Estuaries and Coasts Vol. 29, No. 6A, p. 1026–1032 December 2006

Possible Effects of the 2004 and 2005 Hurricanes on Manatee Survival Rates and Movement

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ABSTRACT: Prior research on manatee (*Trichechus manatus latirostris*) survival in northwest Florida, based on mark-resighting photo-identification data from 1982–1998, showed that annual adult apparent survival rate was significantly lower during years with extreme storms. Mechanisms that we proposed could have led to lower estimates included stranding, injury from debris, being fatally swept out to sea, or displacement into poorly monitored areas due to storm-generated longshore currents or storm-related loss of habitat. In 2004 and 2005, seven major hurricanes impacted areas of Florida encompassing three regional manatee subpopulations, enabling us to further examine some of these mechanisms. Data from a group of manatees tracked in southwest Florida with satellite transmitters during Hurricanes Charley, Katrina, and Wilma showed that these animals made no significant movement before and during storm passage. Mark-resighting data are being collected to determine if survival rates were lower with the 2004 and 2005 storms.

Introduction

Intermittent natural disturbances are known to affect survival and reproduction in animal populations. These stochastic events, especially if severe or frequent, can have huge consequences for the long-term persistence of populations (Mangel and Tier 1994). The endangered Florida manatee (*Trichechus manatus latirostris*) inhabits the subtropical coastal waters of the southeastern United States, where hurricanes are normal events (Lefebvre et al. 2001). In a previously published analysis for the Northwest Florida manatee subpopulation we detected significantly lower adult apparent survival rates when Hurricanes Elena and Kate (1985), the March ''Storm of the Century'' (1993), and Hurricanes Alison, Erin, and Opal (1995) hit the northern coast of the Gulf of Mexico (Langtimm and Beck 2003). Survival was estimated from long-term photo-identification data (Beck and Reid 1995) of scarred individuals in the Manatee Individual Photo-identification System (MIPS), and the application of capture-recapture statistical models (Williams et al. 2001) to the resighting data (Langtimm et al. 1998). This was the first empirical evidence suggesting a cause-effect relationship between storms and manatee survival and movement. In 2004 and 2005, seven major hurricanes hit Florida and three coastal manatee subpopulations (Northwest, Southwest, Atlantic Coast [USFWS 2001]). These events provided a series of natural experiments that will enable us to further evaluate the survival pattern in the Northwest subpopulation, to test for effects in other subpopulations, and to evaluate possible causal mechanisms proposed with the previous analysis. Here we present the first satellite telemetry data on individual manatee movements during extreme storms and relate storm characteristics of the 2004 and 2005 hurricanes with likely outcomes for planned analyses of movement and survival of manatees in the different regional subpopulations.

Hypotheses of Causal Mechanisms

Mechanisms responsible for our previously observed pattern of lower survival rates were unknown and we proposed several hypotheses of cause and effect (Langtimm and Beck 2003). Apparently these storms prevented the return of marked individuals to the winter sites, either as a consequence of death or voluntary or forced emigration from the study area. Sources of direct mortality from storm forces include stranding due to storm surge or injury from debris in turbulent water. Indirect deaths could occur if animals either swim or get swept offshore due to storm currents. In the colder waters that well up in the wake of a hurricane (surface waters can cool as much as 5°C; Simpson and Riehl 1981), exhaustion and debilitating cold could dull the senses and the integration of information necessary for navigation. Manatees are a nearshore, shallow-water species (Hartman 1979) and unless they find

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their way back to coastal waters, they would likely die from lack of food and freshwater or be subject to deep water predators. Indirect death from cold stress in the colder waters following these storms could be possible if the hurricane occurs late in the season when temperatures are cooler and manatees are more vulnerable to cold stress. Alternatively, individuals could be alive, but no longer within the study area. They could voluntarily leave if the food base is degraded or destroyed, as has been documented with dugongs and cyclone devastation of seagrasses in Australia (Heinsohn and Spain 1974; Preen and Marsh 1995), or they could be forced from the area by storm-generated longshore currents pushing them along the shoreline. Discerning the relative effect of mortality versus emigration has important implications to the recovery and persistence of the Florida manatee population. No single mechanism emerges as the best hypothesis. One, several, or all could contribute to the observed decreases in apparent survival rates.

