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Ship and Satellite Studies of Mesoscale Circulation and Sperm Whale Habitats in the Northeast Gulf of Mexico During GulfCet II

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Eighty-three encounters with sperm whales (*Physeter macrocephalus*) occurred on two cruises that made expendable bathythermograph + conductivity-temperature-depth surveys of cyclone–anticyclone eddy pairs in the Northeast Gulf of Mexico (NEGOM). In late summer 1996, 41 sightings of sperm whales were made and 10 acoustic contacts were registered. Of these 51 encounters, 90% were in a cyclonic area of lower than average dynamic height offshore that was surveyed from space by near-real-time altimetric sea surface height anomaly and then mapped in high resolution with shipboard measurements or within 100 km of SW Pass of the Mississippi River. In midsummer 1997, 23 sightings and nine acoustic contacts were made. Of these 32 encounters, 81% were in an offshore cyclonic area of lower than average dynamic height or within 100 km of the mouth of the Mississippi River. Time series animation of the 1996 and 1997 altimetric data indicated these cyclones are typically associated with Loop Current excursions into the NEGOM and that the two cyclones we surveyed had spun up 4–6 mo previous to our fieldwork. Although cyclones in the NEGOM are temporally persistent, their geographic location is spatially variable: the cyclone surveyed in 1996 was centered 150–200 km south and east of the Mississippi River delta in water 2–3 km deep, whereas that surveyed in 1997 was centered farther east in water 2–3 km deep over DeSoto Canyon. Sperm whales appear to have affinity for cyclonic eddies because the largest numbers of encounters with sperm whales also shifted east in 1997 compared with 1996.

From 1992 to 1994 and from 1996 to 1997, the U.S. Minerals Management Service and U.S. Geological Survey, respectively, sponsored surveys with ship and aircraft to determine the distribution and abundance of cetaceans on the continental margin of the northern Gulf of Mexico. These cetacean field studies, which have become known as GulfCet I and GulfCet II, respectively, were conducted jointly by Texas A&M University and the United States National Marine Fisheries Service, Southeast Fisheries Science Center (Davis et al., 1996, 2000; Mullin and Hansen, 1999). Shipboard surveys during GulfCet I were conducted seasonally for 2 yr from April 1992 to May 1994. In all, 2×10^5 km of transect were surveyed with high-power (×25), large-format "Big Eye" binoculars on eight cruises, within a 1.5×10^5 km^2 area of the continental shelf and slope between water depths of 100 m and 2,000 m. An additional 5×10^5 km were visually surveyed during eight aerial surveys (Davis et al., 1996). However, despite this extensive aerial and seasonal coverage, the GulfCet I surveys failed to establish any particularly strong correlations between cetacean distributions and oceanographic habitat variables such as surface temperature, surface salinity, or subsurface temperature. Instead, the strongest correlations of cetacean species distributions were with bottom depth and bathymetric depth gradient (Davis et al., 1998). That is, some groups of cetacean species appeared to prefer the continental shelf whereas others were most abundant over the upper slope or in deeper water.

Because periodic intrusions of the Loop Current (LC) from the southeast are followed by the separation of warm-core LC eddies that then drift west and interact with the continental slope, the continental margin of the northern Gulf of Mexico is oceanographically quite dynamic. Unfortunately, none of the GulfCet I cruises surveyed far enough seaward to completely transect one of these LC (anticyclonic) eddies nor did any of the GulfCet I cruises completely survey the companion cold-core (cyclonic) eddies that are often found in close association. So, in addition to time spent in predetermined locations doing cross-margin transects, the follow-on GulfCet II program was designed to spend "focal" time surveying LC eddies and cyclones in an effort to identify possible associations between cetacean high-use habitats and mesoscale physical variability. The locations of the cyclones and anticyclones were determined precruise from near-real-time satellite altimetry (Leben et al., 1993; Lillibridge et al., 1997), and research vessel survey time was then allocated to spend roughly equal amounts of time searching for cetaceans in an LC eddy (sea surface high) as well as in a companion cyclonic eddy (sea surface low). This paper describes two such surveys of a cyclone and an LC eddy on each of two cruises during GulfCet II.

