Gulf of Mexico Science

Volume 25
Number 2 *Number 2*

Article 1

2007

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DOI: 10.18785/goms.2502.01

Gulf of Mexico Science, 2007(2), pp. 97–108

Deep Scattering Layers of the Northern Gulf of Mexico Observed With a Shipboard 38-kHz Acoustic Doppler Current Profiler

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Midwater sound-scattering layers containing aggregations of zooplankton and micronekton prey form in response to a trade-off between predator avoidance at depth and optimal foraging near the surface. Although the volume backscatter strength of zooplankton aggregations have been extensively studied in the past, fewer studies have specifically examined other descriptive characteristics of these layers such as depth of layers, timing of migrations, and the presence of secondary scattering layers below the main scattering layer. In the present study, patterns of deep scattering layers (DSLs) were characterized using relative acoustic backscatter from a ship-mounted 38-kHz phased-array, acoustic Doppler current profiler (ADCP) in the northern Gulf of Mexico in summers 2002 and 2003. Temporal patterns of scattering layers were analyzed with respect to the timing of the daytime and nighttime diel vertical migrations, and spatial patterns of scattering layers were analyzed with respect to their proximity to mesoscale circulation features associated with upwelling, downwelling, and water depth. The most prominent main scattering layer was consistently found at daytime depth of 450 to 550 m below the surface except during an unusual shoaling event in which a significant shallowing of the layer was observed at 200 to 300 m below the surface. This event coincided with the crossing of a strong frontal boundary between high salinity, blue water and low salinity, green water from the Mississippi River plume. Less prominent secondary scattering layers found deeper than the main scattering layer showed regional variability and appear to be more frequently associated with shallower shelf depths than in the deepwater basin. Variability among deep scattering layers in this region may have important implications for the behavior and interactions of higher trophic levels dependent on these prey layers.

The Gulf of Mexico is a semienclosed subtropical basin in which physical circulation is dominated by the Loop Current that extends variably northward into the basin. Mesoscale anticyclonic eddies are shed from the Loop Current with an irregular periodicity of between 6 and 12 mo (Sturges and Leben, 2000). Around the periphery of these anticyclones are often one or more cyclonic eddies. In the deepwater Gulf of Mexico biological productivity is modified by presence or absence of these mesoscale circulation features. Enhanced near-surface chlorophyll standing stocks may occur when and where cyclonic eddies cause the doming up of deepwater nutrients. Cyclonic eddies of enhanced productivity may attract higher trophic-level predators and are considered biological hotspots, whereas their anticyclonic counterparts are considered biological deserts of low productivity (Biggs, 1992; Wormuth et al., 2000; Biggs et al., 2005). In the northern Gulf of Mexico sea surface salinity may be strongly influenced by river inputs from the Mississippi and Atchafalaya rivers. Sea surface salinity can be highly variable geographically or seasonally as the plume of buoyant freshwater is advected by interactions with local mesoscale eddies (Morey et al., 2003). Apex predators are often geographically associated with biological hotspots around cyclonic eddies. Sperm whales forage in the range between 500 and 1,000 m in this region, yet relatively little is known about the predator–prey dynamics of this deepwater prey community or how oceanographic forces influence the biology of the community.

Common taxa in the mesopelagic community, including copepods, euphausiids, mysids, decapods, etc., undergo diel vertical migrations (DVMs) out of surface waters during daytime (Hopkins and Baird, 1985; Hays, 2003), and form layers in the mid-water column. DVM is a universal phenomenon occurring in all the world's oceans as well as many freshwater systems and is widely accepted as a predator avoidance mechanism. Organisms descend out of the surface during daytime light hours and ascend back to the surface at night for optimal feeding (Iwasa, 1982; Lampert, 1989; Ohman, 1990). The most commonly hypothesized reason for DVM is that it leads to a reduced rate of predation on the migrating animals, since in the dark animals are not detectable by most visually orientated predators (Pearre, 1979; Han and Straskraba, 2001). Evidence supporting this hypothesis includes the observation that DVM is more common in larger and more highly pigmented species (those most susceptible to visual detection by predators) and that DVM is more common when planktivorous fish are abundantly present than times when they are not (Bollens and Frost, 1989; Hays, 1995; von Elert and Pohnert, 2000). Other factors contributing to the diel pattern include seasonality of phytoplankton blooms (Dagg et al., 1998), population size of the migrating species (Andersen and Sardou, 1994), ultraviolet radiation exposure at the surface during the daytime (Rhode et al., 2001), and individual energy reserves, in which individual variability in daily migration is influenced by their physical condition. Animals with larger lipid stores generally will migrate to the surface less often than those individuals that metabolically cannot afford a lower feeding rate (Hays et al., 2001).

Acoustic Doppler current profilers (ADCPs) are being increasingly used for biological studies of zooplankton and micronekton despite being originally intended to measure ocean currents by the Doppler shift of sound scattered off passive biological and other scatterers. Although many acoustic scatterers are essentially passive with the currents in the horizontal plane, some may undergo daily vertical migrations on the order of hundreds of meters into and out of the surface waters, forming deep scattering layers (DSLs) at depth (Franceschini et al., 1970; Pearcy et al., 1977; Andersen and Sardou, 1994). Most research vessels now have ADCPs available, thus providing data of opportunity for investigation of important biological questions that would otherwise not be feasible to study. Previous spatial surveys of zooplankton and micronekton using shipboard ADCPs operating at 153 kHz have documented diel patterns of zooplankton abundance in the Gulf of Mexico, but were limited to only about 300 m in vertical range (Heywood et al., 1991; Zimmerman and Biggs, 1999; Wade and Heywood, 2001; Ressler, 2002).

The objective of this study is to present the results of an initial investigation using a ship-mounted 38-kHz ADCP to examine the biological layers and aggregations in and below a main DSL usually found between 350 and 550 m. Possible relationships between DSLs were correlated with variability of important oceanographic parameters including river influence and mesoscale eddy proximity. This study represents a necessary first step for future studies attempting to explore the predator–prey relationship between DSLs and larger foraging predators.