The magnitude of effect may vary with the destructiveness of the storms, which depends on wind speed, size, storm wave and surge height, speed of forward motion, and nearshore bathymetry that would affect storm surge and storm currents. Other factors can also exacerbate or ameliorate risk, such as density of manatees within the strike area, the number of storms within a season, protective features of the coastline such as barrier islands, or occurrence of other mortality factors during the same year, such as toxic red tide blooms (O'Shea et al. 1991; Bossart et al. 1998) or severe cold weather (Buergelt et al. 1984). Florida manatees, endangered and living at the northern limit of their natural range, are subject to multiple sublethal stresses that can have chronic and debilitating effects, possibly making individuals more vulnerable to storm death.

Individual Manatee Movements During Hurricanes, 2004 and 2005

The potential of the proposed mechanisms to affect apparent survival rates will depend on the manatee's response to storm forces. As a tropical species, one might expect manatees to have evolved behaviors to cope with these kinds of storms. During the 2004 and 2005 hurricane seasons, we were tracking a number of individuals with satellite-monitored radio tags as part of a study to model and predict the effects of the Everglades hydrological restoration on manatees. The path of three storms (Charley, Katrina, and Wilma) crossed or came near the location of 6 of these individuals, providing an opportunity to scrutinize data on movements of individuals before, during, and after passage of a storm.

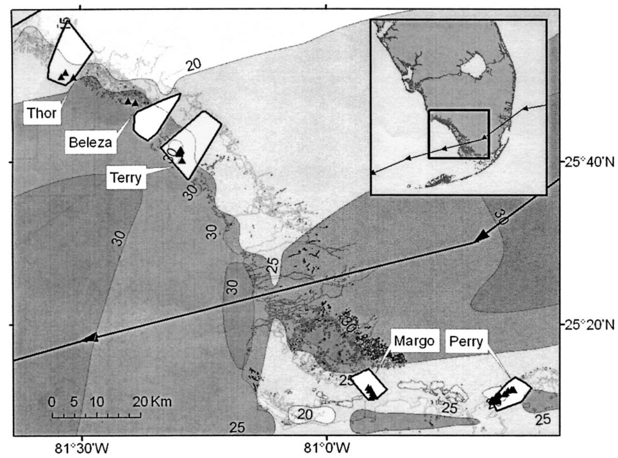

Fig. 1. Locations of satellite-tagged manatees before and during the passage of Hurricane Katrina. Locations during the 2-wk period prior to the storm are contained within the convex hull polygons; locations during the 24-h storm period are indicated with triangles. The storm track and direction is represented by the solid line with arrows. Shaded contour lines and associated numbers indicate the estimated maximum sustained surface winds compiled and analyzed by the NOAA Hurricane Research Division of the Atlantic Oceanographic Marine Laboratory. Hurricane Katrina is presented here because the HRD wind swath analysis for the more intense Hurricane Wilma was not available as of April 2006. http://www.aoml.noaa.gov/hrd/Storm_pages/wilma2005/wind.html

Methods

We used satellite-monitored radio tags to track individuals. Manatees were fitted with two types of tags: Argos Platform Terminal Transmitters (PTT) transmitters and Global Positioning System (GPS) tags that provided a location approximately every 6 h or 30 min, respectively. We plotted manatee locations 2 wk prior to and during close passage of the storms, using a convex hull polygon to define the home range of each animal prior to the hurricane with an overlay of locations for a 24-h period during the storm (Fig. 1). We chose a 2-wk interval for the home range locations to capture both the extended foraging periods (usually offshore) and the short, periodic forays to more inland freshwater sites to drink, which we documented with earlier studies (Stith et al. 2004). We also looked for unusual movements during the 2-wk period following the storm's passage. We estimated each manatee's proximity to the storm as a minimum distance between the individual's central location during the storm's passage and the storm track coordinates provided by the National Hurricane Center. As an index of storm intensity experienced by the manatee, we estimated maximum surface wind speed by overlaying manatee locations on the storm's surface wind field (Table 1), developed and made available to the public by the National

