OCS Study
MMS 2006-034

Sperm Whale Seismic Study in the Gulf of Mexico

Summary Report: 2002-2004

U.S. Department of the Interior
Minerals Management Service
Gulf of Mexico OCS Region

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Prepared under MMS Contract
1435-01-02-CA-85186
by
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Published by

U.S. Department of the Interior
Minerals Management Service
Gulf of Mexico OCS Region

New Orleans
June 2006

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New Orleans, Louisiana 70123-2394

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CITATION

Suggested citation:

Jochens, A., D. Biggs, D. Engelhaupt, J. Gordon, N. Jaquet, M. Johnson, R. Leben, B. Mate, P. Miller, J. Ortega-Ortiz, A. Thode, P. Tyack, J. Wormuth, and B. Würsig. 2006. Sperm whale seismic study in the Gulf of Mexico; Summary Report, 2002-2004. U.S. Dept. of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA. OCS Study MMS 2006-034. 352 pp.

ABOUT THE COVER

The cover art shows photographs of sperm whales taken on SWSS cruises in 2002-2004. The upper photos show sperm whales seen in Mississippi Canyon in 2003 (photos taken by D. Lewer, Oregon State University). The middle photo shows a sperm whale mother and calf pair (photo taken on 24 July 2004 by Nathalie Jaquet of Texas A&M University-Galveston). The lower photos show examples of a head-out during socializing behavior (left; Nathalie Jaquet, 2004) and of a breach (right; Ricardo Antunes, 2004).

ACKNOWLEDGMENTS

This report would not have been possible without the contributions of a large number of people. Each principal investigator (PI) of the Sperm Whale Seismic Study (SWSS) contributed ideas to and authorship of portions of the text, and many participated in the cruises and in data reduction and processing. The principal investigators, their affiliations, and their tasks are:

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Peter Tyack	WHOI	PI for D-tag/CEE study
Bernd Würsig	TAMUG	Co-PI for Photo-ID and mesoscale survey

For habitat characterization, Steve DiMarco and John Wormuth of TAMU contributed to the authorship of this report, as well as to processing and analysis of data sets. Leila Belabbassi assisted with preparation of the report and data archive, and Amanda Olson Kaltenberg, Xiaoqian Zhangadn, and Mike Lalime contributed to data processing and analysis. We appreciate the extensive contributions of Dr. Chuanmin Hu, Executive Director of the Institute for Marine Remote Sensing at the College of Marine Science of the University of South Florida (USF), for providing ocean color images and ideas. We also thank Frank Müller-Karger of USF (ocean color) and Keith Mullin of NMFS (SWAMP) for their contributions to this work. USF support for SeaWiFS analyses came from NASA contracts NAS5-97128 and NAG5-10738.

Ricardo Antunes and Luke Rendell, University of St. Andrews, assisted Jonathan Gordon with analyses of data sets associated with the mesoscale population study and authorship of portions of the resulting chapter. Martha Winsor of OSU assisted Bruce Mate with the analysis of and reporting on the S-tagged sperm whale locations with the seismic source shot locations.

Collection of sperm whale samples used in the study of molecular ecology involved may people working on SWSS as well as other projects around the world. Thanks to Keith Mullin, Wayne Hoggard, Tony Martinez and all the scientists and crew at the Pascagoula and Miami SEFSC labs that participated in the 2000 – 2001 SWAMP fieldwork aboard the NOAA ship Gordon Gunter. Special thanks to the following that have collected sperm whale samples or sequences from around the globe which were incorporated into this project: Sarah Mesnick (SWFSC), Texas Marine Mammal Stranding Network, Nelio Barros (Hubbs Sea World Research Institute),

---

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Antonio A. Mignucci-Giannoni (Caribbean Marine Mammal Stranding Network), Clearwater Marine Park, Alexandros Frantzis, Bob Reid, Sabina Airoldi, Ana Canadas, Mark Johnson, Patrick Miller, and Renaud de Stephanis.

The 3-D passive acoustic tracking work of Aaron Thode involved the assistance of many people. Thanks to Bill Burgess of Greeneridge Sciences Inc., Tim Pinnington and Craig Douglas of SEAMAP, Inc., Jonathan Gordon of Ecologic, Inc., Anthony Martinez of SE Fisheries Science Center, Tom Norris of SAIC, and Mark Johnson, Patrick Miller, and Alessandro Bocconcelli of Woods Hole Oceanographic Institution (WHOI), for providing the opportunity to use their passive acoustic equipment for this work. Mark Johnson in particular was very generous with technical advice and assistance during the 2003 SWSS D-tag cruise. Jonathan Gordon, Jonathan Vallarta, Peter Tyack, and Kimberly Hiland provided useful comments and encouragement for the research. Acoustic observers that helped log and monitor the data included Natascha Aguilar de Soto, Matt Grund, Valeria Teloni, Sarah Tsoflias, and Sue Rocca in 2002 and 2003. The 2004 acoustic observers included Tom Norris, Elizabeth Zele, Alyson Azzara, and Sarah Tsoflias. Dave Mellinger modified his software program Ishmael to meet some specialized needs, while Matt Howard of Texas A&M University and John Diebold of Lamont-Doherty Earth Observatory provided data on the water depth beneath the R/V *Gyre* in 2002 and the R/V *Ewing* in 2003. The crews of the R/V *Gyre* and R/V *Ewing* were always good-natured, even at odd hours, and in particular the author thanks Marc and Mike of Pacific Geophysical Services, who provided the rope and autonomous recorder attachment in 2003.

To all who participated on the 2002-2004 SWSS cruises we extend our great appreciation for making the field program a great success. The first and second annual reports acknowledge participants on the 2002 and 2003 cruises, respectively. Here we extend our appreciation to the participants of the 2004 cruises. We thank the science team of the S-tag cruise: Alyson Azzara (TAMU College Station), Doug Biggs (TAMU College Station), Marty Bohn (TAMU GERG), Paul Clark (TAMU GERG), Rocio Cooley (OSU), Carol Delancey (OSU Newport), Dan Engelhaupt (Durham University, UK), Deborah Epperson (MMS New Orleans), Glenn Gailey (OSU), Bill Green (TAMU Galveston), Ladd Irvine (OSU Newport), Rhoni Lahn (OSU), Dan Lewer (OSU Newport), Bruce Mate (OSU Newport), Mary Lou Mate (OSU Newport), Michael Noack (OSU), Tom Norris (SAIC), Joel Ortega-Ortiz (OSU Newport), Carol Roden (MMS New Orleans), Aaron Thode (SIO), Sarah Tsoflias (MMS), Eddie Webb (TAMU College Station), and Elizabeth Zele (OSU). We also thank the science team on the Mesoscale Population Study cruise: Ricardo Antunes (Whale Museum, Madeira, Portugal), Steve Brown (sailboat's captain, Florida), Raul Diaz-Gamboa (Instituto Politécnico Nacional, Mexico), Jonathan Gordon (Ecologic Ltd., UK), Thomas Gordon (Vanishing Point, Plymouth, UK), Nathalie Jaquet (TAMU Galveston), Christoph Richter (Queens University, Kingston, ONT, Canada), and Trudi Webster (New Zealand).

Without the hard work of the ships' masters and crew, the science teams would not have been able to complete their tasks successfully and safely. So we extend sincere thanks to Captain Dana O. Dyer III and the crew of the *R/V Gyre* and Captain Steve Brown and the crew of the *Summer Breeze* for jobs well done. The dedicated shore-based efforts of Desmond Rolf, Sandy Green, and Bill Green of the *Gyre* TAMU Marine Operations went above and beyond the call of duty and contributed to the success of the study. We also thank Dr. Norman Guinasso and Mr. John Walpert of TAMU GERG for their assistance with preparing the 38-kHz ADCP, and Mr. Tomas

Follett of OSU for facilitating delivery of S-tag whale location information to SWSS scientists during their cruises.

The field program in 2004 was greatly enhanced by contributions from the National Fish and Wildlife Foundation (NFWF) and the Industry Research Funders Coalition (IRFC). NFWF provided the support to lease and outfit the 46' Hunter sailboat, *Summer Breeze*, used for the Mesoscale Population Study cruise. IRFC, which consists of BP Corporation, ExxonMobil Exploration Company, Shell Exploration & Production Company, ConocoPhillips, ChevronTexaco Exploration & Production Company, and the International Association of Geophysical Contractors (IAGC) on behalf of its members, provided substantial support for the Mesoscale Population Study component of SWSS in 2004, as well as support for the 3-D passive acoustic tracking hydrophone array and the work of examining sperm whale locations from S-tags with locations of seismic survey activities. IRFC also made crucial contributions of seismic source vessels for use on the CEEs conducted in 2002 and 2003. SWSS scientists extend thanks to Chip Gill of IAGC, as well as all members of IRFC, for their enthusiastic work in support of SWSS. We also thank industry personnel working through IAGC: Phil Fontana (Veritas DGC) and Jack Caldwell (formerly WesternGeco) throughout, Jim Thompson (Fairfield Industries) in 2002 and 2003, Alastair Fenwick (WesternGeco) in 2003, and Bernard Padovani (CGG) in 2004.

The enthusiastic and timely support of Dr. William Lang, the MMS Project Officer, is greatly appreciated. We extend thanks to Deborah Epperson, Carol Roden, and Sarah Tsoflias of MMS for their participation in the S-tag cruise as well as their thoughtful support. Thanks also to Dr. Robert Gisiner of ONR and Dr. Alexander Shor of NSF for their contributions, both in support of tag development and in supporting the use of the *R/V Ewing* in field year 2003.

The SWSS Science Review Board provided many insightful recommendations and a thorough review of this report. We thank them all: Daniel Costa of the University of California-Santa Cruz, Phil Fontana of Veritas DGC, Robert Hofman retired from the Marine Mammal Commission, Debra Palka of NOAA, and Doug Wartzok of Florida International University.

Finally, any program as large and complex as this one needs the help of many in the coordination and administration of the project. We thank Stacie Arms of TAMUG, Carol Delancey and Cyndee Pekar of OSU, Charlene Miller, Tracie Robertson and the many other helpful personnel at TAMRF, and Mary Jane Tucci and Amanda Hansen of WHOI for their many efforts in support of SWSS.

SWSS Program Management

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ACRONYMS

ADCP	acoustic Doppler current profiler
AGU	American Geophysical Union
ANOVA	Analysis of variance
CA	correspondence analysis
CCAR	Colorado Center for Astrodynamics Research, University of Colorado
CDT	Central Daylight Time
CEE	controlled exposure experiment
CHL	chlorophyll
CTD	conductivity-temperature-depth sensor
CU	University of Colorado
DGPS	Differential Global Positioning System
DNA	deoxyribose nucleic acid
D-tag	Digital-recording acoustic tag
DTAG	Digital-recording acoustic tag
DV	displacement volume
EARS	Environmental Acoustic Recording System
ESU	Evolutionary Significant Unit
GAMS	General Additive Models
GDAS	*Gyre* Data Acquisition System
GERG	Geochemical and Environmental Research Group at TAMU
GIS	Geographical Information System
GOM	Gulf of Mexico
GPS	Global Positioning System
GulfCet	Gulf of Mexico Cetacean Study
HC	habitat characterization
HWE	Hardy Weinberg Equilibrium
IAGC	International Association of Geophysical Contractors
IFAW	International Fund for Animal Welfare
IKMT	Isaacs-Kidd Midwater Trawl
IMaRS	Institute for Marine Remote Sensing
IPI	inter pulse interval
IRFC	Industry Research Funders Coalition
ITM	MMS' Information Transfer Meeting
IWC	International Whaling Commission
LC	Loop Current
LCE	Loop Current eddy
LDEO	Lamont-Doherty Earth Observatory
MCS	middle continental slope
MED	Mediterranean Sea
MMS	Minerals Management Service, U.S. Department of the Interior
MOCNESS	Multiple Opening-Closing Net and Environmental Sampling System
MPS	Mesoscale Population Study
MC	Mississippi Canyon
MRD	Mississippi River Delta
mtDNA	mitochondrial DNA (deoxyribonucleic acid)

ACRONYMS
(continued)

M/V	Motor Vessel
NAMSC	North Atlantic-Mediterranean Sperm Whale Catalogue
NAO	North Atlantic Ocean
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NEFSC	Northeast Fisheries Science Center
NEGOM	Northeastern Gulf of Mexico
NFWF	National Fish and Wildlife Foundation
NMEA	National Marine Electronic Association, standard protocol for GPS receivers to transmit data
NMFS	National Marine Fisheries Service (now NOAA Fisheries)
NOAA	National Oceanic and Atmospheric Administration
NRL	Naval Research Laboratory
NSEA	North Sea
NSF	National Science Foundation
OCS	outer continental shelf
ONR	Office of Naval Research
OSU	Oregon State University
PAM	passive acoustic monitoring
PAT	passive acoustic tracking
Photo-ID	Photographic-Identification
PI	Principal Investigator
PMEL	Pacific Marine Environmental Laboratory
QE	LCE Quick Eddy
QA/QC	quality assurance/quality control
RDI	RD Instruments
RHIB	Rigid-Hulled Inflatable Boat
RL	Received Level
R/V	research vessel
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SIO	Scripps Institution of Oceanography
SRB	Science Review Board
SCF	sea surface chlorophyll-fluorescence
SSH	sea surface height
SSS	sea surface salinity
SST	sea surface temperature
S-tag	Satellite-tracked radio tag
SWAMP	Sperm Whale Acoustic Monitoring Program
SWSS	Sperm Whale Seismic Study
TAMU	Texas A&M University
TAMUG	Texas A&M University-Galveston
TAMRF	Texas A&M Research Foundation
UD	utilization distribution
UD-UK	University of Durham, UK

ACRONYMS
(continued)

USF	University of South Florida
UStA	University of Saint Andrews
UTC	Universal Coordinated Time
VHF	Very High Frequency
WHOI	Woods Hole Oceanographic Institution
WSE	Warm Slope Eddy
WSHC	Sperm Whale Survey and Habitat Characterization
XBT	expendable bathythermograph probe

1 SYNOPSIS OF THE SPERM WHALE SEISMIC STUDY 2002-2004

1.1 MMS Activities in Marine Mammal Research in the Gulf of Mexico

In managing the oil and gas resources of the Outer Continental Shelf (OCS), the U.S. Minerals Management Service (MMS) seeks "to ensure that all activities on the OCS are conducted with appropriate environmental protection and impact mitigation" (MMS 2002). The MMS sponsors studies to evaluate environmental impacts of OCS activities and to identify appropriate mitigation measures. Since the 1970s, one environmental focus has been the potential for impact of anthropogenic noise on marine mammals. Marine mammals are adapted to use sound in the ocean for communication, navigation, prey identification and location, and sensing of the environment. These animals have evolved in an ocean that is filled with natural sounds. Humans began to introduce additional sound sources with the advent of the industrial age in the mid-nineteenth century. As these sounds increase, the potential for impacting marine mammals increases as well. Of concern are the potentials for negative behavioral and physiological responses to human-generated sound, at both the individual and population levels.

MMS sponsored a comprehensive literature review that detailed the state of the worldwide knowledge through 1990 of human-generated and natural underwater noise and impacts on marine mammals (Richardson et al. 1991). The Office of Naval Research (ONR) then funded a project to convert the review into the book by Richardson et al. (1995). Since that time, research into the effects of noise on marine mammals has increased. Four reports of the National Research Council (1994, 2000, 2003, and 2005) provide extensive information on noise and marine mammals with recommendations for research needs. A common recommendation of these reports was to determine the normal behaviors of marine mammals and their responses to human-generated sounds (NRC 1994). Suggested was research that would study the sound exposure, as received level, at the individual animal and that would allow tagging of animals for study of behavior and possible responses to human-generated sound.

In the late 1980s, oil and gas activities were planned for development in the deepwater Gulf of Mexico off the continental shelf (> 200 m depth). As a result, MMS supported a series of major environmental studies beginning in 1989 to investigate the distribution and abundance of marine mammals over the continental slope waters of the northern Gulf. The MMS and the National Marine Fisheries Service (NMFS) of the National Oceanic and Atmospheric Administration (NOAA) conducted aerial surveys for cetaceans over the upper continental slope in the north-central Gulf (Mullin et al. 1991). In surveys of the U.S. waters of the northern Gulf, the MMS-sponsored GulfCet Studies then used ships, aircraft, and passive acoustical techniques throughout the 1990s to determine seasonal variability in the occurrence and distribution of marine mammals (Davis and Fargion 1996; Davis et al. 2000).

As oil and gas activities moved into ever deeper water in the Gulf, MMS recognized that the opportunity increased for them to occur in regions frequented by deepwater species of cetaceans. One species of particular concern was the sperm whale (*Physeter macrocephalus*), which is listed as endangered under the Endangered Species Act (ESA). In 1999, MMS hosted a Gulf of Mexico Protected Species Workshop (McKay et al. 2001) to review past research, evaluate new issues, and recommend research priorities. A panel of experts identified the potential effects of noise from seismic exploration operations on sperm whales as a key research priority. MMS, NMFS, and the Office of Naval Research (ONR) then sponsored the Sperm Whale Acoustic Monitoring Program (SWAMP).

SWAMP was conducted in fiscal years 2000 and 2001 under MMS Interagency Agreement No. 15958. The goals of SWAMP were to contribute to an assessment of sperm whales in the Gulf of Mexico and to study the ambient noise environment to support a determination of the effects of seismic exploration on sperm whales in the Gulf. SWAMP essentially was a pilot study that developed new methods for studying the behavior of sperm whales and their responses to the underwater acoustic environment. The SWAMP study, as well as earlier survey results, indicated that in the northern Gulf sperm whales tended to be most likely observed near the 1000-m isobath (MMS 2002). Most SWAMP work in the Gulf of Mexico under this Interagency Agreement concluded in September 2001. However, one additional NMFS cruise off the U.S. Mid-Atlantic coast was partially supported under this Interagency Agreement in 2003. Tasks on that cruise tested upgraded digital-recording acoustic tags (D-tags) and obtained comparative sperm whale dive data outside the Gulf (see Section 7).

1.2 Rationale for the Sperm Whale Seismic Study

During the January 2002 MMS Information Transfer Meeting in New Orleans, LA, the International Association of Geophysical Contractors (IAGC) hosted an informal meeting to discuss future acoustic research relevant to seismic operations, and in particular, as related to understanding the effects of seismic exploration on sperm whales in the Gulf of Mexico. IAGC offered its support for sperm whale research through contribution of a seismic source vessel for controlled exposure experiments. In response, the Sperm Whale Seismic Study (SWSS) was proposed to and approved by MMS in 2002. In subsequent years, IAGC was joined by a number of oil and gas companies to form the Industry Research Funders Coalition (IRFC) that has continued to provide contributions in support of SWSS studies.

SWSS is a multi-institutional, interdisciplinary research project supported by MMS under Cooperative Agreement 1435-01-02-CA-85186 for *Cooperative Research on Sperm Whales and their Response to Seismic Exploration in the Gulf of Mexico* through the Texas A&M Research Foundation. Texas A&M University (TAMU) provides program management and data management. Scientists from Ecologic, Oregon State University (OSU), Scripps Institution of Oceanography (SIO), Texas A&M University (TAMU), Texas A&M University-Galveston (TAMUG), University of Colorado (CU), University of Durham (UD in the UK), University of Saint Andrews (UStA in the UK), and Woods Hole Oceanographic Institution (WHOI) develop and implement scientific research plans associated with study of sperm whales in the northern Gulf of Mexico. Sponsors are MMS, National Science Foundation (NSF), ONR, IRFC, and the National Fish and Wildlife Foundation (NFWF). A five-member Science Review Board (SRB), established in year 2, provides recommendations and review of this Report. All activities associated with sperm whales are conducted under permits issued by NMFS.

The objectives of SWSS are to

(1) establish the normal behavior of sperm whales in the northern Gulf of Mexico,
(2) characterize sperm whale habitat use in the northern Gulf of Mexico, and

(3) determine possible changes in behavior of sperm whales when subjected to man-made noise, particularly from seismic airgun arrays used for offshore petroleum exploration and geological monitoring.

To achieve each of these objectives, a set of study tasks was developed and implemented.

Five tasks were aimed at developing a better understanding of sperm whale behavior and spatial use of Gulf waters. Long-term (months to seasonal) movements and distributions of sperm whales were studied by OSU using satellite-tracked radio telemetry tags (S-tag). Short-term (hours) diving and swimming behavior and vocalizations of sperm whales were examined by WHOI using recoverable digital-recording acoustic tags (D-tags) that logged whale orientation (i.e., pitch, roll, and heading) and depth and the sounds made by and received at the whale from the environment. Social behaviors of sperm whale groups were observed directly by Ecologic and TAMUG using photo-identification and mesoscale population studies. Visual observations of surface behavior coupled with passive acoustic studies of underwater activities were obtained during the cruises conducted for these three tasks. Biopsy samples were taken for genetic analyses by UD that determined the sex of the animal and its relatedness to other individuals sampled in the Gulf of Mexico, North Atlantic Ocean, and Mediterranean Sea. Diving depths and movements were examined by SIO using 3-D passive acoustic tracking techniques.

Tasks contributing to the habitat characterization objective were three-fold. Remote sensing fields of sea surface height and ocean color provided information on dynamical currents, such as generated by eddies and fronts, and on chlorophyll-rich surface waters that might create locally good feeding conditions for the vertically-migrating prey of the sperm whale, which dives to forage at depth. *In situ* data, such as temperature, salinity, fluorescence/chlorophyll, currents, and acoustic backscatterance data, enabled further characterization of the epipelagic environment. Habitat characterization descriptions from these data collected by TAMU and CU and the relation of these to the locations of sperm whales as determined by the tag and direct observational data of OSU, WHOI, UD, TAMUG, and Ecologic will allow correlations of near-surface habitat characteristics with sperm whale usage of areas within the Gulf.

To examine potential changes in behavior of sperm whales when subjected to seismic airgun sounds, controlled exposure experiments (CEEs) were conducted by WHOI using the D-tags in conjunction with a seismic source vessel. The location and level of airgun sound delivered at the tagged sperm whale(s) were controlled by the science team. These CEEs provided data on the immediate and short-term (hours) response of sperm whales to airgun sounds. Longer-term avoidance or displacement behaviors of sperm whales to seismic vessel airgun sounds were examined by OSU using location data from S-tags and proprietary commercial seismic shot data. Opportunistic studies of behaviors in the presence and absence of airgun sounds occurring during the SWSS cruises were conducted by Ecologic.

This report summarizes three years of field research conducted during the summers of 2002 through 2004 in the northern Gulf of Mexico. The preliminary results of the individual tasks are presented here. A draft of this report was reviewed by the SWSS Science Review Board. The research focus for 2002-2004 was on the region off the Mississippi River Delta between 86°W and 91°W (study area). A two-year extension of SWSS provided for additional, limited field work in summer 2005 that is focused westward and farther offshore than the 2002-2004 study region. This fourth summer of field work will be followed by analysis, synthesis, and integration in 2006. Additional results and overall integration of results from the 5-year SWSS study will be presented in the SWSS Final Report to be completed in 2007 after consideration of SRB and MMS review comments on a working draft synthesis report.

A brief discussion of the field measurements is presented in Section 1.3, with a fuller description given in Section 2. This is followed in Section 1.4 by a summary of the preliminary results of the SWSS components grouped by objective. Details for each component are presented in Sections 3 through 9, which are referenced in Section 1.4.

1.3 SWSS Fieldwork in 2002-2004

Field cruises were conducted during the summers of 2002, 2003, and 2004. Those conducted in 2002 were in support of S-tag deployments for long term study of sperm whale movements and D-tag/CEE work for analysis of small scale sperm whale behavior patterns in the absence and presence of seismic survey sounds. The R/V *Gyre* was used for both cruises and small tag boats were launched from *Gyre* to approach and photograph and/or tag sperm whales. The offshore industry work boat M/V *Rylan T*, with the shallow-water airgun boat M/V *Speculator* attached to the rear work deck, provided an airgun array with characteristics equivalent to those used by commercial seismic vessels in the Gulf of Mexico. This ship configuration was used as the sound source for the CEEs conducted in 2002. Habitat characterization data, collected on both cruises, included currents from 153 kHz and 38 kHz acoustic Doppler current profilers (ADCP); temperature and salinity profiles using both conductivity-temperature-depth (CTD) and expendable bathythermograph (XBT) profilers; continuous, near-surface temperature, salinity, and fluorescence/chlorophyll observations; and sea surface height (SSH) fields and ocean color from remote sensing. Visual and passive acoustic observations of sperm whales also were collected, as were skin samples for genetic observations. Fluke photographs were taken for photo-identification. Preliminary analysis was done to consider the viability of 3-D passive acoustic tracking of sperm whales using information from the hydrophone arrays.

Field cruises conducted in 2003 consisted of, concurrently, a Whale Survey and Habitat Characterization cruise (WSHC) on the R/V *Gyre* and a D-tag/CEE cruise aboard the R/V *Maurice Ewing* for science operations and the M/V *Kondor Explorer* for the airgun sound source. The WSHC cruise was designed to provide the full suite of habitat characterization data for the time period of the D-tag/CEE cruise and to conduct sperm whale population studies from small boats launched from the R/V *Gyre.* XBT profiles of temperature also were collected fro the R/V *Ewing*. The WSHC and D-tag/CEE cruises were followed by an S-tag/habitat characterization cruise on the R/V *Gyre*. In addition to data types collected in 2002, a test of 3-D passive acoustic tracking was conducted from the *Kondor* and *Ewing*.

In 2004, two cruises were conducted. The first cruise included S-tag deployments from R/V *Gyre* and a full complement of habitat characterization data, skin sampling, visual and acoustic observations, and a 3-D passive acoustic tracking study. The second cruise used an acoustically quiet vessel, the 46' Hunter sailboat *Summer Breeze*, to study sperm whales using classical techniques. Scientists studied the social behavior of sperm whale groups as they followed groups for 1-3 days each. In addition, photographs, photogrammetry data, passive acoustic recordings, visual data, continuous near-surface temperature, and CTD profiles were collected on this cruise. A planned third summer of D-tag/CEE fieldwork in 2004 was cancelled; this severely impacted the CEE sample size and therefore its statistical power. It should be noted that while the sample size was suboptimal, the data sets obtained in 2002 and 2003 were able to demonstrate statistically significant changes in foraging behavior at sound exposures ranging from < 130-162 dBp-p re 1 μPa.

1.4 Preliminary Results

1.4.1 Behavior of Sperm Whales in the Northern Gulf of Mexico

Objective 1 of SWSS is to establish the normal behavior of sperm whales in the northern Gulf of Mexico. It is intended under this objective for a baseline behavior to be described. However, there has been a long history of human activity and human-generated sound in the Gulf of Mexico, including the regions in which sperm whales have been observed. SWSS was not designed to determine what level of habituation there may have been of the Gulf's sperm whale population to these activities and their associated sounds. The SWSS data, therefore, should not be considered truly baseline in the sense of defining normal behavior of totally unexposed animals.

The focus of the study in 2002-2004 was in the region south of the Mississippi River Delta between the Mississippi Canyon and DeSoto Canyon along and about the 1000-m isobath. Earlier studies have identified that sperm whales are present over the slope east of the Texas-Mexico border, north of the Florida Keys, and in deep waters throughout the northern Gulf (see e.g., Würsig 2001, Würsig et al. 2000, Waring et al. 2004). These studies also have found sperm whales to be present in the northern Gulf in all seasons. As will be seen in Section 6.1, sperm whales tagged in the study area of the SWSS study also travel to other portions of the Gulf and into deeper waters. However, because of limited observations in SWSS from areas outside the SWSS study area, the results presented here for the 2002-2004 observations may not include variations, if any, in behaviors associated with other geographic regions in the Gulf. Broader geographic studies will be needed to identify whether populations and their behaviors in the SWSS study area are the same as in other areas of the Gulf.

The behavior of the sperm whale population in the northern Gulf of Mexico was studied using satellite-tracked tags for seasonal movements over large distances (Section 6), digital-recording tags for fine scale movements over hours (Section 7), group follow studies for group structure and movements over days (Section 4), and genetic analyses of biopsy samples (Section 5). This research allows a description of the sperm whale population and its structure in the northern Gulf. A brief summary is given below; additional details can be found in the sections identified.

The National Marine Fisheries Service provisionally considers the sperm whale population in the northern Gulf of Mexico as a stock distinct from the U.S. Atlantic stock (Waring et al. 2004). The preliminary results of SWSS also indicate that sperm whales in the Gulf of Mexico are different from other populations. In particular, the genetic analyses, coda vocalizations, and population structure support this result. Comparisons of mitochondrial DNA (mtDNA) and other molecular markers of tissue samples from sperm whales in the northern Gulf, Mediterranean Sea, North Sea, and North Atlantic Ocean reveal a significant genetic differentiation between the Gulf of Mexico population and populations of the other three regions (see Section 5). Preliminary analyses of coda vocalizations suggest there are significant differences in repertoires between the Gulf of Mexico population and the populations of the rest of the Atlantic (see Section 4.3). The available recorded coda vocalizations indicate that the mixed groups in the Gulf of Mexico belong to an acoustic clan that is rarely encountered in other areas and, from this, it is inferred that groups from other clans rarely enter the northern Gulf of Mexico.

The 2004 MPS cruise provided a first opportunity to study in detail the population structure of sperm whales located in the northern Gulf between Mississippi Canyon and DeSoto Canyon (see Section 4.1). The population structure of the groups studied in this area exhibits variations from the structure of populations outside the Gulf that also have been studied in similar detail. The mean group size in the study area is 9-11 individuals, which is about one-half the size of groups elsewhere. Individual whales are significantly smaller in length (1.5 to 2 m smaller) than what would be expected on the basis of whaling data from the Gulf of Mexico. Similarly, the lengths of Gulf of Mexico sperm whales studied in SWSS are smaller than those of sperm whales in the Gulf of California that were measured using the same technique applied in SWSS. These length measurements were confirmed with measurements made using passive acoustic techniques. Mature males seem to have either a different behavior or a different seasonality to those in other regions as no large breeding males were observed in 2004. Groups of females/immatures have a high site fidelity, comparable to bachelor males off Kaikoura, New Zealand, but not described elsewhere for females/immatures. Furthermore, there is no evidence of long-distance movements as no matches were found between the 185 individuals identified in the northern Gulf of Mexico and the ~2500 individuals identified in the rest of the Atlantic (North Atlantic and Mediterranean Sperm Whale Catalogue). These results indicate a degree of segregation between sperm whales in the Gulf of Mexico and the rest of the Atlantic, likely spanning temporal scales of years (absence of matches) to decades (differences in coda repertoire). These results suggest that, for management questions, sperm whales in the northern Gulf of Mexico should be treated as a separate population.

Based on data pooled from 1996 to 2001, NMFS estimated the minimum population size for the northern Gulf of Mexico as approximately 1,100 sperm whales (Waring et al. 2004). This estimate includes results from all U.S. waters in the Gulf, and so covers roughly 3-4 times more area than the SWSS 2002-2004 study area. To characterize the sperm whale population within the SWSS study area, two 3-week cruises aboard the R/V *Gyre* in 2002 and 2003 and one 7-week cruise aboard the sailing vessel *Summer Breeze* in 2004 were conducted. During these cruises, 185 individual sperm whales were identified and mark-recapture analyses suggested that 398 individuals utilized the study area, with a range of 253-607 individuals at the 95% confidence interval. Sperm whales were encountered along the continental slope from the longitude of Galveston, TX, to the longitude of Tampa, FL.

The social organization of the sperm whale groups in the northern Gulf of Mexico was examined using visual and acoustic observations and genetic analyses. Observations of group structure were made from inflatable boats launched from the R/V *Gyre* in 2002 and 2003 and from a sailboat in 2004. A strong segregation was found in the distribution between groups of female/immature sperm whales and bachelor or lone males in the 2004 MPS observations. The former were mainly found in the region south of the Mississippi River Delta and Mississippi Canyon and in the western Gulf, while the latter were mainly found in the DeSoto Canyon and along the Florida slope. Groups of females and immature sperm whales showed a high site fidelity for the region south of the Mississippi River Delta and Mississippi Canyon. Only one individual that was first sighted west of the study area was resighted within the study area. Incidental genetic resampling of a few individuals over periods of days, months and years adds support for site-fidelity to the northern Gulf of Mexico exhibited by at least some whales. The S-tag data also suggest the females tend to have an affinity for specific areas. However, site fidelity has not been studied for other areas such as the western and southeastern Gulf.

In 2002 and 2003 from inflatable boats launched from the R/V *Gyre*, few first-year calves were observed, initially raising concern for the well being of the population. However, in 2004, a first-year calf was observed with most groups of female/immature sperm whales that were followed visually for more than 12 hours, providing an overall proportion of calves to group size of 11.5%. This proportion of calves is of similar magnitude to that in several areas of the South Pacific. The differences in calf counts between the sailing vessel and the R/V *Gyre* inflatable boats likely are due to the types of vessels used, rather than to population differences between years. It is difficult to observe sperm whale groups unobtrusively from a acoustically noisy platforms, so the less conspicuous animals, such as first-year calves, likely were missed. It also was impractical to follow groups for over 12 hours from R/V *Gyre* or its away boats.

The molecular genetic markers of the sampled individuals can be compared to provide additional insights into the structure of the Gulf of Mexico population. The majority of the Gulf of Mexico samples were from females and young males believed to be sexually immature based on rough size estimates. Furthermore, being limited to the northern Gulf of Mexico, the sample set compares the genetic analyses of individuals from a more restricted geographic area than previous studies. Nevertheless, the results show a lack of significant nuclear differentiation between neighboring populations. This suggests that sexually mature males disperse from their natal populations and spread their genes to the females who tend to remain in or habitually return to particular areas (i.e., who exhibit more philopatric behavior than the males).

The genetic composition of Gulf of Mexico sperm whale groups fits the mixed sex and bachelor group type common in other areas of the world. Relatedness within the Gulf of Mexico female-dominated groups was significantly greater than that found between groups. However, relatedness within groups is surprisingly low and is composed of both single and multiple matrilines (i.e., where the line of descent is from female ancestors). Highly related whales (i.e., parent-offspring) were present within groups, but infrequently. The most common relationship found was that of half-siblings. The all-male bachelor groups were comprised of multiple matrilines and members were generally unrelated, although cases for half-sibling pairs were present.

S-tag data provide information on the large scale movements and seasonal distribution of sperm whales in the gulf of Mexico. Movements and home range were studied for 39 sperm whales tagged with satellite-monitored implantable radio tags in the Gulf of Mexico. A total of 2,826 locations were received from 8 August 2001 to 15 October 2004. Quality of satellite-estimated locations was very good: 45.5% of them were classified as Argos standard locations classes (LC3, LC2, and LC1, which are predicted to be within 50m, 350m, and 1000 m of the actual location respectively). To 5 November 2004, the active life of tags (number of days between deployment and last satellite location) ranged from 17 to 607 days and the number of locations per tag ranged from three to 183. Whales were tracked for at least 106,743 km during 6,477 whale-tracking days with individual and yearly average distances up to 17,068 km and 3,719 km, respectively, and travel speeds ranging from 0.2 - 2.3 km/hr (average 0.7 km/hr).

Tagged female whales tended to more routinely occupy the upper slope edge with far less representation over deep water than males. Only two tagged females actually moved out over deep water, while several males and individuals of unknown sex moved offshore and traveled to the southern reaches of the Gulf (Bay of Campeche). One of the male whales moved into the north Atlantic and, after getting near the path of Hurricane Isabel in 2003, turned around and went back into the Gulf of Mexico. These S-tag data indicate that males have a larger individual range than females, with emphasis over deeper waters. Moreover, home range estimates for each month indicate the year round importance of the Mississippi River Delta for whales tagged in that region. No significant negative effect was observed on re-sighted tagged whales; none of them appeared emaciated and all observed surface behavior was normal.

During the 2004 MPS cruise, groups of sperm whales that were followed closely for 12 to 50 hours in the region south of the Mississippi River Delta showed an average horizontal daily displacement of 35 km. Such a small horizontal daily displacement, as well as the pattern of their small-scale movements, appear to suggest a high feeding success. As compared to displacement patterns of sperm whales in other oceans, the pattern of movements of the observed Gulf whales consists of zig-zags over a smaller area and longer periods during which the animal stays within a particular area. These results lead to the idea that sperm whales may be feeding on small but dense patches of prey, and thus represent an insight into possible sperm whale foraging behavior in the northern Gulf of Mexico.

Foraging behavior and diving were examined in detail with the D-tag, which recorded data digitally for between 10 and 24 hours, depending on sampling rate, with enough resolution to track individual fluke strokes. Three cruises were conducted to collect the baseline D-tag data sets. Two were conducted in the Gulf of Mexico in summer 2002 and summer 2003, and one in the North Atlantic in summer 2003. The Gulf of Mexico cruises included CEEs, the North Atlantic cruise did not. The number of sperm whales tagged (hours recorded/number of dives recorded) were 19 (76/65) for SWSS 2002, 11 (69/50) for SWSS 2003, and 12 (28/18) for North Atlantic 2003.

The dives made by the D-tagged sperm whales in both the Gulf of Mexico and North Atlantic fell into two distinct categories: dives of less than 150 m and "deep" dives to greater than 300 m. A typical deep dive of a tagged whale lasted 46 minutes (range 14.2-63.9 min). Ninety-five percent of recorded deep dives lasted more than 30 minutes and less than 57 minutes. Whales descended at an average vertical velocity of 1.2 m/s, and began producing regular clicks at a depth of approximately 200 m. They continued descending and producing regular clicks until they reached the apparent depth of prey. Whales stopped descending and began the bottom phase of the dive, where they moved up and down through the apparent prey layer. Whales dove to 966 m in the Atlantic (range 830.3 - 1202.2 m) and 659 m in the Gulf of Mexico (range 326.8 - 972.0 m). The deepest dive recorded was to 1202 m by a whale in the Atlantic.