The distribution and abundance of sperm whales (*Physeter macrocephalus*) were of special interest during this GulfCet II survey work because sperm whales are listed as an endangered species. Sperm whales were also of primary interest because they are the only large whale that is common in the Gulf of Mexico (they had been sighted more than 70 times during the GulfCet I shipboard visual surveys and more than 20 times during the aerial surveys), and as a result, they may be ecologically important apex predators because of their annual food requirements (see companion paper by Wormuth et al., 2000). Sperm whale minimum population abundance in the northern Gulf has been estimated to be about 300 animals (Davis et al., 1998; Mullin and Hansen, 1999), where it was apparent that there were local concentrations of sperm whales in regions of lower than average sea surface height (Sparks, 1997). For example, chi-square analysis of deepwater acoustic contacts with sperm whales when combined for eight cruises of GulfCet I demonstrated that there were over three times the number of observed acoustic contacts with sperm whales in regions of low sea surface height (−10 to −30 cm) than might be expected from chance alone (Sparks, 1997).

Methods

Two cruises of R/V *Gyre* in summers 1996 and 1997 surveyed the continental margin of the northeast Gulf of Mexico (NEGOM) between 89°W and 85°W, but they surveyed farther seaward as well, within a deepwater "focal area" where near-real-time altimetry maps of sea surface height anomaly produced at the University of Colorado Center for Astrodynamics Research (CCAR) indicated there was a mesoscale cyclone (cold-core eddy) and anticyclone (warm-core eddy) pair. Tandem remote sensing of sea surface height with the TOPEX/POSEIDON and ERS-2 satellite altimeters was used to first locate a deepwater cyclone–anticyclone pair in the NEGOM and to determine the approximate dimensions of and center locations for the cyclone and anticyclone. Cruise tracks were then plotted to cross the cyclone with five or six long lines of closely spaced expendable bathythermograph (XBT) stations, each of which would also extend into the northern part of the anticyclone. In late summer (October) 1996, the ship dropped 144 XBTs and made eight conductivity-temperature-depth (CTD) stations to profile the temperature and density structure of the upper 760 m of LC Eddy "C" and a companion cyclone. In midsummer (August) 1997, the ship dropped 102 XBTs and made five CTD stations in LC Eddy "E" and a companion cyclone.

XBT data were combined with CTD data to compute the local geostrophic circulation field, following procedures published previously (Biggs, 1992). All of the geopotential computations were referenced to the 800 m because this is the deepest depth generally available from T-7 XBT probes after XBT raw data are corrected for drop-rate errors (Biggs, 1992). However, the basis for this geopotential anomaly computation changes seasonally as the near surface water is heated to stand about 10 cm higher in midsummer than in early summer. In early summer, the mean dynamic height for the deepwater continental margin away from the LC or its associated eddies is about 95 dyn cm relative to 800 m. This mean dynamic height increases to 105 dyn cm by midsummer (August) and then relaxes to 100 dyn cm by late summer (October) as the near surface water begins to lose heat after passage of atmospheric cold fronts in September and October. Operationally, 100 cm and 105 cm, respectively, were subtracted from dynamic heights calculated from August 1997 and October 1996 data in order to compute the dynamic height anomaly fields that are presented in the Results and plotted in Figure 3. When sperm whales were encountered in water depths <800 m, we used the depth of the 15 C isotherm of the main thermocline to determine whether we were inside or outside a cyclone; 15 C is a useful proxy for dynamic height over the upper slope because 15 C is domed to <170 m in cyclones and depressed to >250 m in anticyclones (Biggs et al., 1996).

The dynamic height and 15 C data were used to define five hydrographic regimes: 1) cyclone; 2) LC eddy; 3) surface flow confluence between the two; 4) mouth of the Mississippi River (MOM), and 5) other margin. MOM was operationally defined as the continental margin within a radius of 100 km from the SW Pass of the Mississippi River (Burrwood, LA: 28°58.1′N; 89°22.6′W), and any area outside the influence of 1–4 was classed as other margin. During GulfCet II cruises, two ob-