TABLE 1. Summary of satellite-tagged manatee locations in 2004 and 2005 two weeks prior to, during, and two weeks after individuals experienced tropical storm force or hurricane force winds. Maximum surface wind speeds at the manatees' location estimated from contour maps of surfaces wind analyses, developed by the Hurricane Research Division (HRD) of the Atlantic Oceanographic Marine Laboratory (AOML), National Oceanic and Atmospheric Administration (NOAA). Locations for Hurricane Katrina are plotted in Fig. 1.

Hurricane	Manatee ID	Habitat at Manatee Location	Minimum Distance and Direction from Center of Storm Track	Estimated Maximum Surface Wind Speed*	Change of Location from Core Area?
Charley, August 2004	TNP 27 Giffer	coastal lagoon	14 km, WNW	18–23 m s^{-1}	No
Katrina, August 2005	TNP 30 Thor	offshore seagrass beds	55 km, N	21–23 m s^{-1}	No
	TEP 01 Terry	offshore seagrass beds	33 km, N	29 m s^{-1}	No
	TEP 03 Margo	inland bay	27 km, S	23–26 m s^{-1}	No
	TEP 02 Perry	inland bay	35 km, S	21–23 m s^{-1}	No
	TNP 31 Beleza	offshore seagrass beds	49 km, N	26–29 m s^{-1}	1–2 km move
Wilma, October 2005	TNP 30 Thor	offshore seagrass beds	0 km, direct hit	56 m s^{-1}	No
	TEP 01 Terry	offshore seagrass beds	22 km, SSE	51–56 m s^{-1}	No
	TEP 03 Margo	inland creek	65 km, SSE	41 m s^{-1}	No
	TEP 02 Perry	inland bay	115 km, SSE	41 m s^{-1}	No

*Estimates for Hurricanes Charley and Katrina were derived from the wind swaths synthesized by HRD from a time series of data to project the peak sustained winds along the observed track of the storm (http://www.aoml.noaa.gov/hrd/data_sub/wind.html). The HRD wind swath analysis for Hurricane Wilma was not available as of April 2006, so estimates were inferred from individual analyses for two time periods prior to and at landfall (7:30 and 10:30 Universal Time Coordinated (UTC) 24 October 2005, http://www.aoml.noaa.gov/hrd/Storm_pages/wilma2005/wind.html).

Oceanic and Atmospheric Administration Hurricane Research Division of Atlantic Oceanographic Marine Laboratory (AOML) (http://www.aoml.noaa.gov/hrd/data_sub/wind.html, 29 December 2005).

Results and Discussion

The tagged manatees varied in their proximities to the storm track and the maximum sustained surface wind speed they experienced. Six individuals experienced winds of tropical storm force or greater (Table 1). Four experienced the leading and trailing eye wall of Wilma as it came ashore in south Florida as a category 3 storm; these same individuals were also in the vicinity of Katrina as it exited Florida after its first landfall (Fig. 1). None of the tracked manatees demonstrated any movement away from its 2-wk pre-hurricane home range during the storm (Fig. 1, Table 1) or for a 2-wk period after the storm, with the exception of a minor 1–2 km move for one individual (Beleza).

Although sample sizes were small, our analysis of movements during hurricanes suggests that manatees stay where they are to ride out the storm, rather than making large lateral movements or smaller movements further inland or offshore to deeper water. The same pattern was seen for individuals occupying inland bays and creeks, coastal lagoons, and offshore seagrass beds (Table 1). We assume that within a given home range, some locations may provide better protection from storm forces than others, but the telemetry data did not show any apparent directed movements to seek these out, despite the fact that previous location data documented a much broader year-round home range for these individuals than indicated by the 2-wk polygons. We plan further analysis of our data to determine what types of microhabitats manatees used during these storms, if short moves to new locations were made as wind and storm surge directions changed between onshore and offshore during a storm's passage, and if there were common patterns among individuals and storms.

