisms' distribution and interaction.
Contiguity Index (Contig)	Measure contiguity of cells within a binary grid providing an index on the shape of patch boundaries.	Gives an index of patches boundaries configuration, reflecting connectedness.

Table 2: Results for the best generalized linear model for the number of pygmy sperm whales stranded in a month along the Atlantic coast of the southeastern U.S from 1992 to 2006, based on meteorological conditions the week prior to an event (AIC = 497.48, compared to 516.16 for the null). Significant variables are bolded. WSP: wind speed, WVHT: wave height, APD: average wave period, BAR: barometric pressure, WTMP: water temperature.

Independent variables in the final model	Estimate	Std. Error	z value	P(>|z|)
(Intercept)	-4.88771	25.10402	-0.2	0.845629
minWSP_min	**-0.247**	**0.11188**	**-2.21**	**0.02726**
maxWSP_max	**0.08646**	**0.02693**	**3.21**	**0.001325**
rangeWSP_median	**-0.10577**	**0.03683**	**-2.87**	**0.004084**
meanWSP_median	0.12348	0.08601	1.436	0.151103
meanWVHT_median	**-0.83077**	**0.2572**	**-3.23**	**0.001238**
sdWVHT_median	**1.05633**	**0.40024**	**2.639**	**0.00831**
minAPD_min	-0.16245	0.10706	-1.52	0.129186
maxAPD_max	**0.2895**	**0.07024**	**4.122**	**3.76E-05**
rangeAPD_median	**-0.402**	**0.0887**	**-4.53**	**5.83E-06**
minBAR_min	**-0.03347**	**0.01494**	**-2.24**	**0.025119**
maxBAR_max	**0.09682**	**0.02531**	**3.825**	**0.000131**
meanBAR_median	-0.06008	0.03998	-1.5	0.132916
sdBAR_median	**-0.24684**	**0.05702**	**-4.33**	**1.50E-05**
minWTMP_min	-0.05169	0.0314	-1.65	0.099713
maxWTMP_max	**0.10957**	**0.04177**	**2.623**	**0.008711**

Table 3: Analysis of deviance on the best generalized linear model for the number of pygmy sperm whales stranded in a month along the Atlantic coast of the southeastern U.S. from 1992 to 2006, based on meteorological conditions the week prior to an event. Significant variables are bolded. WSP: wind speed, WVHT: wave height, APD: average wave period, BAR: barometric pressure, WTMP: water temperature.

Independent variables in the final model	d.f.	Deviance	Resid. d.f.	Resid. Dev	P(>|Chi|)*
NULL			162	337.57	
minWSP_min	**1**	**43.67**	**161**	**293.91**	**3.89E-11**
maxWSP_max	**1**	**23.19**	**160**	**270.71**	**1.47E-06**
rangeWSP_median	**1**	**41.96**	**159**	**228.76**	**9.34E-11**
meanWSP_median	1	0.03	158	228.72	0.85
meanWVHT_median	**1**	**10.44**	**157**	**218.29**	**1.24E-03**
sdWVHT_median	1	2.03	156	216.25	0.15
minAPD_min	1	1.86	155	214.39	0.17
maxAPD_max	**1**	**5.11**	**154**	**209.29**	**0.02**
rangeAPD_median	**1**	**39.01**	**153**	**170.28**	**4.22E-10**
minBAR_min	**1**	**4.98**	**152**	**165.3**	**0.03**
maxBAR_max	1	0.75	151	164.55	0.39
meanBAR_median	1	0.77	150	163.78	0.38
sdBAR_median	**1**	**26.56**	**149**	**137.22**	**2.56E-07**
minWTMP_min	1	0.34	148	136.88	0.56
maxWTMP_max	**1**	**6.79**	**147**	**130.09**	**0.01**

*It should be noted that the p-values given by the analysis of deviance would change slightly depending on the order in which the variables are entered in the model.

Table 4: Results for the best generalized linear model for the number of pygmy sperm whales stranded in a month along the Atlantic coast of the southeastern U.S. from 1992 to 2006, based on seascape metrics (AIC = 718.73, compared to 735.67 for the null). Significant variables are bolded. MEI: multivariate El Niño index, SST: sea surface temperature, TNP: total number of patches, Gyrate: radius of gyration, FRAC: fractal dimension, Bathy: depth.

Independent variables in the final model	Estimate	Std. Error	z value	P(>|z|)
(Intercept)	1.40E+01	8.26E+00	1.691	0.09083
Month	**-4.13E-02**	**2.00E-02**	**-2.07**	**0.03863**
MEI	**1.57E-01**	**5.67E-02**	**2.766**	**0.00568**
AverageSST	**1.13E-01**	**5.10E-02**	**2.22**	**0.02641**
stdevSST	-3.20E-01	2.37E-01	-1.35	0.17622
TNP	**-2.03E-03**	**8.74E-04**	**-2.33**	**0.01995**
GYRATE_AM	1.10E-05	6.29E-06	1.752	0.07972
FRAC_AM	-1.60E+01	8.29E+00	-1.93	0.05362
FRAC_CV	7.06E-01	3.70E-01	1.911	0.05606
Bathy	3.65E-06	2.18E-06	1.679	0.0931

Table 5: Analysis of deviance on the best generalized linear model for the number of pygmy sperm whales stranded in a month along the Atlantic coast of the southeastern U.S. from 1992 to 2006, based on seascape metrics. Significant variables are bolded. MEI: multivariate El Niño index, SST: sea surface temperature, TNP: total number of patches, Gyrate: radius of gyration, FRAC: fractal dimension, Bathy: depth.