ADCPs at 38 kHz have not been routinely used in the past for studying biological processes from acoustic backscatter because of their relatively low vertical resolution. However, the trade-off of range to resolution means that it has a greater vertical range, allowing the deep scattering community down to 1,000 m to be descriptively analyzed. It also returns sound signal from larger targets (>1 cm) that are likely important prey organisms for deep-diving apex predators. The detection size is a function of instrument frequency and sound speed (MacLennan and Simmons, 1992). Relative acoustic backscatter from a haul-mounted 38-kHz ADCP was used to describe acoustic scattering layers and deep aggregations in an attempt to understand the variability that occurs in the DSL community in the northern Gulf of Mexico. The presence and behavior of DSLs were analyzed with respect to water depth, proximity to mesoscale circulation features, and the influence of the Mississippi River plume.

Methods

Data collection.—Acoustic backscatter data were collected from the upper 1,000 m of the northern Gulf of Mexico continental slope and deep basin using a hull-mounted, phased-array 38-kHz ADCP (R.D. Instruments, 1996). The single phased-array transducer of the ADCP produces four acoustic beams, each at 30° from vertical. Individual ping backscatter data are averaged over 16-m vertical bins and over a 5-min sampling frequency by the manufacturer's software. Surveys were conducted on six cruises in summers 2002 and 2003 onboard the R/V *Gyre* supported by two different research programs; the Sperm Whale Seismic Study and the Deep Gulf of Mexico Benthic study (DGoMB). The first of these projects included simultaneous visual and three-dimensional passive acoustic tracking of sperm whales over the northern continental slope (ship track from these cruises is shown in Fig. 1), whereas the second carried out oceanographic sampling of the Gulf of Mexico deepwater basin (cruise stations are shown in Fig. 2). Sea surface temperature, salinity, and fluorescence were sampled using an onboard flow-through conductivity–temperature–depth (CTD) sampling system (intake 3 m below surface, mid-ship), and 15°C depths used to characterize eddy circulation were obtained from either CTD or expendable bathythermograph temperature profiles. The regional sea surface height (SSH) anomaly field was characterized from TOPEX/POSEIDON and ERS satellite data (courtesy of R. Leben, University

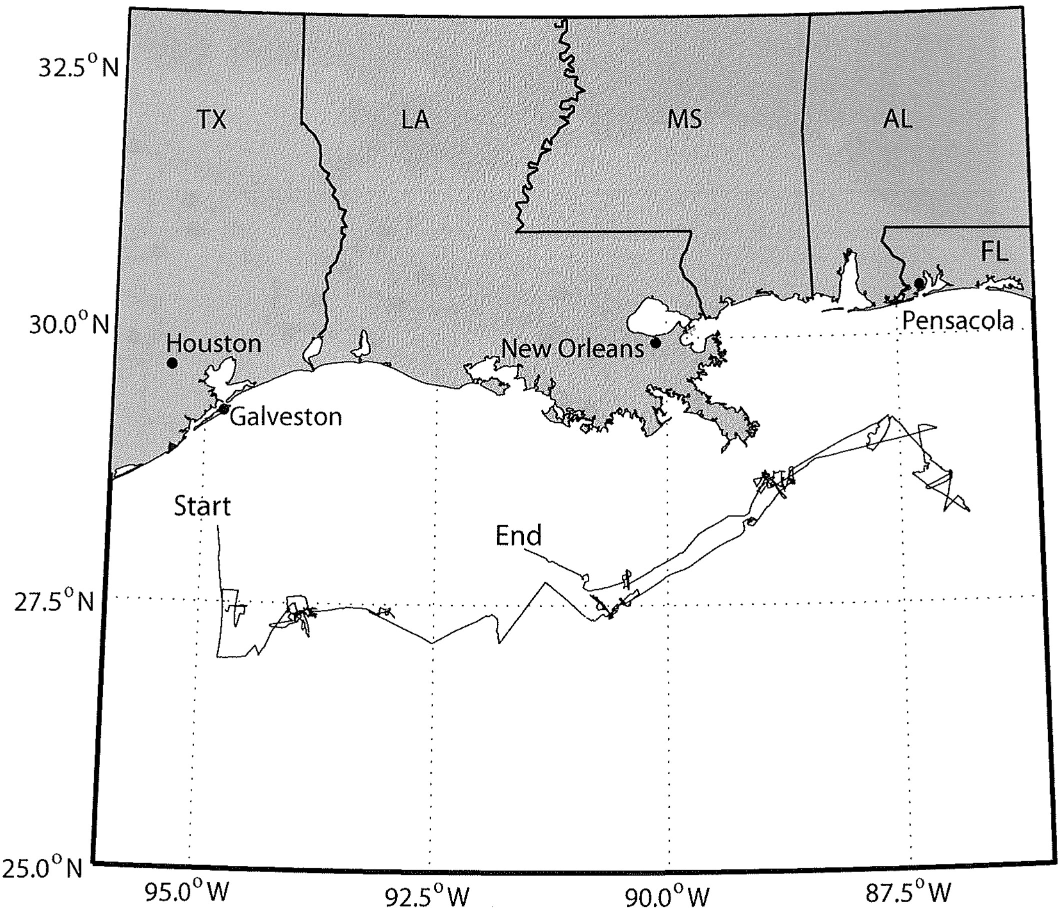

Fig. 1. Ship track for June 2003 SWSS cruise along the northern Gulf of Mexico continental slope. Five other SWSS cruises in summers 2002 and 2003 followed similar tracks.

of Colorado Center for Astrodynamics Research, http://ccar.colorado.edu/~realtime/gsfc_gom-real-time_ssh/) and used to identify mesoscale eddy circulation features. Relative acoustic backscatter intensity (RABI) and beam correlation, a measure of the correlation of intensity signal among the four acoustic beams, were measured with the 38-kHz ADCP and viewed using the manufacturer's software, WinADCP. The timing and vertical migration rate of organisms of the DSL were calculated and then exported for additional analysis in MATLAB. Because the beam pattern of the phased-array instrument has not yet been described, data were compared and reported in relative raw counts (RABI) rather than using a conversion to decibels (Deines, 1999).