Bottom duration was similar in both locations, although on average whales in the Gulf of Mexico stayed in the bottom phase longer. Analyses of the behavior of tagged sperm whales corroborate similar data from bats and beaked whales to indicate strongly that buzzes are produced by sperm whales during prey capture attempts. The number of buzzes per dive was similar in both regions and averaged 17.9 buzzes per dive with whales producing between 5 and 44 buzzes in 95% of the dives. Shortly after the last buzz, whales stopped regular clicking and returned to the surface. Judging by the apparent correlation between buzzes and attempts to capture prey, the majority of active foraging occurred in the bottom phase of the dive cycle. Based upon these results, the foraging phase was defined as lasting from the first to last buzz. Foraging phase duration also was similar, averaging 29 minutes, and accounting for 60 percent of the dive duration. Foraging phase duration also was similar, averaging 29 minutes, and accounting for 60 percent of the dive duration. During the ascent, vertical velocities were higher than during the descent phase of the dive for whales in both the Gulf and the Atlantic. Whales in the Gulf of Mexico had shorter ascent durations, due to the shallower depths of their dives. Whales spent on average 11 minutes at the surface following a deep dive.

D-tags recorded coda vocalizations during both cruises in the Gulf of Mexico and the North Atlantic, allowing a comparison of behavior during such vocalizations. Codas were produced primarily in the first 300 m of the water column in both locations. No codas were recorded from the bottom phase of the dive. On average, focal whales in the Atlantic Ocean produced more codas at the surface per tag than whales in the Gulf of Mexico. Whales produced about equal number of codas during dives in both regions. More nonfocal codas were recorded on average from the Gulf of Mexico than from the Atlantic Ocean. On average, focal whales produced codas on about half of their dives, and hear nonfocal codas on a similar percentage. A significant portion of codas were recorded during the descent phase of foraging dives. Therefore, codas are not simply produced when whales are returning to the surface and attempting to come back together after separating for foraging.

The D-tag data also were used to measure the distance between whales. Although sperm whales are well-known to form close aggregations while swimming at the surface, little is known about their separation distances while diving. A method for estimating the distance between pairs of diving sperm whales as well as their relative orientation was developed under SWSS using the acoustic recording D-tags. The method enables studies of synchronization and movement during foraging, with relevance to measuring group-level responses to anthropogenic sounds. These analyses are important for analyzing CEEs where more than one whale has been tagged, increasing the sample size of individual subjects.

Four multiple-tag data sets were collected during the SWSS cruises. Two of these included an airgun controlled exposure. Preliminary estimates of the distance between whales for one of the deployments using this method exemplify both the practicality of the method and the scope of new biological insight possible. A 13-hour tag deployment on three sperm whales in a loosely-coordinated group made it possible to track the inter-whale ranges over a large percentage of the deployment. The whales were initially close together with slant ranges of less than 500 m and horizontal ranges considerably smaller where dives coincided. After some three hours, one of the whales separated from the other two reaching a distance of some 1500 m while the other two drew close together. Finally, all three whales separated to distances of 1500 - 3000 m which was maintained before and after an extended surface interval. Intriguingly, the times of greatest separation coincided with the greatest synchrony in dive cycle suggesting that the click sounds may serve a dual purpose of coordinating movement between whales in addition to their function in echolocation.

Also undertaken as part of SWSS was a project to use 3 dimensional passive acoustic tracking to study sperm whales. Because sperm whales are a vocally active species, detecting their signals, or "clicks," using towed passive acoustic arrays has become a standard procedure for locating and monitoring for the presence of these animals. Most passive array systems also have the ability to estimate the direction from which a particular sound is arriving, by measuring the signal's arrival time difference at two hydrophones spaced a few meters apart. The range to a whale can be estimated by measuring how the observed bearings from a particular animal shift over time while the observation platform is moving. If the velocity of the platform is much larger than that of the animal, then the bearings will converge to a particular range over a 3-10 minute interval. Unfortunately, the speed of seismic vessels is not much faster than sperm whale swimming speeds, so at present there is no reliable way for ranging sperm whales using standard mitigation procedures. In addition, knowledge of the animal's depth becomes important for mitigation purposes whenever the animal of concern is deep-diving and the acoustic source is highly directional at certain frequencies, as is the case with seismic airgun arrays.

In 2003 and 2004, the SWSS project supported efforts to develop a three-dimensional tracking method for sperm whales using various combinations of towed acoustic gear. All methods rely on the fact that sperm whale sounds have such a short time duration that the surface-reflected acoustic path can often be distinguished in time from the direct path arrival. The basic concept was first demonstrated during the 2002 SWSS D-tag cruise, using data from two towed arrays. The idea was demonstrated again in 2003 by simulating a large-aperture towed array, by attaching an autonomous acoustic recorder to a rope attached to a standard passive acoustic array. Based on these results, the IRFC provided funds to build a dedicated towed array to demonstrate routine 3-D tracking of sperm whales during the 2004 SWSS S-tag cruise. The 400 m long "tandem" towed-array system was successfully deployed from the R/V *Gyre* during the entire cruise, and over two weeks of acoustic data were recorded, mostly at night, and a near real-time ranging algorithm was assembled in the field. Some initial 3-D tracks have been analyzed, and their veracity checked using a variety of methods. The effects of ray-refraction from a depth-dependent sound speed profile have also been evaluated, and to date seem to be negligible for ranges of 1 km or less. Aspects of this algorithm have been published in the peer-reviewed literature, and currently plans are underway to develop and test a real-time tracking system during SWSS 2005.

1.4.2 Characterization of Habitat Use

Objective 2 of SWSS is to characterize the habitat being used by sperm whales in the northern Gulf of Mexico. The 2002-2004 SWSS cruises searched for whales mainly in the region between the Mississippi Canyon and DeSoto Canyon along the 1000-m isobath, in water depths typically of 800-1200 m. Physical and biological habitat conditions during those cruises are being merged with sperm whale encounter locations to describe the environment in which sperm whales were present or absent.

Specifically, the physical and biological conditions of the environment were determined from remote sensing fields of sea surface height and ocean color in the Gulf of Mexico and *in situ* measurements from the research vessel of currents, temperature, salinity, and near-surface chlorophyll in the waters being traversed. These data were coupled with information on the presence or absence of sperm whales within approximately 5-10 km of the ship. Sperm whales were detected by daytime visual surveys using high-powered (25x) BigEye binoculars and by 24-hour passive acoustic observations from 1-2 towed hydrophone arrays. During the non-summer periods when no cruises were in the field, remote sensing fields that indicate both physical and biological conditions are being coupled with location data from sperm whales tagged with the OSU satellite-tracked S-tags.

The circulation regime of the northern Gulf of Mexico is characterized by an energetic eddy field that includes Loop Current eddies and warm slope eddies, which are anticyclonically (clockwise) circulating features, and cyclonic eddies, which are cyclonically (counterclockwise) circulating features. The eddy-forced variations in on-margin and off-margin flow have been found to have profound effects on the dynamics of circulation along the 1000-m isobath regime frequented by sperm whales in the study area (e.g., Biggs et al. 2000, Davis et al. 2002, Biggs et al. 2005). Results from the GulfCet II and SWAMP cruises of 1996-2001 showed that the temporal and spatial variations in the geometry of the eddy field along the 800-1200 m isobaths determined whether low salinity, high chlorophyll "green water" flowed off-margin or high salinity, low chlorophyll "blue water" flowed on-margin. "Green water" is biologically rich and will support more food for the squid or fishes upon which whales prey. In addition to the on- and off-margin surface water flow induced by cyclonic and anticyclonic eddies occurring over the slope, cyclonic eddies upwell nutrient-rich waters into the photic zone and so represent new biological production in the region. GulfCet II and SWAMP studies found that cetaceans, including sperm whales, were more likely to be seen in areas where the sea surface height anomaly was negative, indicative of cyclonic circulation, and surface chlorophyll concentrations were moderately high, indicative of off-shelf flow and the higher nutrient availability that supports new biological productivity (Davis et al. 2002; Biggs et al. 2005). These findings lead to the hypothesis that locally high chlorophyll features, particularly cyclonic eddies or eddy-induced off-margin flows, that persist for 3-4 months, provide sustained primary production that then can support the higher biological production that is important for the development of feeding grounds for sperm whales along the continental slope.

The fine-scale resolution of the SWSS ship surveys, combined with the mesoscale resolution of the remote sensing fields, documented summer-to-summer variability in intensity and geographic location of Loop Current eddies, warm slope eddies, and areas of cyclonic eddy circulation (Section 3.1 provides details). These variations forced striking year-to-year differences in the locations along the 1000-m isobath where there was on-margin and off-margin flow and resulted in significant differences in the current structure and water properties on the northern slope. The physical and biological data on the 2002-2004 S-tag cruises and the WSHC cruise of 2003 have been integrated with the locations where sperm whales were encountered along the 1000-m isobath (see Section 3.1). In summers 2002 and 2003, most sperm whales were encountered in regions of negative sea surface height anomaly and/or higher-than-average surface chlorophyll. This is consistent with the hypothesis that cyclonic eddies, which are features of negative sea surface height anomaly and new biological production, may support the feeding grounds for sperm whales. In contrast, however, only a few of the whale encounters in summer 2004 were in regions of negative sea surface height anomaly and/or higher-than-average surface chlorophyll. These habitat associations in 2004 are anomalous when compared to the GulfCet II, SWAMP, and 2002-2003 SWSS results. These summer-to-summer differences in environmental conditions and sperm whale presence or absence will be further evaluated with comparable data sets from the 2005 S-tag cruise and the 2004 and 2005 MPS cruises.

In addition to considerable summer-to-summer variability, local oceanographic conditions also changed during the course of a single summer, with resultant changes in encounter rates with whales. GulfCet, SWAMP, and SWSS fieldwork showed that the Mississippi Canyon region is a north central Gulf area in which sperm whales are observed to be present with some frequency. In early summer 2003, however, a Loop Current eddy was located seaward of but in close proximity to Mississippi Canyon. There was on-margin flow in this region that effectively "flushed" the canyon with low chlorophyll, low nutrient Caribbean water originating from the Loop Current eddy. Sperm whales were rarely seen or heard in the Mississippi Canyon region during this time. In contrast, approximately one month later that same summer, sperm whales were encountered in the Mississippi Canyon region. Remote sensing fields showed the Loop Current eddy had rebounded to move farther seaward from the continental margin and along-margin and off-margin flow in the region had been re-established.

How deep below surface does the habitat influence of the cyclonic and anticyclonic oceanic eddies actually extend? Although SWSS was not designed to fully address this question, a first look at the subsurface biota was done in conjunction with the 2003 WSHC cruise. The midwater trawling during the 2003 field year was designed to compare and contrast zooplankton and midwater fish in the 0-400 m, 0-600 m and 0-800 m depth horizons. Quantitative taxonomic analyses of the trawl collection samples showed significant differences between cyclonic and anticyclonic features in the 0-400 m depth horizon. However, deeper than 400 m, no significant differences in species composition or abundances were seen in these trawl collections (see Section 3.2 for details). Since sperm whales were not observed to feed at shallow depths (< 400 m) in the northern Gulf, it remains an open question whether there is a tight coupling between surface features and sperm whale prey and whether traditional methods of deep sea trawling sample enough volume of deep water to accurately assess sperm whale prey.

The SWSS *in situ* observations of sperm whales are limited to cruises in the summer months. However, sperm whales are present in the Gulf of Mexico year-round (Davis et al. 2002). To study the seasonal utilization of physical habitat by sperm whales in the northern Gulf of Mexico, three environmental variables were analyzed at the spatial and temporal locations of 39 whales tagged with satellite transmitters (see Section 6.2). Ocean bottom depth, bottom slope, and sea surface height were determined for each sperm whale location (see also Section 4.2 for additional discussion of bottom depth and slope with respect to population densities from cruise data). Movement paths of the satellite-tracked whales were categorized as being either meandering or transit type, and each location was assigned to one of the two categories. The sex of each animal was determined by genetic analysis of skin biopsy samples (see Section 5). Of the 39 whales, 24 were female, 6 were male, and 9 were of unknown sex because a biopsy sample could not be obtained. None of the environmental variables analyzed had a normal distribution or equal variances among compared groups; therefore, non-parametric statistics were applied.

Comparisons were made between sex classes and movement types. Statistically significant differences were observed in the median values of bottom depth at locations for satellite-tracked females and males. The median depth at the locations of the females was 884 m, which is shallower than the median bottom depth of 1171 m for the males. Locations of males and females relative to bottom depth overlapped, but female sperm whales were located more frequently on the upper continental slope of the northern Gulf of Mexico. Males were also located in this region, but some satellite-tracked males moved into the central Gulf or over the lower continental slope and abyssal plain. Hence, males tended to be located on average in deeper water depths. Significant differences were observed in the median depth for locations assigned to meandering (895 m) and transit (968 m) move types. Median values of bottom slope also were different between females and males. Females tended to be located where the bottom slope was steeper (3.06 degrees) than the slope at the locations of males (2.39 degrees). Median bottom slope was not different between meandering and transit categories.

No significant differences between females and males were found in sea surface height values at animal locations. However, the median value of sea surface height was different between meandering (-3.9 cm) and transit (-7.1 cm) locations. Note that the median value for both types is negative, which is consistent with the hypothesis of a preference for regions of cyclonic circulation. Interestingly, the difference in mean sea surface height between meandering and transit movement types may indicate that sperm whales have differential use for various areas of the Gulf. This difference is statistically significant. Moreover, movements of tracked whales showed that, although most individuals frequented the Mississippi Canyon and the Mississippi River Delta regions, there are differences between males and females, as well as among individuals, in the specific areas frequented during the year. A trend was observed for satellite-tracked whales to aggregate near the Mississippi Canyon and Mississippi River Delta regions in the summer. While some individuals may spend several months in those areas, others disperse in different directions the rest of the year. Because most of the satellite tracked whales were tagged in the Mississippi Canyon and Mississippi River Delta regions, we do not know whether other groups of sperm whale have similar site-fidelity patterns in other regions of the Gulf. Studies in other regions (i.e., western, eastern, or deep water Gulf) are necessary to resolve this question.

1.4.3 Sperm Whales and Man-made Noise

Sound transmitted in the ocean has the potential to adversely impact marine mammals, including sperm whales. Sound may have several classes of adverse impacts. Close proximity to an intense sound source may result in injury or other trauma, such as hearing loss, to the individual. At lower exposure levels and greater range, sound exposure may initiate behavioral or subtle physiological responses or masking. SWSS objective 3 was designed to investigate the sound exposure level at which behavioral changes begin to occur.

The primary goal pf the D-tag CEEs was to quantify changes in behavior of sperm whales throughout the dive cycle when whales were subjected to man-made noise, particularly from seismic survey arrays. To achieve this objective a series of controlled exposure experiments was undertaken to examine the fine-scale behavior of sperm whales and their possible responses to exposures to airgun sounds. Additionally, two studies were undertaken to statistically compare the locations of opportunistic commercial seismic survey operations with the locations of satellite-tracked sperm whales and of visual and acoustic observations of sperm whales on SWSS cruises. Because the sample sizes for each of the three approaches are small, all results are preliminary.

<u>Controlled Exposure Experiments</u>: Two D-tag/CEE cruises directly examined the behavior of sperm whales and their possible responses to airgun sounds (see Section 7). For these studies, the WHOI D-tag was attached to sperm whales to record sound received from a geophysical exploration airgun sound source during carefully planned and executed controlled exposure experiments. The D-tag/CEEs under SWSS were designed to evaluate effects of airguns on avoidance, foraging, and communication of sperm whales in the northern Gulf of Mexico. The synopses in Section 7 of this report consider the potential effects of airgun sound exposure in terms of avoidance and changes in foraging effort during the course of several dive cycles.

Each CEE subject was followed after tagging and before exposure to provide a pre-exposure control. Most animals carried the D-tag for long enough after exposure stopped that a post-exposure control period could be used in analysis. Analysis of data sets shows that the first dive after tagging was affected by the response of the animal to the tagging itself, while the second dive is not statistically different from later ones. If the first dive is removed from pre-exposure data collected from 2002, the duration is not long enough to use for a pre-exposure control period. This problem was remedied in 2003 by modifications to the D-tag that allowed longer pre-exposure periods. However, to be able to include the 2002 data in the statistical analyses, only comparisons of post-exposure data were made to exposure data.

The movement and sound-recording D-tag was used to record acoustic exposure and foraging behaviors of 8 sperm whales before, during and after 1-2 hr controlled sound exposures of industry-provided airgun arrays in the Gulf of Mexico in 2002 and 2003. In 2002, two CEEs were conducted involving 4 subjects. In 2003, three CEEs were completed also with a total of 4 subjects. The 8 whales for which these CEEs were conducted were all exposed to maximum sound levels between 130 and at least 162 dBp-p re 1 μPa at ranges of roughly 1.4-12 km from the sound source.

Avoidance Behavior: The location data from tagged whales and the airgun source vessel allowed us to track the tagged animal and determine the orientation and movement of the tagged whale relative to the airgun source. Neither gross diving behavior nor direction of movement changed for any of the eight exposed whales at the onset of gradual ramp-up at ranges of 7.3-12.5 km, nor during full power exposures at ranges of 1.5-12.8 km. Acoustic exposure ranged from <130 to 162 dBp-p re 1 μPa. These results raise questions about the efficacy of ramp-up and about whether sperm whales swim away from oncoming seismic vessels, but may not be relevant to sperm whales in habitat with less historical seismic exploration than the Gulf of Mexico.

Foraging Behavior: The effects of airguns on the foraging behavior of sperm whales was assessed following the proposed study design. The whale that was approached most closely prolonged a surface resting bout hours longer than typical, but resumed foraging immediately after the airguns ceased. While this whale showed no horizontal avoidance, the alteration of diving behavior could be considered a vertical avoidance response. Differences of foraging response measures between exposure and post-exposure control periods in the remaining 7 exposed whales (which made foraging dives during both conditions) were compared to sham exposure and post-exposure control periods in 13 unexposed whales. Pitching movements generated by swimming motion were 6% lower during exposure (P=0.014). Distinctive echolocation sounds, called buzzes, produced when whales attempt to capture prey were 19% lower during the exposure condition, but this effect was not statistically significant (P=0.141).

Given the low sample size of exposure subjects, we followed the advice of Ellison (1996) and conducted a Bayesian analysis to quantify the odds-ratio for whether our data support models of increase, decrease, or no change in buzz rate and pitching movement. The result indicates that a decrease in buzz rate is 3.6 times more likely than no change given our data; this is a Bayes factor considered to be "substantial" or "positive" evidence for an effect (Jeffereys 1961; Kass & Raftery 1995, summarized in Ellison 1996). The same analysis indicates that a decrease in pitching movement is 2.9 times more likely than no change. Clearly more research is needed to define the effects of seismic on foraging behavior on sperm whales, but our analysis suggests that a 20% decrease in foraging attempts at exposure levels ranging from <130 to 162 dBp-p re 1 μPa at distances of roughly 1-12 km from the sound source is more likely than no effect.

RMS Measures as Safety Thresholds: Evaluations of the CEE data sets also considered the consequences of using of the maximum root-mean-square (rms) sound pressures of 180 dB re 1µPa (rms) for cetaceans as safety thresholds for transients impinging on marine mammals. There are three main problems with this approach. First, the rms measure does not take the overall energy exposure into account. Second, different rms measures can be derived for waveforms with identical peak pressure depending on the duration over which the squared pressure is averaged. Third, the rms measure does not represent the exposure level of transients with high peak pressure and a slowly decaying tail as is common in reverberant underwater environments. Because of these limitations, it was concluded that rms safety measures are unsuited as a stand alone mitigative measure for transient noise effects on marine mammals irrespective of what the absolute level is. It is recommended that safety levels for noise transients include a maximum peak-peak received sound pressure level in concert with a maximum received energy flux density level.

Quantitative Measures of Airgun Pulses Impinging on Sperm Whales: Analyses show that sperm whales are exposed to a series of pulses with different spectral, energetic and temporal properties for each duty cycle of the airgun array. The analysis shows that some of the direct arrivals have dominant energy at much higher frequencies than currently reported or modeled for airgun arrays. While this energy is radiated off the axis of the array, the absolute levels of these high frequency pulses may reach received levels of more than 140 dB re 1µPa (rms).

Seismic Survey Activity and the Proximity of S-Tagged Whales: Whale locations from the S-tags were compared to positions of active seismic vessels in the Gulf of Mexico in an attempt to determine whether satellite-tracked sperm whales occurred less frequently than expected in the vicinity of active seismic vessels (a possible indication of vessel avoidance). High-quality locations, numbering 1,167, from S-tags on 33 sperm whales were correlated with 6,821 seismic lines from 6 June 2002 through 16 August 2004. A total of 30 high quality locations from 12 animals were determined to be within 25 km of an active vessel. The time differences between start of the seismic line and whale location varied from 0.65 h to 4.8 h, with a mean of 2.2 h and standard deviation of 1.24 h. Distances were tabulated into 5 km classes. No distances were less than 5 km and five of the 30 locations were 5 to 10 km from a vessel. When more than one observation was obtained from an individual, its contribution to the distance class was inversely weighted by the total number of observations for that animal. This addressed possible effects of pseudoreplication, maintaining a total sample size of 12 animals yet utilizing all the observations.

Chi-square testing and Monte Carlo simulations were applied to compare the observed with the expected number of observations for the various distance classes. There was no evidence that the data were non-randomly distributed. Although distances between whales and active vessels appear to be randomly distributed, due to a lack of sufficient sample size, these results cannot refute a possible behavioral response. The number of individuals would need to be doubled to have the power to detect a non-random distribution from 5 km and further. A much larger sample size (75) is needed for analysis closer than 5 km. An additional source of uncertainty is the lack of controlled positional errors from the Argos-derived locations.

Fine Scale Movements in Response to Seismic Line Starts: In the course of work surveying for sperm whales and keeping track of groups at the surface to support tagging, genetic sampling and photo-identification, the visual teams on the *Gyre* logged the location, general behavior, and heading of every cluster of sperm whales seen at the surface. These data were analyzed to investigate medium term responses of whales to seismic surveys which were occurring in the area. No significant responses were observed in (1) heading relative to the bearing to seismic surveys, (2) time spent at the surface, or (3) surfacing rate in the comparisons of matched pairs two hours before and two hours after line starts and line ends for survey lines within 100, 50, or 25 miles.

Summary: The results of the three independent approaches suggest that there is no horizontal avoidance of sperm whales in the Gulf of Mexico to seismic survey activities. These data do not support the assumption that whales swim away from an airgun array as it ramps up or approaches the whale at full power. However, there were few exposures above 160 dBp-p re 1 μPa. Further research would be required to test for avoidance at higher received levels. The whales were tagged in a region with substantial human activity, and they are not naïve to human-generated sounds. Gulf of Mexico sperm whales, at least in the area studied, may have some level of acclimation to seismic airgun sounds. Follow-on studies in regions not as affected by human activities are needed to address the issue of habituation.

Results of fine-scale changes in behavior in the presence of controlled exposures to airgun sounds are not definitive due to the small sample size that resulted when a planned third year of CEEs was not carried out. Attachment of the tag itself influenced the first dive after tagging, but subsequent dives showed no such effect. The 2002 data did not have a long enough period before the airguns were started to use a pre-exposure control after deletion of the first dive. With these caveats, the data demonstrate a significant change in feeding behavior associated with exposure to seismic airgun sounds with received levels ranging from <130 to 162 dBp-p re 1 μPa (decrease in fluking movement at $p < 0.02$). Bayesian analysis of the CEEs suggests the odds are about three times more likely that there is a 20% reduction in foraging during airgun exposure than that there is no effect. Additional CEEs are necessary to increase the sample size to numbers yielding the desired statistical power. Until further studies are conducted, the odds favor the conclusion that foraging behavior of sperm whales is disrupted by airguns at exposures ranging from <130-162 dBp-p re 1 μPa.

2 INTRODUCTION

The Sperm Whale Seismic Study (SWSS) is supported by the Minerals Management Service (MMS) of the U.S. Department of the Interior under Cooperative Agreement 1435-01-02-CA-85186. This report describes the SWSS program and participants and summarizes preliminary results for years 2002-2004 of the study.

2.1 SWSS Background and Objectives

MMS core responsibilities in managing the Outer Continental Shelf (OCS) activities include safe offshore operations and environmental protection. Under its environmental responsibilities, MMS seeks "to ensure that all activities on the OCS are conducted with appropriate environmental protection and impact mitigation" (MMS 2002). Oil and gas activities in the deepwater region of the Gulf of Mexico have increased over the last decade and are projected to continue to increase in coming years. This region is frequented by the sperm whale, which is listed as endangered under the Endangered Species Act (ESA).

MMS hosted a Gulf of Mexico Protected Species Workshop in 1999 to review past research, evaluate new issues, and recommend research priorities (McKay et al. 2001). The potential effects of noise from seismic operations on sperm whales was identified as a key research priority. MMS, the Office of Naval Research (ONR), and the National Marine Fisheries Service (NMFS) of the National Oceanic and Atmospheric Administration (NOAA) sponsored the Sperm Whale Acoustic Monitoring Program (SWAMP), which was conducted in fiscal years 2000 and 2001 under the MMS Interagency Agreement No. 15958. SWAMP was a pilot study that developed methods for sperm whale tagging, began documenting a baseline on "usual" behavior of sperm whales in the Gulf of Mexico, and made observations on the underwater acoustic environment. This study, as well as earlier survey results, indicated that sperm whales tend to be most likely observed near the 1000-m isobath (MMS 2002). Work in the Gulf of Mexico under this Interagency Agreement concluded in September 2001. However, one additional NMFS cruise off the U.S. mid-Atlantic coast was partially supported under this Interagency Agreement in 2003 to test D-tags and obtain comparative sperm whale dive data outside of the Gulf; preliminary results of these data are included in this Report (see Section 7).

During the January 2002 MMS Information Transfer Meeting, the International Association of Geophysical Contractors (IAGC) hosted a meeting to discuss future acoustic research relevant to seismic operations, and, in particular, as related to understanding the effects of seismic exploration on sperm whales in the Gulf of Mexico. IAGC offered its support for sperm whale research through contribution of a seismic source vessel for controlled exposure experiments. In response, the study entitled *Cooperative Research on Sperm Whales and their Response to Seismic Exploration in the Gulf of Mexico* was proposed to the MMS. It was approved by MMS in April 2002. The Cooperative Agreement was finalized in June 2002.

The study consisted initially of three years of field research in the northern Gulf of Mexico. The preliminary results completed through 2004 are presented in this Synthesis Report. The research focus for 2002-2004 has been on the region off the Mississippi River Delta between 86°W and 90°W. A two-year extension of SWSS is planned to allow additional, limited field work in summer 2005 and analysis and synthesis in 2006. Plans for the 2005 field work will extend the focus westward. Additional results from the 5-year SWSS study will be presented in the SWSS Final Report to be completed in 2007.

The objectives of SWSS are to

(1) establish the normal behavior of sperm whales in the northern Gulf of Mexico,
(2) characterize habitat use, and
(3) determine possible changes in behavior of sperm whales when subjected to man-made noise, particularly from seismic air gun arrays.

2.2 Program Participants and Sponsors

SWSS is a multi-institutional, interdisciplinary study involving personnel from many groups (Table 2.1). The principal academic scientists are from Ecologic, Oregon State University (OSU), Scripps Institution of Oceanography (SIO), Texas A&M University (TAMU), Texas A&M University-Galveston (TAMUG), University of Colorado (CU), University of Durham (UD-UK), University of Saint Andrews (UStA) and Woods Hole Oceanographic Institution (WHOI). SWSS scientists and their areas of effort , together with the funding entities and Science Review Board members, are given in Table 2.1.

The principal study tasks and associated institutions are: Satellite-tracked radio tags (S-tags) by OSU; Digital-recording acoustic tags (D-tags) and controlled exposure experiments (CEEs) by WHOI/UStA; Habitat characterization by TAMU and CU; Photo-identification and mesoscale population studies by Ecologic/UStA and TAMUG; Biopsy/genetic analyses by UD-UK; 3-D passive acoustic tracking by SIO; Program management by TAMU; and Data management by TAMU. All activities associated with marine mammals are conducted pursuant to approved permits from NMFS.

SWSS is supported by MMS. Additional support for SWSS activities is provided by the Office of Naval Research (ONR), the National Science Foundation (NSF), the National Fish and Wildlife Foundation (NFWF), and the Industry Research Funders Coalition (IRFC), which is a coalition of the IAGC and five oil and gas exploration and production companies. ONR supports tag development for both the D-tags and the S-tags used in the study. NSF provided year 2 support through a grant to Lamont-Doherty Earth Observatory (LDEO) for use of the R/V *Maurice Ewing* in D-tag work for SWSS 2003.

In addition to providing funding for SWSS, MMS has substantial direct involvement under this Cooperative Agreement. MMS scientists are actively involved in project oversight and coordination of study activities with academic scientists, ONR, NSF, and IRFC. They participate in the cruises on the visual and acoustic teams. MMS coordinates the Information Transfer Meeting and internal planning sessions on sperm whales and the SWSS project. Finally MMS personnel are involved in public outreach related to Gulf of Mexico marine mammals. MMS also is the lead agency for funding and decisions on program activities.

Table 2.1

Major Tasks in SWSS

Task	Description	Principal Investigators
Project Coordination	Funding and support planning and coordination	A. Jochens, TAMU, Program Manager W. Lang, MMS, Project Coordinator R. Gisiner, ONR, Agency Coordinator A. Shore, NSF, Agency Coordinator C. Gill, IAGC, Group Coordinator A. Wigton, IRFC, Group Coordinator
Program Management	Management of the program, including scientific, operational, and fiscal; oversight of preparation of deliverables; data management, including data archival	A. Jochens, TAMU, Program Manager D. Biggs, TAMU, Project Scientist M. Howard, TAMU, Data Manager
S-tag Study	S-tag logistics, data collection, data analysis, and reporting for S-tag work	B. Mate, OSU, PI J. Ortega-Ortiz, OSU, co-PI
D-tag/CEE Study	D-tag logistics, data collection, data analysis, and reporting for D-tag work	P. Tyack, WHOI, PI M. Johnson, WHOI, co-PI P. Miller, UStA/WHOI, co-PI
Mesoscale Population Study/Photo-ID	Population observations, photography, coda analysis, passive acoustic data collection, data analysis, and reporting	J. Gordon, Ecologic/UStA, co-PI N. Jaquet, TAMUG, co-PI B. Würsig, TAMUG, co-PI
Genetic Analyses	Skin and biopsy sampling, genetic analyses for group relatedness, and reporting	D. Engelhaupt, UD, PI
Habitat Characterization	Habitat characterization logistics, data collection, data analysis, and reporting for physical and biological habitat characterization	D. Biggs, TAMU, PI A. Jochens, TAMU, co-PI R. Leben, CU, co-PI John Wormuth, TAMU, co-PI
3-D Passive Acoustic Tracking	3-D passive acoustic tracking, data analysis, and reporting	A. Thode, SIO, PI
Science Review Board	Independent review and comment of 3-year summary and Final reports	D. Costa, Univ. of California-Santa Cruz P. Fontana, Veritas DGC R. Hofman, Marine Mammal Comm, ret. D. Palka, NOAA D. Wartzok, Florida International Univ.

NFWF provided support for the lease and provisioning of a 46' Hunter sailboat to conduct the Mesoscale Population Study (MPS). MPS was a classical, observational sperm whale population study in the northern Gulf of Mexico in summer 2004. IRFC provided the non-federal match that allowed SWSS scientists to obtain the NFWF funding, as well as funding supplementary to that provided by MMS to support the Mesoscale Population Study.

The seismic source vessel is a critical component the D-tag/CEE effort because it provides the sound source for the controlled exposure experiments. For the 2002 field year, IAGC contributed the seismic source vessel, M/V *Speculator*, mounted on the back deck of the M/V *Rylan T*, and its crew for use in the D-tag CEEs. SEAMAP, Inc. contributed a hydrophone array for the seismic source vessel during this cruise. For 2003, the IRFC contributed the seismic source vessel, M/V *Kondor Explorer*, and its crew for use in the D-tag CEEs. IRFC also provided support under SWSS for the towed hydrophone array used in 3-D passive acoustic tracking study in 2004 and, in 2003 and 2004, for analysis of S-tag whale locations and seismic survey lines. IRFC provided separate funding to OSU in support of further development of the S-tags and also provided support for calibration tests with *Kondor* airguns of the Environmental Acoustic Recording System (EARS) buoy that is part of a separate MMS-sponsored study.

A SWSS Science Review Board (SRB) was established to provide review and comments on the draft Synthesis Report. The SRB consists of one federal representative (Debra Palka, NOAA), one industry representative (Phil Fontana, Veritas DGC), and three academic/science representatives (Daniel Costa of the University of California-Santa Cruz, Robert Hofman retired from the Marine Mammal Commission, and Doug Wartzok of Florida International University).

2.3 Summary of Cruises and Data Collection

Table 2.2 lists the SWSS field cruises conducted in the summers of 2002, 2003, and 2004. Information on cruises in 2002 is reported in Jochens and Biggs (2003), and information on cruises conducted in 2003 is in Jochens and Biggs (2004). Details of data collection from cruises in 2004 are given in the Appendix of this report. Also shown in Table 2.2 is an associated, MMS-supported cruise, conducted immediately after the 2003 D-tag/CEE cruise, to calibrate the airgun array from the EARS buoy. Data collection on each SWSS cruise is described below.

Field cruises conducted in 2002 were in support of S-tag deployments for long term study of sperm whale movements and D-tag/CEE work for analysis of small scale sperm whale behavior patterns in the absence and presence of seismic sounds. R/V *Gyre* was used for both cruises and rigid-hull inflatable boats (RHIBs) were launched from *Gyre* to approach and photograph and/or tag sperm whales (Figure 2.1). The M/V *Rylan T* with the *Speculator* providing the seismic source, was used for the CEEs. Habitat characterization data collection was done on both cruises. This consisted of currents from 153 kHz and 38 kHz acoustic Doppler current profilers (ADCP), temperature and salinity profiles using both CTD and XBT profilers, continuous, near-surface temperature, salinity, and fluorescence/chlorophyll observations, and sea surface height (SSH) fields from remote sensing. Visual and passive acoustic observations were collected as were skin samples for genetic observations. Fluke photographs were taken for photo-identification. Preliminary analysis was done to consider the viability of 3-D passive acoustic tracking of sperm whales using information from the hydrophone arrays. See Jochens and Biggs (2003) for details.

Field cruises conducted in 2003 consisted of, concurrently, a Whale Survey and Habitat Characterization cruise (WSHC) on the R/V *Gyre* and a D-tag/CEE cruise aboard the R/V *Maurice Ewing* and M/V *Kondor Explorer*. The WSHC cruise was designed to provide habitat characterization data for the time period of the D-tag/CEE cruise and to conduct sperm whale population studies from small boats launched from the R/V *Gyre*. These two cruises were followed by an S-tag/habitat characterization cruise on the R/V *Gyre*. In addition to data types collected in 2002, a test of 3-D passive acoustic tracking was conducted from the *Kondor* and *Ewing*. Habitat characterization data collection on the D-tag/CEE cruise was limited to XBT profiles of temperature and remote sensing data. See Jochens and Biggs (2004) for details.

Table 2.2

Cruises Conducted in 2002, 2003, and 2004 and Associated Data Collection Activities
(X denotes full data collection; x denotes limited data collection due to cruise limitations.)

Year	**Ship**	**Cruise**	**Dates**	**D-tag**	**S-tag**	**Vis**	**PAM**	**HC**	**GA**	**3D**	**Pop**
2002	R/V *Gyre*	S-tag	06/20/2002 - 07/08/2002		X	X	X	X	X		X
2002	R/V *Gyre*	D-tag	08/19/2002 - 09/15/2002	X		X	X	X	X	X	
2002	M/V *Rylan T*	CEE with *Gyre*	08/29/2002 - 09/12/2002	X		x	X				
2003	R/V *Gyre*	Habitat survey	05/31/2003 - 06/21/2003			X	X	X	X		X
2003	R/V *Maurice Ewing*	D-tag	06/03/2003 - 06/24/2003	X		X	X	x	X	x	
2003	M/V *Kondor Explorer*	CEE with *Ewing*	06/07/2003 - 06/22/2003	X		x	x			x	
2003	M/V *Kondor Explorer*	EARS buoy*	06/22/2003 - 06/25/2003								
2003	R/V *Gyre*	S-tag	06/26/2003 - 07/14/2003		X	X	X	X	X		
2004	R/V *Gyre*	S-tag	05/24/2004 - 06/19/2004		X	X	X	X	X	X	
2004	*Summer Breeze*	MPS**	06/20/2004 - 08/15/2004			X	X	x	X		X

* EARS is not part of SWSS, but is a sister program supported by MMS and IRFC
**MPS denotes the Mesoscale Population Study
D-tag: Digital sound-recording tag deployments and CEE data collection
S-tag: Satellite-tracked radio tag deployments
Vis: Visual observations of sperm whales and, opportunistically, other marine mammals
PAM: Passive acoustic monitoring for sperm whales
HC: Habitat characterization data on currents, temperature, salinity, and/or chlorophyll
GA: Genetic analyses of skin samples collected
3D: 3-D passive acoustic tracking
Pop: collection of sperm whale population and behavior data and fluke photographs

In 2004, two cruises were conducted. The S-tag cruise included S-tag deployments from R/V *Gyre* with a full complement of habitat characterization data, skin sampling, and visual and acoustic observations, and a full 3-D passive acoustic tracking study. The second cruise consisted of use of a quiet vessel, the 46' Hunter sailboat *Summer Breeze*, to study sperm whales using classical techniques. Scientists studied the social behavior of sperm whale groups as they followed as series of group for 1-3 days each. In addition to photographs, photogrammetry, passive acoustic recordings, and visual data, continuous near-surface temperature and CTD profiles were collected on this cruise. See the Appendix for details.

2.4 Report Organization

Section 1 is a Synopsis that summarizes the report. Preliminary summaries of the habitat characterization, mesoscale population study, genetic analyses and typing, satellite-monitored radio tag, digital acoustic recording tag and controlled exposure experiments work are presented in Sections 3 through 7. Section 8 gives a comparison between sperm whale locations and seismic survey lines, and Section 9 presents a discussion of the 3-D passive acoustic tracking study. References are provided in Section 10.

Figure 2.1. R/V *Gyre* and the MMS R2 tag boat at sea during the 2003 S-tag cruise. The R2 was one of four small boats used during the S-tag, D-tag/CEE, and WSHC cruises to approach sperm whales for photo-identification, photogrammetry, and/or tagging.

