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ENVIRONMENTAL CORRELATES OF CETACEAN MASS STRANDING SITES IN FLORIDA

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The cause(s) of cetacean strandings remain uncertain, and though numerous theories abound, relatively few are supported by substantial evidence. Mass strandings (*i.e.*, more than two animals of the same species) can span one or more days and range over miles of shoreline (Walsh *et al.* 2001). Recent explanations for such strandings include bottom topography, coastal configuration, or geomagnetic topography; meteorological or oceanographic events; extreme conditions in the environment; auditory trauma; toxicity of pollutants in the environment; and parasitism (Perrin and Geraci 2002). Contributory factors may also include unusual tides, sea state, nature of the adjacent seafloor, and meteorological events such as electrical storms (Warneke 1983). It is important not to make generalizations about the causes of mass strandings (Odell 1987). Although many strandings may be due to a common cause, others may simply be a result of experiencing conditions for which a group of animals was not prepared. A stranding may also reflect prior events while the animals were some distance out to sea (Best 1982; Walsh *et al.* 1991, 2001).

One factor that has not been examined in depth is the effect of seasonal environmental parameters on the frequency of mass strandings. The effect of wind on nearshore oceanic circulation is highly variable and also changes between and within seasons. The effects of wind-forcing on across-shelf ocean circulation have been noted as an important aspect of the ocean environment and shelf dynamics (Lentz 2001, Fiedler 2002). Although it is unlikely that wind alone could cause a mass stranding, the wind does influence across-shelf exchange and water mass characteristics. This may affect prey assemblages, and in turn influence cetaceans. Wind-driven transport in the near-surface water layer is deflected by the Coriolis force at 90° to the right in the northern hemisphere (Ekman transport). Since the

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water moves perpendicular to the wind, alongshore wind produces across-shore Ekman transport (Barber and Smith 1981).

Coastal upwelling occurs in the northern hemisphere when wind blows with the coast on its left, driving surface water offshore and bringing deeper water to the surface near the coast. Downwelling is the opposite; it occurs when wind blows with the coast on its right, thus piling up surface water and deepening the surface layer at the coast (Brink 1991). The average prevailing winds during the winter are southward, that is, upwelling-favorable on the west coast of Florida and downwelling-favorable on the east coast (Fernald and Purdum 1981). In contrast, during the summer average prevailing winds are northward, which is downwelling-favorable on the west coast and upwelling-favorable on the east coast.

Cetacean distribution varies with the physical, chemical, and biological characteristics of water masses (Forcada 2002). Cetaceans respond to changes in water properties, and thus upwelling and downwelling conditions may influence their movements. The interface between water masses of different properties, termed thermal fronts, is associated with high biological productivity (Mann and Lazier 1991). These fronts are among the abiotic factors that have been shown to influence the distribution of cetaceans (Polacheck 1987, Evans 2002). Interactions between bathymetry and frontal structure similarly increase primary and secondary productivity by affecting circulation patterns, increasing the availability of prey and generating areas able to sustain cetaceans (Owen 1981, Tynan 1997). The objective of this study was to investigate seasonal and other abiotic factors that may be correlated to cetacean mass strandings in Florida.

Data collected by the Southeastern United States Marine Mammal Stranding Network contained 76 mass stranding occurrences between 1977 and 2001 in Florida. Restranding events were discarded to ensure specific events were not over-represented in the data set. The total number of mass strandings reported during each month was determined. In addition, a seasonal index of the number of strandings each month (Spiegel and Stephens 1999) was calculated with December–February representing winter; March–May representing spring; June–August representing summer; and September–November representing fall. Figure 1 shows the location of the 76 reported mass strandings in Florida between 1977 and 2001. The total number of mass strandings reported during each month in Figure 2 shows a bimodal trend with more strandings occurring in the winter and summer seasons. Seasonal indices indicated the same bimodal tendency.

Short-finned pilot whales (*Globicephala macrorhynchus*) mass stranded more frequently than all other species (32 of 76 events) and, therefore, stranding events for this species were examined separately to determine if seasonal trends existed. A two-sample *t*-test did not show a significant difference between the seasonality of *G. macrorhynchus* mass strandings and the mass stranding of other species ($P > 0.05$). June and December had frequent strandings by species other than *G. macrorhynchus*, but none of that species, perhaps due to seasonal differences in proximity to shore.