Independent variables in the final model	d.f.	Deviance	Resid. d.f.	Resid. Dev	P(>|Chi|)*
NULL			179	366.9	
Month	1	0.45	178	366.44	0.5
MEI	**1**	**9.81**	**177**	**356.64**	**0.001738**
AverageSST	**1**	**4.89**	**176**	**351.75**	**0.03**
stdevSST	1	1.49	175	350.26	0.22
TNP	**1**	**4.21**	**174**	**346.04**	**0.04**
GYRATE_AM	1	0.01	173	346.03	0.93
FRAC_AM	1	2.19	172	343.84	0.14
FRAC_CV	1	3.5	171	340.34	0.06
Bathy	1	2.83	170	337.51	0.09

*It should be noted that the p-values given by the analysis of deviance would change slightly depending on the order in which the variables are entered in the model.

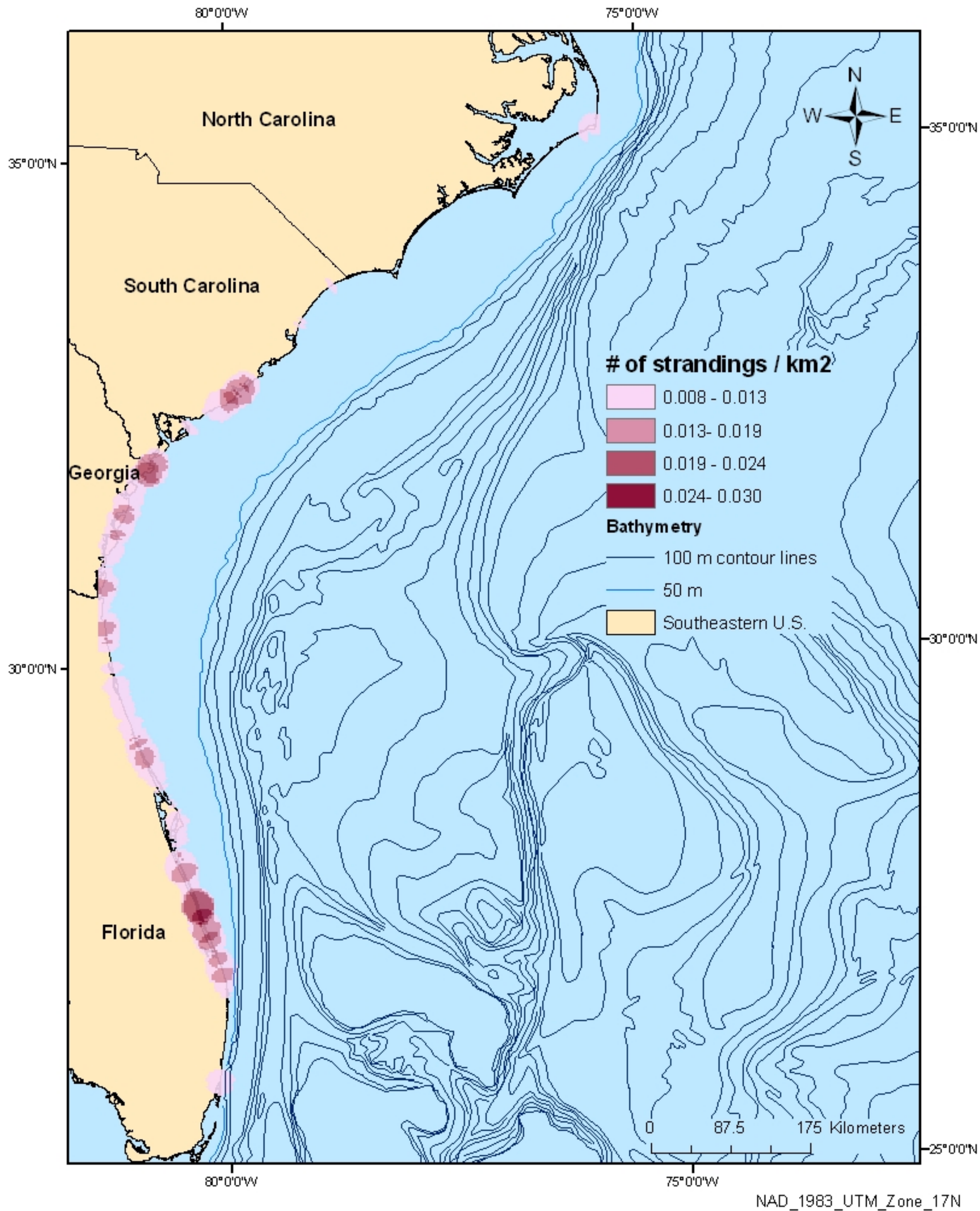

Figure 1: Density of *Kogia breviceps* strandings along the southern U.S. Atlantic coast from 1992 to 2007.