Data analysis.—Timing and rates of vertical migrations of organisms into and out of the main DSL were calculated from RABI color contour plots, similar to the slope method used by Luo et al. (2000). Presence–absence evaluations of deeper, secondary scattering layers between 600 and 800 m were quantified by counting the number of days in which a significant scattering layer could be visually detected from color contour plots. Significant scattering layers were defined as a persistent (>1 hr, to discriminate against local patches) layer of higher than the local average backscatter return. Visible layers in the data represent at least 25% higher backscatter counts than the signal from that depth in adjacent areas. Forty-five daily echograms were analyzed from the upper continental slope region (800 to 1,000 m water depth) and the deeper slope region (>1,000 m water depth). Thirty-four daily echograms were used to analyze the influence of mesoscale circulation features (cyclone, anticyclone, confluence, no eddies) on the basis of SSH (from satellite altimetry). Eddy environments were characterized on the basis of the proximity to eddies as determined from SSH altimeter maps.

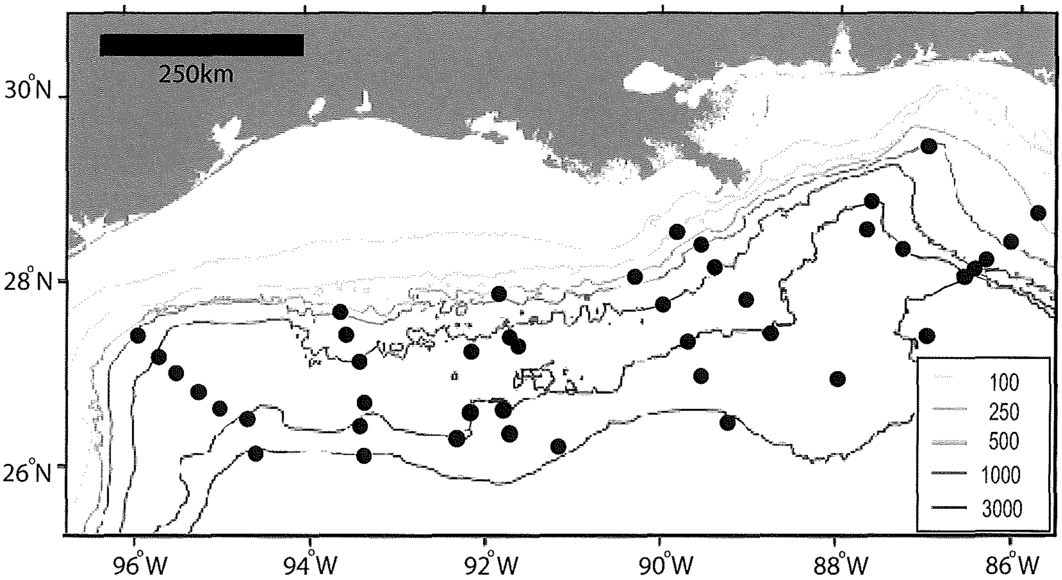

Fig. 2. Stations visited during DGoMB benthic ecology cruises in the Gulf of Mexico are represented by black circles. ADCP (38-kHz) data were collected while research vessel was underway between stations.

Backscatter data quality was variable and found to be a function of ship speed. Beam correlation is a parameter recorded by the ADCP that was used as an indicator of data quality. When the ship was traveling at slow to moderate speeds (generally less than 6 knots), there was relatively high agreement in the intensity recorded by the four beams, resulting in high beam correlation throughout the observational range (Fig. 3A). The associated backscatter intensity profile for good beam correlation resolves detail of the scattering layers. Increased ship speed (generally >6 knots) was associated with low beam correlation, particularly at mid to far ranges (past 500 m) (Fig. 3B). Backscatter intensity during low beam correlation was associated with a masking of the backscatter signal, resulting in a constant high backscatter profile. When the ship was moving at fast speeds, noise was high compared with the signal and detail of the signal was masked. This was most likely due to turbulent noise produced when the ship was underway from the flow of water over the transducer. As ship speeds increased, there may have also been air bubbles flowing across the transducer that could magnify the noise (cavitation). When the ship was maneuvering to hold station, one or both propellers variably produced bubbles so the beam correlation also generally decreased on station. For all analysis of 38 kHz ADCP backscatter, profiles where beam correlation measured less than 80% (200 of 250 raw counts) were not included in the analysis.

Results

Diel vertical migrations and the main DSL.—The average RBI profile for a June 2003 cruise is shown in Figure 4. A peak at roughly 500 m corresponding to the main DSL is superimposed over the gradual signal loss with depth associated with spherical spreading and sound absorption. For each diel migration, there were usually one to four visually distinct migrating scattering layers detected. Although the layers usually overlapped to some degree, especially near the surface, they were distinguishable either because they began migrating earlier or later in the day in relation to each other (Fig. 5A), they migrated at a different rate and the layers become separated (Fig. 5B), or they stopped their migrations at different depths and formed separate DSLs (Fig. 5C). The average rate of descending and ascending vertical migration of the scattering layers was 6.1 cm/sec and 6.6 cm/sec respectively (Table 1). These rates ranged from 1.6 cm/sec to 12.4 cm/sec. Assuming that vertically migrating animals larger than 1 cm are resolved at this frequency, the vertical migration rates suggest that the ADCP resolved vertically migrating organisms moving on the order of one to several body lengths per second.