Due to the physical and oceanographic differences of the two coasts of Florida, data were divided by the month and the location of stranding. This analysis was separate from the previous analysis and all species were considered. The orientation

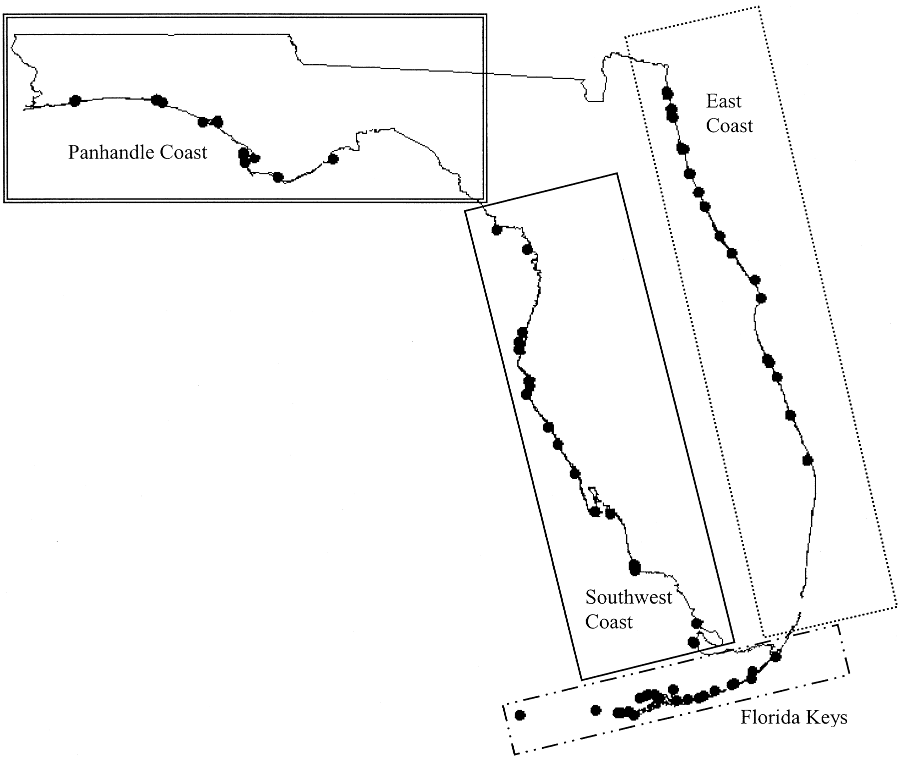

Figure 1. Map of locations of reported cetacean mass stranding events in Florida from 1977 to 2001. Boxed sections represent defined areas used for analysis by stranding location.

of the west coast of Florida is such that the Panhandle area and the southwest coast may be influenced by different factors, so four categories resulted: east coast, Keys, southwest coast, and Panhandle coast. Analysis of strandings by location suggested an influence of wind forcing on stranding patterns. Of the 76 events, 21 occurred on the east coast, 23 occurred in the Keys, and 32 occurred on the west coast (12 on the Panhandle and 20 on the southwest coast). Figure 3 shows the number of strandings for all four coastal divisions. The east coast and Panhandle had more strandings in the winter, while the southwest coast and Florida Keys had more strandings in the summer. The seasons during which strandings more likely occurred on the east and southwest coasts coincided with the occurrence of downwelling-favorable winds as mentioned above. Again, seasonal indices agreed with the trends.

Analysis of the importance of wind-forcing focused on the east coast of Florida. When coastlines are straight, alongshore winds create upwelling or downwelling conditions (Brooks and Mooers 1977). Coastline irregularities complicate water flow, making shelf responses to wind forcing difficult to determine (Li and Weisberg 1999). Due to the complexity of the coastline and the difficulty obtaining *in situ* historical data, the effects of wind on water circulation in the Panhandle, west coast, and the Florida Keys were not investigated.