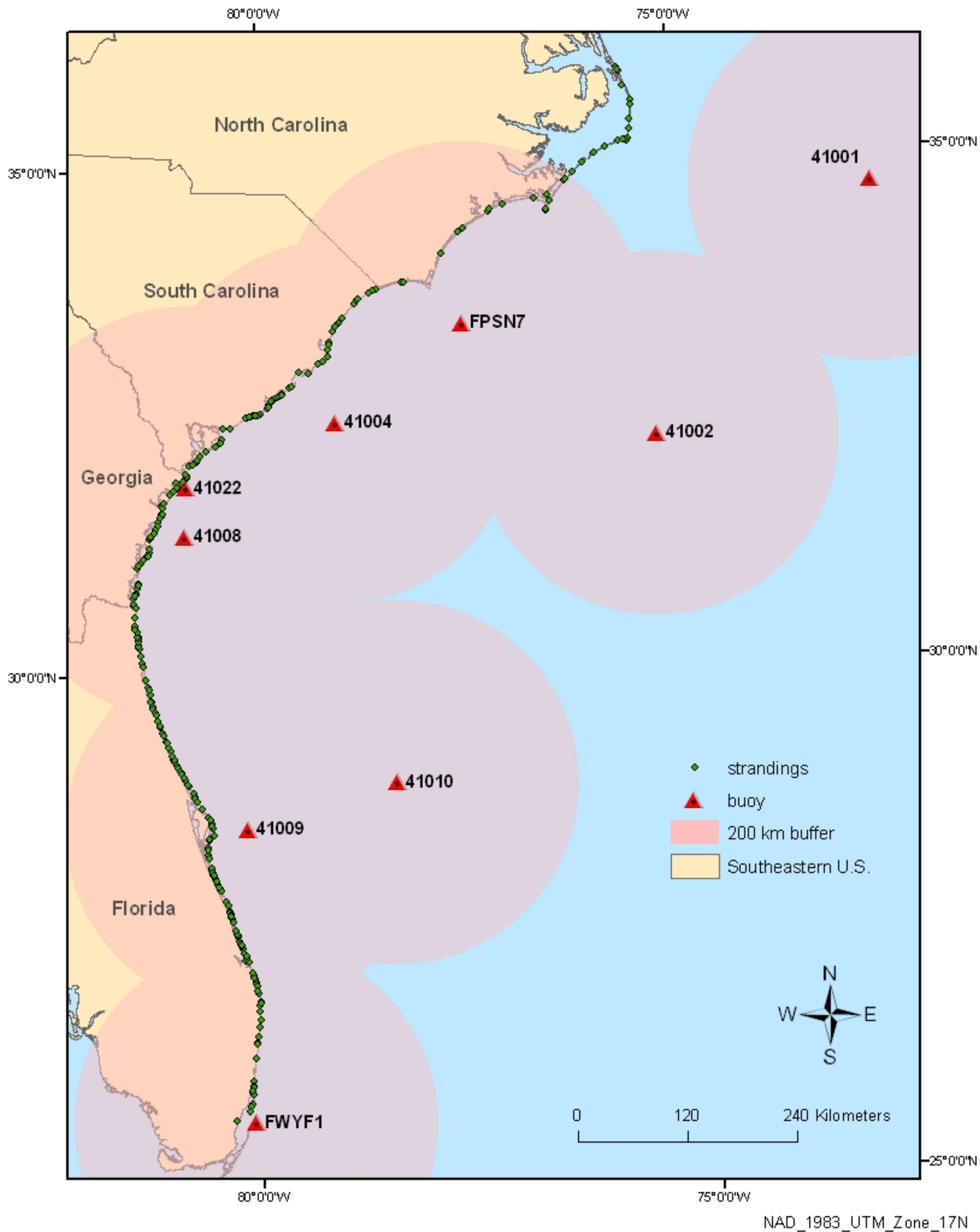

Figure 2: NOAA buoys used to retrieve meteorological data in order to analyze correlation with pygmy sperm whale strandings from 1992 to 2007.