Vertical migrations followed a consistent day/night cycle. For DVM during the June 2003 cruise, scattering layers began the descending migration out of the surface waters between 0400 hr and 0515 hr Central Daylight Time

DOI: 10.18785/goms.2502.01

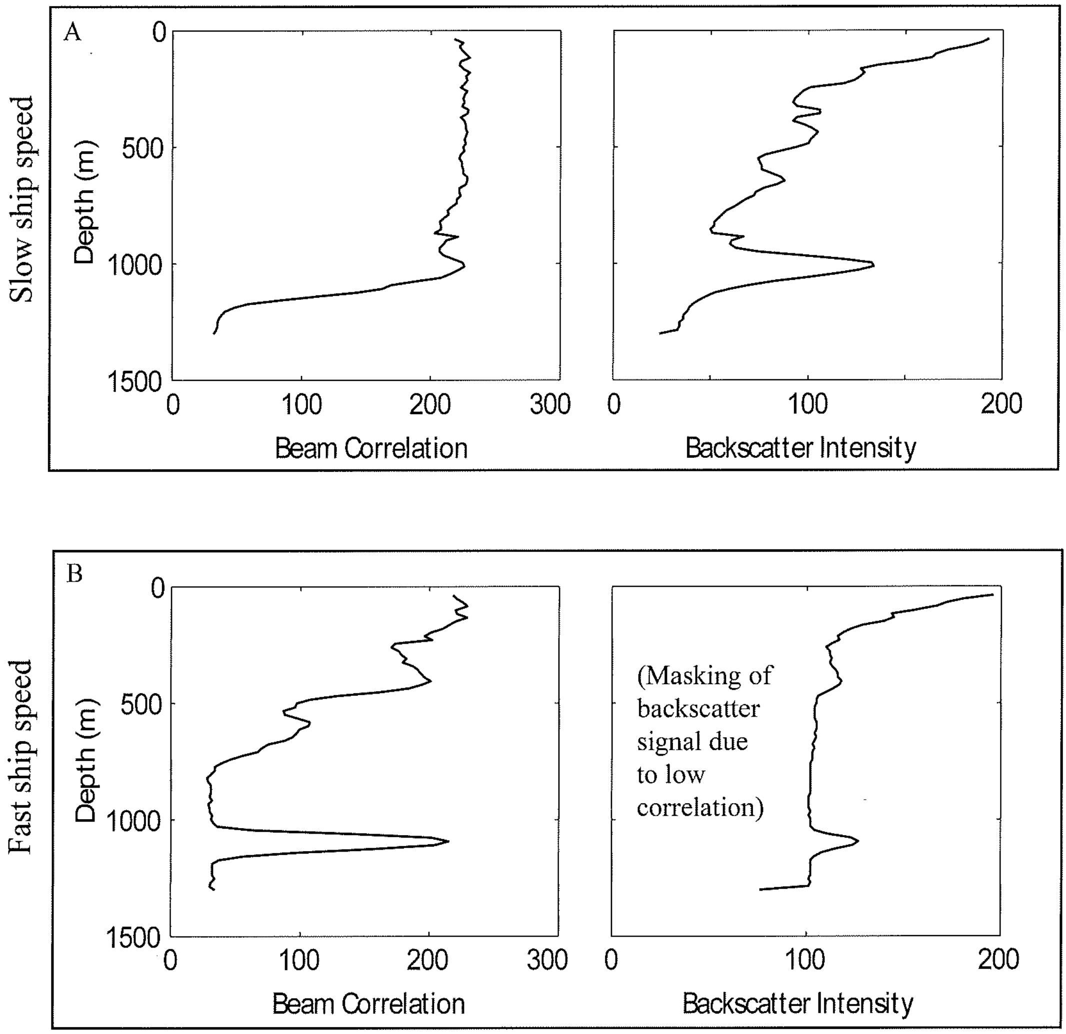

Fig. 3. Example of the effect of ship speed on 38-kHz ADCP beam correlation and backscatter intensity. In all panels the sea bottom is near 1,000 m. Beam correlation is an estimate of the correlation of the signal recorded by four acoustic beams and is shown when the ship was surveying at slow and fast ship speeds. (A) High beam correlation at a slow survey speed (4 knots) was associated with good backscatter intensity signal detailing scattering layers. (B) Low beam correlation was associated with a masking on the detailed backscatter intensity signal at a fast ship speed (9 knots).

(CDT). This was nearly 1 hr ahead of the mean June sunrise time, 0617 hr CDT, obtained from the U.S. Naval Observatory online database (available at http://aa.usno.navy.mil/data). Migrations were roughly associated with the timing of nautical twilight, well before sunrise. The scattering layers then rose to the surface just after sunset between 2030 hr and 2100 hr local CDT, when the sunset time was 2004 hr. An appropriate shift in migration timing was observed during an August 2003 cruise. In August, the mean sunrise time was at 0640 hr, roughly half an hour later than the cruise in June. Descending migrations out of the surface left between 0440 hr and 0540 hr, and migrations returned back to the surface between 2015 hr and 2030 hr when the mean sunset time was 1950 hr.

A shoaling event of the main DSL occurred, in which a significant shallowing of the daytime depth was observed while crossing the Mississippi River plume in June 2003. During this cruise, SSH data showed that a large clockwise rotating Loop Current eddy called "Eddy Sargassum" extended far north onto the continental margin, and was adjacent to a counterclockwise rotating cyclonic eddy (Fig. 6). These features set up conditions near the mouth of the Mississippi

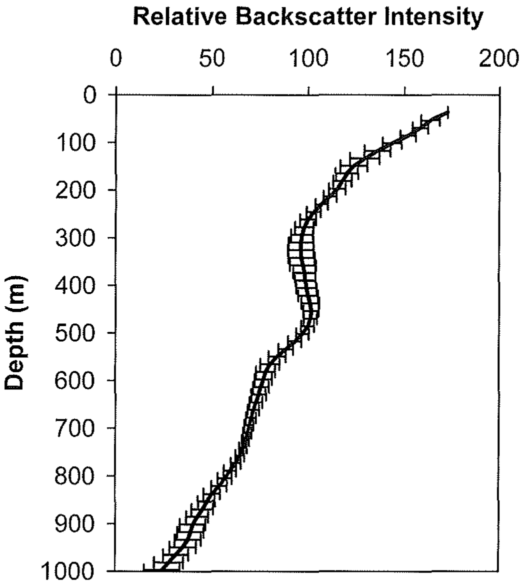

Fig. 4. Cruise-long average RBI profile and standard deviation for 38-kHz ADCP data collected 29 May–20 June 2003.