None of our radio-tagged manatees died or were swept out to sea. We are still left with two questions: was the previously published pattern of storm-related lower apparent survival indicative of processes operating in other regions with other extreme storms, and if extreme storm effects are a common phenomenon, what mechanisms may be operating to produce the effects? To address the first question we continue to collect data to estimate apparent survival during the most recent storms. To address the second question we have developed and described below a set of expectations of the magnitude of detectable effect based on storm characteristics and hypothesized causal mechanisms.

The satellite telemetry data suggest that manatees do not flee from extreme storms, but remain in familiar territory. If these data are representative of manatee behavior in general, we can assume that storm effects will be confined to those animals inhabiting areas within the swath of the destructive elements of the storm. Because survival rates are estimated on a relatively large regional scale, we hypothesize that effects will only be detectable in years in which a region is affected by a large, destructive storm or a series of smaller major storms throughout the region. Duration of the storm should also have an effect, as the longer manatees are exposed to storm forces, the more likely a negative outcome will occur. The timing of storms near cold weather periods, when manatees are vulnerable to cold stress could exacerbate effects. In our previous analysis of north Gulf coast data

(Langtimm and Beck 2003), lower apparent survival was detected with the 1993 ''Storm of the Century'', which occurred in spring just after manatees had dispersed from the winter refuges and produced substantial cold weather and snow in the Florida panhandle and along the entire U.S. east coast (Lott 1993, p. 1). In 1985 and 1995, Hurricanes Kate and Opal all occurred late in the season just prior to or as manatees began returning to the winter refuges. All of the major hurricanes affecting Florida in 2004 and 2005 hit during the warm summer months, and timing with seasonal cold stress conditions should not be a factor influencing survival. Wilma occurred at the end of the 2005 hurricane season, but water temperatures in southern Florida were still sufficiently warm, so temperatures would not likely affect manatee survival.

Physiographic features also can affect the location and strength of storm forces. Bays and estuaries, where manatees most frequently occur, can experience up to 50% higher surges than open coast basins, and open coast basins along the Gulf coast experience higher storm surges than basins along the Atlantic coast due to higher shoaling factors influenced by bathymetry profiles (Simpson and Riehl 1981). Protected lagoons sheltered by extensive barrier islands could afford protection from winds and waves. Strong wind-generated currents at inlets could sweep manatees offshore. Given the complexity of the processes at work as hurricanes make landfall, what little we know of the mortality risk imposed on manatees by storm currents or storm surge, and no evidence from the tracking data to suggest that manatees seek out particular features, at this time we focus only on hypotheses related to size, intensity, and duration of the storms. The outcome of the analysis of the 2004 and 2005 survival estimates will allow us to assess and modify our hypotheses and direct our efforts to the most promising areas of research.

We identified several general physical attributes indicative of size and intensity of each storm near landfall, based on reports from the National Hurricane Center (Table 2). Measures include: width of the eye, radius of hurricane force winds and tropical storm force winds from center, forward speed of the storm, direction of the storm's path, maximum sustained winds, rating on the Saffir-Simpson scale, and estimated storm surge. Hartman (1979) reported that fast currents can affect manatee activity and movement and that animals migrating via the Intracoastal Waterway on the Atlantic were never seen during aerial surveys to swim against currents greater than 6 km h^{-1}. Although the science of rapidly predicting and modeling storm winds is fairly advanced, predicting and modeling storm-generated water currents remains a time-consuming and complex task and no values were available for this analysis.

Considerable variation in storm attributes among individual storms and among regions is apparent (Table 2). The northwest region sustained two consecutive years of direct strikes by Hurricanes Ivan, Dennis, and Katrina in the vicinity of the area hit by Hurricanes Erin and Opal, the apparent cause for a lower survival rate documented for 1995 (Langtimm and Beck 2003). Extreme coastal erosion from Katrina was observed on Dauphin Island, Alabama, south of Mobile Bay, making it likely that the storm significantly affected the northwest region, even though landfall was over 135 km to the west of Florida. The large size and high intensities of all three storms suggests a likely detectable effect on adult survival in the Northwest subpopulation. The region also was affected by additional tropical storms or minor hurricanes, including the exit of Hurricanes Frances and Jeanne into the northern Gulf of Mexico in 2004 and Tropical Storm Arlene and Hurricane Cindy in 2005.