3 HABITAT CHARACTERIZATION

Section 3 describes sperm whale habitat in the northern Gulf of Mexico by summarizing our coordinated ship and satellite characterization of oceanographic circulation regimes in which sperm whales were encountered, as well as mid-water trawling for the potential prey of these whales. On- and off-margin flows along the 1000-m isobath in relation to where sperm whales were encountered in summers 2002, 2003, and 2004, are summarized in Section 3.1. Results of trawling in summer 2003 for zooplankton and micronekton are presented in Section 3.2.

3.1 Summertime Circulation and Sperm Whale Encounters Along the Middle Continental Slope of the Northern Gulf of Mexico, 2002-2004

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Abstract
Considerable summer-to-summer variability in the intensity and geographic location of Loop Current eddies, warm slope eddies, and areas of cyclonic circulation was documented in summers 2002-2004 over the middle continental slope, centered around the 1000-m isobath, of the northern Gulf of Mexico. These variations resulted in striking year-to-year differences in the locations where there was on-margin and off-margin flow and in locations where sperm whales were encountered along the 1000-m isobath. In summers 2002 and 2003, most sperm whales were encountered in regions of negative SSH and/or higher-than-average surface chlorophyll. However, in summer 2004, only a few of the whale encounters were in regions of negative SSH and/or higher-than-average surface chlorophyll. In addition to summer-to-summer variability, when local oceanographic conditions changed during the course of a single summer, encounter rates with whales also changed. In early summer 2003, sperm whales were rarely seen or heard in Mississippi Canyon when there was on-margin flow there that effectively "flushed" the canyon with low chlorophyll, Caribbean water originating from a Loop Current eddy seaward of but in close proximity to the Canyon region. In contrast, later that same summer when this Loop Current eddy had rebounded to move farther seaward from the continental margin, as well as during the summers when flow was along-margin or off-margin in the Mississippi Canyon region, we again encountered sperm whales in the Canyon region.

Introduction
Prior to SWSS, a number of ship and aircraft surveys for marine mammals were carried out in different seasons in the Gulf of Mexico under the sponsorship of several federal agencies. The GulfCet fieldwork of the 1990s and follow-on SWAMP fieldwork of 2000-2001 fostered partnerships among MMS, NOAA, USGS, and academic scientists. These surveys showed that, in the northern Gulf of Mexico, sperm whales (*Physeter macrocephalus*) were most frequently

encountered over the middle continental slope in water depths of 800-1200 m (Davis et al. 2002; Mullin and Fulling 2004). The Gulf of Mexico sperm whales, however, did not appear to be randomly distributed along the 1000-m isobath, either in space or through time. Instead, sperm whale distribution and abundance in the Gulf of Mexico appeared to be patchy (aggregated) and sensitive to oceanographic processes that couple time-space variations between the continental margin and the deep ocean (Biggs et al. 2000).

Local variability in these oceanographic processes likely alters the distribution and abundance of potential food for the prey on which the Gulf of Mexico whales are presumed to feed (Wormuth et al. 2000). Although we really know surprisingly little about what Gulf of Mexico sperm whales actually eat, we hypothesize that the prey on which sperm whales forage is sustained by food ultimately derived from surface waters, and that this deep prey field is non-randomly distributed in time and space. We also think that since sperm whales are predators at the apex of the oceanic food chain, they presumably have evolved to locate and exploit local aggregations of their prey.

To begin to characterize sperm whale habitat, we also make the tacit assumption that nutrient-phytoplankton-zooplankton (NPZ) biological relationships will be fundamental to sperm whale habitat use. NPZ theory predicts that variations in plankton stocks should in turn drive variations in the number and kinds of NPZ predators (i.e., the "big fish eat little fish eat plankton" approach). Sperm whales are thought to feed on squid and/or fish, and the basic paradigm is that such prey likely will be locally more abundant in areas when and where there is more food on which these potential prey can feed. We examined the sperm whale encounters during three different summers 2002, 2003, and 2004 in the light of this paradigm. Specifically we examined how encounters correlate with eddy-forced variations in off-margin flow of plant plankton chlorophyll; this phytoplankton is at the base of the oceanic food chain. As a general rule, this plant plankton chlorophyll is more abundant in surface waters of the continental shelf than over the slope and rise, so where there is green water flow off shelf, there will be net import of phytoplankton food to the pelagic communities of the middle slope. As a corollary, oligotrophic "ocean desert" conditions should prevail in surface waters when and where there is on-margin blue water flow. As we will show, there were substantial summer-to-summer differences in the locations along the 1000-m isobath where there was on-margin and off-margin flow, and there were similar summer-to-summer differences in where sperm whales were encountered.

The Loop Current is a main driving force for circulation in the deepwater Gulf of Mexico. This current enters the semi-enclosed Gulf basin through the Yucatan Channel, turns anticyclonically (clockwise), and exits through the Straits of Florida. This energetic current episodically sheds large warm-core anticyclonic eddies that are clockwise circulating and approximately 200-400 km in diameter. Northward intrusions of the Loop Current into the Gulf of Mexico, along with the characteristics of the large anticyclonic eddies that separate during these northward intrusions, have been studied since in the 1980s by a combination of ship surveys, TOPEX and ERS altimetry, and numerous ARGOS-tracked drifter studies (e.g., Elliott 1982; Berger et al. 1996; Biggs et al. 1996; Hamilton et al. 1999; Leben et al. 2002). The Gulf of Mexico is a dynamic body of water in which one or more Loop Current eddies (LCEs) are often present. One distinguishing characteristic of Loop Current and LCE waters is the presence of the Subtropical

Underwater, which is a water mass that has a subsurface salinity maximum of more than 36.5 in the upper 250 m of the water column.

When LCEs interact with the continental margin, they may spin down, shed filaments to form smaller-scale, anticyclonically-rotating warm slope eddies, or shed counter-rotating cold slope eddies. Along or near the 1000-m isobath, the surface currents created by such counter-rotating eddy geometries may intensify or can temporarily reverse what is otherwise a typical middle slope climatological pattern. As they interact with the continental margin, the anticyclones can spin up cyclones. The cyclones can be distinguished from the anticyclones by measuring the depth of their 15°C isotherm. In cyclones, this isotherm domes upward and nutrient-rich mid-depth water is uplifted close to the surface. This nutrient-rich water has been shown to increase primary productivity in the mixed layer and to support increased zooplankton and micronekton biomass, making the interiors of cyclones biological "oases". In contrast, surface water downwells in anticyclones, so the interior regions are nutrient-poor biological "deserts".

The continental margin waters of the northern Gulf of Mexico are a region in which there is close coupling of biological and physical variability (Wiseman and Sturges 1999; Biggs and Ressler 2001; Morey et al. 2003). Satellite ocean color data show this region undergoes seasonal changes which generally elevate by two-fold or so the phytoplankton biomass in November-February (Muller-Karger et al. 1991; Melo-Gonzalez et al. 2000; Hu et al. 2003). The Northeastern Gulf of Mexico-Chemical Oceanography and Hydrography Study (NEGOM study) which conducted nine survey cruises between November 1997 and August 2000 over the continental margin in the northeastern Gulf of Mexico, described the seasonal changes in the general circulation (Jochens et al. 2002). These cruises also documented the spatial and temporal variability of phytoplankton biomass there, based on pigment analysis (Qian et al. 2003). The NEGOM study documented unexpectedly high chlorophyll concentrations over the outer shelf and slope during summertime, particularly over the region east of the Mississippi River Delta to DeSoto Canyon. These concentrations were attributed to the entrainment of low-salinity, high-chlorophyll water from the shelf and its transport off-margin by off-shelf eddies located adjacent to the shelf break (Belabbassi et al. 2006; Hu et al. 2003; Fletcher 2004).

Although new biological production within the high velocity, high shear periphery of deepwater eddies may also result in locally high chlorophyll stocks (Biggs and Ressler 2001), the most important forcing function for patches of high chlorophyll over the outer continental shelf and upper and middle slope seems to be the periodic presence of anticyclonic slope eddies (Belabbassi 2001). Especially when these slope eddies were centered south and east of the Mississippi River Delta, they entrained and so redistributed low salinity green water to a wider area within the NEGOM region than could be predicted by mean monthly stream flow alone (Fletcher 2004). The mean surface chlorophyll concentrations, and in particular the distribution of relatively high surface chlorophyll concentrations offshelf, were strongly dependent upon entrainment of freshwater by these slope eddies, especially during the three NEGOM summer cruises. Interannual variability in the summertime entrainment of low salinity green water was driven by summer-to-summer differences in sea surface height of the slope eddy(s), and in how far they extended on-margin (Morey et al. 2003).

Methods

Both *in situ* observations and remote sensing fields were used to characterize the habitat in which the sperm whales were and were not found in 2002-2004. *In situ* observations were made from the science vessel, R/V *Gyre*, during five SWSS cruises. Table 3.1.1 summarizes the cruises conducted in summers 2000-2004 and the range of longitudes covered by each cruise. Sippican T7 and DeepBlue expendable bathythermographs (XBTs) were used to collect temperature data to a depth of 760 m at 40-90 stations on each cruise (Table 3.1.1). A SeaBird SeaCat conductivity-temperature-depth profiler (CTD) was used to collect temperature and salinity data to a depth of approximately 1000 m at 5-8 stations per cruise. These XBT and CTD data provided information on the depth of the 15°C isotherm used to identify cyclonic and anticyclonic eddy structures. Near-surface water was pumped from the ship's hull depth of 3.5 m through SeaBird temperature and salinity sensors and a Turner Designs Model 10 fluorometer to log surface temperature, salinity, and chlorophyll fluorescence at 1-min intervals. These data provided information on the presence or absence of low-salinity, biologically productive surface waters that might fuel the food web leading to sperm whale prey abundance. Horizontal current velocity was measured with both a 153-kHz RD Instruments (RDI) narrowband acoustic Doppler current profiler (ADCP) that was mounted through the hull in a moon-pool midships, and a 38-kHz RDI phased array ADCP that was mounted in a sea chest about 15 m aft of the moon-pool. Currents were measured to approximately 200-m depth from the 153-kHz ADCP and to 800-1000 m from the 38-kHz ADCP. These data were used to evaluate the type and energy of the eddy field. All *in situ* data were processed using standard oceanographic techniques (for details see Biggs et al. 2005; see also Jochens and Biggs 2003, 2004).

Table 3.1.1

Areas Along the Middle Slope That Were Surveyed in Summers 2002-2004

Ship and Cruise	**Begin Fieldwork**	**End Fieldwork**	**Longitude Range**	**CTDs**	**XBTs**
Gyre 02G06 SWSS 2002 Leg 1	20 Jun 2002	8 Jul 2002	94.7°W to 86.4°W	5	54
Gyre 02G11 SWSS 2002 Leg 2	19 Aug 2002	15 Sep 2002	focus on region 89.7°W to 87.4°W	8	39
Gyre 03G06 SWSS 2003 Leg 1	31 May 2003	20 Jun 2003	94.8°W to 86.8°W	8	89
Gyre 03G07 SWSS 2003 Leg 2	26 Jun 2003	13 Jul 2003	focus on region 89.5°W to 87.2°W	5	51
Gyre 04G05 SWSS 2004 S-tag	25 May 2004	18 Jun 2004	93.5°W to 86.5°W	5	70

In creating this synopsis of summer-to-summer changes in on-margin and off-margin circulation, we merged hydrographic data collected from the research ship with remotely sensed sea surface height (SSH) mapped by satellite altimeters and with ocean color mapped by the SeaWiFS satellite sensor. These satellite fields were used to identify eddy fields (SSH) and regions of high or low biological productivity (ocean color) and to provide a time series of these conditions. Using the combination of remotely-sensed altimetry and ocean color was especially important in this study to identify oceanographic features during summer, since during the six month period from May through October when surface waters become uniformly warm in the Gulf of Mexico, sea surface temperature loses most of its contrast and therefore its ability to detect frontal features. For this synopsis, we examine only SeaWiFS images and SSH fields that were concurrent with sperm whale sightings.

The Colorado Center for Astrodynamics provided the near real-time SSH maps derived from sampling by altimeter missions that showed the location of the Loop Current, LCEs, and other mesoscale circulation features in the Gulf of Mexico. The SSH fields generally have a 100-km decorrelation length scale and are temporally averaged over a 10-day period. Leben et al. (2002) describe the operational altimeter data processing for this mesoscale monitoring. Because water flows downhill and the rotation of the earth's axis deflects flows to the right in the northern hemisphere, the SSH field shows the currents at the sea surface; these are called geostrophic currents. Highs in SSH have currents flowing clockwise (anticyclonically) while lows have counterclockwise (cyclonic) currents. The greater the gradient of SSH, the stronger the currents.

SeaWiFS data are captured in real-time using ground-based tracking antennae at the University of South Florida. They are processed with algorithms that relate ocean color to near-surface chlorophyll concentrations (e.g., Gordon and Wang 1994; O'Reilly et al. 2000; Hooker and Firestone 2003). The SeaWiFS imagery shows the surface phytoplankton abundance to one optical depth, which corresponds to a depth of 30-50 m in clear water and shallower in more turbid water (McClain et al. 1998). This ocean color imagery provides a means to effectively trace water circulation and oceanographic fronts (Hu et al. 2004a; Hu et al. 2004b). Although they inherently have 1-km spatial resolution, the SeaWiFS data had to be composited for a 7-day period to minimize the incidence of missing data due to clouds. [Note: SeaWiFS data are the property of Orbimage Corporation and data use here is in accordance with the SeaWiFS Research Data Use Terms and Conditions Agreement of the SeaWiFS project.]

This synopsis uses the observations on the presence or absence of sperm whales that were made in the region of the research vessel during the five SWSS cruises. Visual and passive acoustic surveys were used to collect these observations. The methods for these surveys are summarized in other sections of this report (e.g., Section 6.1), as well as in Jochens and Biggs (2003, 2004). In brief, marine mammal researchers searched during daylight hours with BigEye telescopic binoculars and listened at night as well as during daytime hours with towed hydrophone arrays.

Results

Correlations of sperm whale encounters with oceanic conditions: To quantitatively evaluate if whale encounters were more frequent in regions of shelf water entrainment, we did a simple spatial statistical analysis to compare the average remotely-sensed SSH and ocean color at locations where whales were encountered with the ensemble average conditions along the 1000-

m isobath. The results are presented in Table 3.1.2. For each of the five ship surveys that are summarized in Table 3.1.1, we computed the average SSH and SeaWiFS chlorophyll concentration along the 1000-m isobath between 91°-86°W for one-week periods at the mid-points in time of each of the field surveys. To compute the mean SSH from daily raw data that are gridded with 1/4 degree x 1/4 degree resolution, we selected for each of the surveys the 36 SSH grid points closest to the 1000-m isobath between 91°-86°W and averaged these (n = 36 x 7 days = 252). The SeaWiFS raw data have much higher (1 km) spatial resolution but they are one-week composites. We picked 121 locations that were about 5 km apart along the 1000-m isobath between 91°-86°W for the calculation of mean along-isobath chlorophyll from the ocean color. For each of the surveys, the number of data points averaged to determine the mean chlorophyll concentration along the 1000-m isobath in Table 3.1.2 ranged from n = 121 when the 1000-m isobath was cloud-free to n = 92 when clouds were present in the composites and obscured some of the 1000-m isobath. The number of data points averaged to summarize conditions where whales were encountered ranged from n = 194 (SWSS 2003, Leg 2) to n = 412 (SWSS 2002, Leg 2). The implications of these results are discussed for each year below.

Table 3.1.2

Comparison of Mean SSH and SeaWiFS Chlorophyll at Locations Where Whales Were Encountered With Ensemble Conditions Along the 1000-m Isobath Between 91°-86°W (See text for explanation of how means were computed. Means highlighted in bold face indicate conditions where whale encounters were significantly different at the 95% confidence level than the ensemble conditions along the 1000-m isobath, i.e., means were different by more than 1.96 times the standard error. CHL denotes SeaWiFS chlorophyll concentrations in mg/L.)

		whales	**whales**	**1000-m**	**1000-m**	**whales**	**whales**	**1000-m**	**1000-m**
Year	Julian Days	Mean SSH	SSH std error	Mean SSH	SSH std error	Mean CHL	CHL std error	Mean CHL	CHL std error
2002	162-168	**-5.81**	0.31	-2.70	0.19	**2.88**	0.26	0.60	0.15
2002	253-259	**-2.59**	0.32	0.47	0.16	**1.41**	0.07	0.41	0.06
2003	155-161	**-14.35**	0.72	-9.49	0.61	**2.15**	0.20	0.37	0.14
2003	190-196	**-19.27**	0.49	-10.67	0.42	0.17	0.03	0.32	0.05
2004	154-160	**-0.9**	0.32	-4.1	0.29	0.33	0.03	0.32	0.04

Summer 2002: The SSH fields show that during the first four months of 2002 there was a temporally persistent although spatially variable region of negative-to-positive sea surface height anomaly with a gradient of increasing SSH from north to south (from shelf to slope) over most of the north central Gulf of Mexico. The region of negative SSH usually included the 800-m to 1000-m isobaths. The doming of nutrient-rich mid-water close to the surface favored enhanced planktonic new production along this continental margin as evidenced by the ocean color imagery. In March, the Loop Current shed a Loop Current Eddy (LCE). In April, this LCE shed a warm filament that extended north into the DeSoto Canyon. By May 2002, this warm filament had consolidated into a warm slope eddy (WSE), the inshore edge of which reached the Mississippi Canyon region south of the Mississippi River Delta (Figure 3.1.1). SeaWiFS ocean color imagery shows that the anticyclonic circulation around this WSE pulled green water offshore into the eastern part of the study area, and that by late May to early June, this off-margin flow was best developed east of 88°W (see Jochens and Biggs 2004). By mid-June, west to east flow was established along most of the 1000-m isobath, but with off margin flow west of 94°W and east of 88°W. Between early July and mid August the large-scale anticyclonic circulation in deepwater south of 27°N broke up into several much smaller anticyclonic eddies (compare SSH fields in the upper and lower panels of Figure 3.1.2). By mid-August, these minor eddies were distributed along much of the continental margin of the north central Gulf. The remote sensing fields show that a pair of WSEs south of Mississippi Canyon and in DeSoto Canyon were entraining green water from the shelf and transporting it off margin (Figure 3.1.3, lower panel).

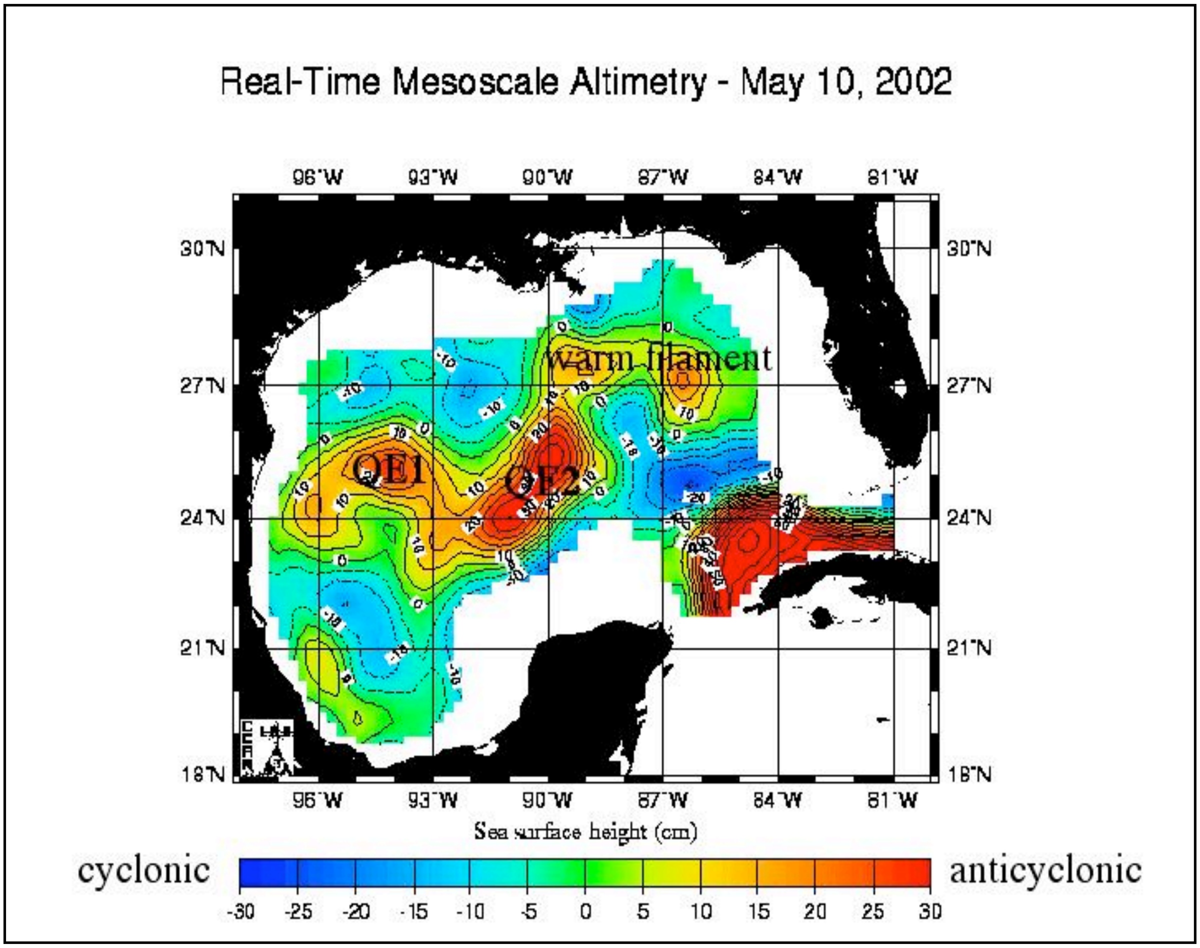

Figure 3.1.1. SSH field for 10 May 2002. This field illustrates the warm filament extending on margin from the northern periphery of Loop Current Eddy QE2.

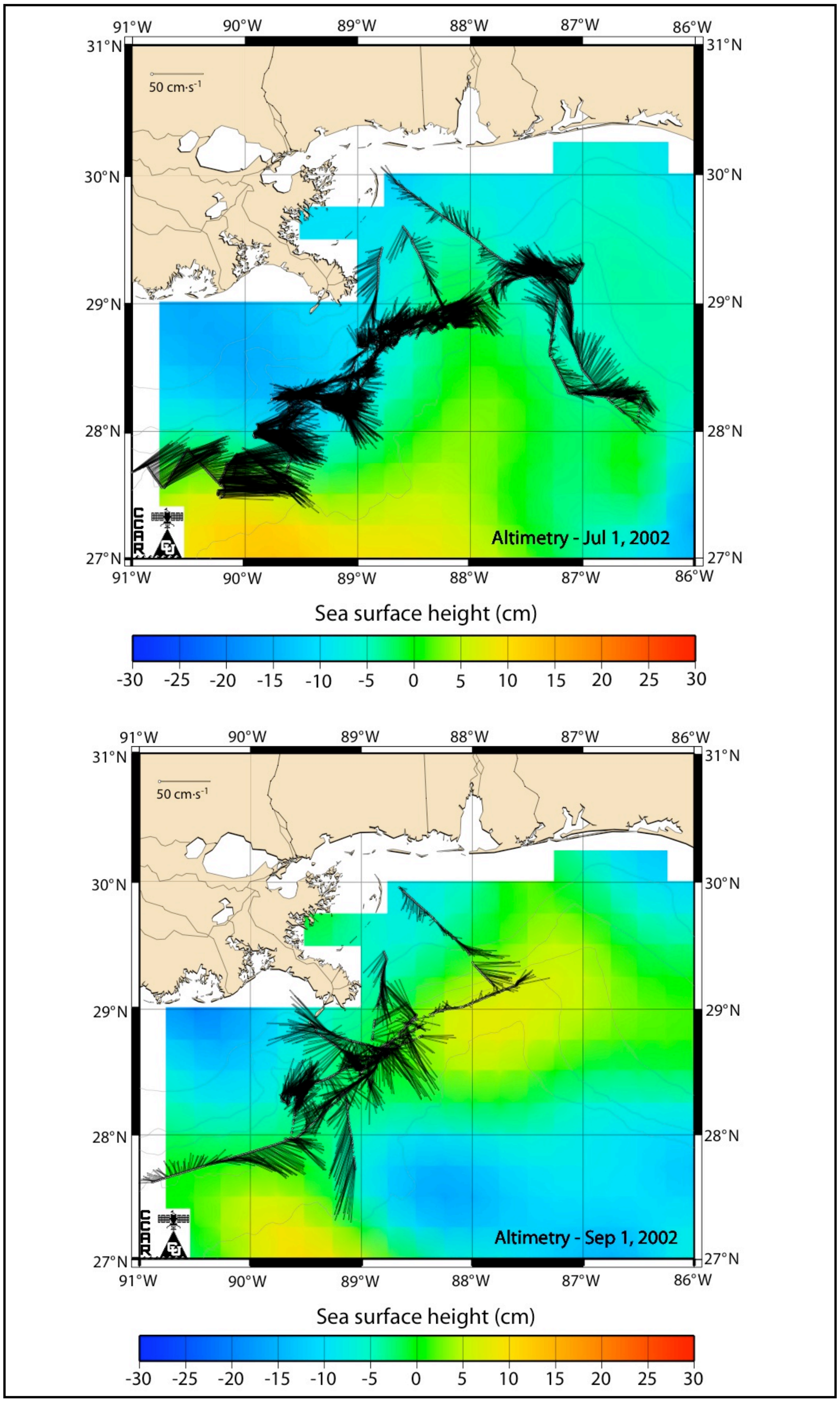

Figure 3.1.2. Current velocity and SSH anomaly in summer 2002. Current velocities, determined from 153-kHz ADCP data collected during Leg 1 of SWSS 2002 (upper) and Leg 2 of SWSS 2002 (lower), are overlaid on SSH anomaly maps for a mid-points in time of each leg. Currents shown are from the 12-m depth.

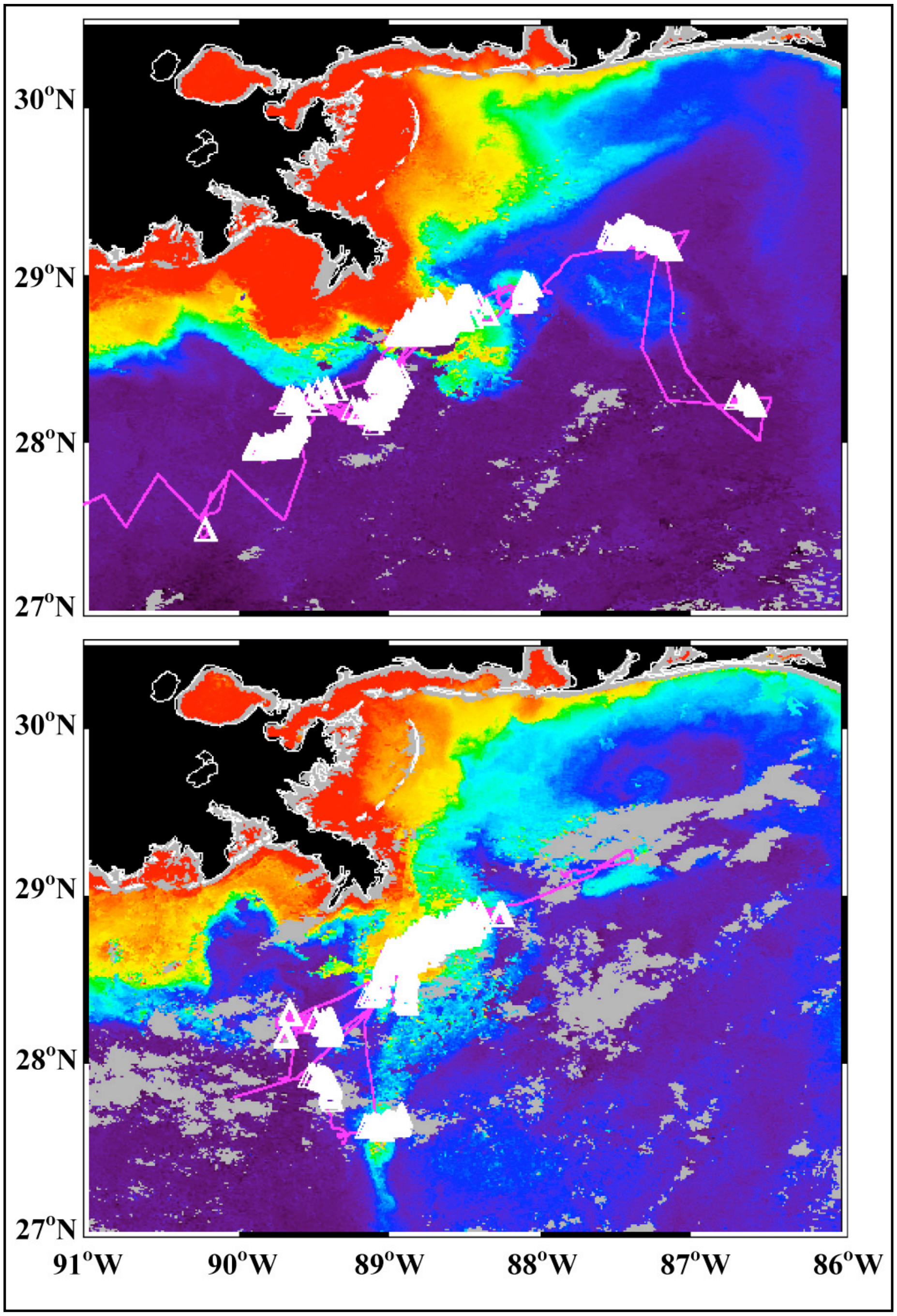

Figure 3.1.3. Sperm whale locations and SeaWiFS composites in summer 2002. Shown are locations where sperm whales were encountered during SWSS 2002 Leg 1 (upper) and Leg 2 (lower), overlaid on SeaWiFS 7-day composites centered on 14 June 2002 and 13 September 2002, respectively.

During the 2002 Leg 1 SWSS survey, much of the surface water along the middle slope was high salinity blue water. The ADCP record shows the currents flowed mostly west to east along-margin, or southwest to northeast on-margin (Figure 3.1.2, upper panel), in agreement with the geostrophic flows indicated by the contours of SSH height. East of 91°W along the 1000-m isobath these currents had a mean speed of about 0.3 m s^{-1} and ran directly onto or along most of the mid-slope, tracking anticyclonically around the northern edge of the WSE seen in the SSH field between 91-89°W.

Although the Leg 1 survey did not extend far enough south to reach the center of the WSE, the 15°C depths were documented by XBTs to be more than 270 m at the southernmost region of the track, downslope from the 1000-m isobath. The 15°C depths of greater than 250 m confirm that the ship penetrated into the northern edge of the WSE. Two CTD casts done along this edge had high surface salinity exceeding 36 but no subsurface salinity greater than 36.5 to indicate the presence of Subtropical Underwater (Figure 3.1.4a).

Off-margin flow was encountered locally near 89°W, along the eastern edge of this WSE (Figure 3.1.2, upper panel). A CTD done here showed surface salinity of 26.5, which is indicative of riverine water influence, and the water color here was green-brown instead of blue, which is indicative of shelf water being transported off shelf. East of 88°W there was some off-margin flow as well, as the current over the middle slope moved anticyclonically along the northern and then down the eastern edge of another WSE that was centered in the deepwater of DeSoto Canyon. Surface salinity from a CTD done in this region was 34.4, but as was the case for the CTDs done in the other WSE to the west, there was no subsurface salinity greater than 36.5 to indicate the presence of Subtropical Underwater (Figure 3.1.4a).

During Leg 1 of SWSS 2002, sperm whales were encountered over several areas of the middle slope that were searched between 91°W and 87°W. The average SeaWiFS chlorophyll concentration where whales were encountered was 2.9 µg/L (Table 3.1.2), but the relatively large standard error of the measurement is a consequence of the fact that SeaWiFS chlorophyll concentrations ranged from 0.1 µg/L to 5.0 µg/L, and in fact numerically more whales were seen in blue water than in green water environments (Figure 3.1.3, upper panel). In contrast, more of the sperm whales encountered during Leg 2 were in green water environments (Figure 3.1.3 lower panel). During Leg 2, when the average SeaWiFS chlorophyll concentration at locations where whales were seen was 1.4 µg/L, which still looked very green to observers aboard ship, most of the encounters were in surface water with about double the ensemble average for SeaWiFS chlorophyll concentrations along the 1000-m isobath.

The SeaWiFS weekly composite for the week of 13 September (Figure 3.1.3, lower panel) indicates that the confluence zone between the small-size and low-SSH anticyclone south of Mississippi Canyon and the small cyclone to the east was entraining green water from the shelf and transporting this off-margin. Entrainment of green water from along-margin to off-margin can also be seen near 29°N, 88°W, along the north side of the small-size and low-SSH anticyclone located near the head of DeSoto Canyon. Because the SWSS 2002 Leg 2 survey was mainly focused within the longitude range 89.7°W to 88.5°W, the Leg 2 ADCP data document that flow was mostly off-margin here (Figure 3.1.2, lower panel).

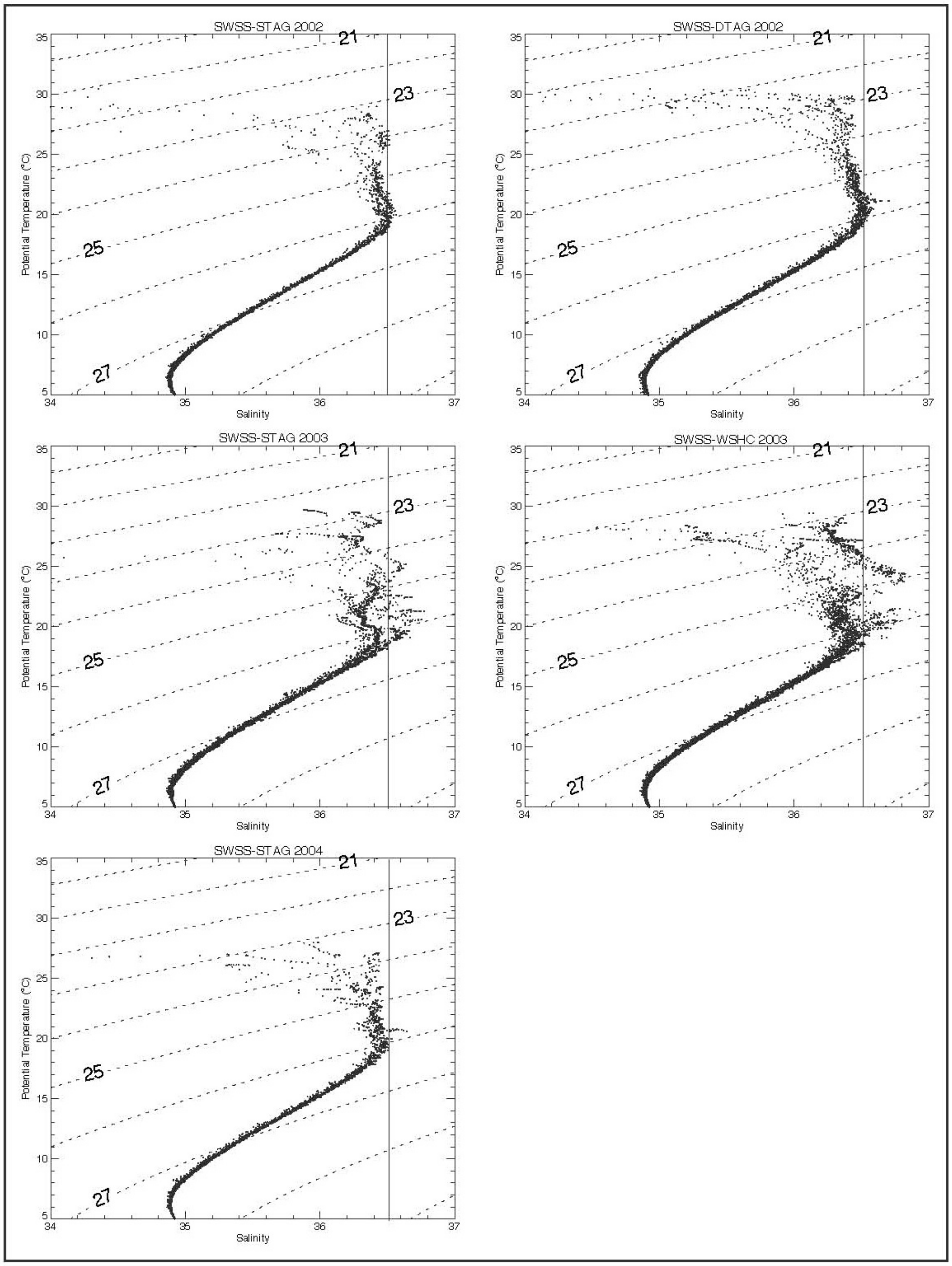

Figure 3.1.4. Temperature-salinity diagrams for SWSS cruises in 2002-2004. Shown are plots from CTD stations done during a) S-tag 2002 (SWSS 2002 Leg 1), b) D-tag 2002 (SWSS 2002 Leg 2), c) S-tag 2003 (SWSS 2003 Leg 2), d) WSHC 2003 (SWSS 2003 Leg 1), and e) S-tag 2004. Isopycnal lines present density as sigma-theta (kg·m^{-3}). The range of salinities shown is limited to 34-37 to better show the presence or absence of Subtropical Underwater (> 36.5) that is characteristic of Loop Current water.

Summer 2003: During the first four months of 2003, as in January-April 2002, circulation was generally cyclonic along the 1000-m isobath in the northeastern Gulf, including Mississippi Canyon and DeSoto Canyon. The Loop Current surged north of 27°N during this four-month period. In late February 2003 it appeared as if a Loop Current Eddy would separate. But separation did not occur until early May. This separation produced a large and energetic LCE, named "Eddy Sargassum" (Figure 3.1.5). SeaWiFS imagery confirms the mid-May 2003 separation. A 7-day composite for 18-24 May shows high-chlorophyll green water being drawn off margin near 86°W and entrained south to about 26°N and then west of about 90°W in the high-velocity periphery of LCE Sargassum (see Jochens and Biggs 2004).