River that created a strong eastward current that pulled a narrow band of fresh Mississippi River offshore water with it, creating a distinct frontal boundary crossed by the ship on June 12. No apparent change in sea surface temperature was observed (Fig. 7A), but sea surface salinity rapidly dropped from 26 to less than 20, indicating that the front had been crossed (Fig. 7B). A CTD cast indicated that this low-salinity layer only extended 5 to 10 m deep. This strong surface salinity gradient and crossing of this boundary was also associated with an observed shallowing of the DSL indicated by ADCP backscatter. The daytime DSL shoaled to a depth only about 200 m below the surface, or less than half the daytime depth found in the adjacent blue water (Fig. 7C).

Secondary scattering layers.—At least one DSL was detected during all slope cruise days. Average profiles consisted of a high-intensity layer at the surface and gradually decreasing signal with depth due to transmission losses. A high-intensity peak was observed in all profiles near 500 m, representing the mean daytime depth of the main DSL. In addition to these features, some profiles also contained a secondary DSL between 600 and 800 m depth (Fig. 8). More frequent and more intense scattering layers in this depth range were consistently observed in the upper continental slope region than in over the deeper slope. Of 34 operating days in the slope region, 21 days (about two-thirds) had noticeable scattering in the targeted depth range below the main DSL (Table 2). When the deeper slope (greater than 1,000 m) was surveyed, only 2 of 11 days (less than one-fifth) had significant scattering below the main DSL. From 0 to 800 m, the two average profiles are highly correlated ($R = 0.94$ from a Spearman rank correlation). This reflects the fact that RABI generally decreased with increasing depth, and that a main DSL was observed between 400 and 600 m on slope surveys as well as on deep-basin cruises. However, the secondary, deeper DSL below the main DSL was observed more frequently in the slope surveys, at depths between 600 and 800 m ($R = 0.39$ from a Spearman rank correlation). This secondary peak may represent a persistent, nonmigrating, secondary DSL found over the slope region covered on slope survey cruises that was not present during the deepwater cruises.

SSH anomaly field detected by satellite altimetry documented large variations in eddy dynamics between cruises and between different regions within cruises. A presence–absence comparison of secondary DSLs indicated that secondary DSLs present at a depth between 600 and 800 m one-third of the time while in a cyclone, three-eighths of the time in a confluence region between hydrographic features, and about half the time in the area away from eddy influence (Table 3). However, a secondary DSL was only detected once out of four periods while inside the anticyclonic circulations. Analysis of the cyclonic and anticyclonic average profiles did not show a significant difference between the depth bins between 600 and 800 m ($R = 0.93$), indicating that the ranking orders are similar.

Discussion

Sound-scattering layers are ecologically important communities because they contain a high concentration of available prey organisms (Greene et al., 1992; Benoit-Bird and Au, 2003). The present study on the basis of RABI collected from a 38-kHz ADCP provides evidence that the behavior of scattering layers can be highly variable both vertically and geographically, and possible parameters contributing to the variability of RABI examined included mesoscale eddy circulation, proximity to a high nutrient river source, and water depth. The most noticeable variation in the pattern of backscatter observed in this study occurred in the main DSL in the region of the Mississippi River plume. Although transmissometer data were not available during our study, we speculate that the daytime depth of the main DSL shoaled approx-