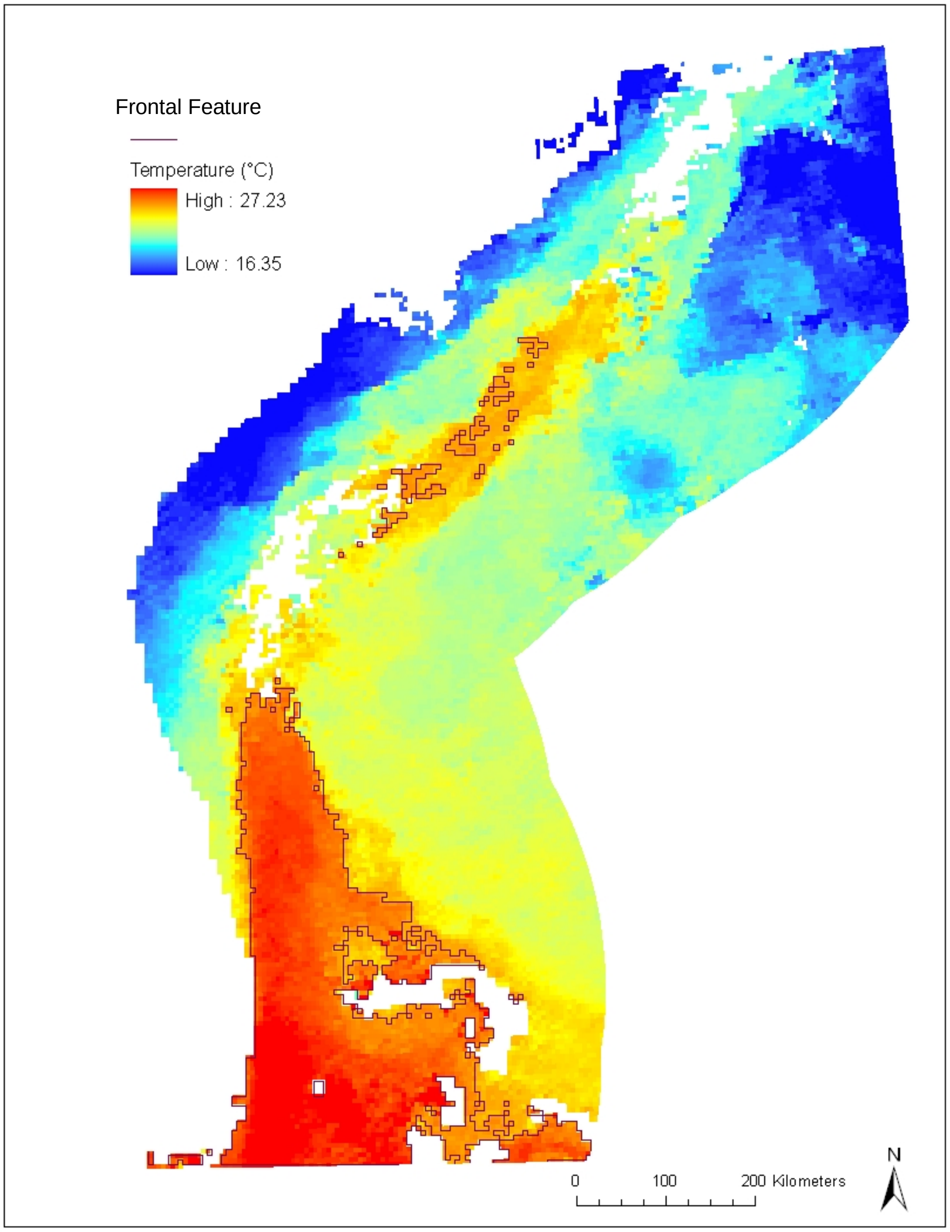

Figure 3: Example of the method used to build the largest warm water frontal feature from sea surface temperature (SST) in GIS ArcMap 9.2. This front delineated SST values above one standard deviation of the entire image.

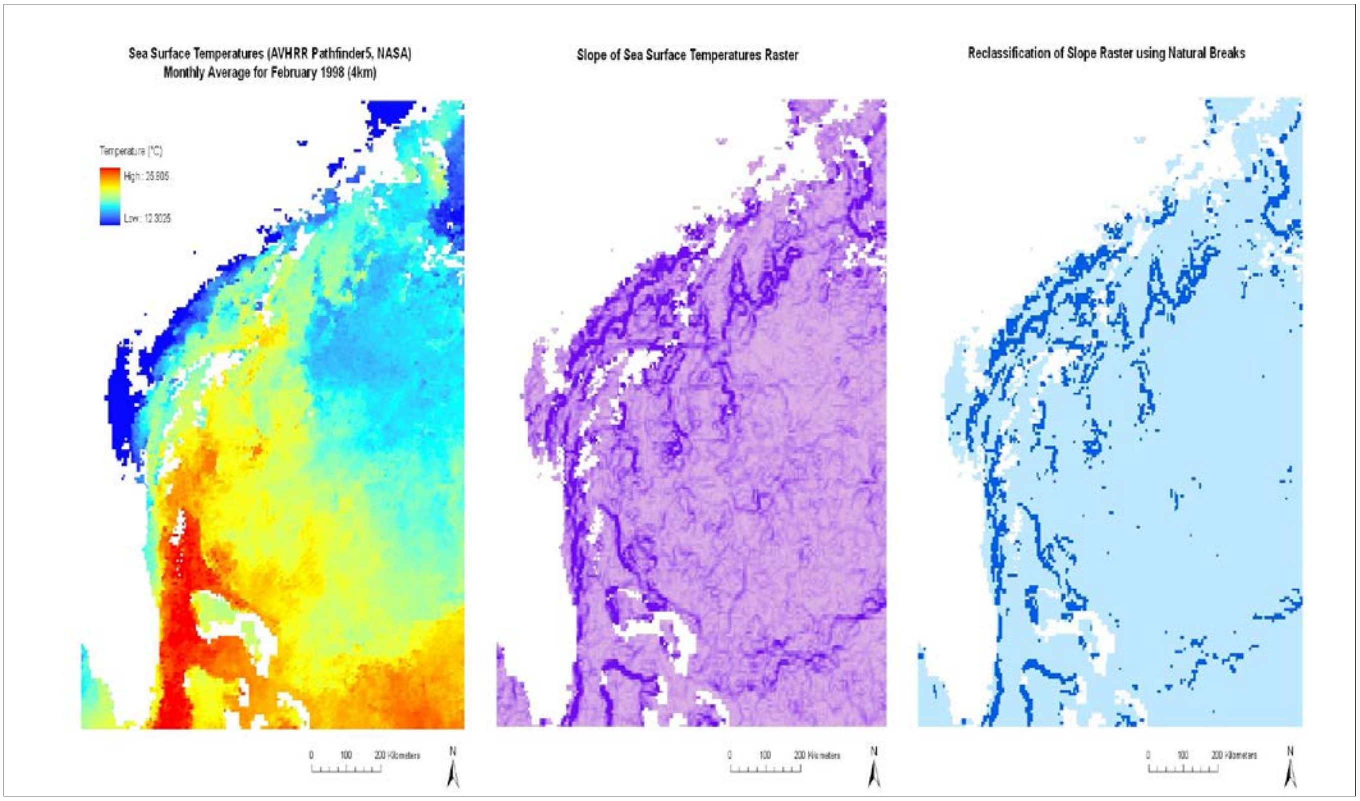

Figure 4: Example of the method used to build frontal features from sea surface temperature values in GIS ArcMap 9.2.