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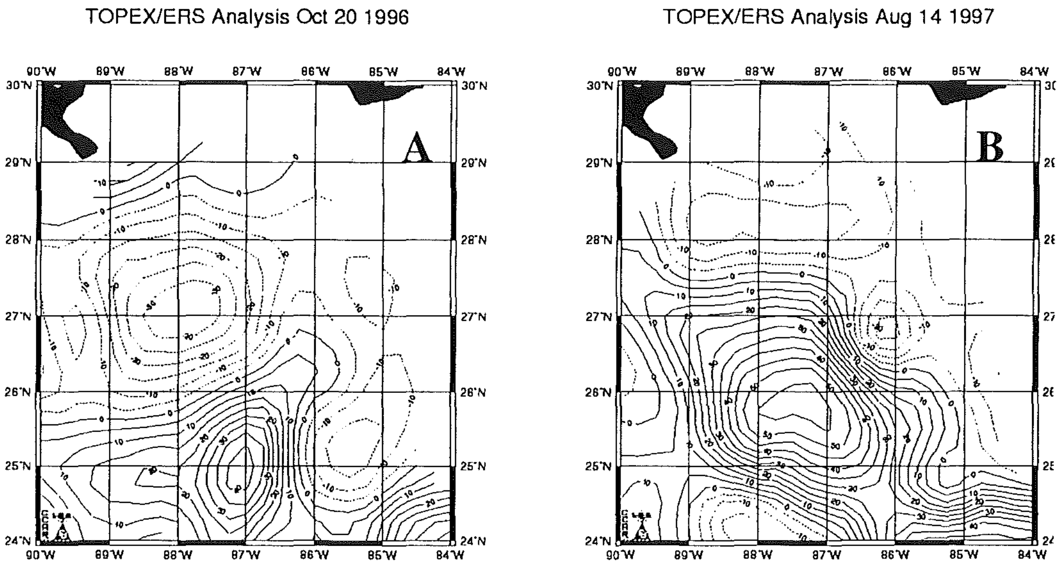

Fig. 1. Sea surface height anomaly for water depths >200 m from satellite altimeter data gridded for the midpoint dates of GulfCet II cruises (A) 96G06 (12–29 Oct. 1996) and (B) 97G08 (6–21 Aug. 1997). The maps are produced from TOPEX and ERS-2 altimeter data processed with archival data and they are interactively available at http://www-ccar.Colorado.EDU/~realtime/gom-historical_ssh/. This historical product is designed to retain the mesoscale sea surface height anomalies associated with fronts and eddies.

servers used "Big Eye" (25 × 150) binoculars and a third observer used handheld (7 × 50) binoculars to survey for cetaceans, while another three-person team used a towed acoustic array to detect sperm whale vocalizations. Effort and survey methods were similar to those employed during GulfCet I, but the acoustic characteristics of the towed array were improved for the GulfCet II fieldwork. Details will not be reported here because these visual and acoustic methods are explained by Davis et al. (2000).

Results

Remote sensing data processed at CCAR show that a broad area of cold-core circulation was located in the NEGOM throughout calendar year 1996. This cyclonic circulation shows up persistently in altimetry maps as a region of <-10 cm of negative sea surface height (SSH). This is evident in the animation of weekly SSH maps for the Gulf (http://www-ccar.colorado.edu/~leben/gulfmex_science/) as a temporally persistent although spatially variable region of negative SSH. This cyclonic feature was seen from January to September in the region of 27–29°N and 89–84°W, even though for much of the year the northern edge of the LC extended north of 25°N and even though the LC shed two eddies during 1996.

In January 1996, the LC extended north of 26°N in the eastern Gulf, with LC Eddy "A" to the west and centered at 90–92°W. This anticyclonic eddy had separated from the LC the previous August–September 1995, so by January 1996, Eddy A was 4–5 mo old. LC Eddy "B" separated from the LC between mid-April and mid-May, but because Eddy B remained centered east of 90°W for several months, its eastern edge apparently interacted with the LC through about mid-July. LC Eddy "C" separated from the LC in August–September 1996, about the time that Eddies A and B were merging and beginning to spin down in the western Gulf. By year's end, secondary LC Eddy "D" was in the process of splitting away from the northeast corner of Eddy C.

In late summer 1996 (Fig. 1A), altimetry indicated that the cyclone was centered between 27 and 28°N and 87 and 89°W, roughly halfway between MOM and the northwest edge of LC Eddy C. The R/V *Gyre* documented a 62-dyn-cm difference in height between the interior of the cyclone and the interior of LC Eddy C (Fig. 2A). This created a flow confluence between the two features in which upper layer geostrophic velocity exceeded 75 $cm \cdot s^{-1}$ (Fig. 2C) and volume transport was 24 × 10^6 $m^3 \cdot s^{-1}$ (24 Sverdrups).