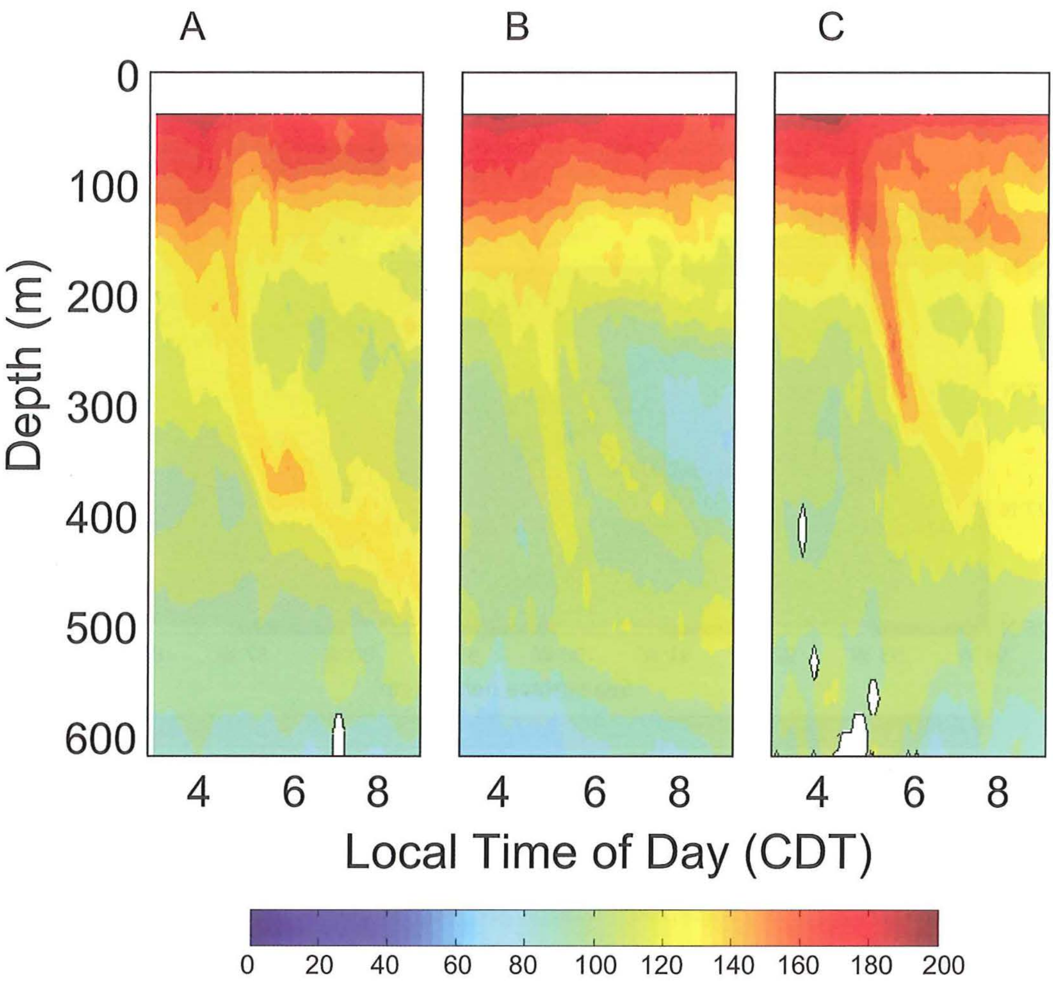

Fig. 5. Daily vertical migration rates were estimated from the change in depth divided by the change in time during mid-migration to estimate the maximum rate. Separate layers were distinguished from the surface scattering layer and the main DSL during descending and ascending migrations either because they (A) began migrating at different times relative to each other, (B) migrated at different rates leading to separation of the layers, or (C) stopped their migrations at different depths and formed separate daytime layers. White regions indicate bad data regions not included in analysis.

imately 200 m closer to the surface because of the organisms attempting to stay at a constant light level while increased concentrations of surface particles blocked light penetration. Outflow from the Mississippi River has a strong influence on many biogeochemical processes of the northern Gulf of Mexico and introduces large amounts of sediments and nutrients that may lead to localized phytoplankton blooms. Analysis of CTD data has shown that as freshwater enters the Gulf of Mexico at Southwest Pass, LA, it is generally maintained as a buoyant plume at the surface and covers a narrow outflow width (Walker et al., 1994, 2005). However, when or where counterrotating deepwater eddies are found close off the Louisiana continental margin, they can entrain and export this river plume water to the middle slope or even farther seaward (Belabbassi et al., 2005). Even with only a relatively thin vertical layer of increased biological or inorganic particles at the surface, decreased light penetration at the surface could have resulted in a daytime shallowing response

Table 1. Summary of vertical migration rates (cm/sec).

	Ascending	Descending
Mean	7.0	6.1
Standard deviation	3.6	2.6
Number of days included	25	28

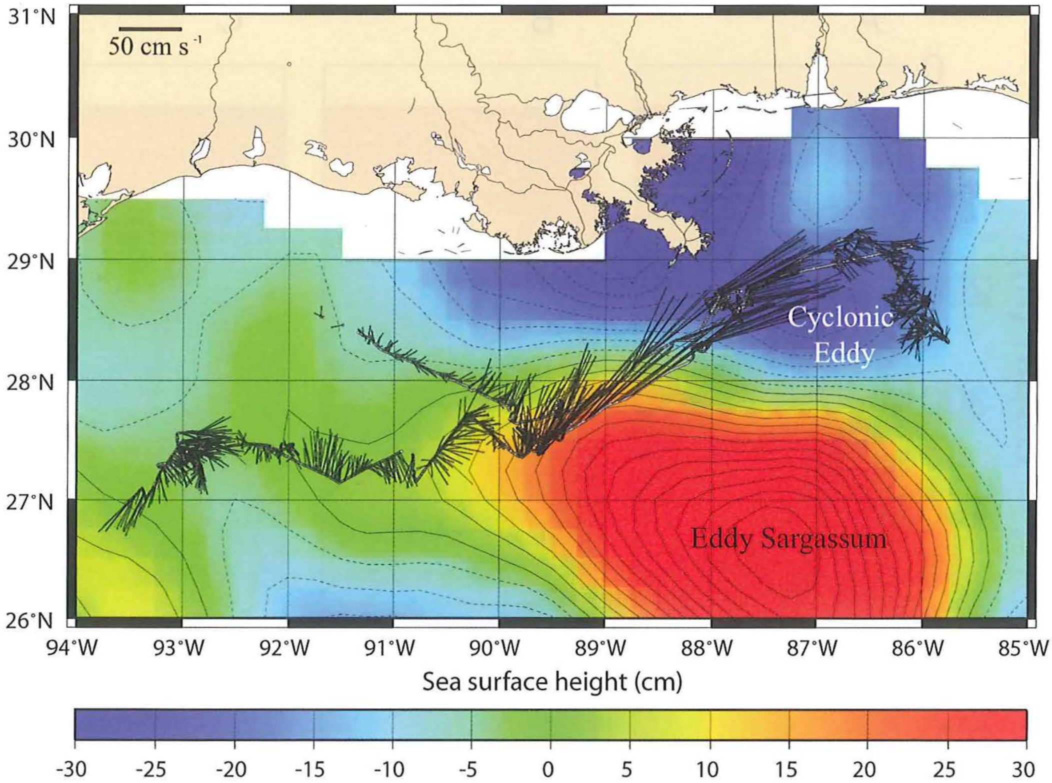

Fig. 6. Surface current velocity vectors calculated from the 38-kHz ADCP superimposed on sea surface height field for the SWSS03 Leg1 cruise, June 2003. A large anticyclonic eddy (red) was in proximity to a smaller cyclonic eddy (blue) over the shelf. Strong surface currents in the boundary between the eddies were on the order of 200 cm s^{-1}. SSH data are courtesy of R. Leben, University of Colorado Center for Astrodynamics Research and available online at: http://ccar.colorado.edu/~realtime/gsfc_gom-real-time_ssh/.

by vertical migrators at depth. Similar responses of vertically migrating organisms to alterations to the normal light level have been linked to an influx of turbidity (Frank and Widder, 2002). DVM of *Daphnia* in a freshwater lake was also significantly reduced in amplitude and magnitude by urban light pollution in a suburban lake (Moore et al., 2000). In the Gulf of Mexico, vertical migrations have even been documented to be triggered at midday during a solar eclipse (Franceschini et al., 1970), which is especially dramatic evidence that some DVMs are triggered by light levels rather than by a biological circadian pattern.