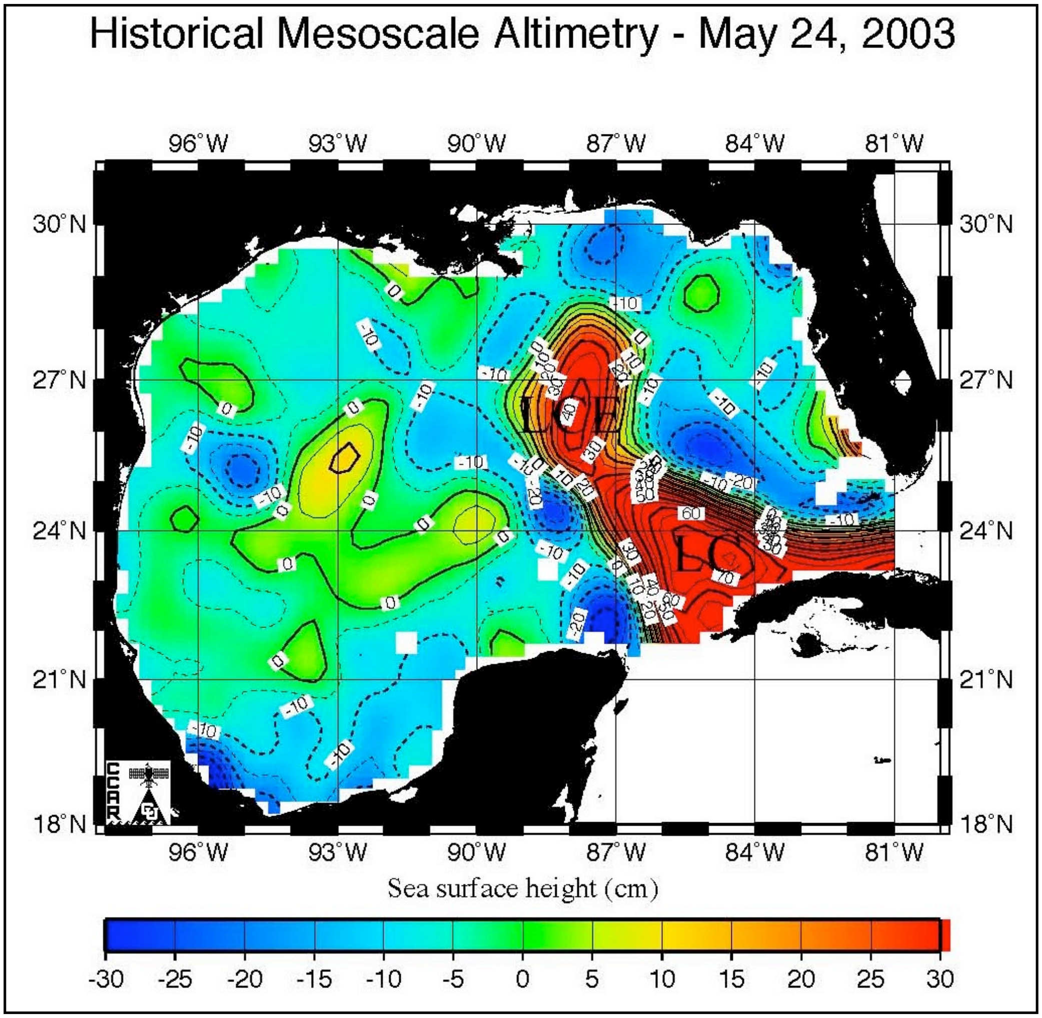

Figure 3.1.5. SSH field for 24 May 2003. This field illustrates the separation of Loop Current Eddy Sargassum (LCE) from the Loop Current (LC). Surface currents flow in a clockwise direction around the LCE.

After separation from the Loop Current, Eddy Sargassum pushed northward on-margin and dominated the circulation along the middle slope throughout the summer of 2003. The long axis, which initially was oriented N-S (Figure 3.1.5), rotated clockwise so that by the middle of June, during the SWSS 2003 cruise Leg 1, the long axis was oriented W-E and its northern periphery extended almost to the shelf-slope break (Figure 3.1.6, upper panel). This configuration resulted in the transport of nutrient-poor, low-productivity waters of Caribbean origin onto the middle slope and Mississippi Canyon.

While currents measured by the ADCPs were generally quiescent west of 91°W, to the east strong currents were encountered on the outer northern limb of this incoming LCE. Mean surface currents along the middle slope from 90.5°W to 88.5°W exceeded 40 cm s^{-1} and although these decreased with depth, the mean currents exceeded 5 cm s^{-1} as deep as 800 m. Maximum surface currents exceeded 120 cm s^{-1}, and decreased to 50 cm s^{-1} at 300 m and 30 cm s^{-1} at 800 m. These energetic currents at surface and depth are in contrast to the case during 2002 Leg 1 when no LCE was pushing on-margin. In 2002, the mean vertical profile of current speed showed speed decreasing with depth from ~30 cm s^{-1} at the surface to 10 cm s^{-1} at 200 m. The maximum speed profile during the Leg 1 SWSS 2002 cruise had also decreased with depth, from 70 cm s^{-1} at the surface to 40 cm s^{-1} at 200 m. Moreover, current speeds during Leg 2 of SWSS 2002 in September had even lower averages. Mean speeds ranged from 20 cm s^{-1} at the surface to 10 cm s^{-1} at 200 m; maximum speeds ranged from 60 cm s^{-1} at surface to 30 cm s^{-1} at 200 m.

A CTD done at 28.4°N, 88.9°W on 11 June 2003 confirmed the presence of Subtropical Underwater (salinity > 36.7) in the upper 200 m (Figure 3.1.4d). This CTD along with the XBTs dropped 9-11 June and again 17-20 June 2003 showed the 15°C depth along the northern margin of LCE Sargassum was deeper than 250 m. These measurements, plus XBTs dropped in mid-June 2003 from a second research vessel (R/V *Ewing*), confirm the on-margin nature of flow in the Mississippi Canyon area between 91°W and 89°W and indicate this canyon was full of Caribbean water that had advected north with the Loop Current.

A comparison of SeaWiFS weekly composites from June 2002 and June 2003 shows that more area was impacted by green water entrained and carried east in summer 2003 than summer 2002 (compare the top panels of Figures 3.1.3 and 3.1.7). This is visual evidence that although WSEs over the middle slope can entrain shelf water and move it along-margin or off-margin, the magnitude of the entrainment and the distance that green water is transported off-margin is not as great as when a full-blown LCE is interacting with the middle slope region. A similar comparison (see Figure 4.6.21 in Jochens and Biggs 2004) contrasts the SeaWiFS monthly composite image for April 2003 (before LCE separation) with June 2003 (LCE close off-margin), to show that maximum entrainment occurred only when LCE Sargassum was close off-margin.

Sperm whales were not encountered in the Mississippi Canyon area between 89.2-90.3°W where and when LCE Sargassum was interacting with the 1000-m isobath (Figure 3.1.7, upper panel). Rather, groups of whales were found west of 90.3°W and east of 89.2°W, where 15°C depths and the SSH maps indicate these areas were outside the core of Eddy Sargassum.

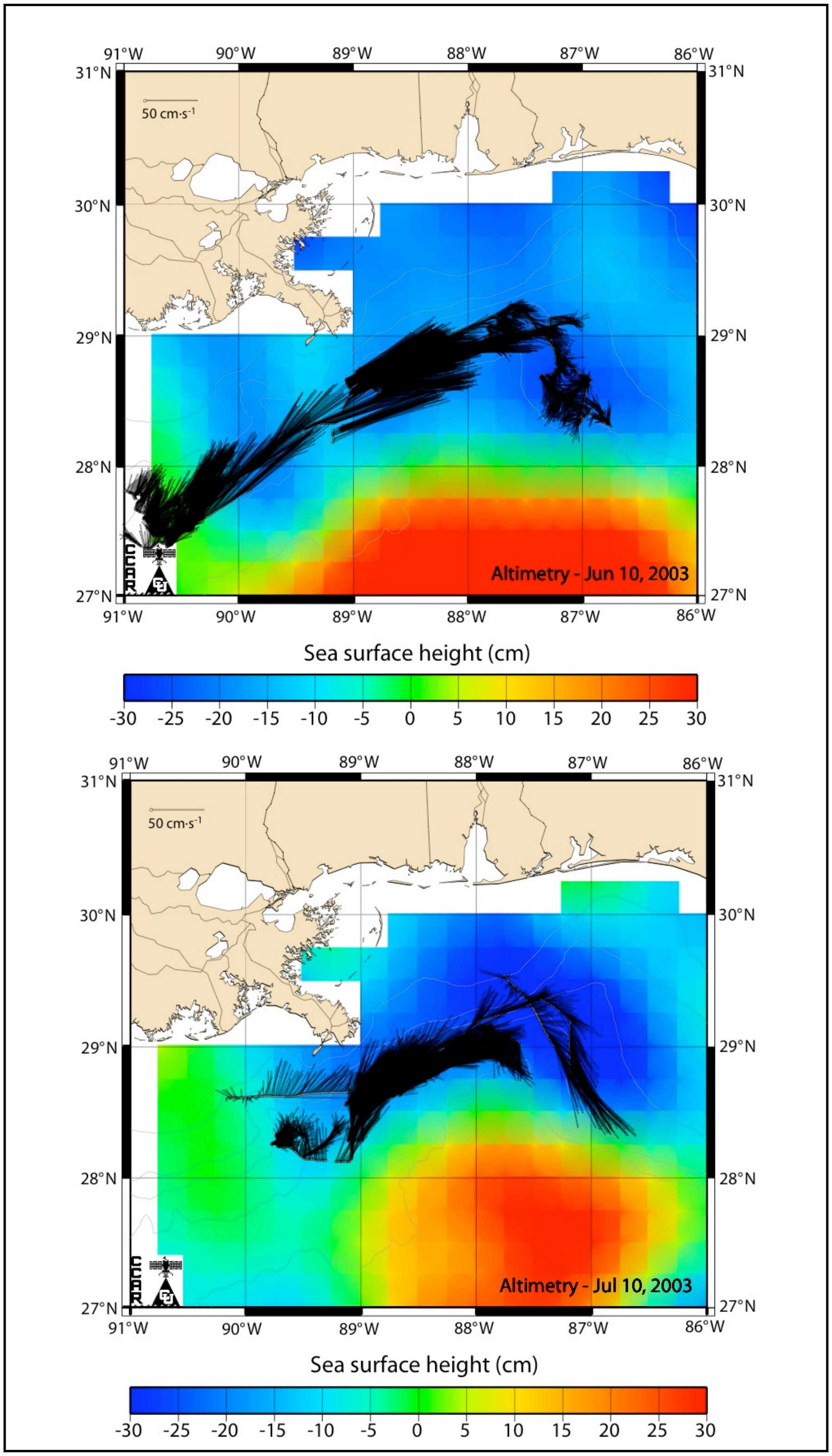

Figure 3.1.6. Current velocity and SSH anomaly in summer 2003. Current velocities, determined from 38-kHz ADCP data collected during a) Leg 1 of SWSS 2003 and b) Leg 2 of SWSS 2003, are overlaid on SSH anomaly maps for the mid-points in time of each leg. Currents shown are from the 41-m depth.

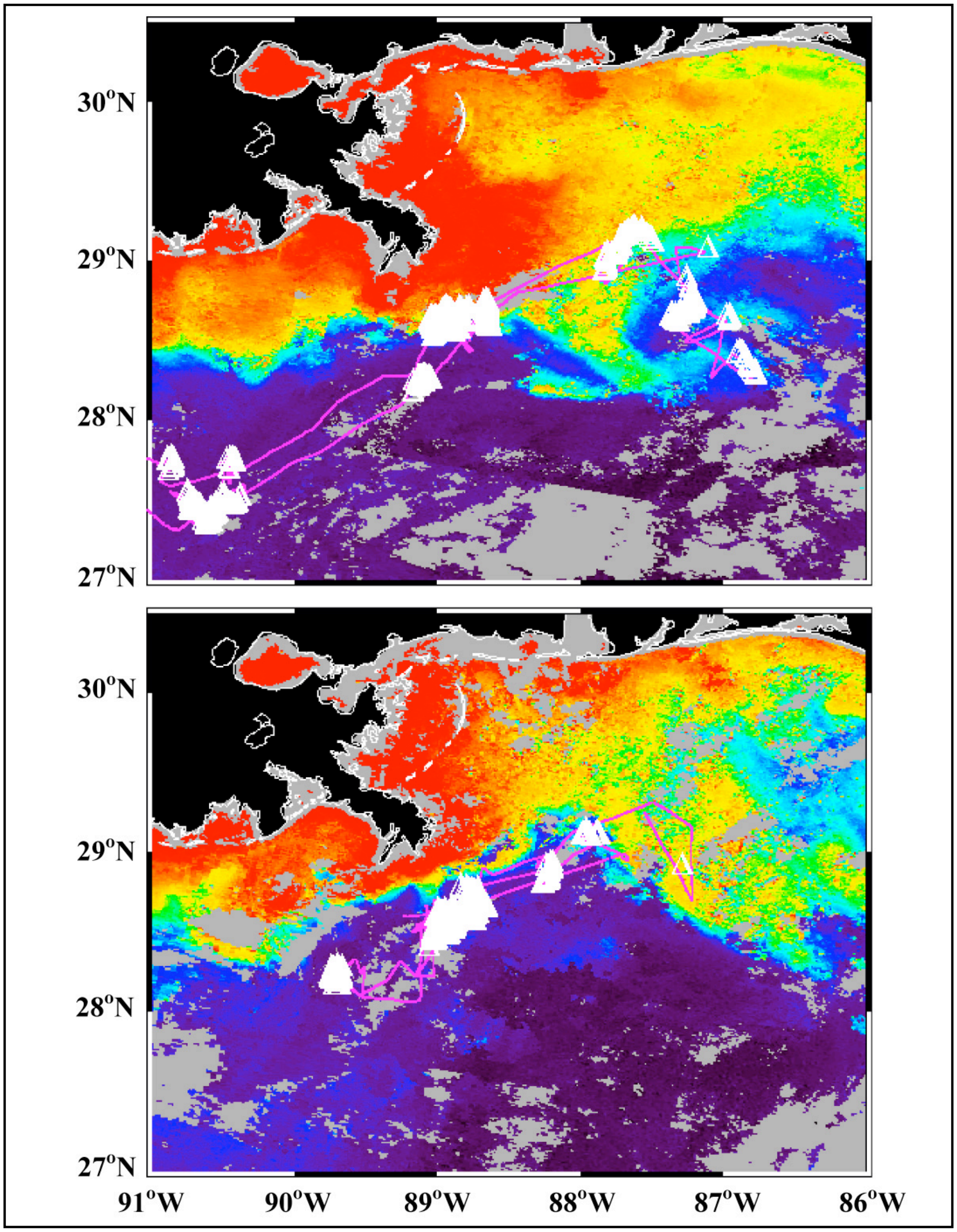

Figure 3.1.7. Sperm whale locations and SeaWiFS composites in summer 2003. Shown are locations where sperm whales were encountered during SWSS 2003 Leg 1 (upper) and Leg 2 (lower), overlaid on SeaWiFS 7-day composites centered on 7 June 2003 and 12 July 2003, respectively.

There was a very sharp surface front at the northern periphery of Eddy Sargassum. On the morning of 16 June 2003, we documented a sharp boundary between low-chlorophyll, blue water and higher-chlorophyll, green water near 28.9°N, 88.3°W. From 16 to 18 June 2003, *Gyre* followed numerous groups of sperm whales in the green water northeast of this front. Table 3.1.2 shows the average SeaWiFS chlorophyll concentration where whales were encountered was 2.1 µg/L, compared to the ensemble average of 0.4 µg/L for the whole of the 1000-m isobath. Only two sightings of whales were made inside the blue water front marking the northern periphery of the LCE between 88°W and 90°W. This was not unexpected, since the GulfCet 2 program also found sperm whales to be uncommon in the interior of LCEs (Biggs et al. 2000; Davis et al. 2002).

During the two weeks that passed between the time the Mississippi Canyon region was surveyed by *Gyre* during Leg 1 and Leg 2 of SWSS 2003, the SSH fields show that LCE Sargassum had rotated clockwise about its major axis and moved away from (rebounded seaward from) the 1000-m isobath (Figure 3.1.6, lower panel). In confirmation of this change in geometry, CTDs taken on Leg 2 show little evidence for Subtropical Underwater (Figure 3.1.4c), and 15°C depths from XBTs dropped on Leg 2 were < 255 m. Cyclonic hydrographic conditions were the norm all along the 1000-m isobath east of 90°W by mid-July 2003. During Leg 2 several groups of sperm whales were encountered in the Mississippi Canyon area near 89.8°W, as well as along the middle slope to the northeast (Figure 3.1.7, lower panel). The average SSH anomaly 91°-86°W where whales were encountered on Leg 2 was -19 cm (Table 3.1.2), and in fact no whales were seen in environments with SSH greater than -7 cm even though some areas along the 1000-m isobath 91°-86°W had SSH anomalies up to +11 cm.

The remote sensing fields, 15°C depth, and ADCP current velocity ship data from summer 2003 indicate that the large, energetic LCE Sargassum displaced the upper hundreds of meters or so of usual water in the Mississippi Canyon area with low-nutrient, low-chlorophyll "ocean desert" water of Caribbean origin, when it interacted with the 1000-m isobath in early June 2003. We hypothesize that sperm whales usually seen in this area (i.e., summers 2000-2002) moved west and/or east out of this area during the time this LCE reached farthest north along the margin (early June through late June 2003). Whales were in greater abundance in summer 2003 west of 90°W and east 89°W than in the Mississippi Canyon region 90°W-89°W where the LCE attained its closest approach to the middle slope. We presume the whales left when their deep-living prey was also displaced by this bolus of northward-moving Caribbean water. Return to normal conditions of hydrography and likely of prey appears to have occurred after this LCE moved back (rebounded) into deeper water, since by early July 2003 the 15°C depth had returned to normal in the region 90°W -89°W, and whales were again encountered in Mississippi Canyon.

Summer 2004: In early May 2004, about 3 weeks before R/V *Gyre* sailed from Galveston to begin the S-tag cruise, the Loop Current was extended northward to about 27°N (Figure 3.1.8). Along the 1000-m isobath, an anticyclonic slope eddy just south of the Mississippi River delta and a cyclonic eddy to the east, over the deep water of DeSoto Canyon, acted as counter-rotating gears to entrain shelf water and move this green water off-margin. A 10-day time-series, showing 7-day composite SeaWiFS chlorophyll concentrations every 3 days in early May, graphically illustrates this green water entrainment and its transport off-margin (Figure 3.1.9).

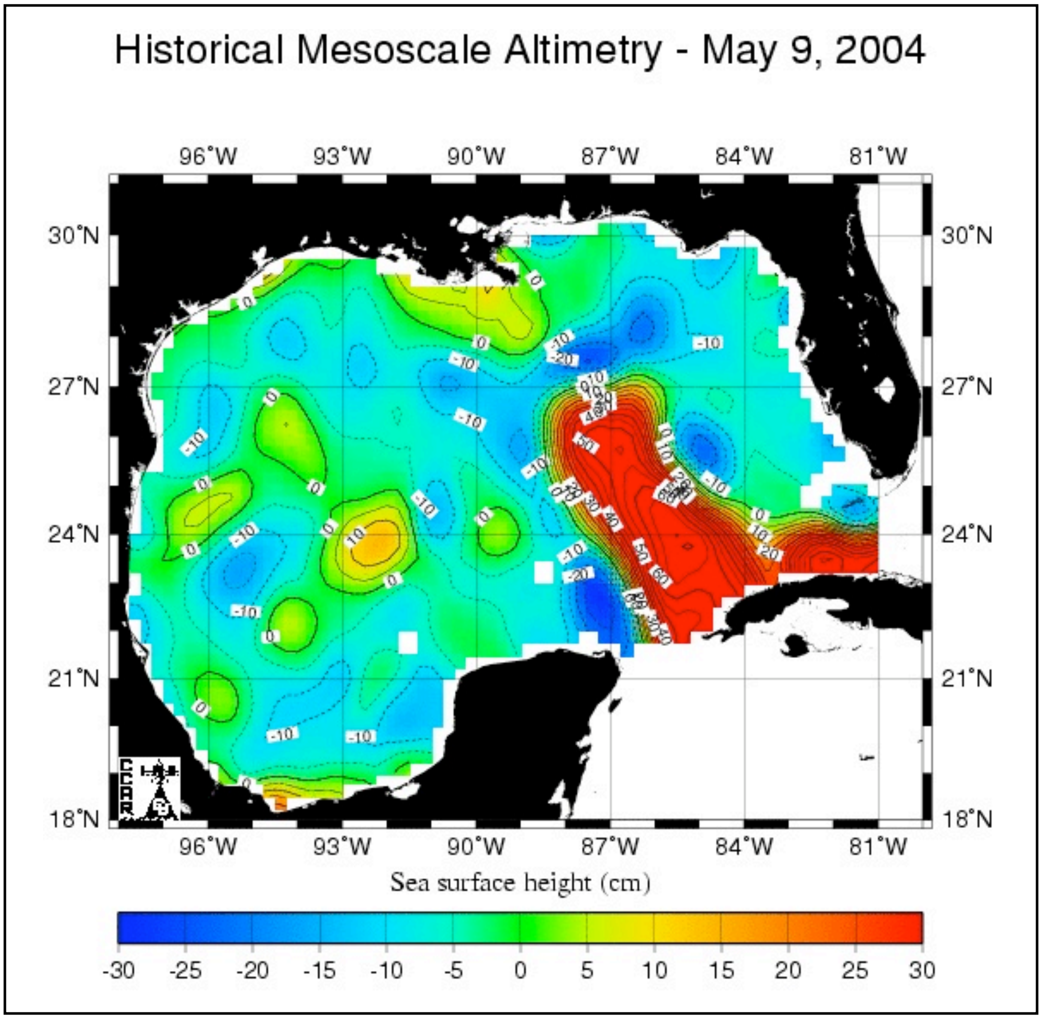

Figure 3.1.8. SSH field for 9 May 2004. This field illustrates a northward extension of the Loop Current with anticyclonic eddy off the Mississippi River Delta and cyclonic eddy in DeSoto Canyon.

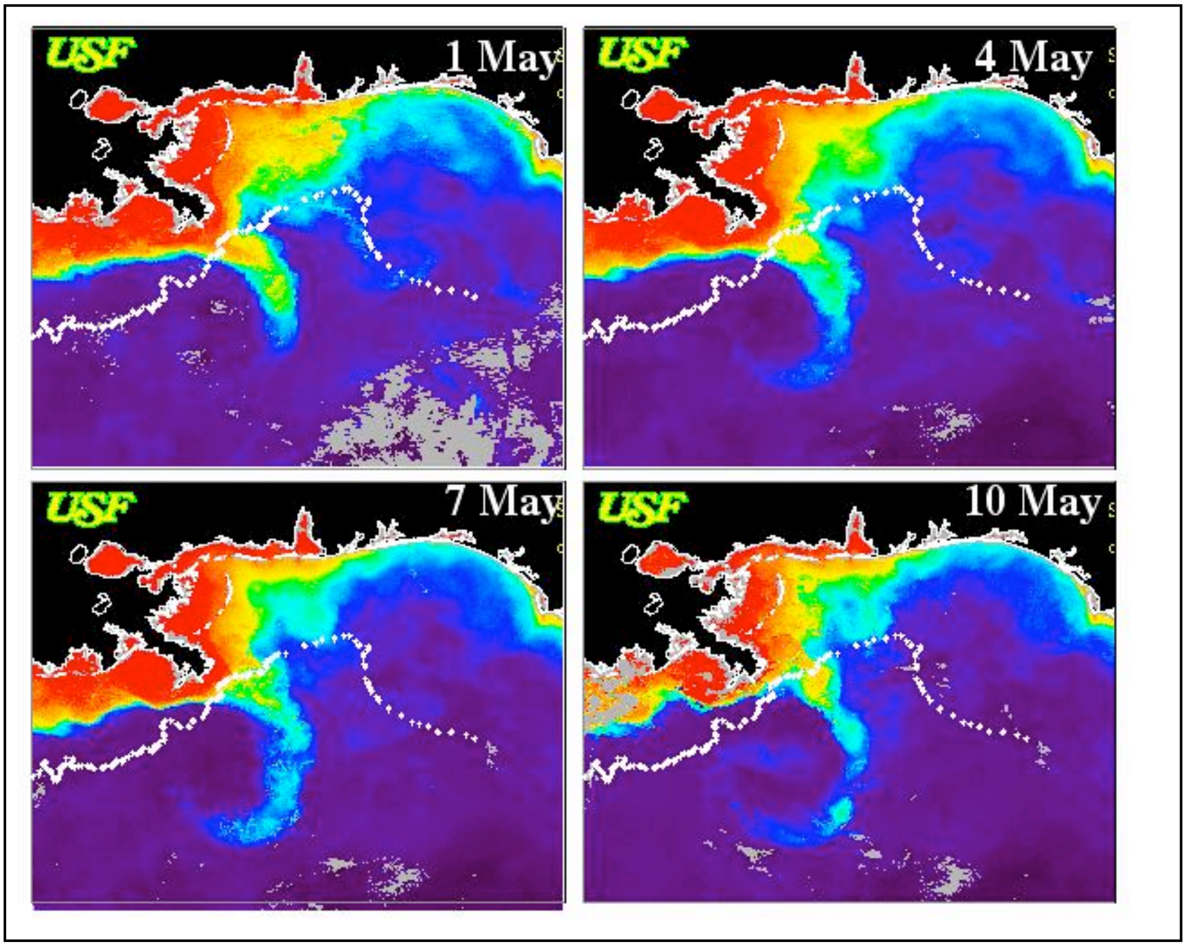

Figure 3.1.9. Off-margin transport of high-chlorophyll Mississippi River water in early May 2004. Dashed line shows location of 200 m isobath.

In early June 2004, at the approximate mid-point in time of the S-tag cruise, the altimetry data continued to show the anticyclone-cyclone slope eddy pair along the 1000-m isobath and the Loop Current to the south of 27°N (Figure 3.1.10). A zoom-in (Figure 3.1.11) shows that the sea surface height of the anticyclone was rather weak (less than +10 cm), although some interior regions of the cyclone to the east were lower than -15 cm. R/V *Gyre* surveyed mostly middle slope depths (800-1200 m) ranging in SSH from +3.5 cm to -20 cm. XBTs dropped between 91°W and 86°W documented the "warmer, deeper" nature of the upper 300 m of the anticyclonic slope eddy. Specifically, 15°C depths deepened to about 300 m between 91°-90°W and shoaled to less than 220 m in the cyclone to the east.

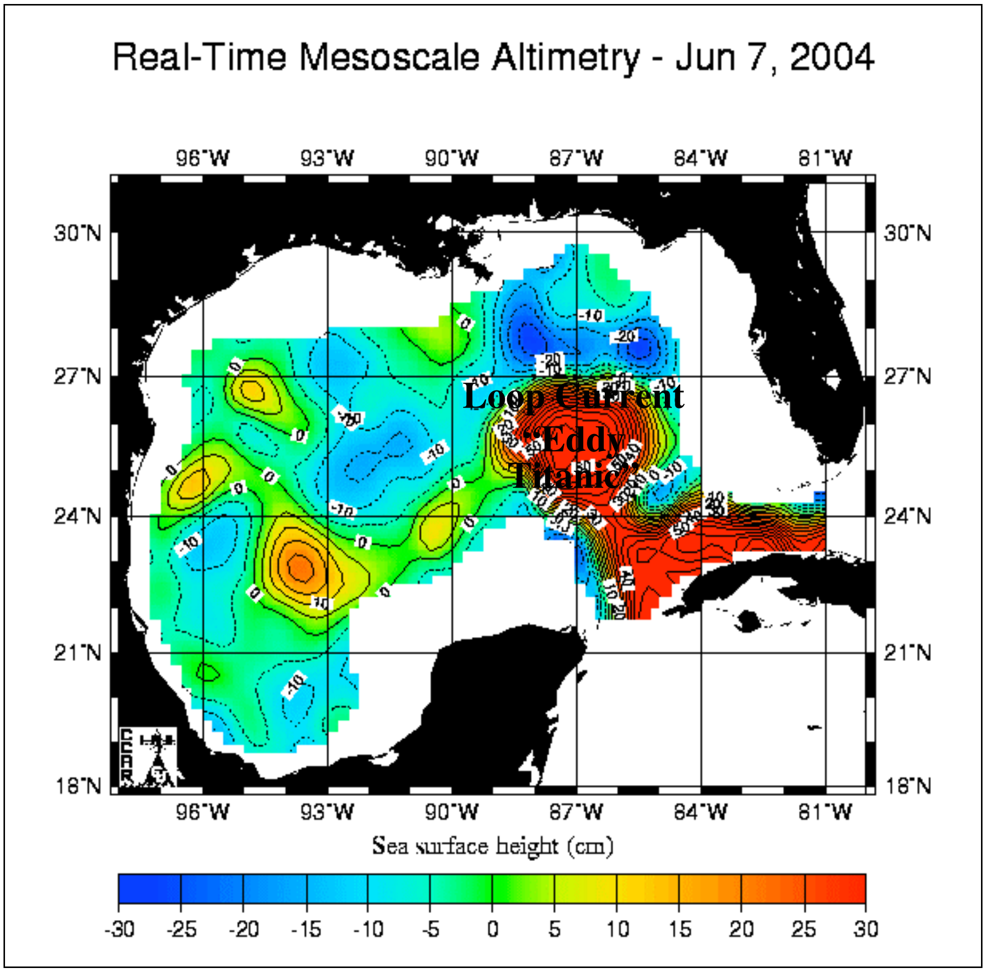

Figure 3.1.10. Basin-wide SSH anomaly map for the mid-point in time of the 2004 S-tag cruise.

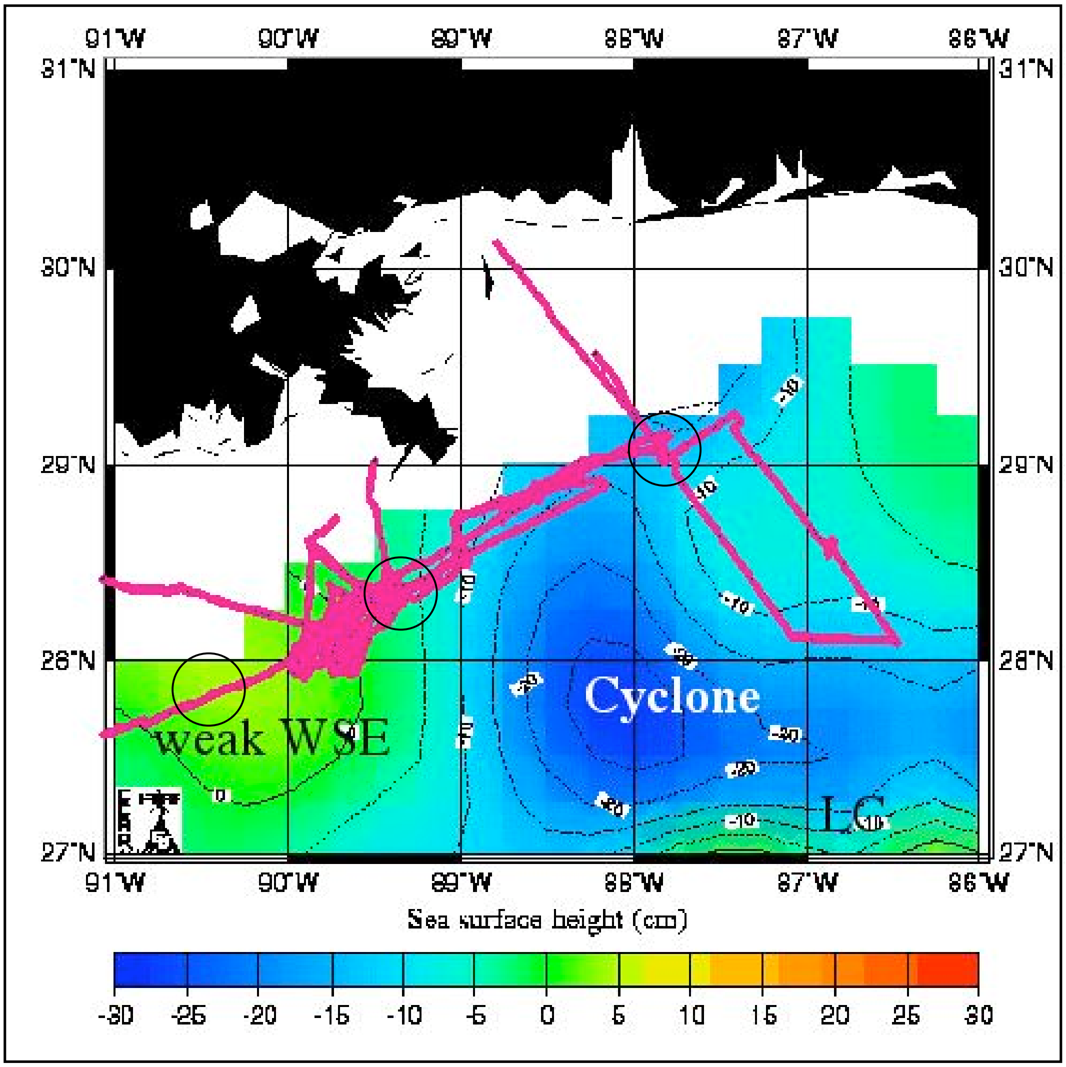

Figure 3.1.11. Zoom-in on SSH anomaly along the 1000-m isobath of the north central Gulf of Mexico, showing ship track along the 1000-m isobath for R/V *Gyre* S-tag cruise 04G05.

Three CTD casts done between 91°W and 86°W show little subsurface evidence for Subtropical Underwater (Figure 3.1.4e). Even though the anticyclonic slope eddy originated in the winter of 2004 as a warm filament that was shed as the Loop Current extended north, these summertime CTD casts are strong evidence that this filament was primarily a surface expression and did not entrain any substantial volume of Caribbean water.

The off-margin flow along the 1000-m isobath between 90°W and 88°W is seen in the ADCP data from the cruise (Figure 3.1.12). The waters being transported off the margin were low in salinity and high in chlorophyll, as documented by the near-surface continuous observations of salinity and chlorophyll (Figures 3.1.13 and 3.1.14). A Gulf-wide SeaWiFS composite image for the two-week period 3-16 June 2004 (Figure 3.1.15) confirms there was off-margin transport of green water between 90°-88°W. The ship track along the 1000-m isobath west of 90°W and east of 88°W was mostly in blue water, but the region 90°-88°W had locally higher surface chlorophyll concentration.

Property-property plots of continuous data (not shown) demonstrate that chlorophyll-salinity curves were generally linear west of 90°W and east of 88°W. This is indicative of conservative mixing of lower salinity, higher chlorophyll concentration shelf water with higher salinity, blue water along the 1000-m isobath. In contrast, in the region between 90°-88°W these property-property plots were non-conservative, with higher-than-expected chlorophyll concentrations in the salinity range 31-33 that are indicative of the new production of chlorophyll.

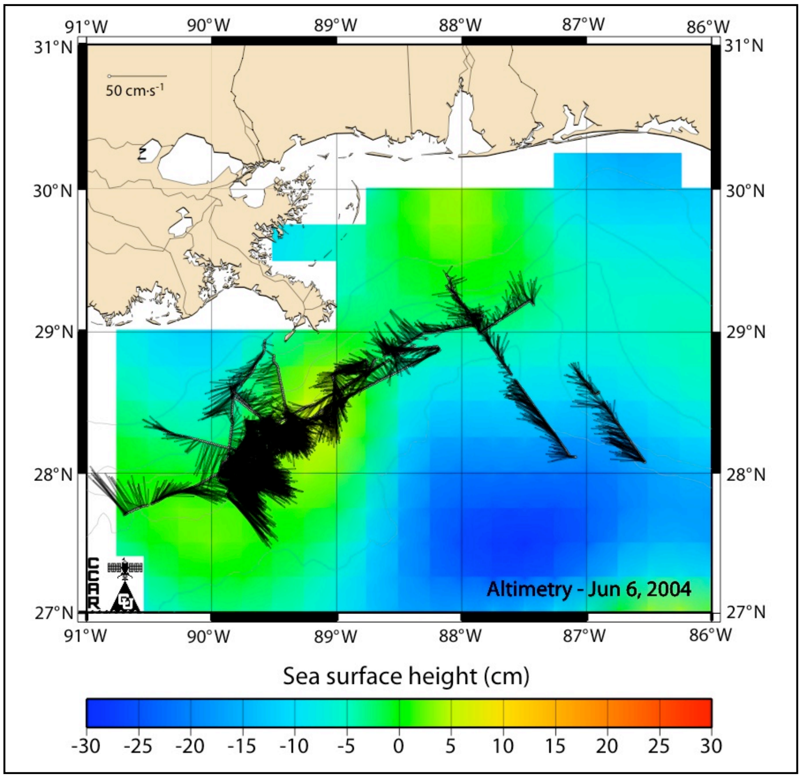

Figure 3.1.12. Current velocity and SSH anomaly in summer 2004. Current velocities, determined from the 38-kHz ADCP data collected during the SWSS 2004 S-tag cruise are overlaid on SSH anomaly map for 6 June 2004. Currents shown are from the 41-m depth.