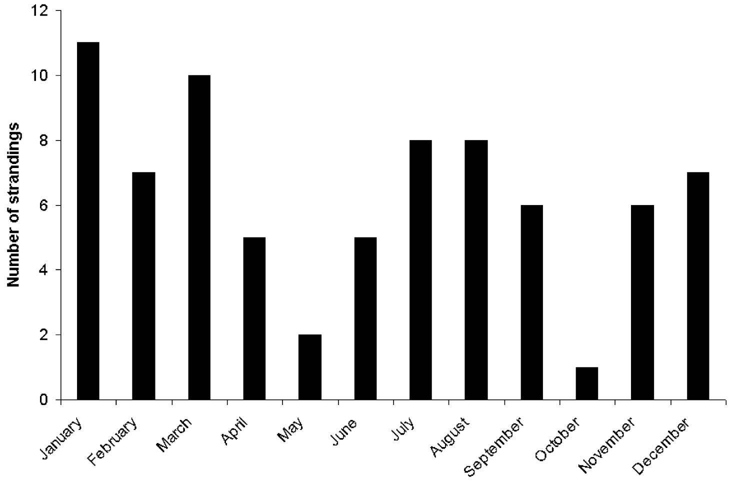

Figure 2. Number of cetacean mass strandings in Florida each month from 1977 to 2001.

Hourly wind data from NOAA National Data Buoy Center (http://www.ndbc.noaa.gov/rmd.shtml) buoys were examined with respect to 15 of the mass stranding events occurring on the east coast of Florida between 1977 and 2001. The orientation of the coastline relative to true north was measured for each stranding point for which wind data were available, and these angles were then used to determine alongshore and across-shore wind components. Alongshore wind speeds were smoothed with a low-pass Gaussian filter to remove fluctuations with periods less than 24 h.

Winds influence the overall movement of the water, which in turn changes local sea levels. However, the sea level can be affected by both local and remote winds.

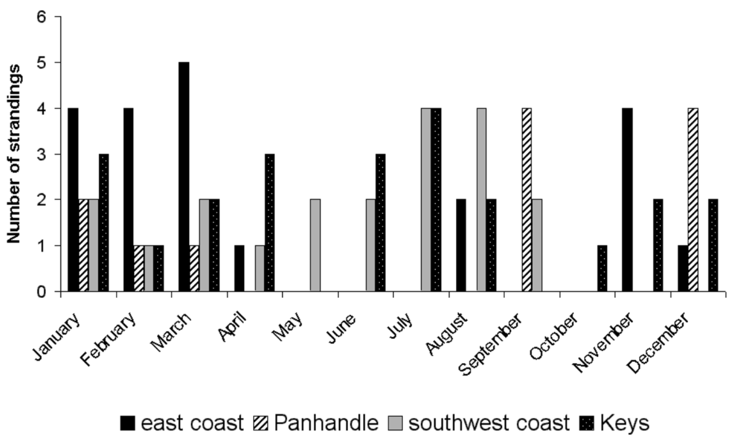

Figure 3. Number of cetacean mass strandings in Florida from 1977 to 2001, separated by coastal location of stranding.

Remote winds generate coastal-trapped, or shelf, waves that spread the ocean's response in the alongshore direction, propagating southward along the US east coast (Yankovsky and Garvine 1998). These waves do not produce upwelling fronts at the surface. Sea level data were, therefore, compared with local winds to determine local response that was likely associated with formation of upwelling fronts as opposed to coastal-trapped waves. Hourly sea level data obtained from NOAA's National Oceanographic Data Center (http://www.nodc.noaa.gov) were corrected for atmospheric pressure changes, filtered, and examined relative to wind changes.