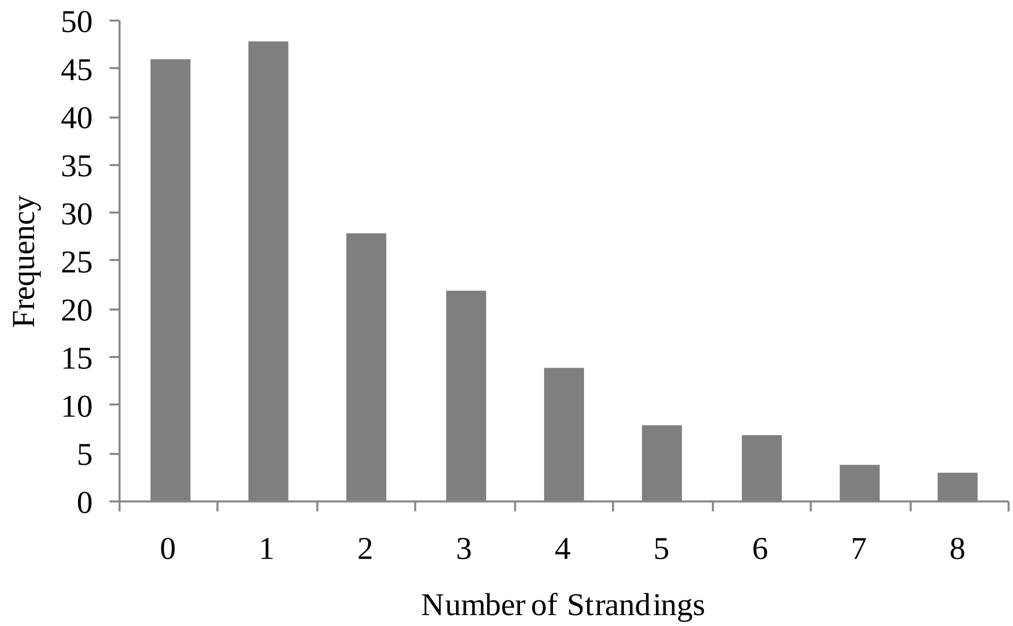

Figure 5: Frequency distribution of the number of pygmy sperm whale stranded in one month along the Atlantic coast of the southeastern U.S. from 1992 to 2006.

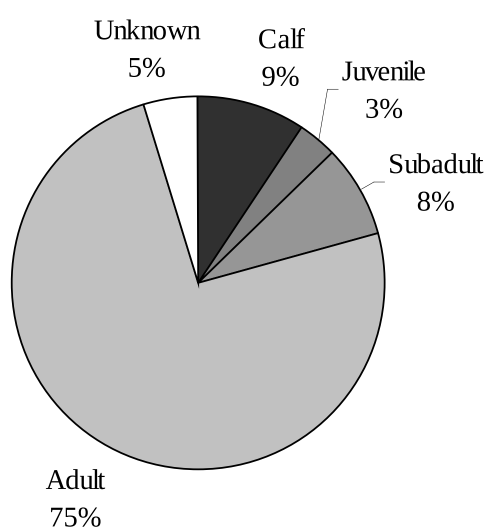

Figure 6: Age class of *Kogia breviceps* found stranded along the southern U.S. Atlantic coast from 1992 to 2007.

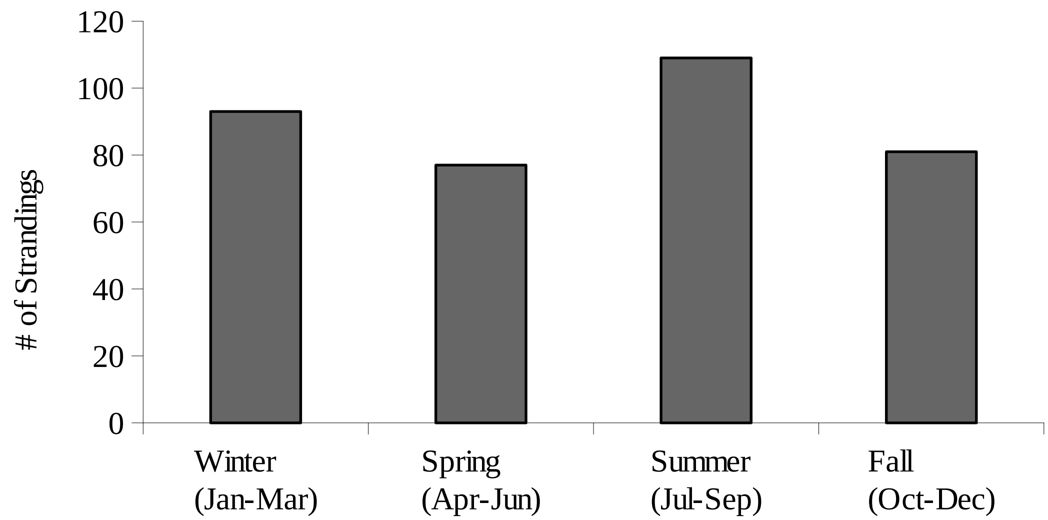

Figure 7: Number of *Kogia breviceps* stranded along the Southern U.S. Atlantic from 1992 to 2007 according to the time of year. No significant difference was found in the number of individuals stranded according to season.