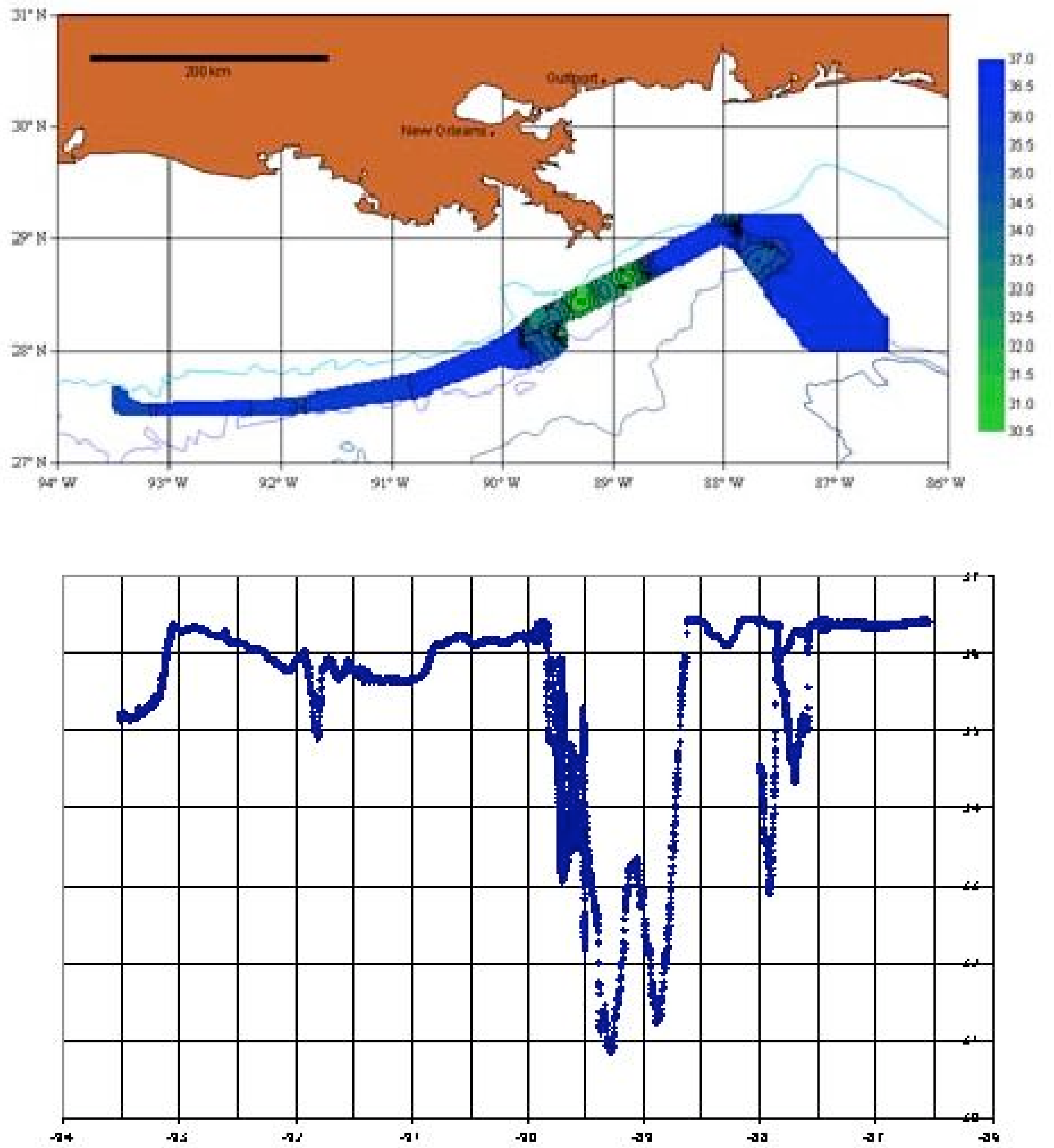

Figure 3.1.13. Off-margin transport of low-salinity Mississippi River water during the 2004 S-tag cruise in the region 90°W-88°W. See Figure 3.1.11 for the cruise track superimposed on the SSH field.

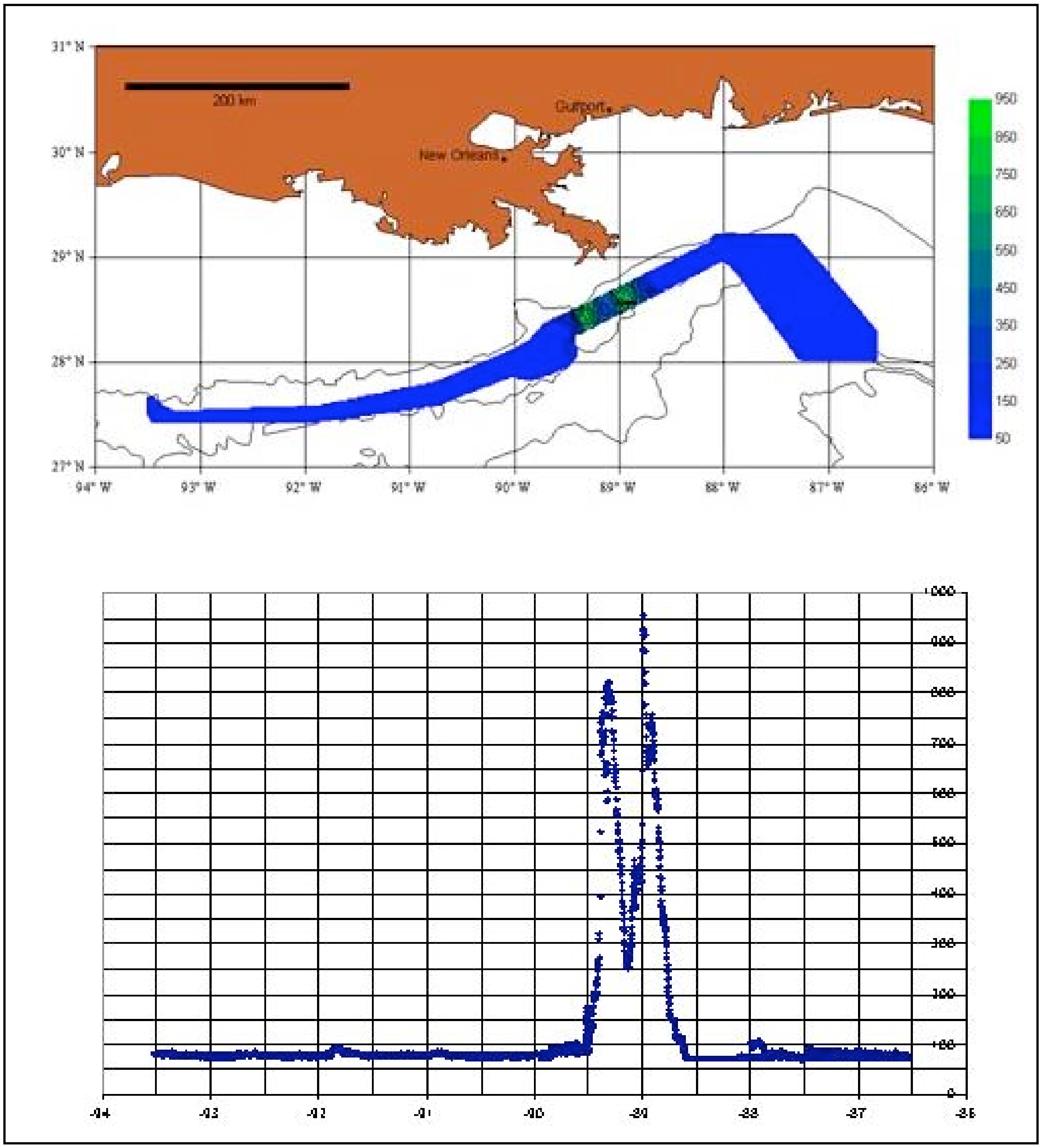

Figure 3.1.14. Off-margin transport of high-chlorophyll surface water during the 2004 S-tag cruise in the region 90°W-88°W. See Figure 3.1.11 for the cruise track superimposed on the SSH field.

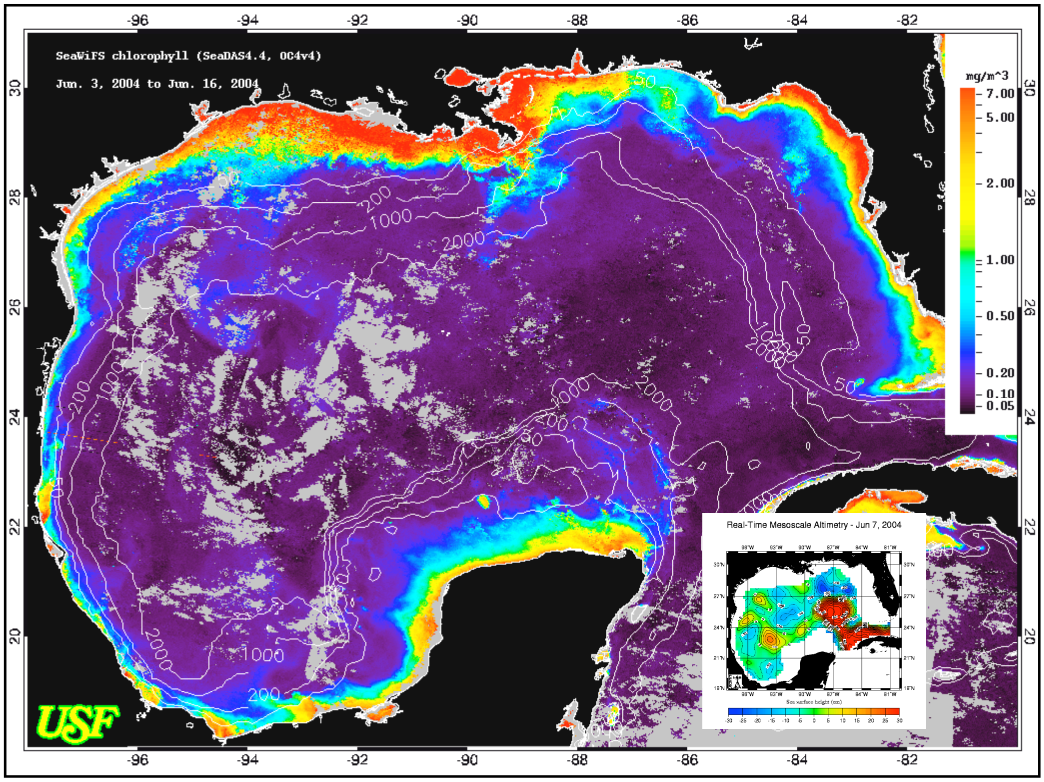

Figure 3.1.15. Basin-wide SeaWiFS composite for the mid-point in time of the 2004 S-tag cruise. Note the off-margin transport of high-chlorophyll water south and east of the Mississippi River Delta. The inset shows the SSH field.

About 3 dozen groups of sperm whales were encountered in 13 different geographic locations along the middle slope in May-June 2004. Figure 3.1.16 shows that most of these whales were seen in or near slightly greenish water, in or near the boundary zone between the weak WSE south of the Mississippi River delta, and the cyclone to the east. Chlorophyll concentrations where these groups of whales were encountered ranged from 0.1 to 0.8 µg/L, with a mean of 0.3 µg/L (Table 3.1.2). Because this was a transition zone from positive to negative SSH, mean SSH in this boundary zone was not significantly different from background (zero) SSH (Table 3.1.2).

The locations where most of the sperm whales were encountered ranged in SSH from +3 cm to -3 cm in the region of off-margin flow, to as low as -9 cm in the area of cyclonic circulation over DeSoto Canyon to the east. In sharp contrast to most of the sperm whale encounters in the previous summers of 2002-2003, only a few of the whale encounters were well inside the region of lower SSH that was representative of the interior of the cyclonic eddy (< -5 cm). Moreover, in summer 2004, most whales were encountered where surface chlorophyll was no higher than the 0.3 µg/L ensemble average along the 1000-m isobath, from 91°-86°W. Sperm whales were only rarely seen in the cyclone to the east of the region of off-margin flow at 90°W-88°W. This is in contrast to the sperm whale encounters from the SWAMP cruise in summer 2001 where an anticyclone-cyclone eddy pair was present along the 1000-m isotherm between 91°W and 86°W and sperm whales were encountered pretty much all along the 1000-m isobath, both in the region of off-margin flow as well as in the cyclone to the east (Biggs et al. 2005). This contrast is under investigation.

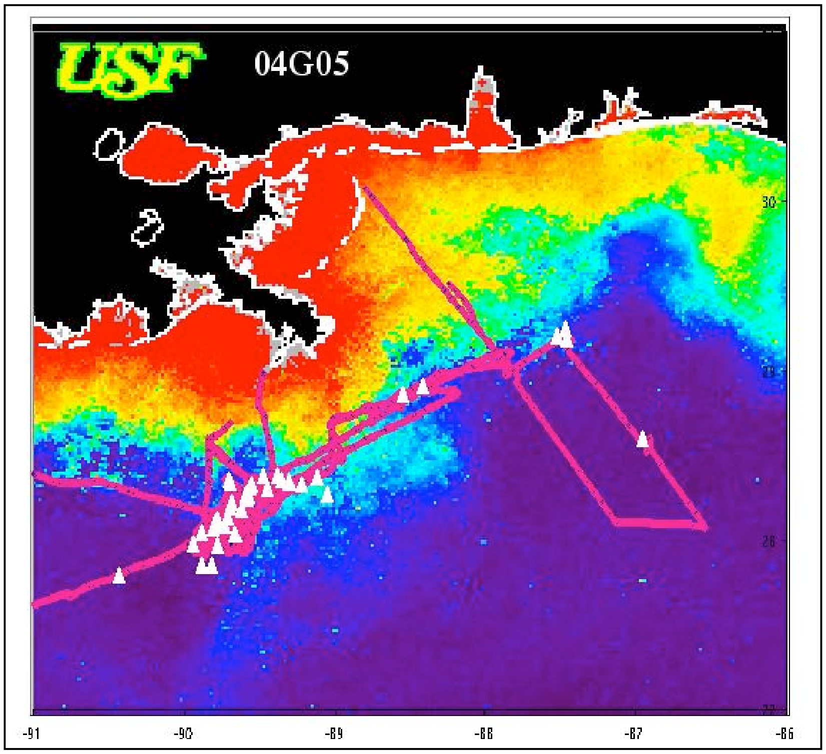

Figure 3.1.16. SeaWiFS composite imagery between 86°W and 91°W, showing the along-track locations of visual or acoustic encounters with sperm whales during the 2004 S-tag cruise.

Plankton stocks from ADCP Volume Backscatter Intensity: ADCP volume backscatter intensity (VBI) data can give indirect information about the spatial and temporal variability of plankton stocks in the Gulf of Mexico (Zimmerman and Biggs 1999; Biggs and Ressler 2001). VBI data from the SWSS 152-kHz ADCP are being analyzed to look for differences among the various hydrographic regimes that were present in summers 2002-2004 along the middle slope. In summers 2002 and 2003, areas of anticyclonic circulation had lower VBI than did areas of low (cyclonic) or near-background SSH anomaly (Kaltenberg 2004; see also Section 4.9 in Jochens and Biggs 2004). However, because sperm whales in the Gulf of Mexico dive to feed at depths generally greater than 600 m, the VBI in the upper 100-250 m that can be obtained from the 153-kHz ADCP is of limited value, at best.

Currently, the use of VBI from lower frequency ADCPs such as the 38-kHz phased-array is being investigated to see whether there is more or more variable VBI in 600-1000 m water depths along the middle slope, than there is in this same depth range over deeper water. Preliminary data (Kaltenberg 2004) indicate that this seems to be the case, although additional work is needed with a calibrated fisheries echosounder or other acoustic system with inherently higher temporal and vertical resolution than the 38-kHz ADCP; such data were taken during the SWSS 2005 S-tag cruise.

Discussion

Loop Current eddies and slope eddies contribute biological and physical heterogeneity along the continental margin of the northern Gulf of Mexico. Temporal and spatial variations in the geometry of the eddy field along the middle slope determine whether low salinity green water flows off-margin, or if high salinity blue water flows on-margin. The eddy fields from the three summers exhibit the interannual and monthly variability that occurs over the margin in the northern Gulf. The summers of 2002 and 2004 had cyclone-anticyclone eddy pairs over the slope, with the cyclone being the western member in 2002 and the eastern member in 2004. These slope eddies occur frequently in the region between Mississippi Canyon and DeSoto Canyon and are persistent. We hypothesize this system provides a mechanism for regular transport of low salinity, high chlorophyll shelf waters out over the slope that then supports a food web structure that provides prey for the squid or other species upon which sperm whales prey. The Loop Current Eddy event in summer of 2003 shows the rapid change in conditions that can occur when a large LCE encroaches over the middle slope. It can result in substantial transport of low chlorophyll onto the slope with possible consequences for the food web structure to which the sperm whales may respond. The encroachment of LCEs over the middle slope in the northeastern Gulf, however, is not a persistent feature as these eddies either move back to reattach to the Loop Current or transit westward into the western Gulf.

A dynamic eddy field that results in the advection of high chlorophyll shelf waters to the middle slope is one important factor in providing biological richness off the Mississippi River Delta. Locally high chlorophyll also can develop at the periphery of both cyclonic and anticyclonic eddies, when and where high velocity currents (>1 m s^{-1}) create vertical shear and thus upwelling of nutrients from midwater depths into the photic zone where they can be used by plankton to fuel growth. Moreover, locally high chlorophyll can develop when and where nutrient-rich water domes upward in cyclonic eddies. Thus cyclonic eddies and other nutrient-rich features that persist for 3-4 months may be important for development of feeding grounds for sperm whales along the Gulf of Mexico continental slope. Nutrient-poor LCEs, in contrast, appear to generate the opposite effect.

The three summers of SWSS fieldwork show that sperm whales were generally encountered in regions with negative SSH and/or higher-than-average surface chlorophyll (Table 3.1.2). Maximum and minimum data for each cruise (not shown) indicate the range of SSH along the 1000-m isobath from 91^{o}-86^{o}W went from +14 cm to -28 cm, but SSH in locations where whales were encountered never exceeded +6 cm. Most of the whales were encountered in locations on average 5 cm lower in SSH than the ensemble average for the 1000-m isobath (Table 3.1.2), and in summer 2003 some of the whales were found in strongly cyclonic locations for which SSH was less than -25 cm. However, in summer 2004, only a few whale encounters were well inside the region of lower SSH associated with a cyclonic eddy. The significance of these results to the concept that sperm whales may frequent regions with persistent cyclonic features will be examined further in future collaborations under the SWSS project, both in analysis of these data together with those from the Mesoscale Population Study cruises (see Section 4) and in analysis of remote sensing data with the S-tag location data (see Section 6).

Biggs et al. (2000) and Davis et al. (2002) reported data from the GulfCet program that suggested sperm whales may be locally abundant in deepwater cyclones, as well as in areas of negative SSH along the 1000 m isobath. None of the cruise tracks during the SWSS fieldwork 2002-2004 extended into deepwater cyclones located over the lower slope and rise. So it is unknown to what degree the groups of sperm whales we encountered in summers 2002-2004 may have extended seaward of the 1000-m isobath. As reported in Section 6, some of the sperm whales tagged with S-tags ventured out into deeper water. Future collaborative work will examine whether the whales that do make these excursions out into deep water may seek out cyclonic or other biologically productive areas of deepwater circulation.

3.2 Analysis of Midwater Trawl Samples from Cruise 03G06 - What the Animals Tell Us About Whale Feeding Areas

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Introduction

The proposed objectives of the midwater trawling program on R/V *Gyre* Cruise 03G06 in June 2003 were to sample (1) the potential prey fields at depths where sperm whales were actively diving to feed, (2) areas where whales were actively feeding, and (3) areas where whales were not observed to be feeding. We made 24 trawls with a 14.8 m^2 Isaacs-Kidd midwater trawl (IKMT) as *Gyre* surveyed the 800-1200 m depth interval from 94°W - 86°W. The IKMT had an inner liner mesh of 4 mm terminating in a 0.333 mm mesh plankton net. The fishing intervals chosen were 0-400 m, 0-400-600 m and 0-600-800 m. The two deeper intervals were selected to partition the feeding depths of whales recorded by our colleagues from WHOI for whales they outfitted with D-tags in the previous field year. At the time, no bottom topography was included in the dive profile, so it was decided to stay approximately 50 m above the bottom to avoid hitting the sea floor with possible resultant damage to the specimens collected and/or the trawl. In November 2003 after our cruise, additional information on dive profiles became available. From this information, it was clear that the whales were diving very close to the bottom, so not all the likely feeding depths were represented by the selected fishing intervals. Although the trawls in the two deeper intervals fished while passing through the 0-400 m interval, slightly more than half of their time fishing was in the targeted interval. The 0-400 m interval was chosen to look at those components the trawl would sample on its way down to and back up from the deeper intervals. Depth and temperature were recorded with a Sea Bird TDR Model 39. Volume filtered was measured with a General Oceanics flow meter.

IKMT operations were generally done at night following the day's completion of over-the-side operations. This limited our ability to sample in areas without whales, but reduced time lost to reacquiring whales prior to dawn. Wire was payed out at 50 m/min at a ship speed of 3 knots. When we estimated that we had reached the top of our targeted depth interval (based on regressions of previously collected data), we decreased the wire out speed to 30 m/min and increased ship speed to 5 knots. When we retrieved the wire and reached the top of the targeted interval, we increased retrieval of wire to 50 m/min and decreased ship speed to 3 knots. This procedure minimized the volume of water that was filtered in non-targeted depths. A total of 24 successful trawls were completed in cyclonic, anticyclonic and "other" environments. Samples were sorted into fish, crustaceans and cephalopods. Displacement volumes (DV) were measured for each component. Temperature profiles for each of the three categories were plotted and showed a high degree uniformity with each category.

Previous reports have discussed analyses of the DV values, fishing characteristics of the trawl and volumes filtered in the three depth intervals sampled (e.g., Jochens and Biggs 2004). This report discusses results from the taxonomic work completed through fall 2004. A total of 84 crustacean taxa, 29 cephalopod taxa, and 11 fish taxa have been identified and counted. Crustacean and cephalopod taxonomy is completed. Fish taxa are incomplete, mainly in the Myctophidae. In this family there are 53 species in 17 genera that occur in the Gulf of Mexico.

Although there are various other taxa of fish in these samples as well, occurrence of these other taxa is sporadic and so is unlikely to affect the analyses.

Results

The taxonomic data matrix is 123 taxa by 24 trawls. Correspondence analysis (CA) was selected as the statistical tool to handle such a large matrix (Greenacre 1993; Palmer 1993). Ordination techniques have evolved from Principal Component Analysis through Factor Analysis to CA. These analyses extract sources of variation in the data matrix that are uncorrelated with each other, that is, the axes are orthogonal to each other. The first axis extracted accounts for the largest amount of the overall variance. After that variance is removed, the second axis is extracted and accounts for the second largest source of variation. The calculations continue until most or all the variance is removed. In our analyses, the first three axes are considered. The main advantage of using CA is that the method of vector analysis allows both row and column categories to be plotted on the same set of eigenvalue axes. In Factor Analysis this cannot be done.

Seven different analyses have been summarized in Table 3.2.1; the first five are presented as figures. The tabled values are the proportion of the total variance in each data set that is accounted for by the first, second, and third eigenvalues. The values for the first two of these eigenvalues for each taxa and trawl are then plotted. The third eigenvalue explains less of the total variance and is not plotted. The first three eigenvalues can be used to plot in three dimensional space, but have not been plotted in this report. Figures 3.2.1 – 3.2.5 illustrate how visual inspection can sometimes be helpful in determining why a particular trawl, or subset of trawls, may differ from others.

The first analysis in Table 3.2.1 used all trawls except trawl number 4 which briefly hit the bottom. Because of the sediment picked up, the specimens in trawl 4 were quite damaged and most identifications were not possible. For the other 23 trawls, 116 taxa (of the total of 124 taxa) were used. Several taxa were combined because they were males and females of the same species. The total amount of variance explained by the first three eigenvalues was low (27%). Figure 3.2.1 shows a plot of the first two axes of correspondence. Only trawls 12 and 24 stand out from the other trawls.

Analyses 2 through 4 in Table 3.2.1 are for just the trawls from each of the three depth strata. Taxa that did not occur in these three subsets of trawls were eliminated from that analysis. Analysis 2 for the three 0-400 meter trawls shows the trawls to be distinct from each other (Figure 3.2.2). There is a cluster of taxa associated with each trawl with most other taxa falling inside the triangle formed by the trawls. Trawl 20 was in a cyclone, 21 was in an anticyclone, and 25 was in an "other" environment. Analysis 3 for the 6 trawls from 0-600 meters separates trawl 12 ("other") from the other five, but trawls 14 and 23 are positive on CA2 as is trawl 12 (Figure 3.2.3). The other three trawls (6, 16 and 17) are all negative on CA1 and CA2 and are all cyclonic. The results show that there is more discrimination among taxa than among trawls. Analysis 4 for the trawls from 0-800 meters again shows more discrimination among taxa than among trawls (Figure 3.2.4). Only trawl 24 stands out by itself.

Table 3.2.1

Results of Correspondence Analysis (CA) Runs for Selected Subsets of Data
(Correspondence analysis eigenvalues 1, 2, and 3 are given)

Description	1	2	3	Comments
ANALYSIS 1				
Percent Variance Explained	10	9	8	All 23 Trawls
Cumulative Percent	10	19	27	116 Taxa
ANALYSIS 2				0-400 meters
Percent Variance Explained	52	48		3 Trawls
Cumulative Percent	52	100		55 Taxa
ANALYSIS 3				400-600 meters
Percent Variance Explained	31	22	18	6 Trawls
Cumulative Percent	31	53	71	80 Taxa
ANALYSIS 4				600-800 meters
Percent Variance Explained	16	12	11	13 Trawls
Cumulative Percent	16	28	39	101 Taxa
ANALYSIS 5				All 23 Trawls
Percent Variance Explained	10	9	8	74 Taxa
Cumulative Percent	10	18	26	<.04 Averages Removed
ANALYSIS 6				23 Trawls (without trawl 4)
Percent Variance Explained	12	10	9	0-400m Taxa Removed
Cumulative Percent	12	22	31	83 Taxa
ANALYSIS 7				23 Trawls (without trawl 4)
Percent Variance Explained	11	11	9	50 taxa
Cumulative Percent	11	22	31	0-400m Taxa Removed
				<.04 Averages Removed

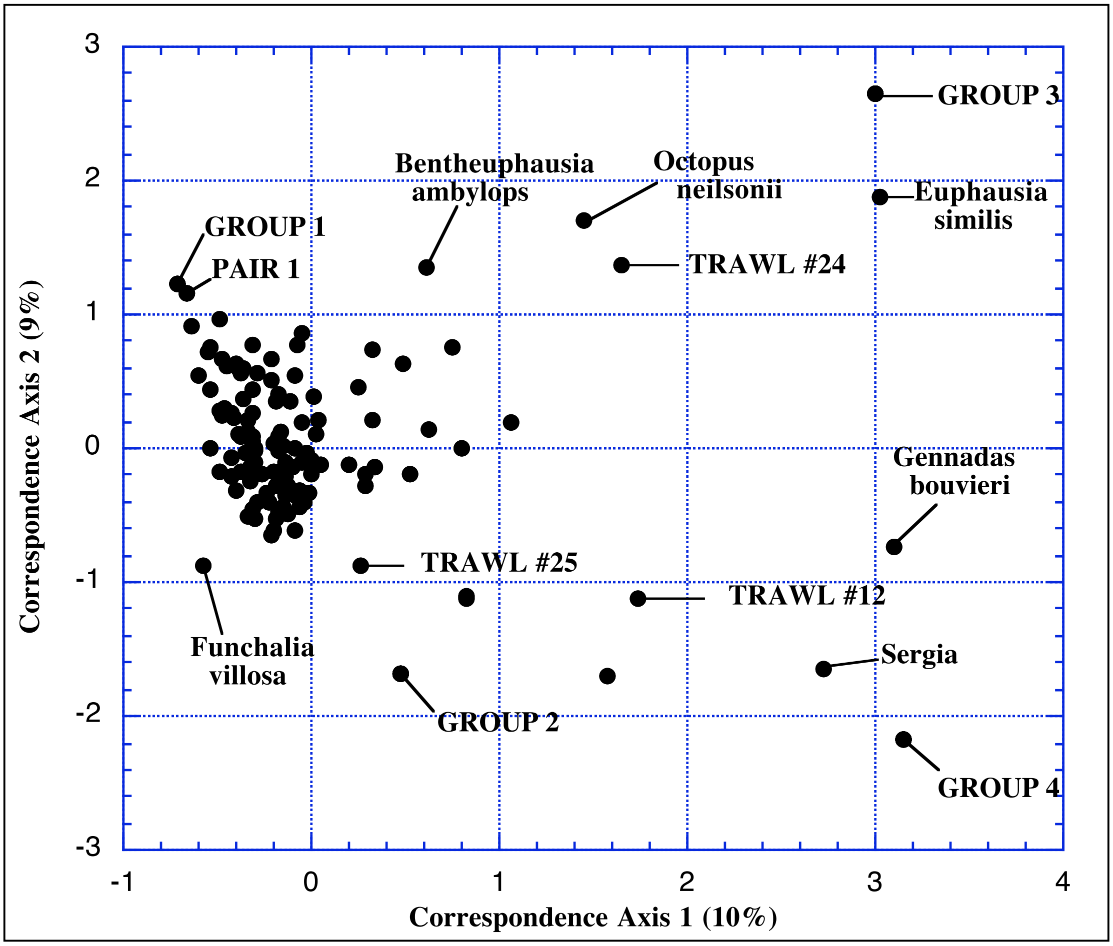

Figure 3.2.1. Correspondence axes 1 and 2 for 23 trawls and 116 taxa. Group 1 includes *Sergestes atlanticus*, *Sergestes pectinat*us (sergestid shrimp) and Ommastrephidae unidentified (a squid family). Pair 1 consists of *Dantecia caudani* (an ophlophorid caridean) and *Pterygioteuthis* sp (a squid genus). Group 2 includes *Meningodora vesca*, *Oplophorus spinosus*, *Plesionika grandis* (crustaceans), *Galaiteuthis* sp., and *Sandalops* sp. (squid). Group 3 includes *Systellapsis cristata*, *Sergestes 'alanticus* group' sp 1, *Euphausia brevis*, and *Euphausia tenera* (all crustaceans). Group 4 is composed of *Sergestes* sp., *Euphausia mutica*, *Euphausia pseudogibba* (crustaceans), and *Haliphron mollis* (squid).

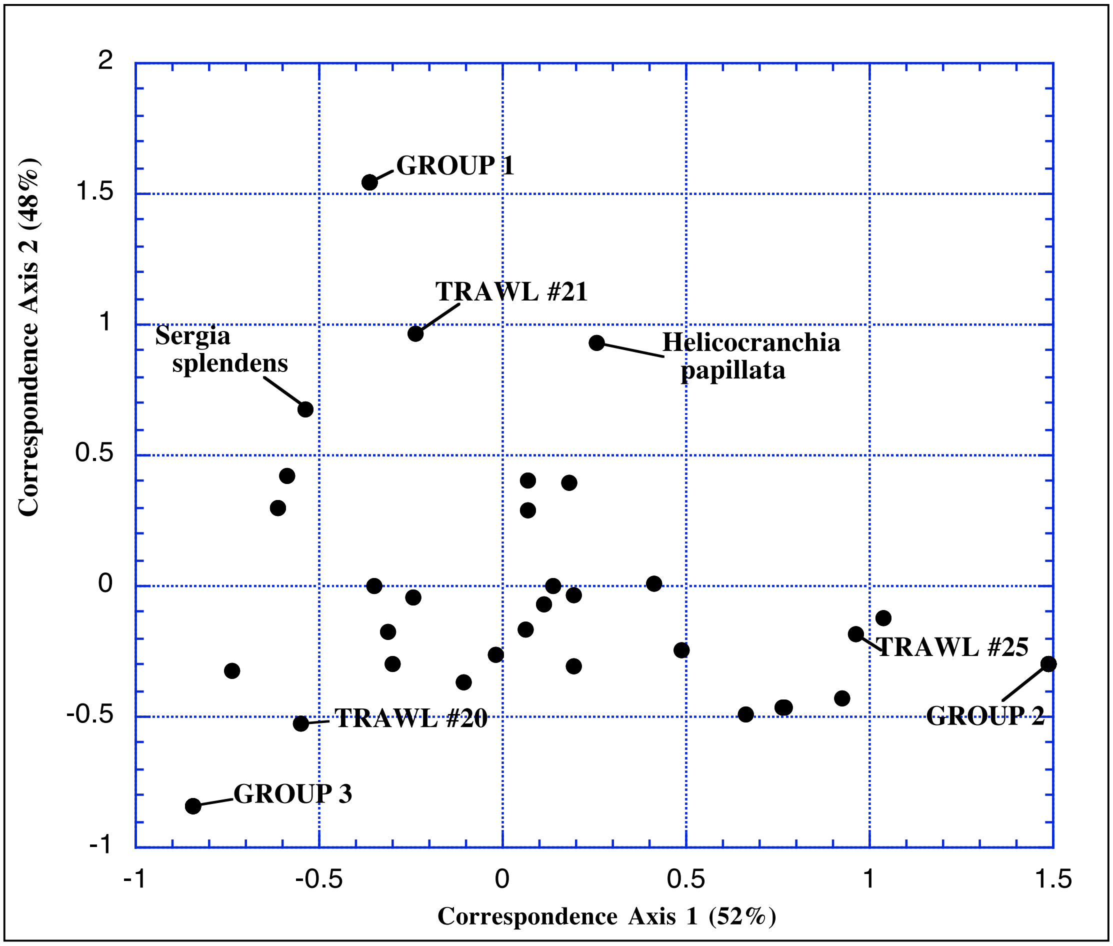

Figure 3.2.2. Correspondence axes 1 and 2 for 3 trawls (0 - 400 meters) and 55 taxa. Group 1 includes *Systellaspsis pellucida*, *Gennadas bouvieri* total, *Thysanopoda monocantha* (Crustaceans*), Abralia atlantica*, *Heteroteuthis* sp., Pyroteuthidae, *Stenoteuthis pteropus* (squid), and *Sternoptyx diaphana* (fish). Group 2 consists of *Meningodora vesca*, *Oplophorus spinosus*, *Plesionika grandis*, *Sergia* sp., *Thysanopoda tricuspidata* (Crustaceans), *Galaiteuthis* sp., *Pyroteuthis margaritifera*, *Sandalops* sp., and Squid unidentified. Group 3 includes *Acanthephyra gracilipes*, *Sergia robustus*, *Sergia tenuiremi*, *Nematoscelis gracilis*, *Nematoscelis microps*, *Stylocheiron abbreviatum*, *Thysanopoda aequalis*, *Thysanopoda obtusifrons* (Crustaceans), Cranchiidae, *Histioteuthis arcturi*, and *Pterygioteuthis giardi* (squid).

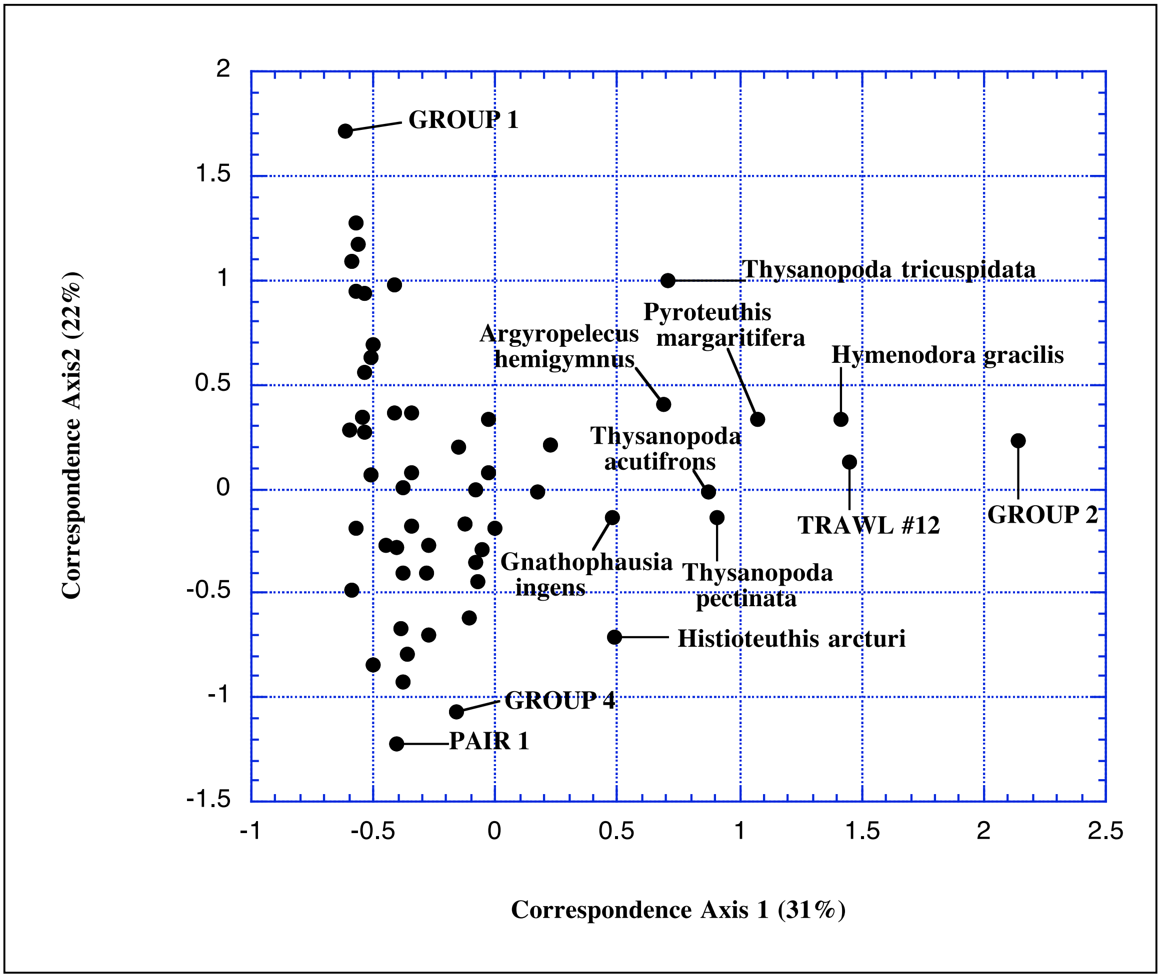

Figure 3.2.3. Correspondence axes 1 and 2 for 6 trawls (400-600 m) and 80 taxa. Group 2 includes *Gennadas bouvieri*, *Sergia* sp., *Sergestes* sp., *Euphausia mutica*, *Euphausia pseudogibba*, *Euphausia similis* (crustaceans), Cranchiidae, *Haliphron mollis*, and Pyroteuthidae (squid). Pair 1 is *Janicella spinicauda* (crustacean), and *Heteroteuthis* sp. (squid). Group 4 consists of *Notostomus elegans*, *Systellaspsis pellucida*, *Bentheogennema intermedi*a, *Thysanopoda egregia*, *Gnathophausia* zoea, *Eucopia sculpticauda* (crustaceans), and *Polyipnus clarus* (fish).