The southwest region was hit by Hurricane Charley in 2004. Although it was a very intense category 4 storm, its small size and fast forward speed suggest minor or no significant effect to the subpopulation. In 2005, Hurricane Wilma struck south of the area in the Ten Thousand Islands-Everglades region. Although slightly less intense but larger, this too was a fast moving storm. Comparison of effects from these two storms would be insightful, but unfortunately photo-identification monitoring is limited in the Everglades, preventing us from estimating survival rates for this particular storm and area.

Florida's Atlantic Coast region incurred two strikes in 2004 by Hurricanes Frances and Jeanne. Frances was a large, slow moving category 2 storm hitting the Indian River lagoon area, a primary use area for manatees along the south-central Atlantic coast (Deutsch et al. 2003). Three weeks later the more intense and equally large Jeanne struck in nearly the same location. Given their size, intensities, and durations, along with the consequences of unprecedented back to back strikes, it is likely there will be a detectable effect on survival. The southernmost Atlantic region in 2005 was hit by Hurricane Katrina as it made its first landfall in Florida as a category 1 storm before its second strike to the north Gulf coast. Its small size and lower intensity makes it unlikely that it would affect survival rates in this region.

The magnitude of effect of the 2004 and 2005 hurricanes on manatee survival rates remains to be seen. At least another year of data collection and processing is required before the first estimates for 2004 will be available; 2 yr will be needed for the

TABLE 2. Description of physical attributes of the 2004 and 2005 hurricanes affecting the habitats of three regional manatee subpopulations. Attributes are limited to those characteristics hypothesized to affect regional apparent survival probabilities: duration of impact (forward speed), geographic scale of impact (radii of hurricane and tropical storm force winds), and measures of storm severity (Saffir-Simpson category, maximum sustained winds, maximum storm surge). Source of data: National Hurricane Center's (NHC) Tropical Cyclone Reports and NHC Public Advisories just prior to landfall (http://www.nhc.noaa.gov/pastall.shtml, 29 December 2005). Estimates are approximate and may change as NHC continues to revise analyses and reports.

Manatee subpopulation region	Northwest			Southwest		Atlantic Coast		
Hurricane name	Ivan	Dennis	Katrina	Charley	Wilma	Frances	Jeanne	Katrina
Date of landfall	September 16, 2004	July 10, 2005	August 29, 2005	August 13, 2004	October 24, 2005	September 5, 2004	September 26, 2004	August 5, 2005
Location of landfall	Gulf Shores, Alabama	Santa Rosa Island, Florida	Pearl River, Mississippi	Cayo Costa, Florida	Cape Romano, Florida	Hutchinson Island, Florida	Hutchinson Island, Florida	Miami-Dade/ Broward County Line, Florida
Coordinates	30.2′N, 87.9′W	30.4′N, 87.1′W	30.2′N, 89.6′W	26.6′N, 82.2′W	25.9′N, 81.7′W	27.2′N, 80.2′W	27.2′N, 80.2′W	26.0′N, 86.1′W
Saffir-Simpson category	3	3	3	4	3	2	3	1
Maximum sustained winds	54 m s^{-1}	54 m s^{-1}	54 m s^{-1}	67 m s^{-1}	54 m s^{-1}	46 m s^{-1}	54 m s^{-1}	36 m s^{-1}
Forward speed	21 km h^{-1} (13 mi h^{-1})	27 km h^{-1} (17 mi h^{-1})	26 km h^{-1} (16 mi h^{-1})	32 km h^{-1} (20 mi h^{-1})	32 km h^{-1} (20 mi h^{-1})	18 km h^{-1} (7 mi h^{-1})	21 km h^{-1} (13 mi h^{-1})	10 km h^{-1} (6 mi h^{-1})
Direction	N	N	N	NNE	NE	WNW	W	SW
Width of eye	74–92 km (46–57 mi)	13 km (8 mi)	50 km* (31 mi)	10 km (6 mi)	121 km (75 mi)	84 km (52 mi)	92 km (57 mi)	74–111 km (46–69 mi)
Radius of hurricane winds	169 km (105 mi)	64 km (40 mi)	201 km (125 mi)	48 km (30 mi)	145 km (90 mi)	137 km (85 mi)	113 km (70 mi)	24 km (15 mi)
Radius of tropical storm winds	467 km (290 mi)	370 km (230 mi)	370 km (230 mi)	169 km (105 mi)	370 km (230 mi)	322 km (200 mi)	330 km (205 mi)	129 km (80 mi)
Maximum estimated storm surge	3.1–4.9 m (10–16 ft)	1.8–2.7 m (6–9 ft)	4.6–8.2 m (15–27 ft)	1.8–2.1 m (6–7 ft)	4–5.5 m (13–18 ft)	1.8–2.4 m (6–8 ft)	1.2–2.1 m (4–7 ft)	0.6–1.2 m (2–4 ft)