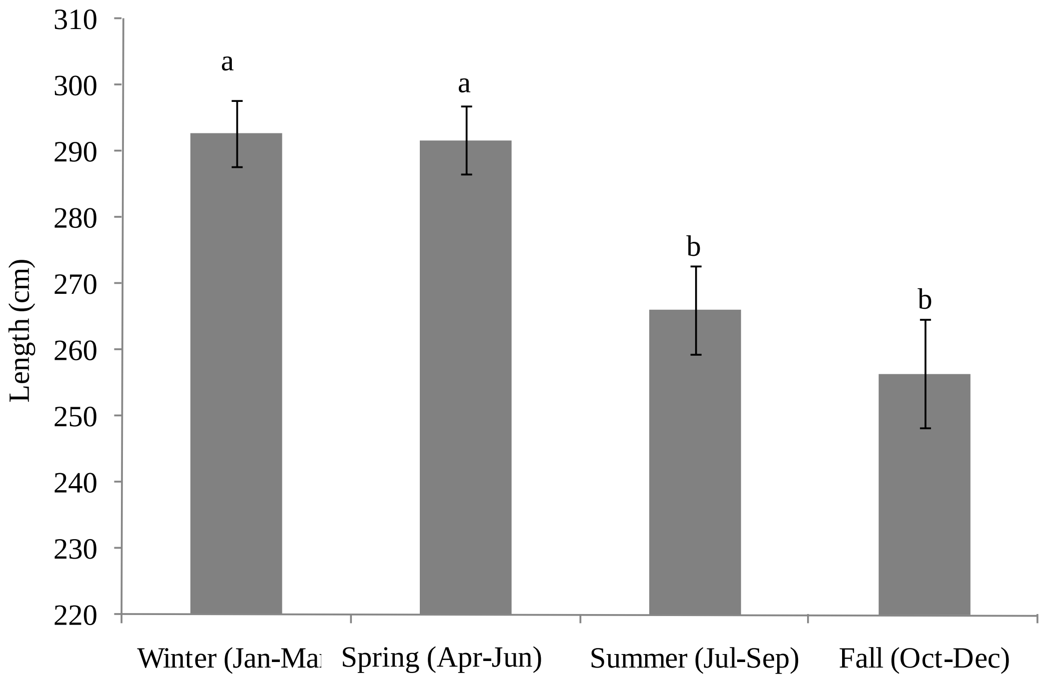

Figure 8: Size of *Kogia breviceps* stranded along the Southern U.S. Atlantic from 1992 to 2007 according to the time of year ($\chi^2_{(3,N=343)}$, $p < 0.001$). Error bars represent standard deviation, different letters (a, b) above the bars represent significance.

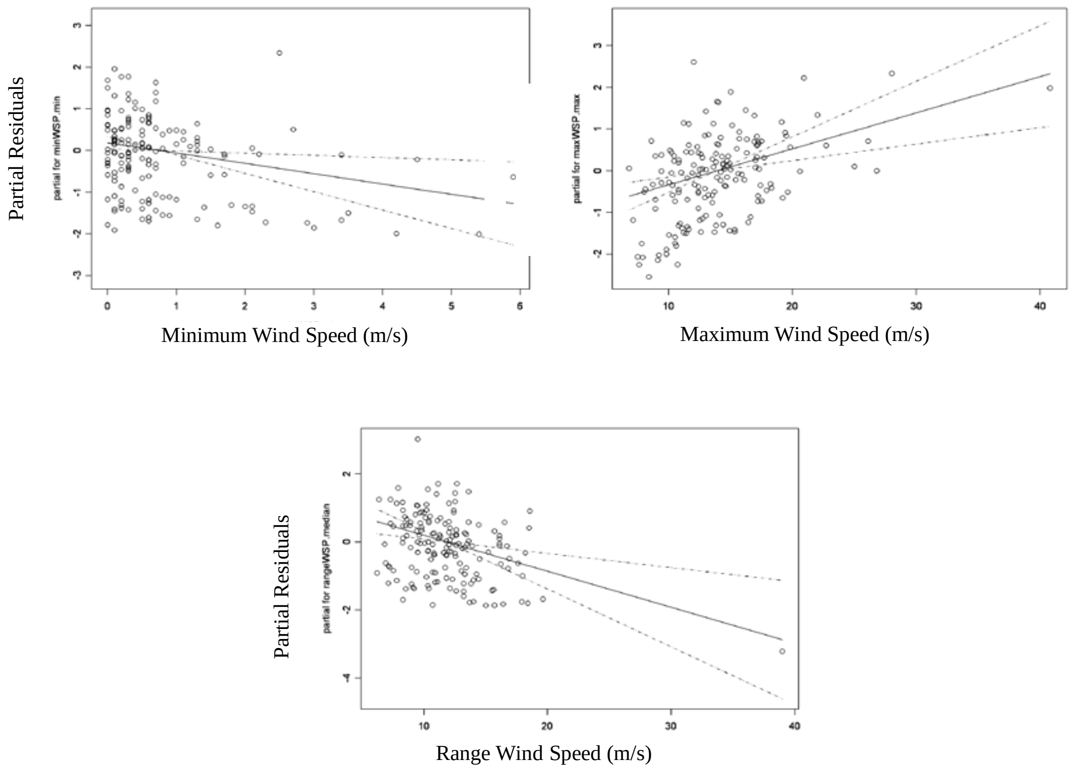

Figure 9: Partial residual plots for the wind speed components from the generalized linear model of *Kogia breviceps* strandings in a month along the southern Atlantic coast of the U.S. from 1992 to 2006, based on NOAA buoy data. The solid lines are the fitted model, dashed lines are 95% confidence interval.