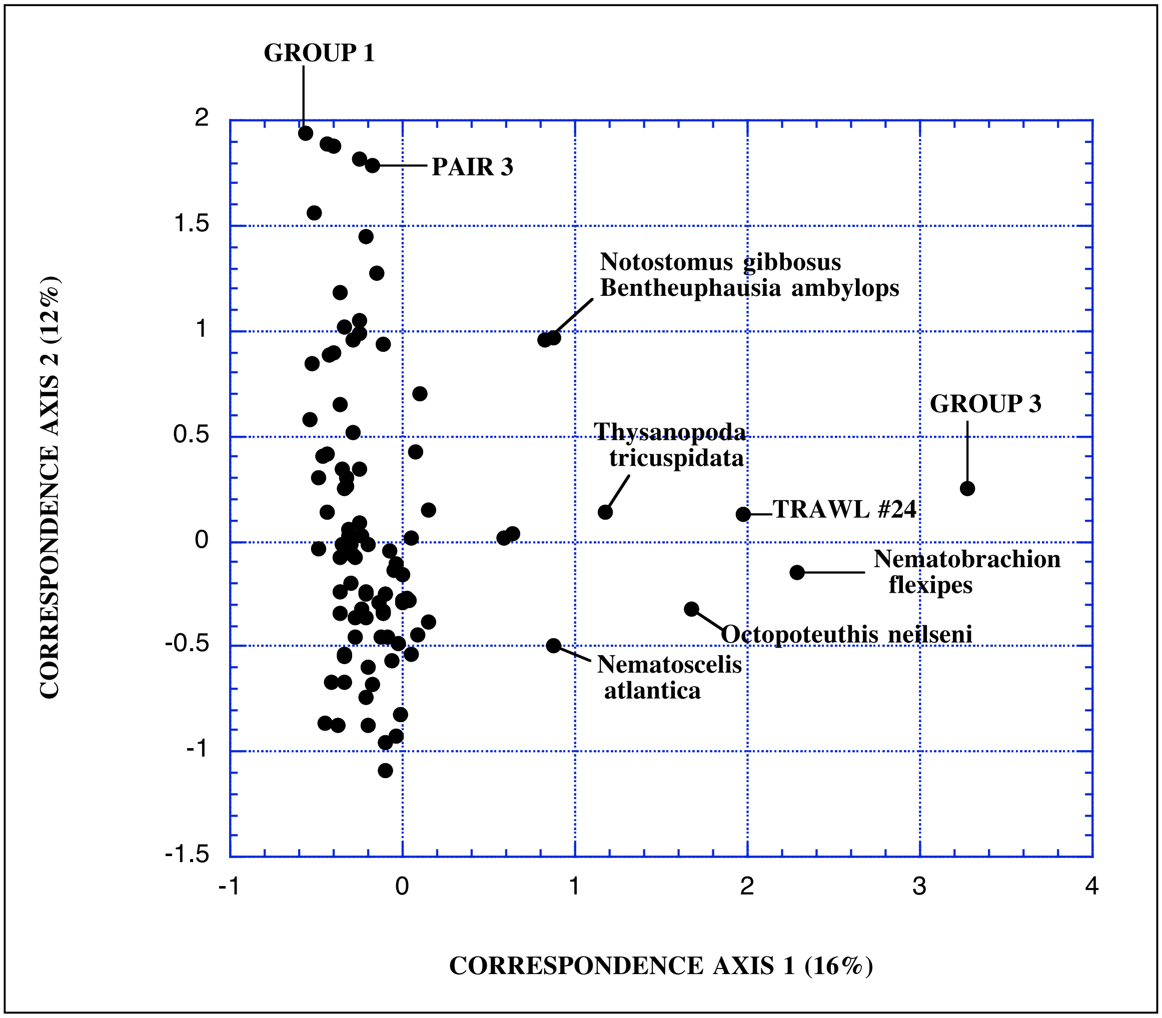

Figure 3.2.4. Correspondence axes 1 and 2 for 13 trawls and 101 taxa. Group 1 includes Sergestes atlantica, Sergestes pectinata (crustaceans), and Ommastrephidae spp. (squid). Group 3 consists of *Systellapsis cristata*, *Gennadas bouvieri*, *Sergia* sp., *Sergestes* 'alantica group' *Euphausia brevis*, *Euphausia similis*, *Euphausia tenera*, *Nematobrachion flexipes*, *Thysanopoda monocantha* (crustaceans), and Enoploteuthidae sp. (squid).

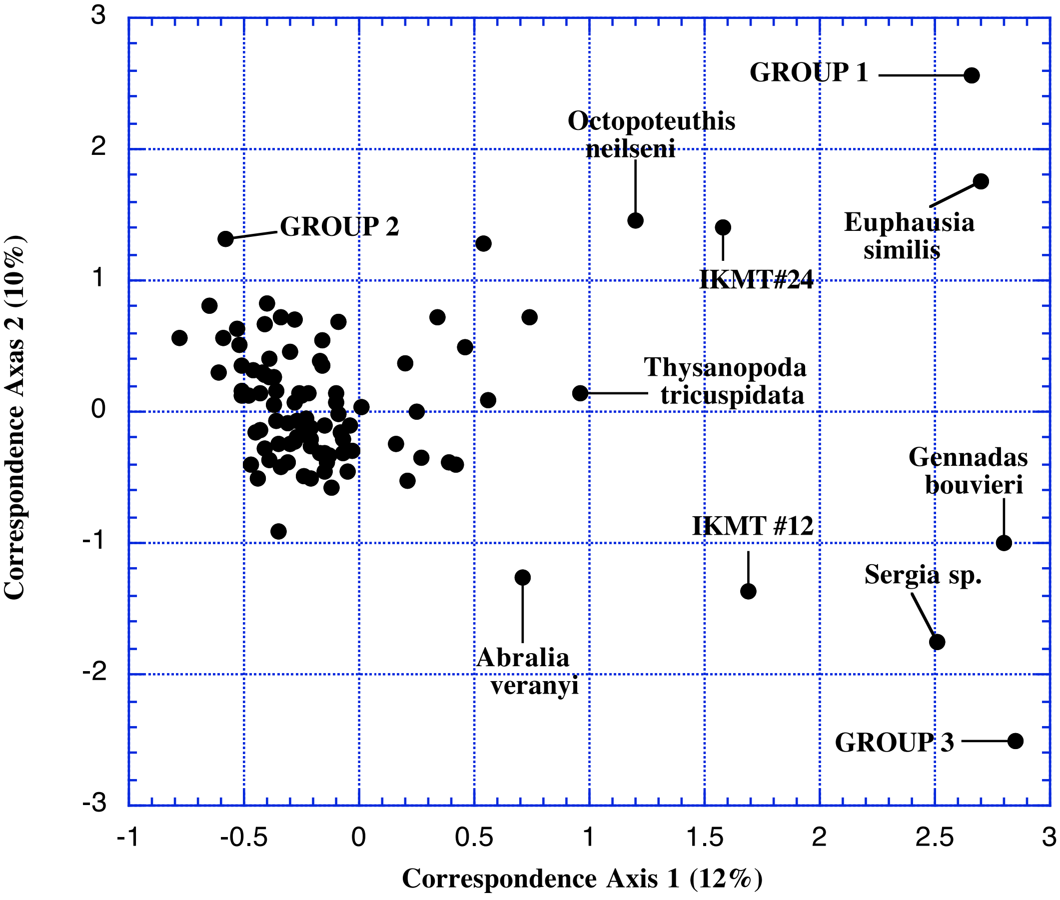

Figure 3.2.5. Correspondence axes 1 and 2 for 23 trawls and 74 taxa. Group 1 includes *Systellapsis cristata*, *Sergestes* 'alanticus group' sp. 1, *Euphausia brevis*, and *Euphausia tenera* (crustaceans). Group 2 consists of *Sergestes atlanticus*, *Sergestes pectinatus* (crustaceans), and Ommastrephidae spp. (squid). Group 3 includes *Sergestes* sp., *Euphausia mutica*, *Euphausia pseudogibba* (crustaceans), and *Haliphron mollis* (squid).

Analysis 5 in Table 3.2.1 is for 23 trawls and the 74 most abundant taxa with average concentrations greater than 0.04 individuals per 1000 m^3 water filtered (see Figure 3.2.5). Trawls 12 and 24 plot by themselves (both are from "other" environments). Again, the amount of variance explained by CA1-CA3, which is only 26%, is low. The removal of the less common taxa had little effect.

Analysis 6 in Table 3.2.1 is also for 23 trawls; this time, however, the species that were collected in the three 0-400 m tows have been removed leaving 83 taxa. The results are very similar to Analysis 5 with only slightly more variance explained. Analysis 7 is for 23 trawls with the restrictions of Analyses 5 and 6 imposed. This left 50 taxa in this analysis. Again, trawls 12 and 24 plotted separately from the others, but with no improvement in the amount of variance explained.

Barros (2003) examined stomach contents from 4 sperm whales stranded in the Gulf of Mexico. The only cephalopod remains were present as beaks. A comparison of the species composition of these beaks and the species collected in the present study are given in Table 3.2.2. Note that *Histioteuthis sp.* has the highest percent for both the Barros (2003) and this study.

Table 3.2.2

A Comparison of the Percent Composition of Squid Beaks from Sperm Whale Stomachs (Barros 2003) and Midwater Trawl Samples (Present Study)

Species (??)	**Barros (2003)**	**Present Study**
Ancistrocheirus lesueurii	2.0	0
Chiroteuthis sp.	0.2	1.8
Galiteuthis sp.	1.5	0.6
Megalocranchia sp.	1.5	0
Taonius pavo	2.7	0
Teuthowenia megalops	1.5	0
Discoteuthis laciniosa	11.9	0
Histioteuthis sp.	66.8	9.5
Lepidoteuthis grimaldii	2.9	0
Pholidoteuthis adami	2.9	0
Octopoteuthis sp.	2.7	1.2
Moroteuthis sp.	1.3	0
Onychoteuthis banksi	1.6	0
Vampyroteuthis infernalis	0.4	0
Total Percent	100	13.1

One of the most common deep living fishes, *Gonostoma elongatum* (commonly known as the bristlemouth), was compared between environments by both number of individuals per volume and weight per volume. A T-test assuming unequal variances was used. In this test, if the probability is less than 0.05, the two environments being compared are significantly different. The results are presented in Table 3.2.3.

Table 3.2.3

A Comparison of Environments for *Gonostoma elongatum* Based on Midwater Trawl Samples from 600-800 m Using a T-Test Assuming Unequal Variances

Description	**Mean**	**Probability**
By Number/1000 m^3		
Anticyclone/Cyclone	.032/.016	0.02*
Anticyclone/Other	.032/.040	0.22
Cyclone/Other	.016/.040	0.02*
By Weight/1000 m^3		
Anticyclone/Cyclone	.076/.107	0.22
Anticyclone/Other	.076/.206	0.06
Cyclone/Other	.107/.206	0.11

* indicates the two environments are significantly different

Discussion

With the exception of Analysis 2, the amount of variance explained by these analyses was disappointingly low. It is obvious from Table 3.2.1 that the number of trawls is much more important than the number of taxa in determining the amount of variance explained. Further analyses with justified smaller sets of trawls will be undertaken in the coming months. Because Analyses 1 and 5 have shown that few trawls stand out from the others, these distinctions will be pursued. In addition, comparison of trawl data and ADCP data collected simultaneously (Kaltenberg 2004) will be examined.

Towed nets are relatively slow moving, straight line samplers as compared to selective, agile predators such as sperm whale prey. A number of papers examine the differences among different size nets, different tow speeds and predator catches of cephalopods (Clarke 1977; Roper 1977 and Wormuth and Roper 1983). Use of a much larger trawl would have been preferable, but would have required a commercial-sized trawler and a double warp. Even these trawls do not mirror the cephalopod composition of sperm whale stomachs very well (see Figures 6 and 7 in Clarke 1977). These studies show that histioteuthid and octopoteuthid squid are much more prominent in sperm whale stomachs than architeuthids in most parts of the world. Based on submersible observations these are often near-bottom species. Towing closer to the bottom with a very large bottom trawl would most likely capture these species. Videos suggest they are not nearly as fast swimming as the very muscular ommastrephid, enoploteuthid and thysanoteuthid species. It is also interesting to note that Barros (2003) did not record any architeuthid beaks in the four whale stomachs he examined, although he has many unidentified beaks to yet process. Voss (1956) recorded the only *Architeuthis* (giant squid) specimen in the Gulf of Mexico, found off the Mississippi Delta region.

The comparisons of environments using both numerical concentrations and weight concentrations of *Gonostoma elongatum* show mixed results - not surprising for small sample sizes. Only two of the six comparisons was significant and only for numbers and not for weight. More samples need to be taken to reduce variability in each of the targeted environments.

Overall, these results suggest that below 400 meters, where water masses are homogeneous, there are only minor differences in community structure. This is not really surprising especially since analyses of zooplankton samples from the upper 200 meters in cyclones, anticyclones and in other regions of the northern Gulf of Mexico found that the differences that exist are restricted to the upper 100 meters of the water column (Wormuth et al. 2000). Why sperm whales show a preference for cyclones over anticyclones does not appear to be related to biomass or species composition of the mesopelagic community as represented by these trawl samples.

From the standpoint of trophodynamics in the 400-800 meter community, the weights of the larger organisms is probably more important than their concentrations. Size frequency and weight data for hatchet fishes and Gonostoma have been completed. Weights have been measured on myctophids and Cyclothoe, but only as single values per trawl. These data will be supplemented with weights of other deep living species.

A set of vertically discrete opening-closing trawls was made in October 1996 in the eastern area of the 2003 SWSS cruise using a 4 m^2 MOCNESS with 4 mm mesh. Each trawl collected 7 discrete samples in the upper 400 meters of the water column. The data from these trawls will be used to further eliminate those taxa that occur in the upper 400 m.

4 SPERM WHALES IN THE NORTHERN GULF OF MEXICO

Section 4 presents preliminary results of mesoscale population studies conducted on the 2002 S-tag cruise, 2003 Whale Survey and Habitat Characterization cruise, and 2004 Mesoscale Population Study cruise. Abundance, habitat use, and other aspects of social organization of sperm whales in the Gulf of Mexico are discussed (Section 4.1). This is followed by discussions of the distribution and relative density (Section 4.2), coda analyses (Section 4.3), and acoustic length measurements (Section 4.4).

4.1 Sperm Whales in the Northern Gulf of Mexico: Abundance, Habitat Use, and Aspects of Social Organization

Nathalie Jaquet[1], Jonathan Gordon[2,3], and Bernd Würsig[1]

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[3]Ecologic LTD.

4.1.1 Methods

Acoustic surveys were conducted in the study area and sperm whales were located by listening every 15 minutes for one minute for their characteristic click vocalizations (Backus and Schevill 1966) through a 2-element towed hydrophone array. Acoustic data (e.g., whether sperm whales were heard, the number heard, the type of vocalization, the type and level of other noise, whether dolphins were heard, etc.) were entered in the Logger program. Once detected, sperm whales were located acoustically using a directional hydrophone and then followed both visually and acoustically for one to two days. Vessel track, individual behavior, dive locations, date, fluke-up time (to the nearest second) and surfacing time (to the nearest 5 sec) were recorded with custom-written software on a Hewlett Packard 200 LX palmtop computer linked to a Garmin 12XL GPS. For individual identification (Arnbom 1987), fluke photographs were taken at the start of each dive with a Canon EOS D1 and a Sigma 100-300 mm zoom lens. To obtain a measure of body size, ranges were measured during fluke-up with a Bushnell 1000 Yard Pro laser range finder and then combined with the fluke span measured from on-perpendicular photographs of whale flukes taken with a lens of known focal length. It has been suggested that calluses (roughness of the surface of the dorsal fin, see Figure 4.1.15 below) are a secondary sexual characteristic present mainly on mature females (Kasuya and Ohsumi 1966). Therefore, the presence or absence of calluses was recorded for all whales for which we obtained a good view of the dorsal fin. The presence or absence of defecation at fluke-up was recorded by driving into the slick just after the whale initiated its deep-dive and checking for a brown patch in the water. The "defecation rate" of a group, defined as the number of slicks with defecation/total number of slicks checked, was calculated to give an estimation of the feeding success for the group during the time it was tracked (Whitehead et al. 1989; Smith and Whitehead 1993; Whitehead 1996a). Acoustic recordings were made for several minutes after the whale fluked up to provide material for acoustic length estimation.

The number of first-year calves, adult males and other whales (adult females and immatures of both sexes) were assessed for each group of whales (Kahn et al. 1993). As first-year calves do not fluke and thus cannot be reliably identified individually the minimum number of calves for each group was recorded. A group was assessed as having two calves only if two of them were observed simultaneously, or if after leaving one calf, the research vessel traveled in a straight line at a speed of over 9 km/h and another calf was sighted ahead of the vessel. To be consistent with other studies (Kahn et al. 1993) and allow comparisons between them, the proportions of mature males or first-year calves to other whales were calculated as the total number of different males identified or minimum number of first-year calves divided by the number of other whales identified (adult females and immatures of both sexes).

Mark-recapture techniques (Hammond 1986; Hammond et al. 1990) were used to estimate the size of the population of sperm whales utilizing the study area in the Gulf of Mexico. Before analysis, all photographs were graded for quality following the standard method described by Arnbom (1987). This takes into consideration both the quality of the image, including the angle, tilt, resolution and focus, and how well the animal was marked. The data were then analyzed using a suit of models in the specially written SOCPROG software (Whitehead 1999a).

To investigate movements and residency, we compared the new identification photographs to the North Atlantic and Mediterranean Sperm Whale catalogue (NAMSC, ~4000 photographs) and to the SWSS sperm whale catalogue (all sperm whale identification photographs taken by the SWSS project in the Gulf of Mexico). The NAMSC catalogue includes some one hundred photographs taken in the Gulf of Mexico between 1994 and 1996 during the GulfCet program and by NMFS in 2000 and 2001. This allowed us to investigate movement and residency over a 10 year time period.

To investigate sperm whale social organization in the Gulf of Mexico, we used all identification photographs collected in the Gulf since 1994. Although the maximum time span of the study was 10 years, most of the identifications came from the last two years, reducing the power of the data set for examining long-term patterns of social organization. To determine the pattern of sperm whale social organization, we used the software SOCPROG (Whitehead 1999a), especially developed for this purpose. Following the methodology described by Whitehead (1999a), individual sperm whales were ascribed to the same group if they were identified on the same day or if more than 50% of the individuals from an existing group were identified during different days.

In sperm whales, females and immatures tend to form large groups of about 20-25 individuals which coordinate their movements, while young bachelor males tend to form small loose aggregations with little movement coordination and older males are usually found singly or in pairs (Rice 1989). Therefore, we assumed that we were in the presence of a group of female/immature when a calf was observed or when all individuals in the group coordinated their movements and at least some individuals had a callus. We assumed that we were with a group of bachelor males, when only a few whales could be seen (≤ 6 individuals), none had calluses, and there were no calves.

4.1.2 Results and Discussion

A large amount of information was collected during the mesoscale population cruise (June-August 2004) and not all data have been analyzed. Thus, the following results and discussions are preliminary. Work in 2005 and 2006 will be used to analyze results in greater detail to incorporate results from the 2005 field season and to prepare peer-review publications. It is possible that some results and conclusions outlined below will change once data are analyzed in greater detail.

In 2004, 37 days were spent at sea covering the study area (Figure 4.1.1). Coverage was not distributed evenly, with greatest effort in the Mississippi River Delta and Mississippi Canyon region (Figure 4.1.2) where most sperm whales and platforms were encountered. In 2002 and 2003, research cruises were conducted aboard the R/V *Gyre* which left from Galveston, Texas. The three cruises that have contributed to this dataset (S-tag 2002, habitat characterization 2003 and mesoscale population study 2004) each had a different research focus, and therefore, study areas and study protocols were slightly different between years (see also annual reports for 2002 and 2003 in Jochens and Biggs 2003 and 2004, respectively). However, in all three years, a large part of the effort was directed south of the Mississippi River Delta and in the Mississippi Canyon area. This area is roughly 120 by 60 nautical miles (Figure 4.1.1).

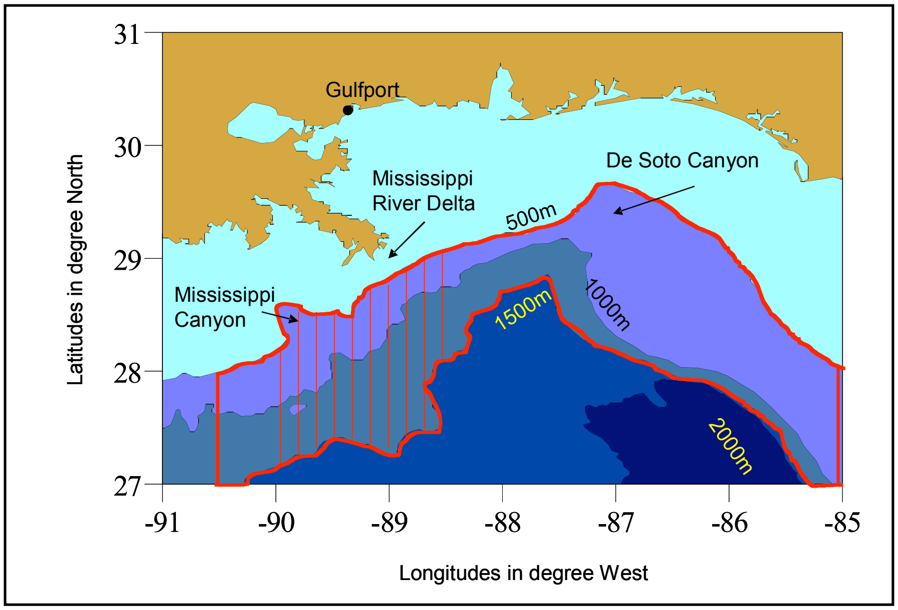

Figure 4.1.1. Study area (outlined in red) for the Mesoscale Population Study 2004. The vertical red lines represent the area where most of the effort took place, south of the Mississippi River Delta and Mississippi Canyon area.

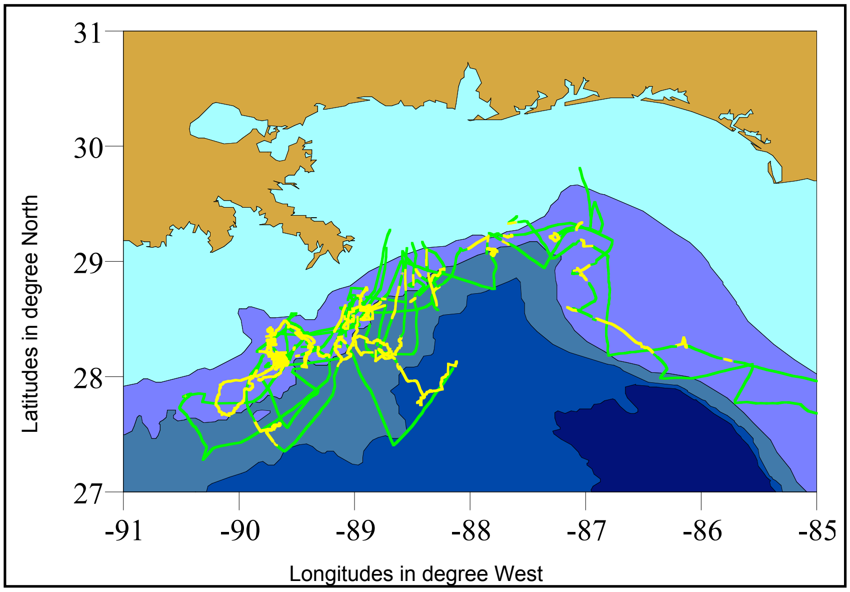

Figure 4.1.2. Track of the research vessel during four legs of the mesoscale population study of 2004 (20 June to 11 August 2004). Green denotes survey tracks when no sperm whales were heard or seen; yellow indicates tracks when the survey was in acoustic and/or visual contact with sperm whales.

Of 37 days at sea in 2004, sperm whales were encountered visually on 32 days (Table 4.1.1), and 434 hours were spent in visual or acoustic contact with whales. During the three field seasons of the SWSS project, 514 good-quality identification photograph sequences were taken and 179 new individuals were identified (Table 4.1.1). The SWSS/GulfCet Catalogue for the Gulf of Mexico (including photo-IDs taken during D-tag cruises and the 2003 S-tag cruise) currently contains identification photographs of 199 different sperm whales.

Distribution and Abundance

In 2004, sperm whales were found in the entire study area: along the west coast of Florida and in the DeSoto Canyon, the Mississippi Canyon, and the area south of the Mississippi River Delta (Figure 4.1.2). In 2003, when effort was roughly evenly distributed along the slope of east Texas, Louisiana, Mississippi, and DeSoto Canyon, sperm whales also were found within all of these areas (see Jochens and Biggs 2004). In 2002, very little effort was spent outside the area of the Mississippi Canyon and Mississippi River Delta (see Jochens and Biggs 2003), and sperm whales were abundant in the area of investigation.

In 2004, the methodology and search patterns were consistent over the 2-month field season. So, the relative abundance of sperm whales was assessed based on search time, which is the mean number of hours of searching required to make contact with whales (Kahn et al. 1993). Search time gives an approximate indication of the relative abundance of whale aggregations (Whitehead and Kahn 1992). As all our detections of sperm whale groups were made acoustically, and since sperm whales vocalize almost continuously both day and night, we consider that we had as much chance of finding sperm whales during the night as we had during daytime. Therefore, around-the-clock data were used to calculate search time.

Table 4.1.1

Summary of Data Collected During the Project

	S-tag 2002	**Habitat 2003**	**Mesoscale 2004**	**Entire project**
Number of days at sea in water deeper than 200m	18	20	37	**75**
Number of days in visual contact with whales	13	18	32	**63**
Number of photo-identifications taken	71	141	302	**514**
Number of different sperm whales identified during each season	43	70	92	-
Number of new individuals	43	60	76	**179**
Number of matches with SWSS/GulfCet catalogue	2	13	16	-
Number of matches with NOAA catalog	5	13	7	**25**
Number of matches with NAMSC catalog	0	0	0	**0**
Number of different large breeding males identified	0	0	0	**0**

Search time was defined as follows: *Search time* = Number of hours between the time we left an encounter with sperm whales and the time we found a new independent encounter. Encounters were considered independent when no whales were heard or seen during two consecutive hours when sailing in a straight line at about 10 kilometers per hour.

Search time does not provide abundance, as no account is taken of the size of each aggregation found. Instead, search time provides a robust index of relative abundance of sperm whale groups, which can be used to make comparisons between areas with similarly sized aggregations, and between types of spatial distributions of sperm whale aggregations, such as clumped, random, or evenly distributed.

Search time could not be calculated for the 2002 and 2003 cruises, as we sometimes had to move to a different area without listening for the vocalizations of whales. Furthermore, the *Gyre* was relatively noisy but had a large and efficient visual team. Therefore, the probability of finding whales was slightly higher during good than poor visual conditions, e.g. rough weather or night.

In 2004, we had a total of 55 encounters with sperm whales, 28 "acoustic only" encounters and 27 "visual + acoustic" ones, 26 with photo-ID (Figure 4.1.3). Initial contact was always made acoustically, "visual + acoustic" encounters were ones in which animals were subsequently seen and photographed. Mean search time was 7.4 hours, with a maximum of 22 hours between 2 encounters. Search time was compared between the "Florida-DeSoto Canyon" area and the "Mississippi" area. The border between these two areas was arbitrarily drawn at 88°W (see

Figure 4.1.1), half way between the Mississippi Delta (89°W) and the head of the DeSoto Canyon (87°W). Sixteen groups were encountered in the "Florida-DeSoto Canyon" area and 39 in the "Mississippi" area. The mean search time for the "Florida-DeSoto Canyon" was 8.2 hrs (standard error or SE = 1.50) and for the "Mississippi" area 7.0 hrs (SE = 0.87). A t-test comparing these two encounter rates was not statistically significant (t = 0.690, p = 0,4932, degrees of freedom or df = 50, not significant or NS), suggesting that both areas had roughly similar relative abundance of sperm whale groups, although group size may have differed between to the two areas.

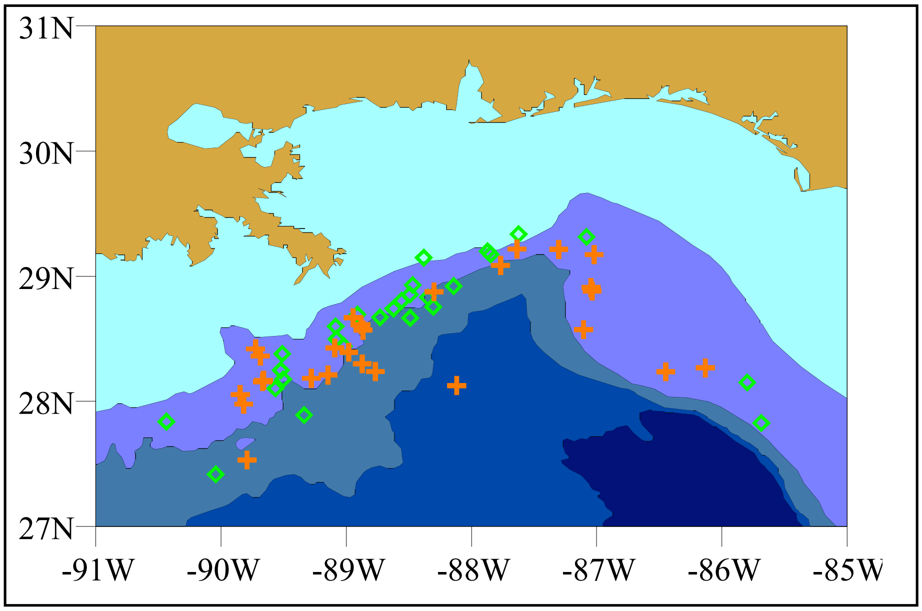

Figure 4.1.3. Visual (bold orange crosses) and acoustic (green open diamonds) encounters during 2004. The positions were taken at the first photo-identification for visual encounters and the first reception of loud clicks for the acoustics.

Mean search time between encounters in the Gulf of Mexico is substantially smaller than in other areas where sperm whales have been investigated with similar methodology (see Table 4.1.2 for Gulf of California, Galápagos Islands, Ecuador, Seychelles; see Whitehead and Kahn 1992; Kahn et al. 1993; Jaquet and Gendron 2002). This suggests that sperm whale groups are abundant in the northeastern Gulf of Mexico. However, in the Gulf of Mexico, most effort was concentrated in an area of known high sperm whale abundance and no effort was spent surveying in deeper waters. Furthermore, group sizes and aggregation sizes were different in the Pacific and Indian Oceans from those in the Gulf of Mexico (Table 4.1.2). It is therefore possible that our results do not reflect a higher density in the Gulf of Mexico generally than in the Pacific Ocean, but that spatial organization is different. These results do directly indicate that research using these "traditional" study techniques can be expected to be even more efficient in the Gulf of Mexico than it has been in other areas.

Table 4.1.2

Mean Search Time Between Sperm Whale Encounters in Different Areas

Area	Mean Search Time	Reference
Gulf of Mexico	7.4 hrs	This project
Gulf of California	16.4 hrs	Jaquet and Gendron 2002
Galapagos	27.5 hrs	Kahn et al. 1993
Seychelles	25.4 hrs	Kahn et al. 1993
Ecuador	47.2 hrs	Kahn et al. 1993

Of the 27 "visual + acoustic" encounters, four were with lone sperm whales. We judged these to be likely maturing males as they were visually assessed, and some were measured to be larger than other whales, but not large enough to be breeding males (Section 4.1.6). Six were with small dispersed groups of whales, likely bachelors groups; 16 were with groups of females and immatures, and one was undetermined. Figure 4.1.4 shows a strong spatial segregation between groups of female and immature whales and bachelors and lone males. All groups of female/immature sperm whales were found in the Mississippi River Delta-Mississippi Canyon area, while lone males and groups of bachelor males were found mainly in the DeSoto Canyon-West Florida area. Such a strong segregation between males and females in tropical water has not been described in the literature, although observations suggesting a similar pattern have been made in the Gulf of California (Diane Gendron, personal communication, October 2004). Such segregation could be due to differences in foraging behaviors, diet or other factors.

Given the spatial segregation mentioned above and the fact that bachelor groups tend to be smaller than groups of female immatures, it is likely that, although there were no significant differences between the mean search time in both areas, that the absolute abundance of sperm whales in the Mississippi region is higher than in the DeSoto-Florida area.

Sperm whale absolute abundance for the SWSS study area was calculated using mark-recapture techniques (Hammond 1986), as many individuals older than calves can be recognized by natural marks on the trailing edge of their flukes (Childerhouse et al. 1996). Mark-recapture techniques provide an estimate of the number of individuals utilizing an area contrasting with line transects which assess the number of animals present in the area at any one time. Therefore, mark-recapture techniques tend to be particularly appropriate for assessing populations for some long-term assessment and management purposes.

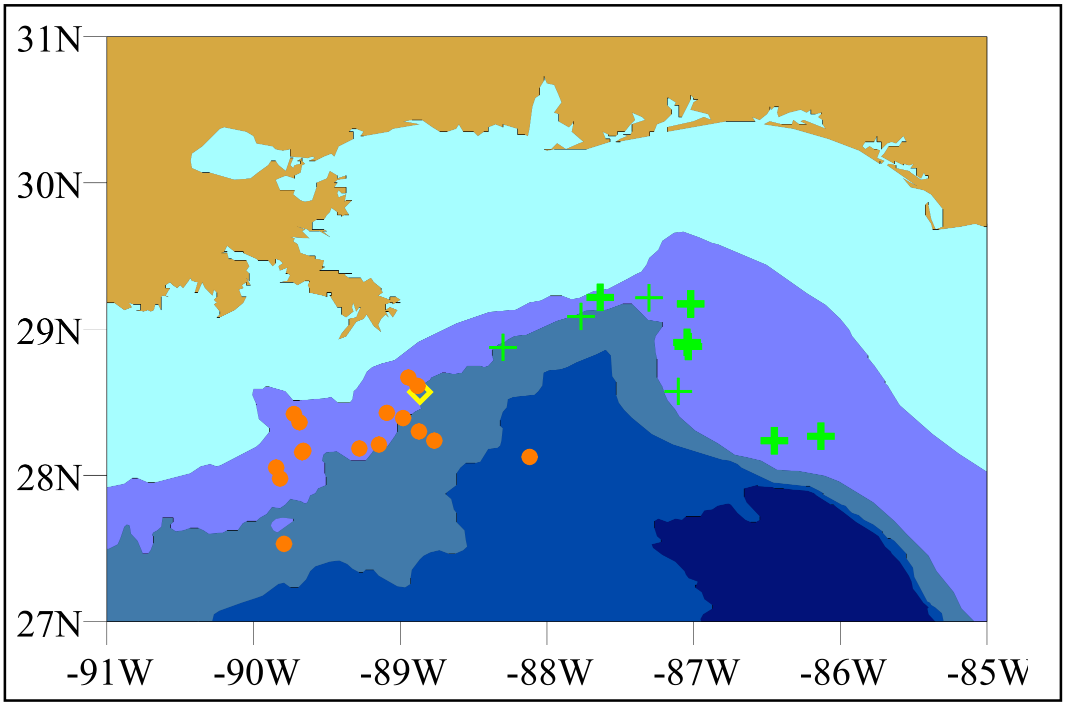

Figure 4.1.4. Visual encounters in the north-central Gulf of Mexico. Solid circles denote groups of females/immature; bold diamonds denote undetermined encounter; bold crosses denote bachelor groups; and light crosses denote lone males.

The data set used to estimate sperm whale population abundance is shown in Figure 4.1.5. As most of the identification photographs came from a short period of time, three weeks each in 2002 and 2003, and 7 weeks in 2004, the full open model described by Whitehead (1990a) could not be applied, and a simple open model was fit to the data (SOCPROG, Whitehead 1999a). The results indicate that approximately 398 individuals utilized our study area (95% Confidence Interval = 253 to 607).

This result is consistent with previous mark-recapture estimates of population size for this area. Analysis of data collected up until 2002, using a closed model due to the paucity of data, indicated that 298 individuals utilized the study area (95% Confidence Interval (CI) = 137 to 890). Analysis of data up to 2003, using an open model that assumes a population of constant size (SOCPROG in Whitehead 1999a) indicated that 262 individuals utilized the study area (95% Confidence Interval = 157 to 509). The latest analysis for all data collected up to 2004 suggests a slightly larger population than for the two previous years (398 compared of 262 or 298), however all mean estimates are within the 95% confidence intervals of the other estimates. As the 2004 estimate was calculated from the largest dataset and had the lowest confidence intervals, we have the most confidence in this estimates.

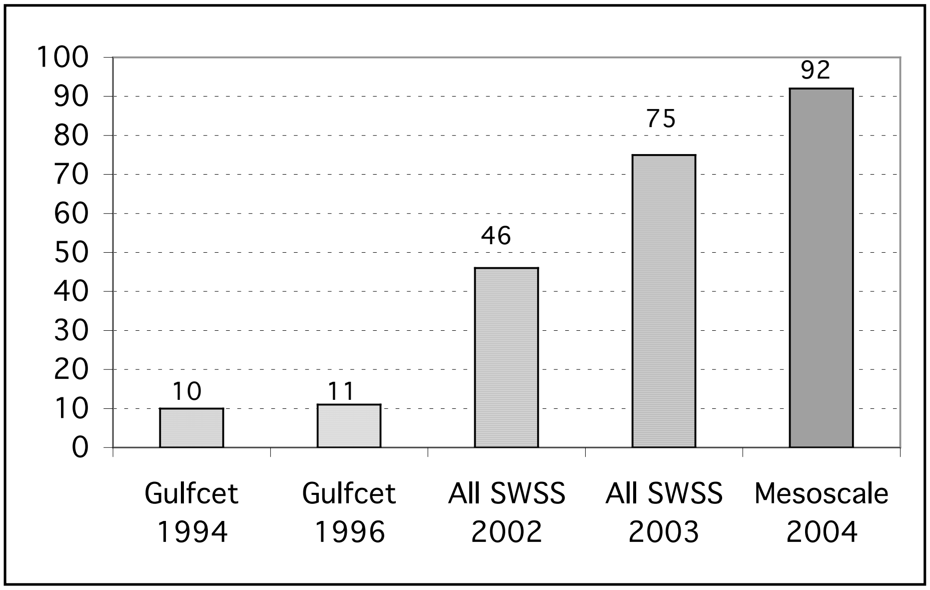

Figure 4.1.5. Number of sperm whales photo-identified each year; data set used for abundance estimates. "All SWSS" also include sperm whales photo-identified by both the S-tag team and the D-tag team.