Eddy E separated from the LC in June–July 1997. As in 1996, a region of cyclonic circu-

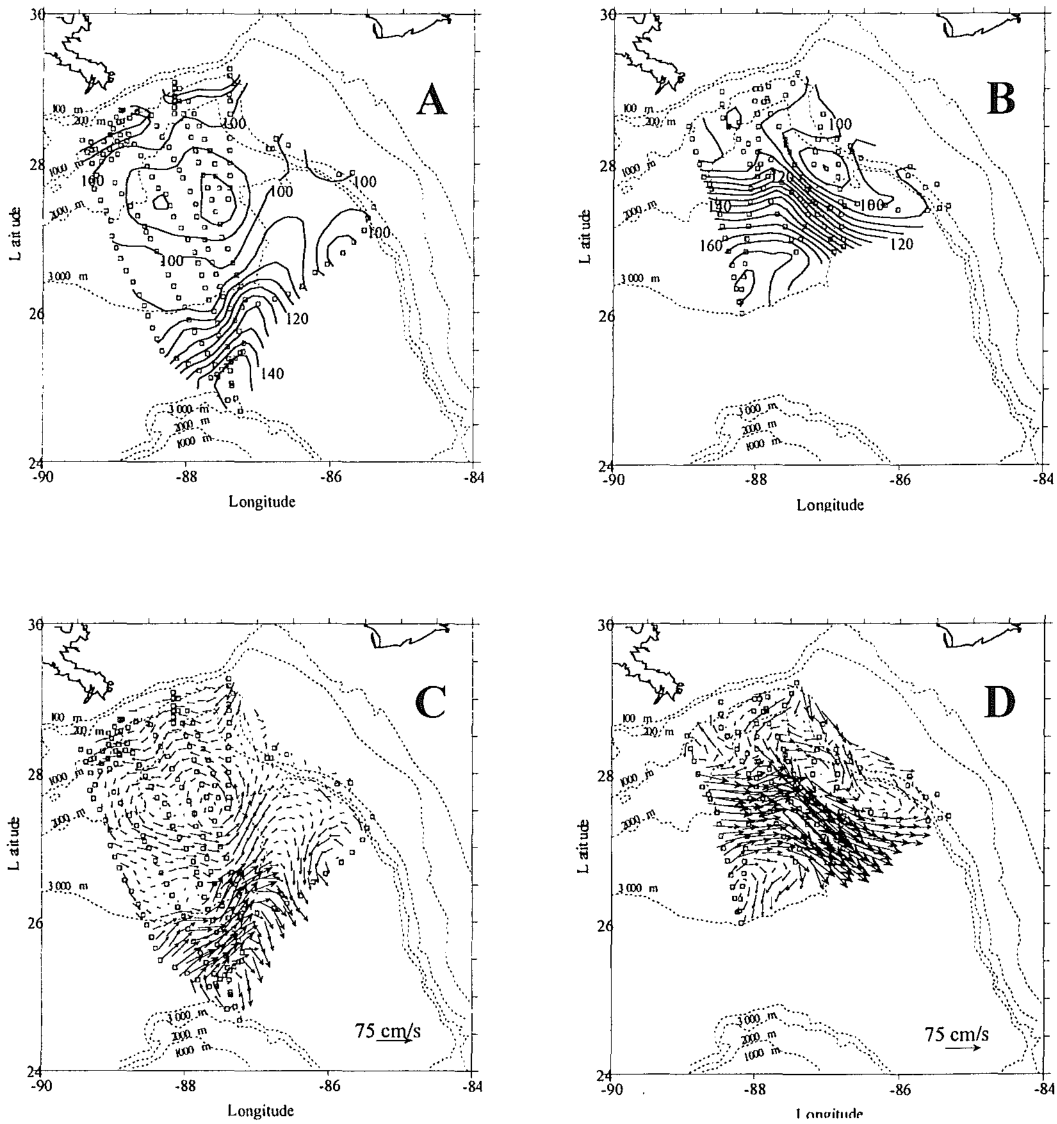

Fig. 2. Dynamic topography (cm, 0 m relative to 800 m) of the deepwater focal area in (A) October 1996, as determined from 152 hydrographic stations made on R/V *Gyre* cruise 96G06, and (B) August 1997, as determined from 107 stations made on R/V *Gyre* cruise 97G08; and gridded upper layer geostrophic velocity (cm/sec, 0 m relative to 800 m) of the deepwater focal area (C) as computed from the October 1996 dynamic topography and (D) as computed from the August 1997 dynamic topography. All from Davis et al. (2000:chapter 2).