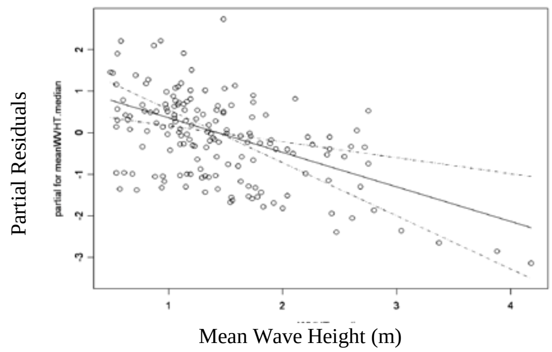

Figure 10: Partial residual plots for the wave height variables from the generalized linear model of *Kogia breviceps* strandings in a month along the southern Atlantic coast of the U.S. from 1992 to 2006, based on NOAA buoy data. The solid lines are the fitted model, dashed lines are 95% confidence interval.

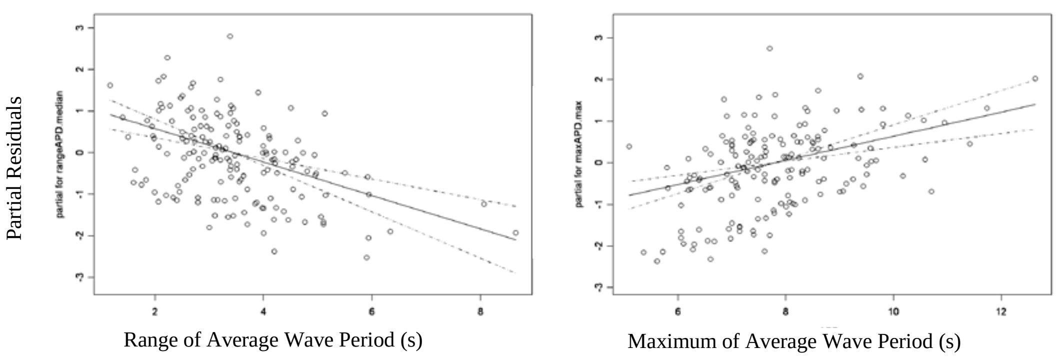

Figure 11: Partial residual plots for the average wave period components from the generalized linear model of *Kogia breviceps* strandings in a month along the southern Atlantic coast of the U.S. from 1992 to 2006, based NOAA buoy data. The solid lines are the fitted model, dashed lines are 95% confidence interval.

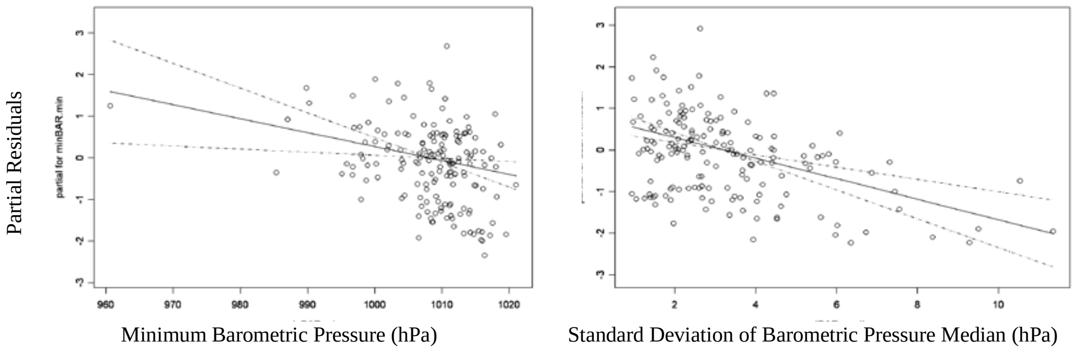

Figure 12: Partial residual plots for the Barometric pressure variables from the generalized linear model explaining monthly *Kogia breviceps* strandings along the southern Atlantic coast of the U.S. from 1992 to 2006, based on NOAA buoy data. The solid lines are the fitted model, dashed lines are 95% confidence interval.

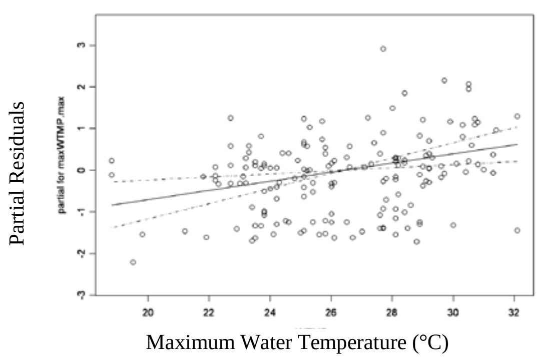

Figure 13: Partial residual plots for the maximum water temperature from the generalized linear model of *Kogia breviceps* strandings in a month along the southern Atlantic coast of the U.S. from 1992 to 2006, based on NOAA buoy data. The solid lines are the fitted model, dashed lines are 95% confidence interval.