To date, 199 different individuals have been identified in the northern Gulf of Mexico. The discovery curve of recognized individuals shows little sign of plateau (Fig. 4.1.6), indicating that there are more individuals to be identified, consistent with a population of more than 250 to 300 whales.

At the time of the 2004 mesoscale population study, the S-tag team had tagged a total of 37 sperm whales in the northern Gulf of Mexico. We can use these artificially-tagged whales as an additional sample for mark-recapture. During the 2004 cruise, we resighted at least 8 different tagged animals (see Section 4.1.7). A Petersen estimate with Chapman's modification of Peterson's two-sample estimator (Seber 1982) gave an estimated population size of 392 individuals and a 95% CI of 191 to 1052. Due to small sample size, the 95% CI is large, but the estimated 392 individuals is similar to our current estimate of 398. The good agreement between data sets suggests that the sperm whale population utilizing our study area of the northern Gulf of Mexico is on the order of 400 individuals.

In summary, about 400 sperm whales utilize the northern Gulf of Mexico. They are found along the slope from Galveston, TX, to Tampa, FL, but they may have a slightly higher relative abundance in the Mississippi Delta and Mississippi Canyon region. Mean search time between different encounters with sperm whale groups was low in the 2004 study area, suggesting that aggregations of several groups that stay together for a matter of days (Jaquet 1996; Whitehead 2003) are rare. Spatial organization is likely to reflect the foraging conditions in the northern Gulf of Mexico. Our results also show that bachelor groups and groups of female/immature sperm whales did not use the same areas, a spatial segregation not reported from other tropical habitats. In the northern Gulf, groups of female and young use the relatively productive area south of the Mississippi River Delta and the Mississippi Canyon, while bachelor males use the DeSoto Canyon and the slope of the Florida coast. A result of this segregation is that maturing males are found in areas with less current anthropogenic activities while female/immatures occur in areas with the highest rig and platform densities in the northern Gulf.

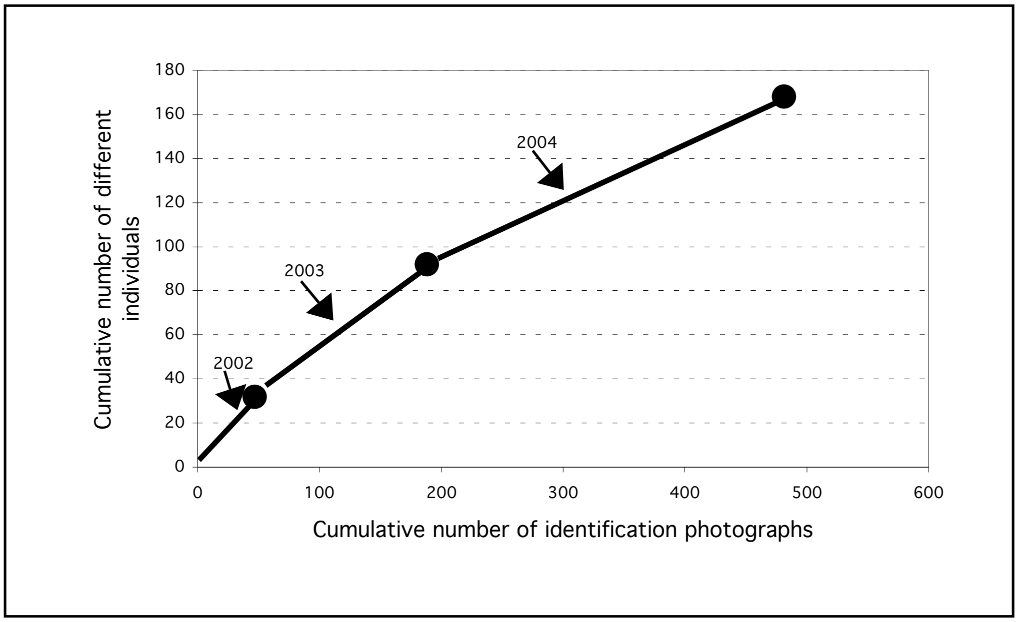

Figure 4.1.6. Discovery curve for 2002, 2003 and 2004 (excluding GulfCet, S-tag Ids and D-tag Ids). Photo-identifications from GulfCet, S-tag and D-tag cruises were not included in the discovery curve, as no information was provided on total number of high quality identification photographs taken during the cruises. Therefore, the total number of different individuals used for the discovery curve was 168 instead of 199.

Residency and Site Fidelity

Site fidelity in cetaceans refers to a tendency for individuals to spend a disproportionate amount of time in a restricted part of their home range and to return to this area in subsequent years. The term does not preclude movements into and out of an area.

In 2003, we had rather even coverage of the area between 94°W and the DeSoto Canyon, and we identified 25 different sperm whales in the western Gulf of Mexico (90.5°W to 94°W), 13 in the DeSoto-Florida area and 32 in the area of the Mississippi River Delta and Canyon. It had been found that re-identifications were not random within the study area. A total of 71% of the resighted individuals were encountered between 90°W and 88°W, or the area just south of the Mississippi River Delta, and 100% were resighted between 91°W and 87°W (Jochens and Biggs 2004). This result suggested a level of high site fidelity for the area south of the Mississippi

River Delta and the Mississippi Canyon. In 2004, we sighted 12 individuals that had been sighted previously in 2003; of these 12, only one sperm whale (8.3%) had been first identified in 2003 away from the Mississippi area, although 54% of all individuals were encountered outside the area. This result again suggests high site fidelity for the Mississippi area (Figure 4.1.1).

Of the 70 sperm whales that were individually identified in 2003 in the study area, 26 (37%) had been sighted previously by either SWSS 2002, GulfCet or NOAA between 1994 and 2002 (~110 individuals). Of the 92 whales identified in 2004, 24 (26%) had been observed previously between 1994 and 2003 (SWSS/GulfCet catalogue of 123 individuals; see also Table 4.1.1). These resighting rates were higher than those observed generally in other regions. In the Gulf of California, for example, resighting rates between field seasons were 4.8%, 20.8%, 23%, 11% and 26% (Jaquet and Gendron 2002; Jaquet unpublished data). Such high resighting rates in the northern Gulf of Mexico (38% and 26%) suggest high site fidelity and/or a relatively small population.

In 2003, the mean resight distance was 34.6 n.miles over a time span of 1 to 9 years (see Section 4.4 in Jochens and Biggs 2004). On average, a group of female/immature sperm whales moves about 50 n.miles per 24 hours. This value includes all zigzag and back tracking and does not represent a net displacement (Whitehead 2003). A mean resighting distance of only 34.6 n.miles over one to nine years is particularly small. In 2004, we identified 16 individuals that had been identified by SWSS/GulfCet projects (Table 4.1.1). The longest period between resightings was 10 years (e.g., whale HL 5 was first identified in 1994 and was resighted in 2002, 2003 and 2004). Seven individuals were identified in two years, six in three years, and three in four years. On average, the mean resighting distance over 1 to 10 years was 45.2 n.miles. Figure 4.1.7 shows mean resighting distance for individuals that were last sighted in 2004. No correlation between time span and resighting distance was found, and the larger resighting distance was over a time span of 1 year while the smallest one was over a time span of 4 years. This result suggests that individuals do not move further away with time. When Figure 4.1.7 is compared to the one for 2003 (see Figure 4.4.4 in Jochens and Biggs 2004), we notice that the resighting distance for a one year time span for 2004 (54.9 n.miles) is over double that for 2003 (25.0 n.miles). This increase in resighting distance likely reflects the shift in distribution observed between 2003 and 2004. In 2003, almost all individuals were encountered south or southeast of the Mississippi River Delta, while in 2004, a majority of whales were identified southwest of the Delta in the Mississippi Canyon area.

In 2004, sperm whales were first found in the Mississippi area on 26 June 2004 and we departed the area late on 4 August 2004. Therefore, the longest residency time that we could have detected is 40 days. Five groups of sperm whales were sighted on two non-consecutive occasions and the time lags between first and last sightings were 3, 5, 11, 15 and 16 days. Therefore, residency time in the area was at least two weeks.

By 11 July, we had identified 37 different individual sperm whales. Over the next 12 days to 23 July, we identified only 3 additional whales, even though we took a further 67 identification sequences during a five more independent group follows. This indicated we had identified most of the whales in the area during the first three weeks and that the area had about 40 individuals. However, in the final two weeks of our research in the Mississippi area, we identified a further

37 new individuals, and did not have a single resight between whales identified before and after 23 July. This suggests that there had been a turn-over of whales by late July, and that there was an average of about 40 individuals present at any one time in the Mississippi area during summer 2004. Figure 4.1.8 shows the discovery curve for individuals identified in the Mississippi area during late June to early August 2004. The curve reaches a plateau on around 20 July and then begins to climb again as new whales are sighted. Gordon et al. (1998) describe a similar situation with one assemblage of whales being replaced by another after an extended period of residence, off the Caribbean Island of Dominica.

In summary, our results suggest that about 40 individuals are present at any one time in the Mississippi Canyon-Delta area (Figure 4.1.1) and that there are movements into and out of this area. In 2004, one aggregation of 40 or so whales may have been displaced by another aggregation. Residency time within the area is at least two weeks, but data on a longer time span are lacking. Individuals tend to return to the Mississippi area year after year, and show a high site fidelity. To date, there has been only one match between the Mississippi region and other areas, suggesting that not all whales from the northern Gulf have an equal probability of being found in the Mississippi area. Similar results were found for bachelor males in the Kaikoura Canyon, New Zealand, where some individuals were seen repeatedly for weeks to months over a time span of 10 years while other individuals were transients and seemed to spend most of their time in areas outside of the Canyon (Jaquet et al. 2000). However, observations of this kind had not previously been described for female/immature groups. The Mississippi Canyon-Delta area is likely a preferred one. Enhanced primary productivity due to the Mississippi River discharge and/or the frequent occurrence of off-margin flow that has been correlated with the presence of slope eddies may increase food availability for sperm whales in this area (Morey et al. 2003; Biggs et al. 2005; see also Section 3.1) and explain this preference.

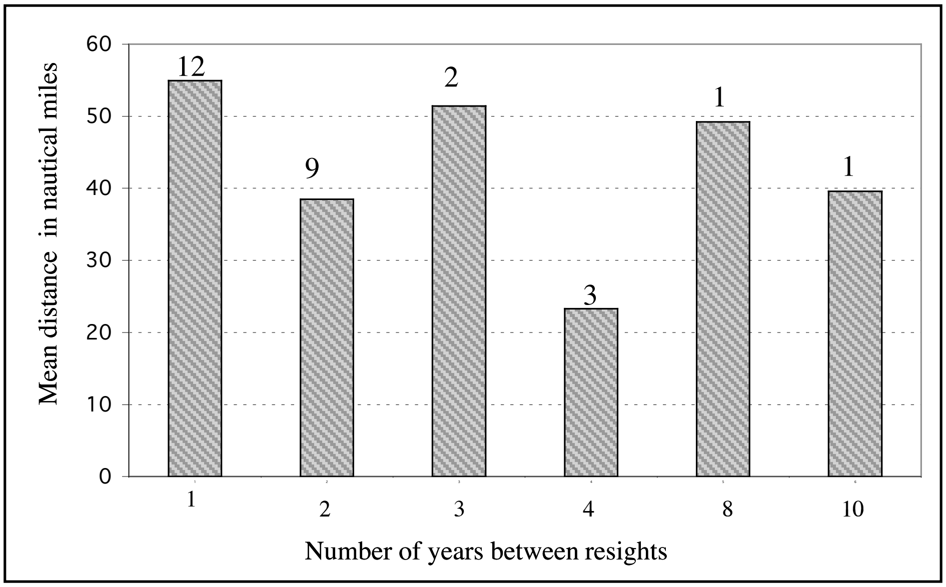

Figure 4.1.7. Mean resight distance for individuals last sighted in 2004. The numbers above each column represent the number of individuals (n).

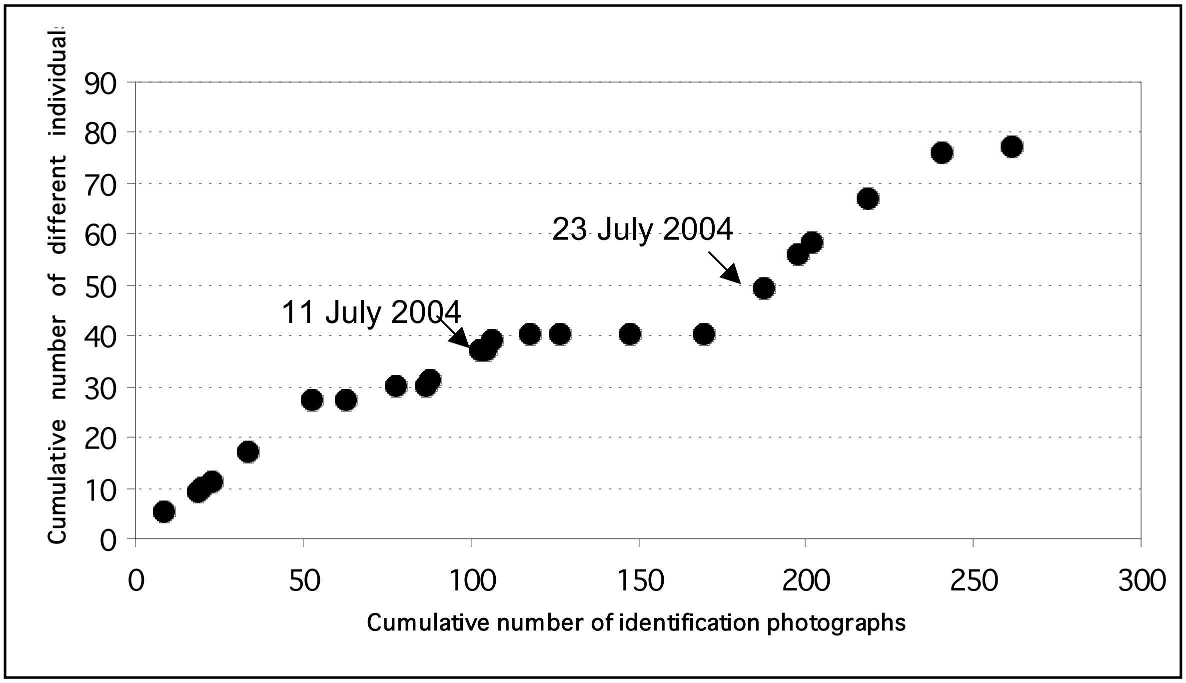

Figure 4.1.8. Discovery curve for the Mississippi area from 26 June to 4 August 2004.

Large-scale Movements

Geographic population structure is a result of large-scale movements, and thus understanding of large-scale movements of Gulf of Mexico sperm whales will provide an understanding of stock identity and whether there are important movements between the Gulf of Mexico and other areas of the Atlantic Ocean. To investigate large-scale movements, we compared our SWSS catalogue to approximately 2500 sperm whales identified in the Atlantic and Mediterranean over the last 15 years. No matches were found with images from other areas, suggesting a low level of interchange between the Gulf of Mexico and the rest of the Atlantic. Large-scale movements, although not common, have been described in the Pacific Ocean. About 400 sperm whales from the Gulf of California were compared with the 1800 sperm whales identified in the Galápagos by Hal Whitehead and colleagues (Dalhousie University, Halifax, Canada). The average distance between the Galápagos and the Gulf of California is 3,800 km. Despite this large distance, eleven matches were found between these two areas (Jaquet et al. 2003; Jaquet and Coakes unpublished data). As no such movements were found in the Gulf of Mexico, it is likely that the Gulf of Mexico population is more isolated than either the Galápagos or Gulf of California ones.

Spatial Organization Around Platforms

Platforms have been called "islands of life" as their structures may harbor and attract a wide variety of fishes and other marine life. Sport fishermen understand this phenomenon and they are often seen trolling near oil and gas platforms in the northern Gulf of Mexico. It is possible that squid, a primary food source of sperm whales (Kawakami 1980; Clarke 1986), also tend to aggregate near platforms and that sperm whales could be found more often in the vicinity of platforms than in other areas in the northern Gulf. On the other hand, active platforms have much ship traffic, with associated crew boats, supply boats, sport fishing vessels, etc., and they also, at times, produce underwater noise themselves which might induce sperm whales to avoid these structures. It is equally possible that platforms have neither a positive nor negative effect on sperm whale distribution or behavior. It is important for management to obtain an understanding of sperm whale movement and spatial organization around rigs and whether the rigs have an impact, either positive or negative, on their distribution.

Most deep platforms (>200m water depth) in our study area are found in water depths between 500 and 1000 m (Figure 4.1.9), which is also the range of water depths where most sperm whales are encountered (Jochens and Biggs 2003 and 2004; Davis et al. 2002). However, a few rigs are also found at greater depths. Figure 4.1.9 also shows whale tracks of the 12 encounters that were followed closely for 10 to 50 hours (see below). If whales were attracted to or avoided platforms, we might expect this to be evident in such tracks. Figure 4.1.9 does not indicate obvious patterns of movement with respect to oil platforms. To gain a more complete understanding of sperm whale spatial organization around platforms, it is necessary to take into account the amount of survey effort spent in close proximity to these structures. Figure 4.1.10 shows locations of platforms, survey effort, and encounters with sperm whales for each of the four cruise legs. These figures tend to confirm that platforms do not appear to dramatically affect spatial distribution of sperm whales (Figure 4.1.9). However, statistical analyses will be conducted to investigate this further.

Our preliminary perception is that sperm whale movements and spatial organization are not greatly affected by platforms. The switch in distribution that we observed between 2003 and 2004 from the areas south of the Delta (high platform concentration) to the Canyon (lower platform concentration) is likely unrelated to the platforms themselves, and may have been induced by differences in food resources between 2003 and 2004.

Small Scale Movement Patterns, Defecation Rates and Feeding Success

Sperm whales are near the top of a long food chain, and diets of females and immatures consist almost exclusively of deep living squid (Kawakami 1980; Clarke 1986). These squid have an average mantle length between 20 and 100 centimeters and tend to escape nets and trawls (Clarke 1985; Clarke et al. 1993). Therefore, except in a few areas (e.g., Gulf of California, Jaquet and Gendron 2002), it has not been possible to relate sperm whale distribution, spatial organization and behavior to the amount of food available. Consequently, researchers have related sperm whale preference for particular areas to other factors that might in turn be related to sperm whale prey densities. Factors investigated have included primary and secondary productivity, sea surface temperature, sea-surface altimetry, slope and measures of underwater relief (Jaquet and Whitehead 1996; Jaquet et al. 1996; Tynan 1998; Griffin 1999; Davis et al. 2002). However, as sperm whales are near the end of a long food chain, there are large temporal lags between peaks in primary or secondary productivity and peaks in sperm whale prey (Sette 1955; Vinogradov 1981) and this can result in a lack of spatial coherence too. Perhaps as a result, significant relationships between oceanographic factors and/or productivity and sperm whale distribution have not been found at spatial scales of less than 100 n.miles and temporal scales shorter than several months (Jaquet and Whitehead 1996; Jaquet et al. 1996; Jaquet and Gendron 2002).

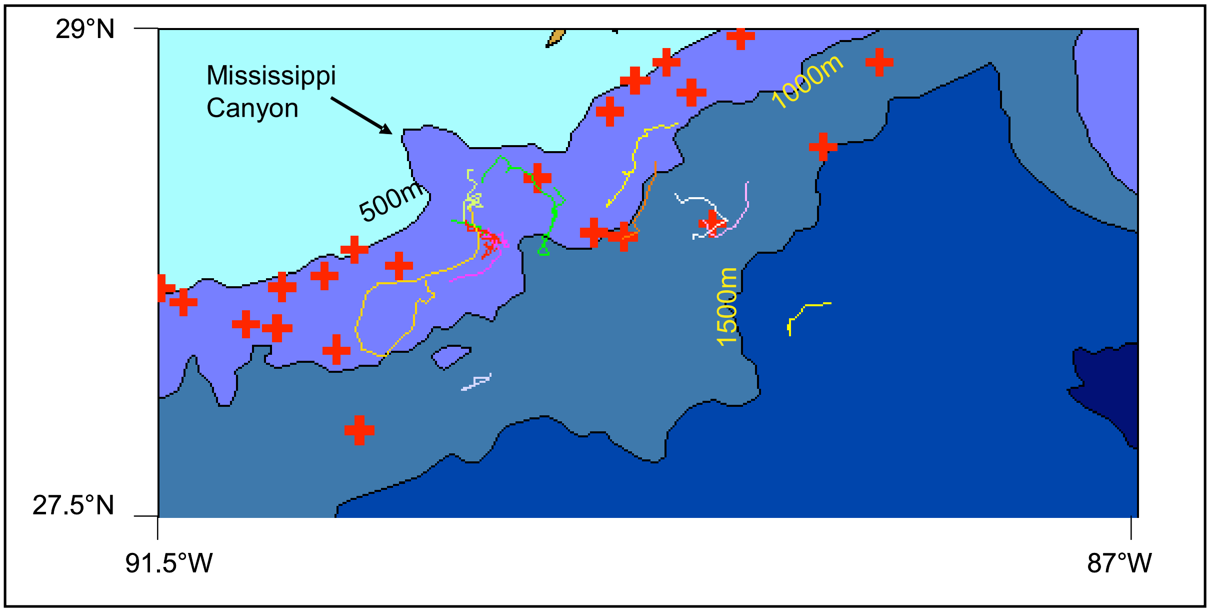

Figure 4.1.9. Positions of deep platforms (>500m) are represented by red crosses and tracks of 12 encounters that lasted 10 to 50 hours by colored lines. The 500m, 1000m and 1500m contour lines are shown.

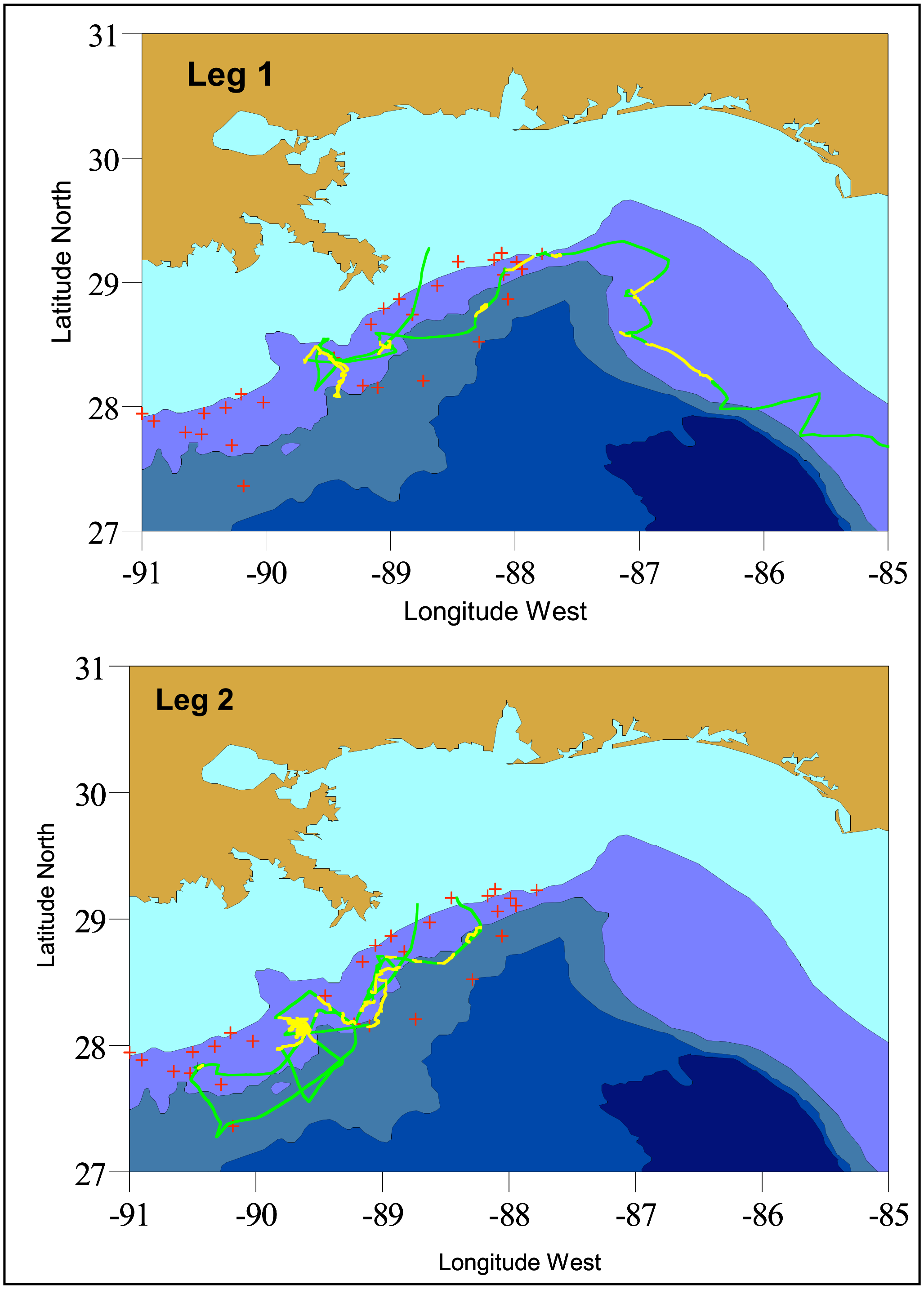

Figure 4.1.10. Locations of platforms, survey effort, and encounters with sperm whales. Positions of deep platforms (>500m) are represented by red crosses. The green line represents survey track when no whales were either seen or heard, and the yellow line represents the time we were in acoustic and/or visual contact with sperm whales.

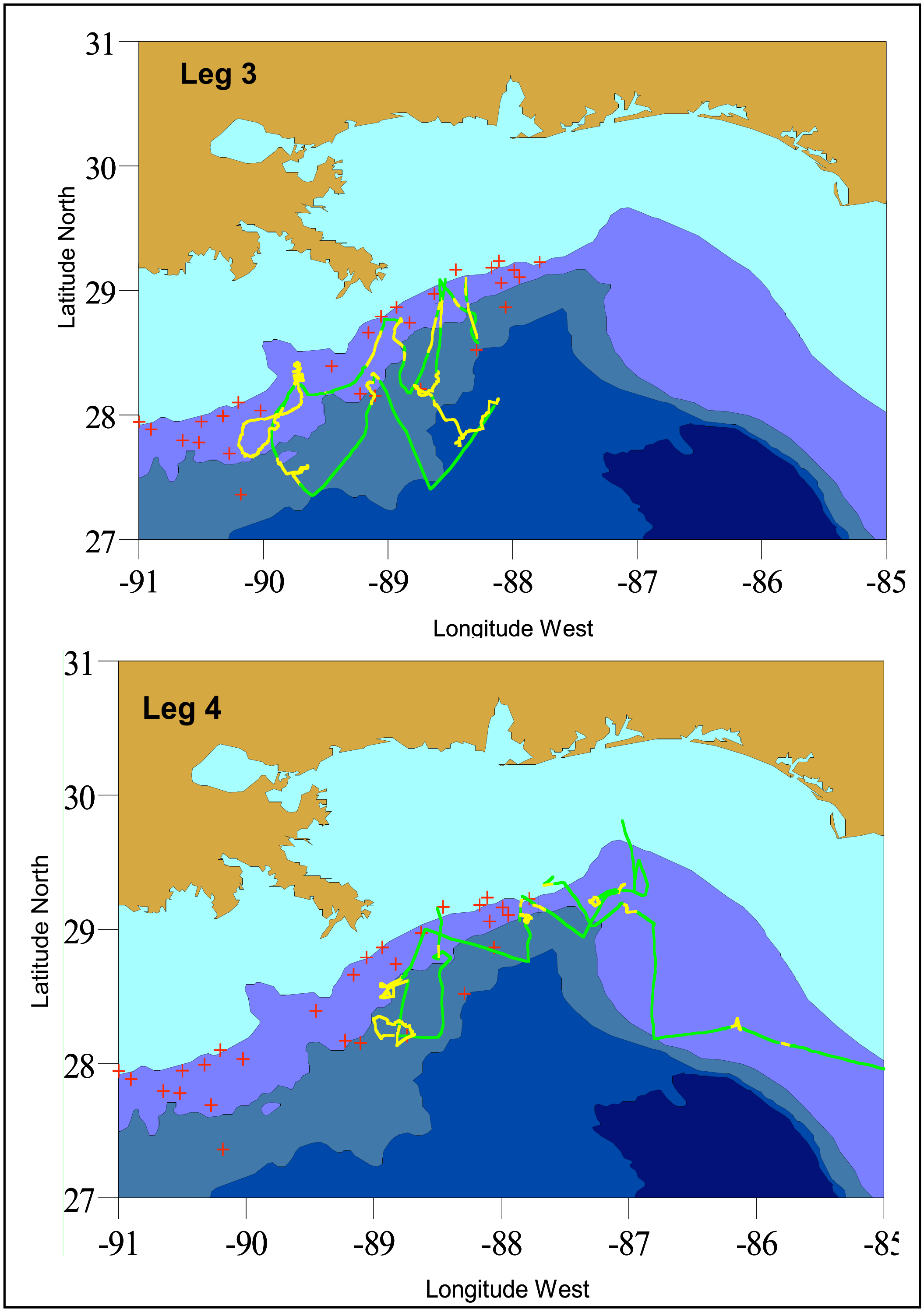

Figure 4.1.10. Locations of platforms, survey effort, and encounters with sperm whales. (continued)

As so little is known about either sperm whale diet in the Gulf of Mexico or the distribution of its likely prey, we need to consider alternative approaches for investigating foraging patterns and success. A variety of creatures from bacteria to vertebrates have a tendency to turn more often and through greater angles when in favorable than when in non-favorable patches of food, and this behavior will tend to maintain them within profitable patches (for example, see Giraldeau 1996). Therefore, small-scale movement patterns can provide an indication of feeding success in particular areas. Furthermore, it has been shown by several studies that sperm whales travel in relatively straight lines when feeding success is poor and zigzag over a smaller area when feeding conditions are good (Whitehead 1996a; Jaquet and Whitehead 1999; Whitehead 2003). Therefore small-scale movement patterns can provide an indication of feeding success in particular areas.

During 2004, we had 16 independent encounters with groups of females/immature sperm whales. Independent encounters were assumed when no whales are heard or seen for at least two hours when sailing in a straight line at a speed of 10km/hour (Kahn et al. 1993; Jaquet and Whitehead 1999). During these encounters whales were followed closely day and night for periods ranging from 5.8 to 52.5 hrs, with a mean of 23.3 hrs. Twelve of the encounters lasted for over 10 hours (Table 4.1.3), and their positions are plotted on Figure 4.1.11. Six encounters were in the Mississippi Canyon in water depths between 500 and 1000 m; four were south of the Mississippi River Delta in water depths of about 1000 m to 1200 m; one was south west of the Canyon and one in water deeper than 1500 m. These 12 encounters represented seven different groups (Table 4.1.3). Figure 4.1.11 shows that the same group was not always resighted in the same area: encounters 8 and 10 represented the same group of 10 individuals, and these individuals were sighted first in the Delta region and 3 days later in the Canyon region. Encounters 5 and 13 represented the same group that was resighted 15 days later in different sub-areas. On the other hand, encounters 9 and 15 represented the same group sighted 14 days apart, both times in the Canyon area. Similarly, encounters 12 and 16 represented the same group sighted in the Canyon 11 days apart, and encounters 20 and 21 represented the same 10 individuals sighted 5 days apart. These results suggest that although we found a high concentration of whales within the Canyon in 2004, groups of sperm whales moved back and forth over a larger area.

Small-scale movements and displacements were calculated for these 12 encounters. Groups were followed closely day and night using visual observations and a directional hydrophone that allowed us to stay close to the group. However, as the groups could be spread over several kilometers, and as the research vessel might be positioned anywhere within the group, tracking data over temporal scales of less than 1 hour were not used to calculate displacements and small-scale movement patterns.

Figure 4.1.12 shows the root mean square (rms) displacement in kilometers against time lag for these 12 encounters. For any time lag of x hours, the rms is the average straight-line distance between the position of the group at time *t* and its position at time *t*+x. Horizontal displacement is the straight line distance and does not take into account zigzag movements.

Table 4.1.3

Description of the 12 Encounters Followed Closely for > 10 Hours

Encounter Number	**Group name**	**Date**	**No. of days seen**	**Total no. hours tracking (Ac+Vis)**	**No. of individuals identified**	**Net displacement**	**Total distance covered in n.miles (including all zigzag)**	**Zig zag index**	**Mean (SD) Depth**	**Mean (SD) Slope**
12	M10	11 July 04	1	15.25	9	9.291	11.442	1.232	682 (82)	4.60 (2.98)
16	M10	21-23 July 04	3	52.50	7	19.489	84.404	4.331	795 (152)	4.18 (2.47)
17	M12	24 July 04	1	17.50	9	0.745	17.777	23.865	1186 (50)	7.40 (4.77)
19	M15	27 July 04	1	12.00	11	9.323	18.851	2.022	2356 (70)	3.41 (1.93)
20	M16	28 July 04	1	18.25	9	13.819	22.348	1.617	1658 (65)	1.14 (0.40)
21	M16	3 Aug 04	2	26.25	9	11.902	24.120	2.027	1561 (131)	2.18 (1.60)
13	M5	12-13 July 04	2	23.50	2	22.888	34.629	1.513	923 (108)	5.43 (2.48)
5	M5	26-27 June 04	2	42.50	9	15.164	64.892	4.279	2321 (86)	3.36 (1.71)
8	M8	4 July 04	1	11.50	7	20.147	22.478	1.116	1165 (73)	2.99 (1.75)
10	M8	7-8 July 04	2	30.75	8	12.244	47.776	3.902	815 (54)	2.83 (1.89)
15	M9	20-21 July 04	2	29.00	5	12.669	35.573	2.808	634 (97)	5.23 (2.78)
9	M9	5-6 July 04	2	41.75	10	4.934	45.740	9.270	700 (105)	4.27 (2.78)

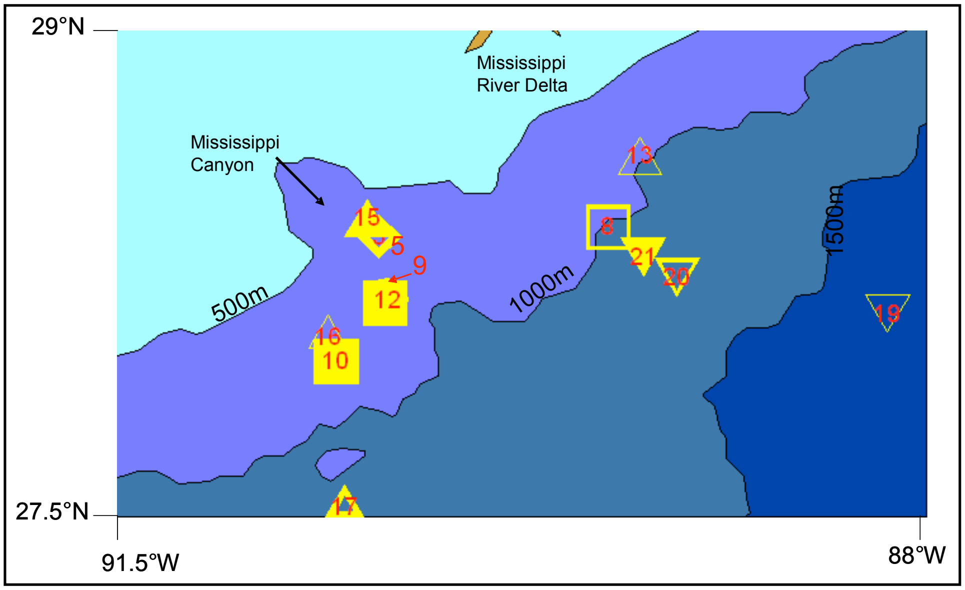

Figure 4.1.11. Position of the 12 encounters followed for 10 to 50 hours and for which displacement was calculated. The numbers represent the identification of each encounter. The 500m, 1000m and 1500m contour lines are shown.