Sound-scattering layers below the main DSL are difficult to study from shipboard acoustics because the distance requires relatively low-frequency acoustics to penetrate deep waters, compensating resolution. DSLs have been observed down to 1,000 m with a narrow-beam echo sounder in the southern Pacific that were not uniform among the regions surveyed (Krause, 1971). A zooplankton scattering layer was also observed at 2,000 m over a hydrothermal vent (Burd et al., 1992).

We did not find a significant link between mesoscale eddy features and secondary DSLs, although the sampling size was small (6 d in cyclone, 4 d in anticyclone). Mesoscale cyclones provide increased nutrient and phytoplankton productivity through upwelling, although most of the biological response from cyclonic eddies occurs in the upper 50 m (Zimmerman and Biggs, 1999; Sindlinger et al., 2005). These circulation features may not play an immediate role at the secondary scattering layer depths.

Sindlinger et al. (2005) used both shipboard and moored 300 kHz to look at diel patterns in the upper 100 m as well as near bottom patterns. A spectral analysis of energy and time showed a peak centered around one cycle per day in the near-bottom moored deepwater ADCP at 880 m, suggesting that some DVM may either descend to as deep as 880 m in the western Gulf of Mexico or that some benthic species may move into and out of the sediments. Our data provided evi-

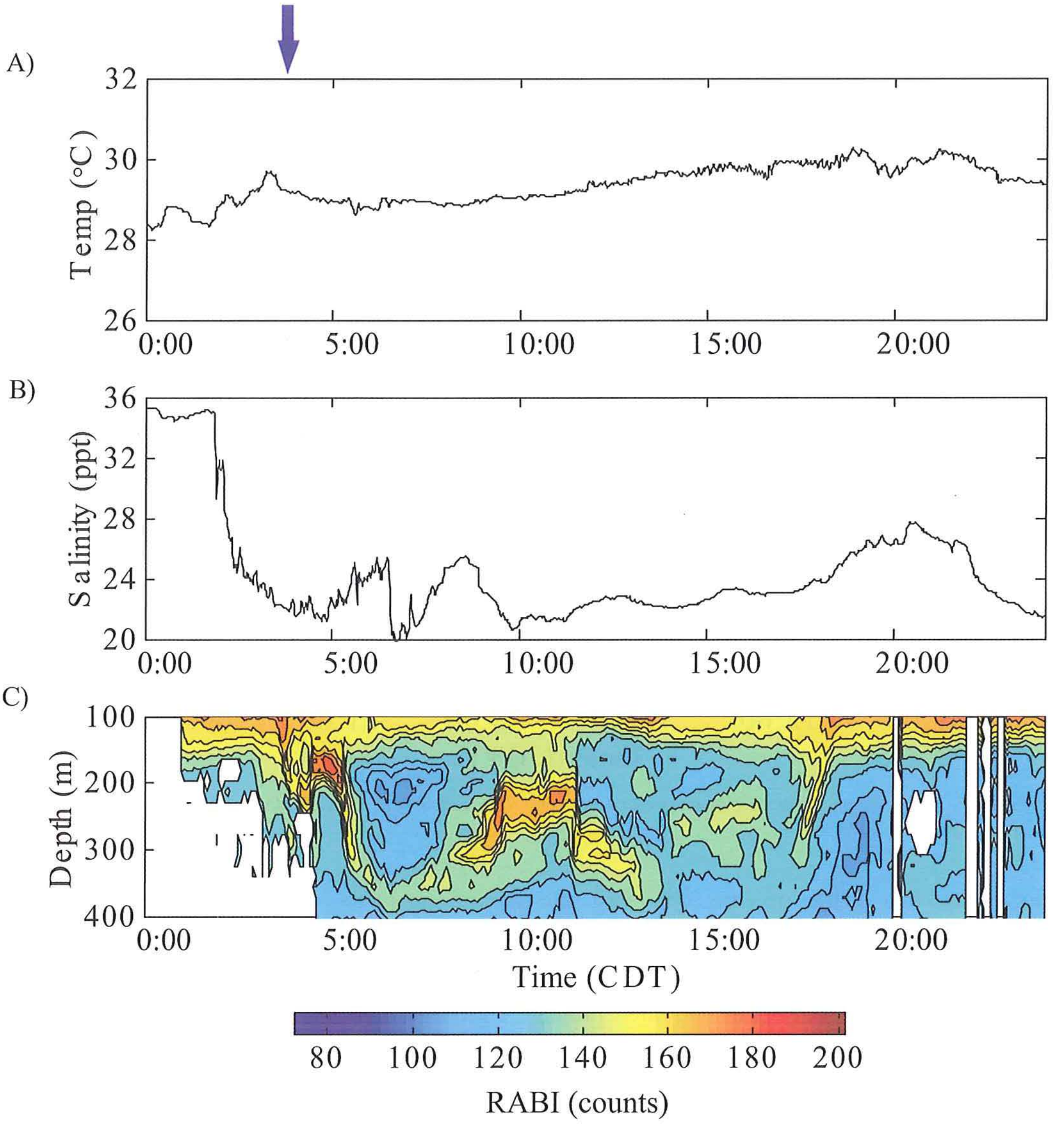

Fig. 7. (A) Sea surface temperature, (B) sea surface salinity, and (C) relative backscatter intensity as the ship transited a frontal boundary near the Mississippi River plume. Crossing the frontal boundary is indicated by the arrow shortly after sea surface salinity rapidly decreased. The daytime depth of the main DSL was observed shoaling to between 200 and 300 m depth, compared with about 500 m on adjacent days outside of the plume area.

dence that secondary scattering layers were more common in shallower waters over the upper continental shelf than in the deeper areas. Further investigation is needed to distinguish whether this is due to entrainment and off-margin transport of coastal primary productivity or if there is interaction with the benthos at shallower depths.