lation persisted in the NEGOM for several months before and after this eddy shedding event. This eddy shedding periodicity, combined with the persistence of cyclonic circulation again in the region 27–29°N, 88–84°W, created mesoscale circulation conditions in the NEGOM in early and late summer 1997 that were remarkably similar to those in early and late summer 1996. In midsummer 1997, the R/V *Gyre* again surveyed a deepwater cyclone–anticyclone pair. This time, the altimetry indicated that the cyclone was centered on the northeast side of the anticyclone and was over the DeSoto Canyon (Fig. 1B). The R/V *Gyre* documented a 84-dyn-cm difference in height between the interior of the cyclone and the interior of LC Eddy E (Fig. 2B). This created a flow confluence between the two features in which upper layer geostrophic velocity exceeded 100 $cm \cdot s^{-1}$ (Fig. 2D) and vol-

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TABLE 1. Summary of dynamic height anomaly (cm) and 19 C depth (m) from CTD + XBT survey and of Big Eye binocular sightings and acoustic contacts with sperm whales, within each of five broad divisions of the hydrographic environment in the NEGOM region (see text for details).

R/V *Gyre* cruise	Hydrographic environment	Dyn ht anomaly (mean ± SD)	19 C depth (mean ± SD)	Big Eye sightings	Acoustic contacts
Oct. 1996	MOM	4 ± 3	97 ± 5	17	2
	Cyclone	−5 ± 3	85 ± 8	22	5
	Confluence	7 ± 7	126 ± 18	0	1
	LC eddy	40 ± 9	227 ± 35	0	0
	Other margin	4 ± 4	104 ± 14	2	2
Aug. 1997	MOM	3 ± 1	97 ± 7	1	1
	Cyclone	−5 ± 4	94 ± 6	18	6
	Confluence	9 ± 8	111 ± 20	3	2
	LC eddy	49 ± 16	240 ± 50	1	0
	Other margin	4 ± 2	100 ± 19	0	0

ume transport was 31 × 10^6 $m^3 \cdot s^{-1}$ (31 Sverdrups). Underway shipboard measurements of sea surface temperature, salinity, and chlorophyll concentration showed that low salinity, high chlorophyll river water that originated in the MOM region was entrained from off the shelf and transported around the periphery of the cyclone.

Bottle sampling at CTD stations showed a significant relationship between water temperatures less than 22 C and nitrate concentration. As a result, the depth of the 19 C isotherm provided a good estimation of the depth of the 10 μM nitrate concentration. Table 1 shows that, within the cyclone, the average depth of the nitracline was 6–19 m shallower than over the other margin and 140–150 m shallower than in an LC eddy. This doming increased the flux of new nitrogen into cyclone surface waters so that the deep chlorophyll maximum was 40–60 m locally shallower and chlorophyll reached higher maximum concentration in the cyclone than in an LC eddy (see Zimmerman and Biggs, 1999:fig. 6). The higher standing stocks of chlorophyll in the upper 100 m of the water column in the cyclones are indirect evidence that cyclones are biological "oases" of locally high productivity, in sharp contrast to the nutrient-poor interiors of the LC eddies, which are biological "ocean deserts" (Biggs, 1992).

Sightings of sperm whales on the two R/V *Gyre* cruises were summarized by Mullin and Hoggard, and acoustic contacts by Norris, Evans, and Rankin, for the final report of the GulfCet II project (Davis et al., 2000). Figure 3 summarizes the search effort for and the location of these sperm whale contacts, superimposed on bathymetry and dynamic height anomaly, and Table 1 shows where they were seen in relation to the five types of hydrographic environments. In October 1996, observers registered 41 sightings (about 60 whales) with Big Eye binoculars and 10 acoustic contacts were made. Table 1 shows that 90% of the combined sightings were in regions of lower than average dynamic height anomaly (cyclone) and in the MOM region. In August 1997, 23 sightings (about 56 whales) and nine acoustic contacts were made. Table 1 shows that 81% of the combined sightings occurred in regions of lower than average dynamic height anomaly and in the MOM region. Comparing panels C and D of Figure 3 shows clearly that, although most sperm whales were seen in or near the MOM area in late summer 1996, in midsummer 1997 more of them were observed some 200 km due east, over deep water of the DeSoto Canyon. Whereas the continental margin SSE of the MOM area was strongly cyclonic in 1996, in 1997 the cyclonic circulation was centered instead in the DeSoto Canyon and sperm whale occurrence shifted similarly.