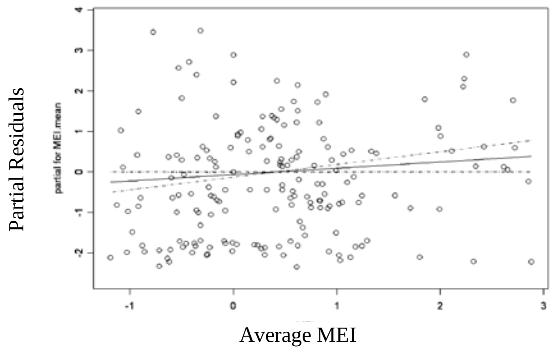

Figure 14: Partial residual plot for the Multivariate El Niño index from the generalized linear model of *Kogia breviceps* strandings in a month along the southern Atlantic coast of the U.S. from 1992 to 2006. The solid line is the fitted model, dashed lines are 95% confidence interval.

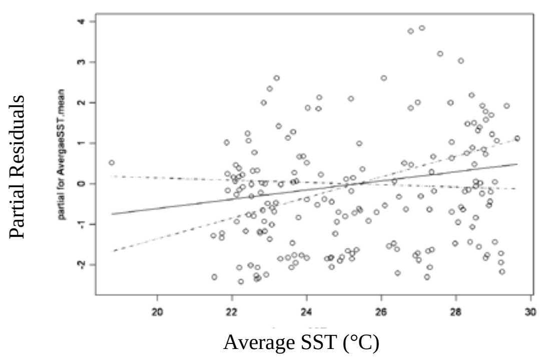

Figure 15: Partial residual plots for the sea surface temperature monthly average from the generalized linear model of *Kogia breviceps* strandings in a month along the southern Atlantic coast of the U.S. from 1992 to 2006, based on satellite imagery. Solid lines are the fitted model, dashed lines are 95% confidence interval.

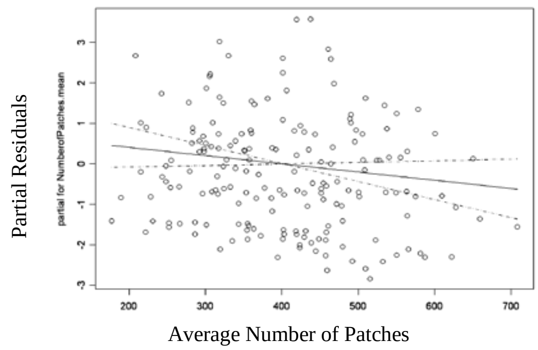

Figure 16: Partial residual plot for the number of frontal features from the generalized linear model of *Kogia breviceps* strandings in a month along the southern Atlantic coast of the U.S. from 1992 to 2006, based on satellite imagery. The solid line is the fitted model, dashed lines are 95% confidence interval.

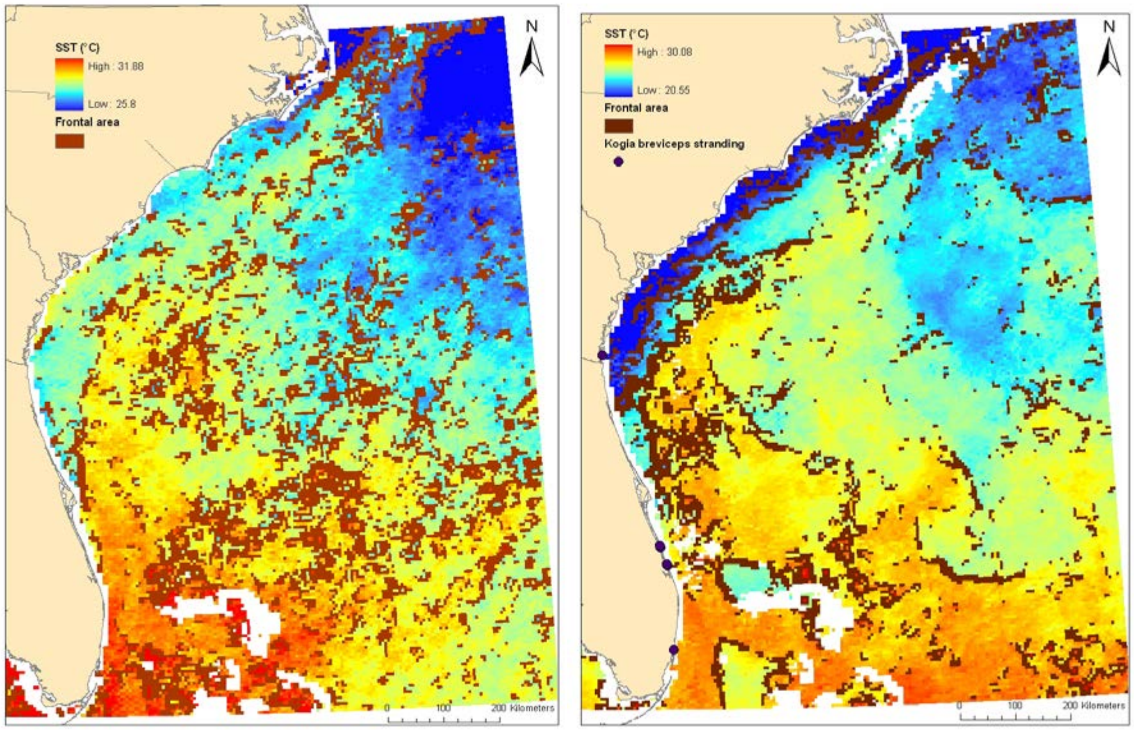

Figure 17: Example of seascape conditions for August (left) and October (right) 2001 with strandings of pygmy sperm whales, based on sea surface temperature from satellite imagery. The left image shows no stranding event and 622 frontal features, while the image on the right shows eight individual strandings in four general locations and 419 frontal features.

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