Only one of the 15 events examined occurred outside of winter, which is the downwelling season on the east coast, as described above. Although this single event occurred during the upwelling season, it was preceded by two weeks of prolonged downwelling-favorable winds. No events occurred during extended upwelling-favorable winds (extended events considered to be $\geq$2 d). In all of the east coast records examined, a change in wind direction from upwelling-favorable to downwelling-favorable conditions occurred during the week prior to the event. In addition, simultaneous oscillations in sea level were apparent and support the hypothesis that changes in wind direction influenced water circulation prior to the stranding. Figure 4 gives an example of plots analyzed for wind and sea level conditions during the two weeks prior to each stranding event. An increase in wind speed and a decrease in sea level indicate an upwelling regime. Alternatively, a reversal of wind speed towards negative values and an increase in sea level indicate a downwelling regime. Figure 4 illustrates the two weeks before 3 January 1998, when seven short-finned pilot whales (*Globicephala macrorhynchus*) came ashore. The shift in wind from upwelling to downwelling can be seen 4 d prior to the stranding event. Each event was analyzed in this way, and the number of days prior to each stranding event when the wind changed from upwelling favorable to downwelling favorable is shown in Figure 5. With the exception of three events, this change occurred within 4 d prior to the stranding, suggesting an importance of winds in the week prior to the stranding.

Distances from all stranding sites to the 10 m, 20 m, and 50 m isobaths were measured. For stranding sites located in the Florida Keys, a straight-line distance from the site to each isobath was measured, bisecting an island if necessary, to obtain the shortest distance to a set isobath. To confirm that Florida shores themselves are not skewed, 76 random points were chosen along the coast and measured to the 10-m, 20-m, and 50-m isobath to compare with stranding data. A Wilcox signed rank test was performed using SPSS (SPSS Inc., Chicago, IL) on each set of isobath data.

The mean distance from shore to all isobaths was significantly shorter for stranding sites than for the random sites (10-m isobath $P = 0.005$; 20-m isobath $P = 0.002$; 50-m isobath $P = 0.011$). In addition, skewness statistics for distance to stranding sites (10-m isobath 1.596; 20-m isobath 0.790; 50-m isobath 0.773) and bottom slope (10-m isobath 2.314; 20-m isobath 1.319; 50-m isobath 1.243) are all positive denoting a tendency towards the shorter distances and steeper slopes.

Strandings in Florida are relatively evenly distributed along the coastline, with the exception of southeastern Florida and the Big Bend region on the west coast (Fig. 1). Increased across-shelf water exchange is one physical condition common

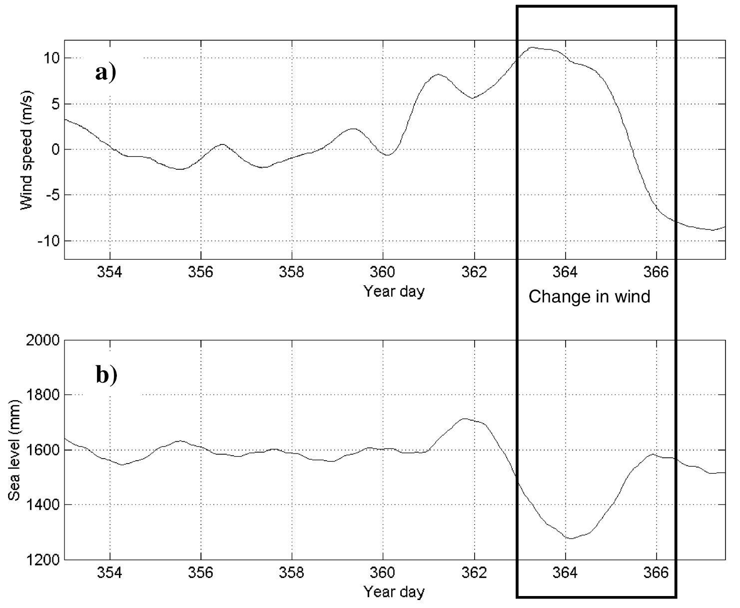

Figure 4. Change in wind speed and sea level during the two weeks prior to a stranding of seven *Globicephala macrorhynchus* in Brevard county, FL (27°54.9′, 80°28.7′) on 3 January 1998. Note the change in wind direction and sea level from upwelling-favorable to downwelling-favorable conditions 4 d prior to the stranding, which is shown as the last day on the chart. a) Positive wind speed values indicate upwelling-favorable winds and negative values indicate downwelling-favorable winds. b) A rise in sea level values indicates downwelling-favorable winds and a fall in values indicates upwelling-favorable winds.

to these two areas. The Gulf Stream passes very close to southeastern Florida, ventilating the inshore water and dominating the physical oceanography of the area. Across-shelf transport is increased in the Big Bend area because of recirculation causing frequent upwelling events (Yang *et al.* 1999).