DISCUSSION

Jaquet (1996) noted that previous reviews of the factors controlling sperm whale distribution often have been equivocal and often appear to contradict each other. She suggested that this apparent confusion is mainly due to "poorly defined spatial and temporal scales, the use of only one scale in most studies, and the absence of consideration of the spatial and temporal scales at which relevant oceanographic processes occur." Jaquet concluded that cetacean survey work needed to be done on spatial scales relevant to the local oceanographic processes to obtain a better under-

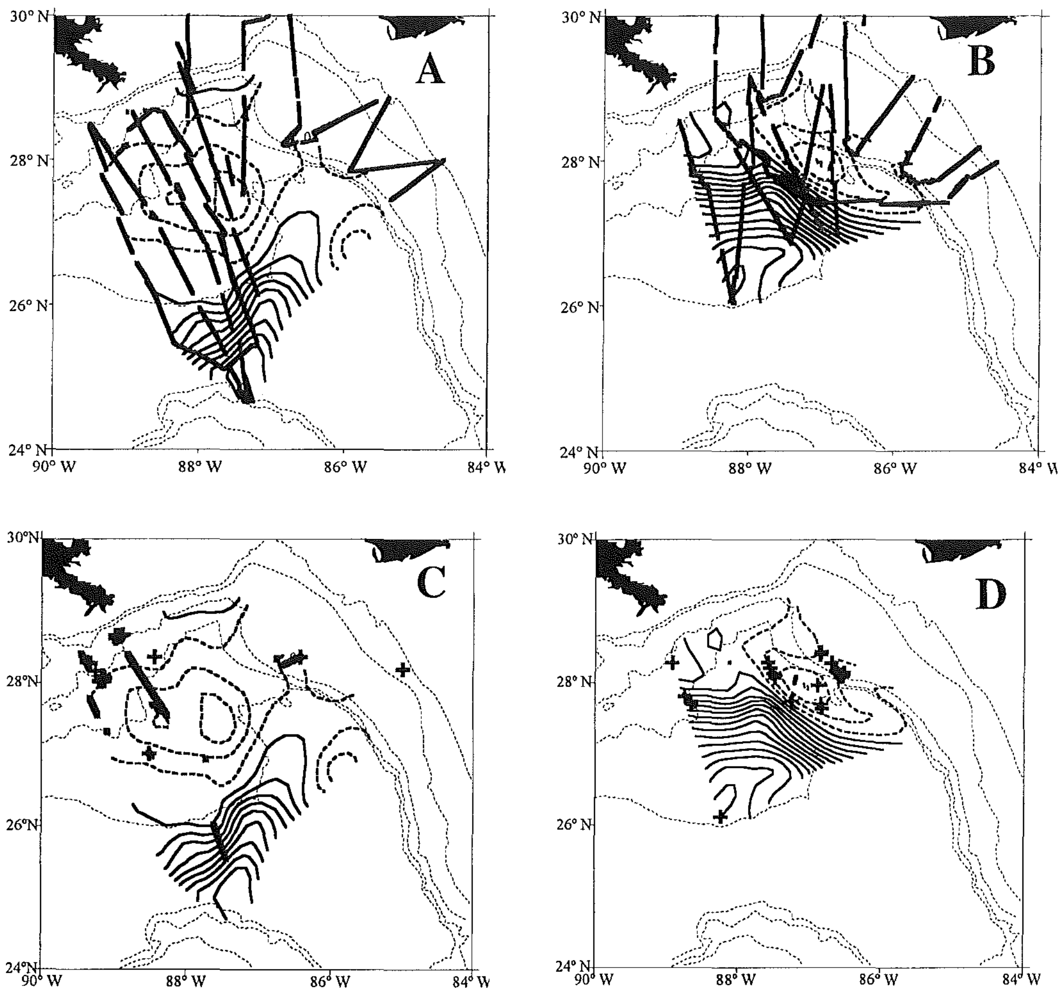

Fig. 3. Alongtrack combined visual and acoustic effort for GulfCet II cetacean survey during (A) October 1996 and (B) August 1997. Sperm whale contacts in (C) October 1996 and (D) August 1997 are superimposed on isolines of bathymetry (m) and dynamic height anomaly (cm, relative to 800 m). Negative height (cyclone) is designated by heavy dashed lines; positive height (anticyclone and flow confluence), by heavy solid lines. Visual contacts are indicated by crosses and acoustic contacts by the heavy lines that cut across bathymetry and across dynamic height anomaly. Length of each of these heavy lines indicates the time/distance of first and last acoustic contact.