Few studies have documented a direct link between diel variations in depth of DSLs and depth of foraging dives by the predators that feed on the DSL. Two examples are Dagorn et al. (2000), who observed a foraging predator (bigeye tuna) simultaneously with the DSL observations, and Horning and Trillmich (1999), who observed diving fur seals. Variability in the timing of migration (Roe et al., 1984), depths to which organisms migrate, and influence of hydrographic parameters may interact and influence the observed behavior of the DSL. Understanding these interactions is essential for describing the ecological link between the

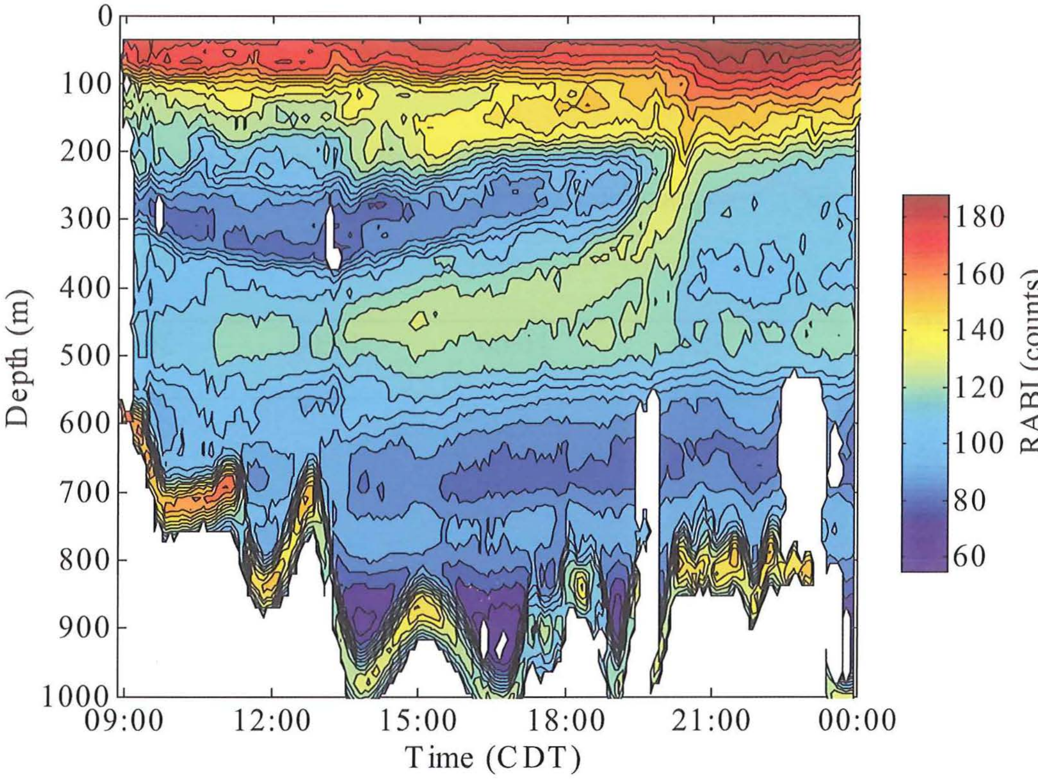

Fig. 8. A secondary scattering layer present between 700 and 800 m, 4 June 2003. The sea bottom is visible between 600 and 1,000 m.

organisms that make up the DSL and the predators that forage on DSLs. Tagged sperm whales in the Gulf of Mexico have been shown to dive to depths from 600 to 800 m, during which they appear to follow layers in midwater, rather than the bottom topography (Watkins et al., 1993; Zimmer et al., 2003). Passively tracked whales have also been shown to be diving to similar depths (Thode et al., 2002). Sperm whales may be attracted to a DSL at this depth or attracted to squid feeding on a DSL at this depth. Foraging predators that are associated with scattering layers are most likely influenced by the patterns of variability of secondary scattering layers, whether there are changes in the presence, intensity, or depth of organisms that make up the layers. Future studies on the predator–prey interactions involving scattering layers below the main DSL should seek to further investigate the link between the presence and intensity of DSLs and the location of foraging predators such as sperm whales.

Table 2. Days characterized with the presence of a secondary DSL out of the total number of days spent in each depth category.

Cruise	<1,000 m	>1,000 m
SWSS02 Leg1	5/9	0/1
DGoMB	0/0	1/5
SWSS03 Leg1	9/15	1/2
SWSS03 Leg2	7/10	0/3
Total	21/34	2/11

Acknowledgments

This research was funded by Minerals Management Service–TAMU cooperative agreement, 1435-01-02-CA-85186, a multidisciplinary effort to study sperm whales and their response to

Table 3. Days characterized with the presence of a secondary DSL out of the total number of days spent in each mesoscale circulation category.

Cruise	Cyclone	Anticyclone	Confluence	Other
SWSS02 Leg1	0/1	0/1	0/0	3/8
SWSS03 Leg1	2/2	1/3	1/1	4/5
SWSS03 Leg2	0/3	0/0	2/7	0/3
Total	2/6	1/4	3/8	7/16

seismic exploration in the Gulf of Mexico. We thank the captain, crew, and technicians of the R/V *Gyre* for their help in collecting these data. We also thank Ann Jochens and Matt Howard (TAMU) for their help in data collection and data management.

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