* Estimated from Doppler radar.

first estimates for 2005. The back-to-back years of intense hurricane strikes to manatee habitat may complicate resolving the magnitude of effect during each year. Results may also be confounded for the Northwest and Southwest subpopulations because toxic red tide blooms occurred in 2004 and 2005, with documented manatee mortality in the southwest. Earlier mark-resighting data and our analysis prior to the new active cycle (Langtimm and Beck 2003) can be used to establish a baseline of estimates specific to hurricane-only or red tide-only years, which then would allow us to gauge the relative contribution of multiple mortality factors. More importantly, though, an ideal natural experiment occurred when Hurricanes Frances and Jeanne struck the Atlantic Coast subpopulation. We know of no unusual additional mortality events, the region was affected only in 2004, and the two large slow-moving storms meet our proposed criteria for detecting a storm effect. If extreme storms are a factor throughout the range of Florida manatees, we would expect to see the effect in 2004 in the Atlantic Coast subpopulation with these storms.

We also have proposed that individual manatees may be forced or voluntarily move out of their core areas as a consequence of extreme storms. In our first analysis (Langtimm and Beck 2003), data to examine this hypothesis were not available for the storm years. The hurricanes of 2004 and 2005 provide a new opportunity to assess some aspects of change in habitat use and movement, particularly between the Northwest and Southwest subpopulations and among monitoring sites along the Atlantic Coast. Manatees show high fidelity to core winter home ranges and warm-water refuges (Deutsch et al. 2003; Langtimm et al. 1998). Although winter photo-identification data cannot document changes in summer home range, individuals displaced to new areas within our monitoring program might switch to a new winter aggregation site. If a significant portion of the subpopulation is affected, this can be documented by the application of multistate capture-recapture statistical models (Brownie et al. 1993) to show changes in estimates of movement rates and site fidelity.

The research we have outlined here is a first step to determine if there is a cause-effect relationship between extreme storms and mortality, if storm-related mortality and home range disruption are factors throughout the range of the Florida manatee, and what storm forces may be involved. We are now in a proposed cycle of increased hurricane activity, expected to continue for another 10–20 yr (Landsea et al. 1996). The consequences of this new hurricane cycle to manatee population dynamics are unknown, but the existing baseline of population data between 1981 and 1999 will allow us to better evaluate this proposed cycle. Documenting and ultimately predicting the magnitude of effect of these and future storms on survival rates and population growth rates will be vital information for managers tasked with recovery of this species.

Acknowledgments

Susan Butler oversees the acquisition of USGS telemetry data and provided us with the first views of manatee movements during these storms. We thank Tom O'Shea, Ken Prestwich, and an anonymous reviewer for helpful comments on the manuscript.

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Received, January 30, 2006
Accepted, March 30, 2006