standing of sperm whale distribution. Griffin (1999) suggested that mesoscale patterns in the biological and physical environments are important in regulating sperm whale habitat usage. Griffin reported sperm whales were seen five times more frequently in the vicinity of a thermal front on the eastern boundary of a Gulf Stream warm-core ring in the northwestern Atlantic Ocean than the pooled rate of sightings in the remainder of his study area. Griffin also stressed that no sperm whale was sighted within the interior of the anticyclonic ring away from frontal boundaries. Griffin concluded that interaction of the warm-core ring with the shelf or slope water was probably indirectly responsible for greater sperm whale presence on the eastern (deepwater) boundary of the ring and noted that entrainment of shelf water by Gulf Stream warm-core rings occurs frequently, providing potential sperm whale habitat in the vicinity of oligotrophic Gulf Stream warm-core rings. Although Griffin did not survey a companion Gulf Stream cold-core ring, the association of historic sperm whale catches with areas of major upwelling has been documented by previous researchers (Cushing, 1975).

In the Gulf of Mexico, most sperm whales

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were concentrated along the continental slope in or near cyclones. These eddies are mesoscale features with locally enhanced plankton stocks (see Wormuth et al., 2000) that appear to develop in response to the doming of nutrient-rich water upward toward the base of the mixed layer. Low salinity, nutrient-rich water from the Mississippi River, which may also contribute to enhanced primary and secondary productivity in the north-central Gulf, may explain the presence of a resident population of sperm whales close off the delta. However, because cyclones in the northern Gulf are dynamic, and because sperm whales are large, warm-blooded mammals whose wide-ranging movements are not physiologically limited by water temperature or by other hydrographic features, the spatial distribution of sperm whales will likely change over temporal scales during which aggregations of squid and other prey "grow in" by feeding more in cyclonic "oases" than in the depauperate anticyclonic "ocean deserts."

Whitehead and Arnborn (1987) categorized sperm whale groups into three main types: mixed, bachelor, and solitary males. Body size estimates, obtained by photogrammetry of individuals, suggest that large males are infrequent visitors to the northern Gulf and that the whales present correspond to mixed groups consisting of females, immature females, immature males, and calves (Weller et al., 2000). Body sizes for most of the sperm whales seen in October 1996 and August 1997 ranged from 7 to 10 m (Weller et al., 2000), sizes that are typical for females and young (Best, 1979). In addition, five sperm whale calves each about 5 m long were seen in the presence of about 15 adults on 20 October 1996. We hypothesize the presence of these young calves means there is reproductive success in the Gulf of Mexico. However, there are not enough baseline data on calf occurrence in the Gulf to allow us to judge whether the presence of five young calves indicates increased regional calf production in 1996.

It is possible that some sperm whales are resident in the Gulf of Mexico. Four of the 37 individuals that were identified on the basis of fluke photos during 1994 and 1996 were resighted within a cruise, and four individuals were resighted in both 1994 and 1996 (Weller et al., 2000). Ultimately, tagging and tracking of Gulf of Mexico sperm whales with satellite telemetry would be desirable to probe this hypothesis.

One of the hypotheses of our GulfCet II focal work was that the distribution and abundance of sperm whales in the NEGOM region would be positively correlated with spatial and temporal variations in regional food stocks of zooplankton and micronekton, for we expected that it would be lower trophic level prey in addition to the apex mammal predators *per se* that would be aggregated differentially among cyclone and anticyclone oceanographic environments. The companion paper that follows (Wormuth et al., 2000) reports the use of nets, trawls, and acoustic backscatter to determine the spatial and temporal variability of the zooplankton and micronekton stocks during the same cruises analyzed in this paper.

In conclusion, sperm whale distributions are likely to be influenced, in part, by food availability, reproductive requirements, and oceanographic features. We recognize that, because cyclones in the northern Gulf are highly dynamic features, sperm whale distribution is not static. However, with near-real-time satellite remote sensing of SSH anomaly, these features can be tracked and used to predict where sperm whales may be concentrated.

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