Mass strandings in Florida show a definite seasonal trend with more occurrences in the winter and summer seasons, and fewer in the spring and fall. There was no significant difference between species, although seasonal changes in proximity to the shoreline may account for the timing of a particular species stranding. When strandings were analyzed relative to the four coastal divisions, strandings were more likely to occur in seasons with downwelling-favorable conditions. The Florida Keys did not show as clear a seasonal change, perhaps due to the convoluted nature of the shoreline that leads to less direct influence by wind-forcing. The tendency for changes in wind direction from upwelling-favorable to downwelling-favorable in the week prior to the event is of interest because this change results in frontal system formation. An upwelling front is formed when cooler upwelled waters meet warmer surface waters (Shanks *et al.* 2000). This front forms close to shore, and then moves offshore, eventually reaching a quasi-stationary regime while wind continues (Mann and Lazier 1991). Wind reversal to downwelling-favorable winds allows the front to move back toward the shore (Shanks *et al.* 2000).

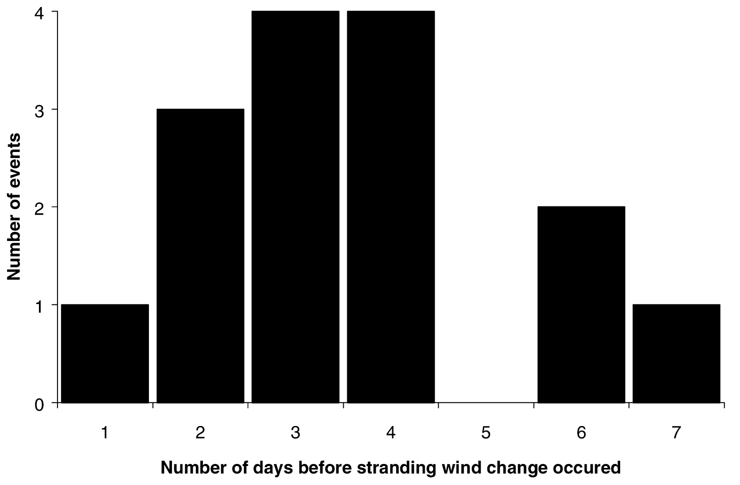

Figure 5. Number of days before each mass stranding event analyzed when wind changed from upwelling to downwelling favorable.

Cetaceans are known to track frontal convergences, and thus might, hypothetically, follow an upwelling front. A change from upwelling-favorable winds to downwelling-favorable winds would cause the front to move inshore, and if cetaceans were following the front, this may explain their movement towards shore. At some point the frontal structure would disappear, perhaps "confusing" the animals. Because every switch from upwelling to downwelling conditions does not cause a stranding it is obvious that this alone does not cause the stranding. This analysis suggests that prevailing winds and their influence on frontal structures near shore may be important during the week prior to an event.

Bathymetry was also be an important factor. A number of studies have concluded that cetaceans are most likely to strand on gently sloping beaches (Mazzuca *et al.* 1999). Our results suggest that cetaceans are more likely to strand on Florida beaches having a gentle slope with a sudden drop in depth close to shore. Some authors attribute the correlation between gently sloping beaches and stranding sites to the possibility that sonar is not reflected properly in these areas. Florida data suggest that the gently sloping beach may be located near an area of rapid depth change, and that this change in sea-floor relief may be the important factor.

Most species that mass strand in Florida occupy offshore, deepwater habitats, and are not coastal inhabitants (Reeves *et al.* 2002). Cetaceans may occur outside their usual habitat because of fluctuations in food availability and oceanographic conditions and they are more likely to be found near regions of high sea-floor relief (Selzer and Payne 1988). Some species will also move farther inshore following migrations of their prey (Reilly 1990), or frontal structure movements, rather than prey directly (Tynan 1997, Bjørge 2001). Analysis of Florida mass strandings found both bathymetry and wind-induced water circulation to be important factors. Both influence oceanic frontal structures, and thus suggest the importance of abiotic factors in the locations of mass stranding events.

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