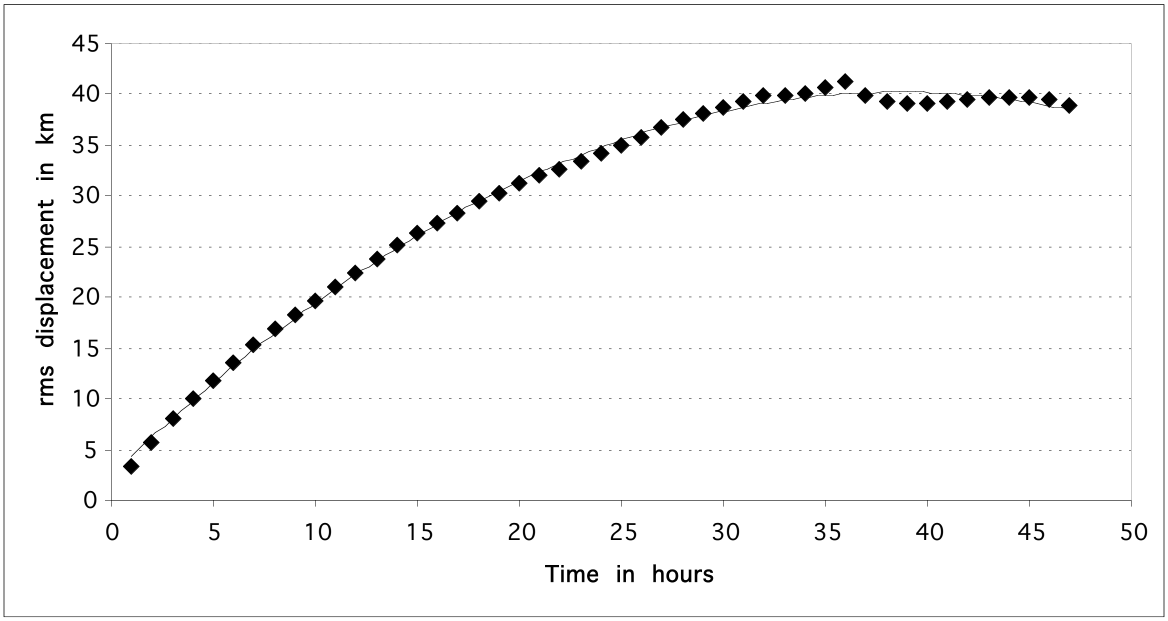

Figure 4.1.12. Root Mean Square (rms) displacement for the 12 groups of female immatures that were followed for more than 10 hours (11 to 50 hours).

Figure 4.1.12 shows that on average, sperm whales move at a speed of 3.3 km per hours in the Mississippi area. This speed is consistent with observations from other areas of the world (3.8 km/hr, Whitehead 1989; 4.3 km/hr, Whitehead 2003; 3.8 km/hr, Jaquet et al. 2003), and is likely an optimum speed that minimizes the cost of transport and maximizes the rate of finding and acquiring food (Whitehead 2003). Figure 4.1.12 also shows that in this area, sperm whales have an average horizontal displacement of about 35 km in 24 hours and 40 km in 48 hours. It has been shown that, in general, the smaller the daily horizontal displacement, the higher the feeding success (Whitehead 1996a; Whitehead 2003). However, daily horizontal displacement is also related to types of prey and its distribution. Therefore, large differences in daily horizontal displacement have been found in different areas of the world (e.g., Whitehead (2003) reports 45 km in the Galápagos, 65 km in Peru/Ecuador, 70 km in Chile, and 85 km in the Western Pacific). These preliminary results in the Gulf of Mexico suggest that the Mississippi area has good feeding conditions for sperm whales and that the patches of squid may possibly be smaller (less horizontal displacement) but denser or longer-lasting (as the whales zigzag over this area for at least a day) than in areas of the South Pacific where small-scale movements have been investigated (Whitehead 2003). These preliminary observations give us a first insight into the northern Gulf of Mexico foraging conditions and prey aggregations, but much more work needs to done.

During the June 2004 S-tag cruise on the *Gyre*, sperm whales were encountered almost exclusively in the Mississippi Canyon (Section 3.1; see also Jochens and Biggs 2006). During the summer 2004 MPS cruise, sperm whales occurred in higher densities within the Canyon than in other areas of the study. This might suggest that feeding conditions in June-July 2004 were better within the Canyon than elsewhere in the study area. Figure 4.1.13 shows the rms displacement for encounters within the Canyon area (n=6), as well as the rms displacement for encounters from the area south of the Mississippi River Delta (n=4). These results are to be taken with caution, as, by splitting the data into two different areas, we are substantially reducing sample size. Nonetheless, Figure 4.1.13 suggests that in both areas, sperm whales traveled at a similar speed of about 3.5 km/h, but that net displacement was slightly less in the Mississippi Canyon than in the Delta area, which would be consistent with the Canyon having better feeding conditions.

It is interesting to compare these travel rates with those from satellite tracking (Section 6). These data show travel speeds of between 0.2 and 2.3 km/h with a mean of 0.7 km/h. This rather lower rate is probably explained by the much longer time periods (several days between fixes) over which travel speed is integrated.

Defecation rates have been postulated as indicators of feeding success in sperm whales (Whitehead 1996a; Jaquet and Whitehead 1999). Thus, during June-August 2004, sperm whale slicks were checked for defecation after most fluke-ups. For all the groups of female/immature sperm whales in the Mississippi region, 102 slicks were checked for defecation and 22 of them had defecations giving an average defecation rate for the period of late July to early August 2004 of 0.216. In comparison, the average defecation rate for the entire South Pacific survey was 0.084 (Jaquet and Whitehead 1999) and for the Galapagos area 0.032 (Whitehead 2003), substantially smaller than that found in the Mississippi area in 2004.

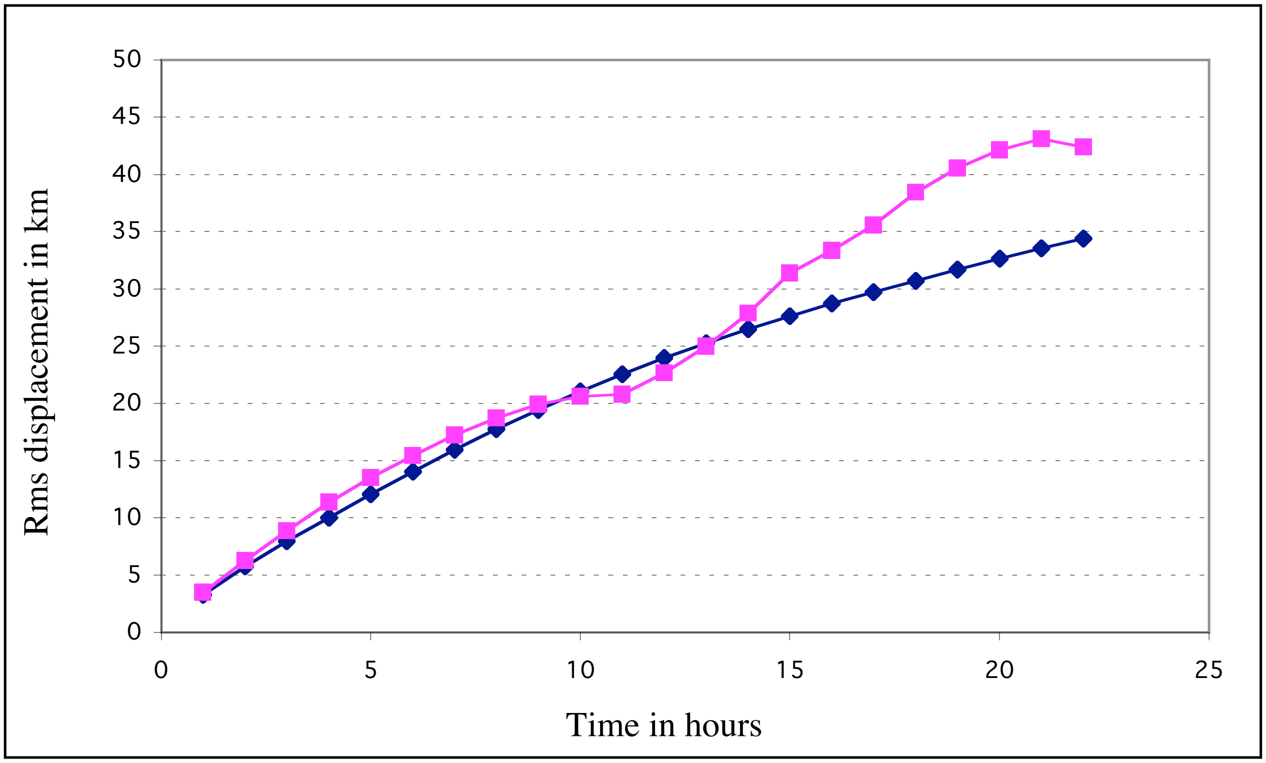

Figure 4.1.13. Root Mean Square (rms) displacement for sperm whale encounters from the Canyon area (diamonds, n=6), the Mississippi River Delta area (square, n=4).

Such a high defecation rate suggests high feeding success in the Mississippi area. Defecation rates can only be compared between different areas and seasons with caution as it is likely that differences in diet also affect defecation rate. It is also clear that the observation platform affects our ability to see defecations. Very few were seen from RHIBs during previous seasons, for example. Nonetheless, the present findings may suggest that the Mississippi region is a good foraging area for sperm whales.

It would be of interest to compare defecation rates between different areas of the Gulf of Mexico. For example, it is possible that the Mississippi area, south of the Delta and Canyon, is an area of especially high food resources for sperm whales, and that this could explain the high site fidelity and possibly preferred residency despite high anthropogenic activities. Such comparison is not possible at the moment as we have little defecation rate data outside the Mississippi region. Defecations are difficult to see reliably from a small RHIB and thus no investigation of defecation rate could be carried out during 2002 or 2003.

In summary, our results and conclusions, though very tentative, provide some insight into sperm whale food resources and foraging behavior in the Mississippi area. Measures of prey availability and foraging behavior may provide a more immediate indication of factors that could lead to population change than measures of population abundance (Watt et al. 2000). In the northern

Gulf of Mexico, sperm whale movement patterns seem to suggest small but dense patches of prey and high feeding success. The high average defecation rates may also suggest high feeding success. However, it could also be a reflection of a different diet than in other areas. The areas south of the Mississippi River Delta and the Mississippi Canyon are likely to be good foraging areas for sperm whales. No data are yet available to investigate whether this area is different from surrounding areas or whether the entire northern Gulf of Mexico is characterized by small and dense patches of prey, and by comparably high feeding success.

Social Organization, Group Size and Group Structure

Sperm whales have a well developed social organization (Caldwell et al. 1966; Whitehead 2003) that may allow them to care for calves communally and defend against predators. In the Pacific, females and immature sperm whales form long-term (>decades) associations of, on average, 10-12 individuals called units (Whitehead et al. 1991; Christal et al. 1998). These units usually associate with one other unit for about one week to form what is commonly called the group or the nursery group (Whitehead et al. 1991; Christal et al. 1998).

Because tight long-term social bonds are thought to be important for the survival and well-being of sperm whales, particularly females and young, knowledge of the social organization of sperm whales in the northern Gulf of Mexico population is important for management. To investigate sperm whale social organization in the northern Gulf, we used identification photographs collected during the SWSS and GulfCet projects (199 individuals). These 199 individuals were also combined with the ~65 photo-identifications taken during the SWAMP project and by NOAA Pascagoula in 2000 - 2002, using the North Atlantic and Mediterranean Sperm Whale Catalogue. Although the maximum time span of the study was 10 years, most of the identifications came from the past two SWSS field seasons, reducing the power of the data set for examining long-term patterns of social organization. Furthermore, due to the difficulties of tracking a known sperm whale group at night using the R/V *Gyre*, individual sperm whales were photographed on subsequent days only during 2004, and thus analysis for the occurrence of casual acquaintances, group structure and composition has been attempted with the 2004 data only. To investigate sperm whale social organization, we used the SOCPROG programs (Whitehead 1999a), software that was specifically developed for this purpose.

The results from SOCPROG using all SWSS identification photographs suggest that sperm whales in the Gulf of Mexico best fit a "casual acquaintance" model with a disassociation rate of 0.0014037/day (SE=0.0012282/day), indicating that "casual acquaintances" disassociate at a rate of approximately once every 2 years. Proper application of the methodologies within SOCPROG requires a large number of sperm whales photo-identified over several years. Most identification photographs were taken during three weeks in 2003 and 8 weeks in 2004. In 2002 and 2003, it had not been possible to follow groups over consecutive days and few individual whales were resighted during the course of the field season. Thus, only the data from 2004 are really appropriate for investigating the internal structure of groups, and whether sperm whales follow the constant companions/casual acquaintances models found in the Pacific (Whitehead 2003). It is likely that we have too few resightings to obtain an accurate picture of social organization and more data are needed before a firm conclusion could be reached.

Although initial indications may be that sperm whales in the Gulf of Mexico do not follow the traditional "constant companions/casual acquaintances" model which was found in all studies of Pacific sperm whales (Whitehead 2003; Coakes and Whitehead 2004; Jaquet et al. 2005), the photo-id database contains some instances of individuals being resighted together up to 4 years apart, as we would expect to see from "constant companions" (see also Jochens and Biggs 2004). Some examples of such reassociations are:

- HL4, MTR2 and MTB3 were seen together in July 2002, June 2003 and June 2004, and SNR11 was with them in June 2003 and June 2004.
- HL 5 and NN 3 were seen together in July 2002, June 2004 and July 2004;
- HR 15 and SNB 12 were seen together in July 2000, June 2003 and July 2004 and HL 13 was seen with them during the last 2 years;
- MTL 4 and SNR 5 were seen together in July 2002 and July 2004;
- MTL 10 and SNB 10 were seen together in June 2003 and July 2004

Our results from 2004 provided one possible indication that groups in the Gulf of Mexico may be formed by two units. On 26 and 27 June 2004, we followed a group that contained HL4, MTR2, MTB3, SNR11 as well as LNL1, SNB31 and SS30. On 11 July 2004, LNL1, SNB31 and SS30 were found with another six new individuals, with no companions from 26-27 June. HL4, MTR2, MTB3, SNR11 had been seen together since 2002, and LNL1, SNB31 and SS30 were seen twice in 2004, each time associated with different individuals. Therefore, it is possible, but remains unproved, that these constitute permanent units.

To determine group size, number of calves per group, and group behavior, it is essential to first define what constitutes a group. However, the definition of a group is not straightforward for sperm whales, as groupings cannot be distinguished in real time and are likely to change membership in a matter of days to weeks (Whitehead 1999b). Photographic identifications of sperm whale individuals can be used to determine which group is present on which day. Groups were considered the same if more than 50% of the individuals identified on day *d1* were also found on day *d2* (Whitehead 1999b).

We identified 22 different groups during summer 2004. Identified were 6 groups of probable bachelor males, 3 lone bachelor males, 12 groups of female immature whales, and one group that was either composed of bachelor males or of females/immatures. The 12 different groups of female/immature sperm whales were all encountered in the Mississippi region and were followed day and night for 1.5 to 67.8 hours with an average of 30.3 hrs. Groups usually were not followed for more than two consecutive days, but on five occasions, groups were re-encountered 3 to 16 days later. This is the first time that identified groups were followed for more than 12 hours in the Gulf of Mexico, and with such data we can begin to investigate group structure and obtain a more accurate estimate of group size.

Estimating group size in the field is difficult, as foraging sperm whales are spread over several kilometers, and spend about 75% of their time underwater. Therefore, group size and composition is usually estimated at a later date using identification photographs. Experience has shown that, on average, two days are required for most individuals in a group to be identified (Whitehead 1999b; authors' personal observations). Group sizes were very consistent; all groups followed for more than 10 hours had 9 to 11 individuals. For the 11 groups with sufficient data, median group size was 9, Min =1 and Max =11. The mean group size was 7.2. Figure 4.1.14 shows group sizes for these 11 groups, with group sizes calculated as the maximum number of different individuals identified within the group. These results suggest that, in the northern Gulf of Mexico, groups contain on average about 9 to 11 individuals, and that group size is consistent between groups.

The results of the 2003 field season suggested a lower group size of 4 to 8 individuals (see Jochens and Biggs 2004). However, as groups were never followed for longer than 12 hours, average group size was likely to have been underestimated. Therefore, group sizes may well be consistent between 2003 and 2004. Our results suggest that groups in the Gulf of Mexico are about half the size of those reported from other areas (~20-22 individuals, Jaquet 2004; Whitehead 2003). We do not yet have sufficient data to elucidate whether these groups are formed by two units, as is common elsewhere (Whitehead et al. 1991), with units about one-half the size, or if groups have only one unit of a normal size.

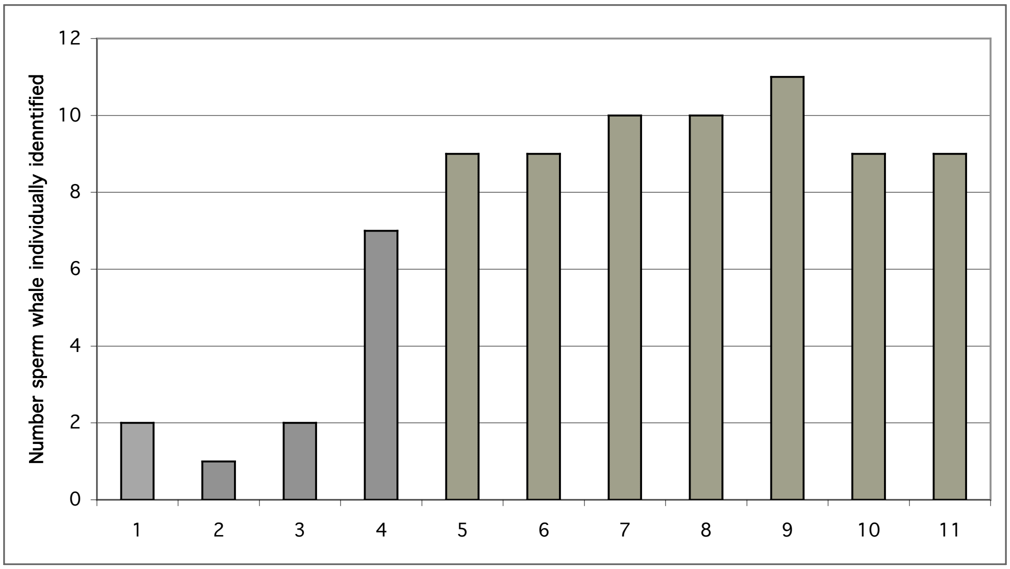

Figure 4.1.14. Estimated group sizes for 11 groups of female/immature whales identified in 2004. Groups followed visually for fewer than 7 hours are in gray. Groups followed visually for 8 to 36.75 hours are striped.

Group size may be related to the size of prey patches that can be exploited efficiently. The analysis of fine scale movements presented above is suggestive of smaller prey patches, which would be consistent with the smaller group size. One function of units is thought to be calf protection and calf care (Whitehead 1996b; Whitehead 2003). Calves cannot dive to depth for at least the first year of their life and thus they are left at the surface while their mothers forage at depth. While left at the surface, they are vulnerable to predation by sharks and killer whales. It has been hypothesized that the primary function of units is the communal care of the calves, and that units of about 10 individuals may be an optimal size for this purpose. It is possible that different conditions may affect the number of adults needed for the care of the calves but there are no indications that this should be the case in the Gulf of Mexico. However, we should caution that the amount of data in the Gulf of Mexico is still insufficient to determine whether groups are formed of one or two units and the size of the units.

Aggregations, defined as two or more groups associating together for several hours, were not seen in 2004, and only one aggregation was observed in 2003 (on 18 July). Aggregations are believed to be related to large/dense patches of food that are exploited simultaneously by several groups of sperm whales (Jaquet 1996). The absence of aggregations also suggests that prey patches in the northern Gulf of Mexico are small.

Calluses: Dorsal fin calluses appear as a roughness on the surface of the dorsal fin. A callus is often brownish in color, but can also be yellow or white (Figure 4.1.15). Calluses are believed to be a secondary sexual characteristic present mainly on mature females but sometimes also on immature males of less than 10 years of age (Kasuya and Ohsumi 1966). Therefore, calluses may help in determining the sex and maturity of sperm whales at sea.

Figure 4.1.15. The callus is the rough patch found on the dorsal fin of some individuals.

To determine the proportion of individuals with and without calluses, each time an individual was approached within about 70 meters, the presence or absence of calluses was investigated with handheld binoculars. In the second half of the 2004 season, gyro-stabilized binoculars were used and found to be helpful. However, in poor light conditions, or when the whale was approached directly from behind, it was not always possible to examine the dorsal fin adequately. For each encounter we recorded whether the whale had been viewed sufficiently well for calluses to be detected, and if it had, whether a callus was present or not. The data were entered into an HP palmtop computer along with information on other individual identification material.

Forty-six different individuals were checked for calluses. Of these 46 individuals, 25 had no calluses and 21 had a callus. Overall, 46% of individuals had a callus. Three probable lone males were checked for calluses and none of them had a callus. Similarly, two individuals from what we believed were bachelor groups were checked and neither of them had a callus. Only one individual that was suckling a young calf was checked, and this individual had a prominent callus. These preliminary results support the hypothesis that calluses are found on mature females but not on males. Unfortunately, so far, we have no genetic information on gender that we can relate to presence or absence of calluses. However, the six biopsies that we took during 2004 have information on identity and presence or absence of calluses, and thus once the sex of these animals is determined and made available, we will be able to relate this to the presence of calluses.

Eight groups of female and immature sperm whales were checked for calluses, and the proportion of individuals checked within a group varied from 21% to 90%. The proportion of individuals with calluses varied between 25% and 100%. However, when we consider only the groups where more than 50% of the individuals were adequately observed, we have a proportion with calluses between 33% and 66% (Figure 4.1.16). These results are consistent with what would be expected in a group of female/immature sperm whales (i.e., a few mature females with several immature of both sexes). This suggestion is made with caution, as we do not yet have definitive information on sex.

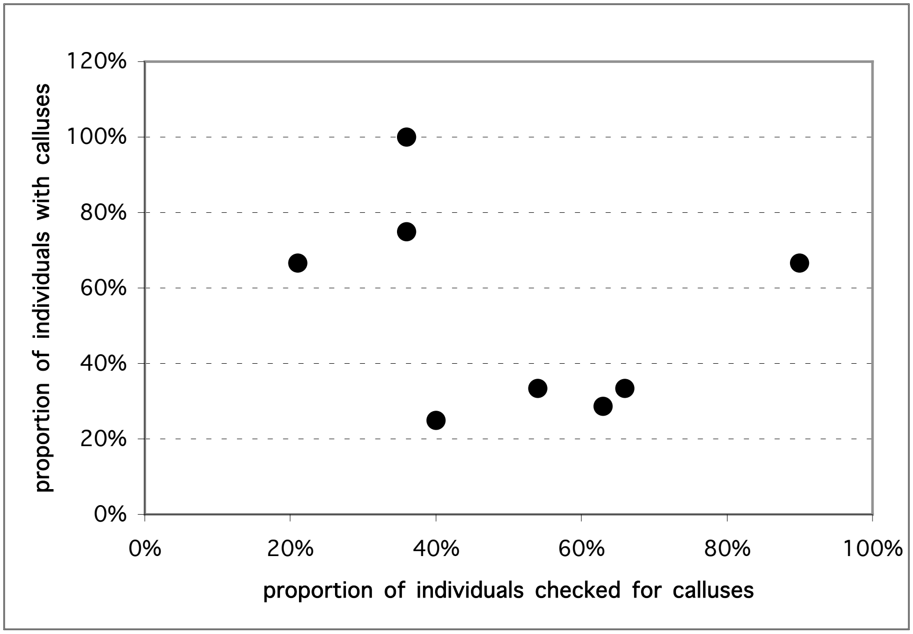

Figure 4.1.16. Proportion of individuals with calluses versus proportion of individuals checked in a group. Results for eight groups of female/immature sperm whales encountered in the Mississippi area in June-August 2004.

Occurrence of calves and large males: Calves were seen with almost every mixed group (Table 4.1.4), and many different juveniles were also sighted. A very small calf whose flukes were still soft and curled, indicating that it was hours or days old, was sighted on 3 May 2003.

During 2002 and 2003, few first year calves were observed, raising potential concerns for the health of the Gulf of Mexico sperm whale population. However, the platforms used to study sperm whales in 2002 and 2003 (R/V *Gyre* and RHIBs) were not very appropriate for making careful field observations. Calves were likely to have been missed due to the difficulty of observing them from a large vessel and the inability of following a group for more than 10 hours. In 2004, we found that 8 groups out of 11 had 1 or 2 calves with them. The overall proportion of calves was 11.5%. This proportion is of similar magnitude to that found in different areas of the South Pacific (Whitehead 2003) and is only slightly lower than in the Gulf of California (Jaquet et al. 2003; Jaquet 2004).

Table 4.1.4

Number of Calves in Each Group in the Gulf of Mexico (GoM) and Comparison with Data Collected During May 2003 in the Gulf of California

	GoM Mesoscale Study 2004	**Gulf of California May 2003**
Number of different group identified	11	13
Median number of individuals per group	9	16
Number of groups with no calves	3	1
Number of groups with 1 calf	7	4
Number of groups with 2 calves	1	5
Number of groups with 3 calves	0	0
Number of groups with 4 calves	0	2
Number of groups with 5 calves	0	0
Number of groups with 6 calves	0	1
Total # of calves	9	28
Number of different individuals identified (excluding bachelor males)	78	160
Proportion of calves	**11.5%**	**17.5%**

Length distribution: Knowledge of whale size (as related to age) is important in many ecological studies. Length measurements of individual whales can provide information on growth rate and allow estimation of population parameters such as pregnancy rate and age at maturity (Waters and Whitehead 1990). Measurement data can also reveal size-class segregation (Cubbage and Calambokidis 1987). Furthermore, changes in length distribution in whale populations can be used to indicate the degree of depletion of a stock, as highly exploited populations are likely to have fewer older and thus larger animals (Cooke and de la Mare 1983).

Measuring whales at sea is challenging as only part of the body is visible for a short time. Therefore, in several studies, lengths of whales have been estimated visually without ground-truthing individual lengths. However, it was shown from whaling data that whale lengths estimated before capture generally agreed poorly with measured lengths after capture (Ohsumi 1966; Best 1984). It is thus clear that reliable length estimates of whales at sea cannot be made even by experienced observers. In the past, two photographic techniques have been used to measure sperm whales (Gordon 1990; Dawson et al. 1995); however, neither of them was suitable to use from the *Gyre*'s RHIBs. Therefore, during the first two years of the SWSS study, we experimented with another technique which capitalizes on the recent availability of affordable laser range finding equipment and can be used from small vessels such as the *Gyre*'s RHIBs (Jochens and Biggs 2004). This technique involves measuring fluke width on digital photographs taken perpendicular to the whale using a known focal length lens and converting this to total length using an equation derived from whaling and stranding data (Fujino 1956; Clarke and Paliza 1972; Evans et al. 2002). The technique has been ground-truthed in studies in Kaikoura, New Zealand (March 2003) and the Gulf of California (May and November 2002, May 2003), and allows us to easily measure a large number of identified individuals (Jaquet 2006).

To obtain both an identification photograph and length measurement, sperm whales were approached slowly from behind to distances of 50 to 80 meters. At the start of each dive, a fluke photograph was taken with a Canon EOS D1 digital camera and a Sigma 100-300 (f4) lens set to maximum zoom. Simultaneously, the distance between the camera and the fluke was measured with a Bushnell 1000 laser range finder. Frame and distance were recorded on a HP 200LX palmtop computer. To ensure that all photographs were taken with the zoom lens set at the maximum focal lens of 300 mm, the setting was checked for each "measuring photograph" in Adobe Photoshop using the Canon utility software. The camera and lens were calibrated by measuring an object of known length (a wooden plank of 152 cm in length) at distances of 23 to 110 meters.

Photographs, in which the fluke was not angled perpendicularly or for which the animal was not recognizable, were not used for measuring. Furthermore, all flukes with large missing tips (see example on Figure 4.1.17) were disregarded for the analyses as the "full" lengths of these flukes could not be determined accurately. In 2004, 115 measuring photographs of 52 different individuals were obtained. Half of these individuals were measured repeatedly (up to 7 times, Figure 4.1.18) with image sequences taken during different encounters. The median coefficient of variation in these repeats was 1.66%. Estimated body lengths ranged from 6.1 to 13.3 meters.

Over the three years of SWSS study, 153 good measuring photographs were taken of 78 different individuals. Thus we have obtained length measurements for almost half of the individuals that have been identified. Of these 78 individuals, three were lone males measured on 5, 6 and 9 August 2004, and two were from a group of whales likely composed of bachelor males. The lengths of these five presumed males are presented in Figure 4.1.19. The length distribution of the 73 females/immatures is presented in Figure 4.1.20. For comparison purposes, we also present the length distribution of female/immature sperm whales from the Gulf of California, Mexico, which were measured using the same technique (154 individuals, Jaquet 2004).

Figure 4.1.17. Individuals with large missing tips cannot be measured using the technique described in this report.

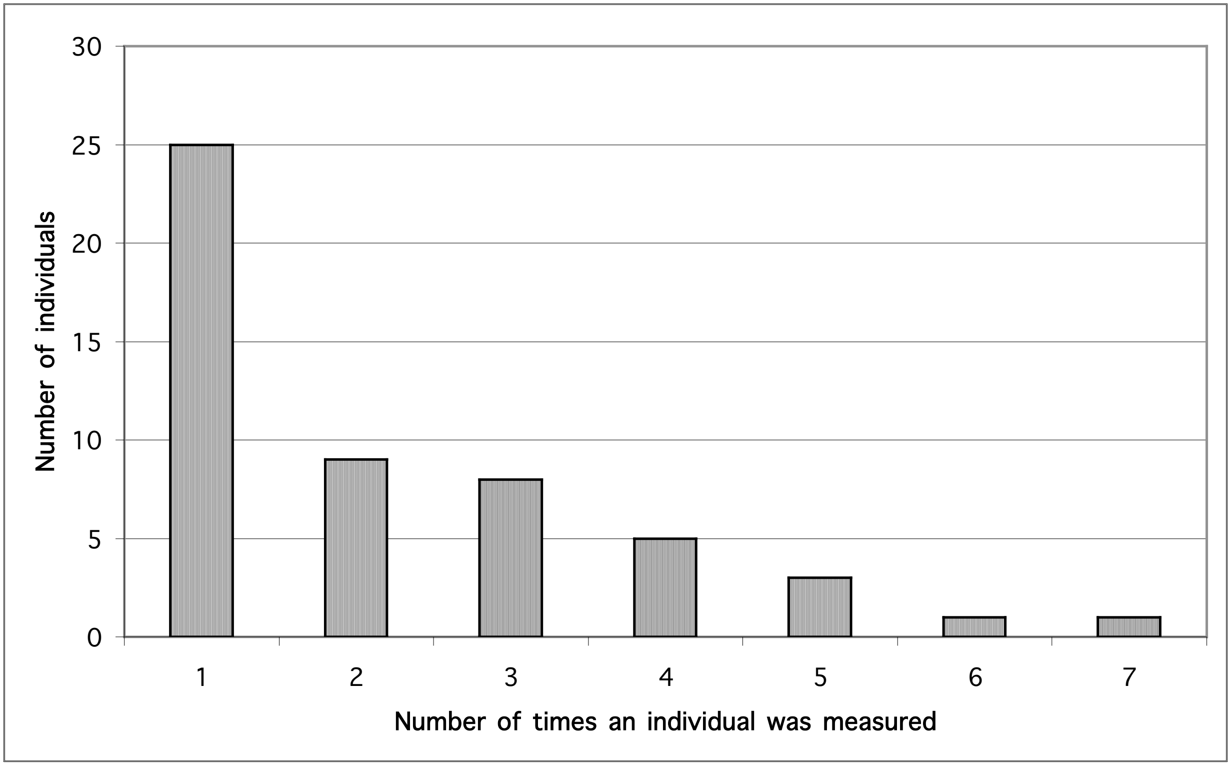

Figure 4.1.18. Frequency of measurements of 52 different individuals (Mesoscale population study 2004).

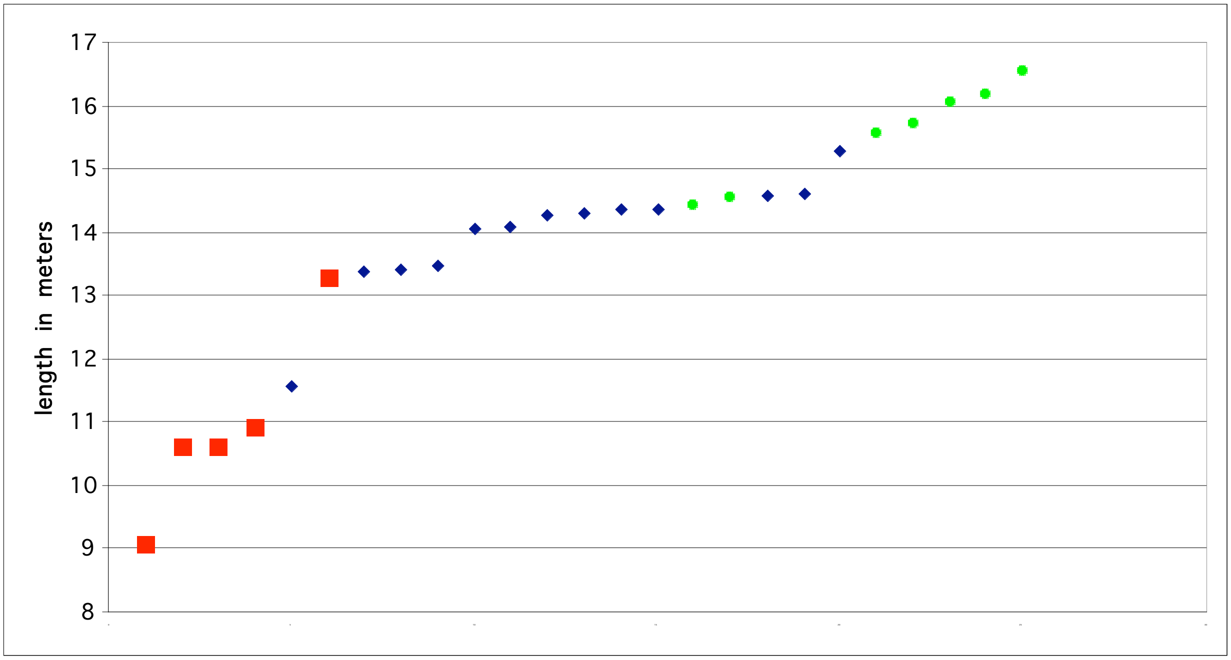

Figure 4.1.19. Length of 5 presumed males in the Gulf of Mexico (red squares), 13 bachelor males off Kaikoura (blue diamonds) and 7 large breeding males in the Gulf of California (green circles).

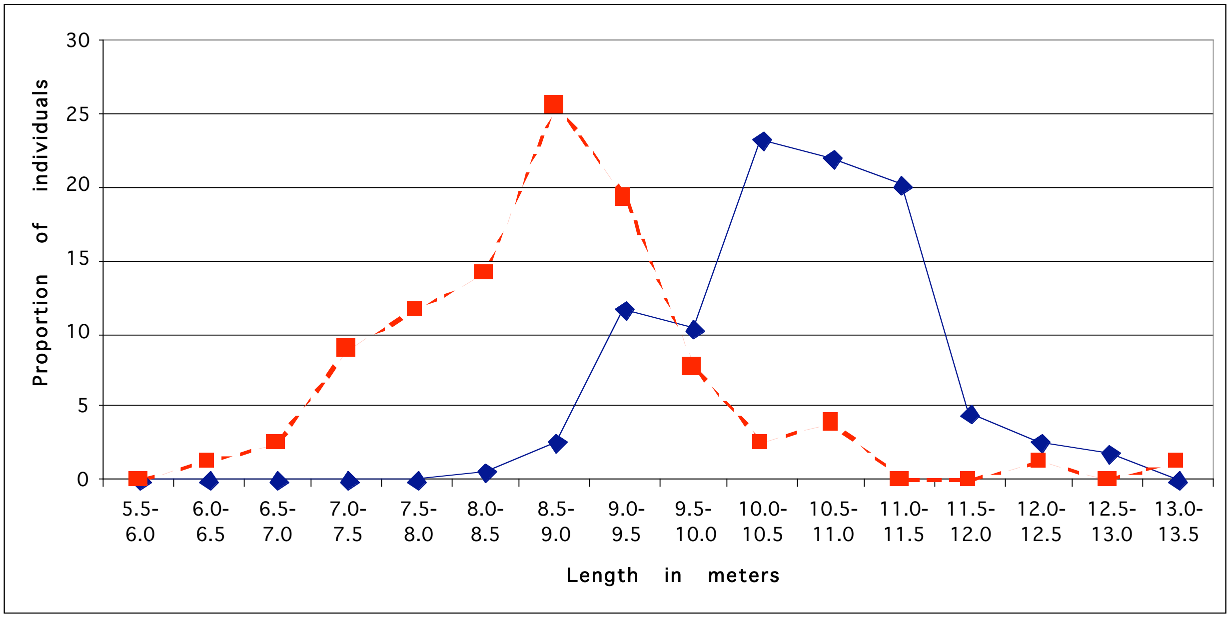

Figure 4.1.20. Length distribution for female/immature sperm whales measured in the Gulf of Mexico from 2002 to 2004 (in red, n=73) and for the Gulf of California in 2002 and 2003 (in blue, n=154).

In the Gulf of California, the modal length bin is that between 10 and 10.2 meters, which is in line with expectation from whaling data (Clarke et al. 1980; Rice 1989; Kahn et al. 1993). However, in the Gulf of Mexico, the whales are significantly smaller than those in the Gulf of California (comparisons of mean lengths, t-test: $p < 0.001$). The smaller size of sperm whales in the Gulf of Mexico is consistent with a resident population, making use of smaller prey field that is consistently available. Large body size, on the other hand, may be adaptive in areas where food resources vary considerably and individuals have to migrate to find areas of high food resources.

There are other factors that could potentially contribute to the small sizes of individuals. In other regions, sperm whales have been found to be fairly genetically homogenous (Lyrholm et al. 1999; Whitehead 2003), so it would seem unlikely that this size is due to genetic difference between populations. However, preliminary results suggest that sperm whales in the Gulf of Mexico are different from all other populations which have been studied in detail: their group size is about half the size of groups elsewhere, mature males seem to have either a different behavior or a different seasonality, groups of females/immatures have a very high site fidelity comparable to bachelor males off Kaikoura New Zealand, but never described elsewhere for females/immatures, and they have significantly higher incidence of markings on their flukes compared to areas in the Pacific Ocean (in Jochens and Biggs 2004 see Section 4.4). Furthermore preliminary genetic analyses suggest differences between individuals from the Gulf of Mexico and the rest of the Atlantic Ocean (Section 5). Similarly, preliminary analyses of codas suggest differences in repertoires between the Gulf of Mexico and the rest of the Atlantic (Section 4.3).

In several species of cetaceans, pygmy forms (e.g., pygmy blue whale, *Balaenoptera musculus brevicauda* or dwarf minke whale, *Balaenoptera acutorostrata*) have been described. In some cases the "normal form" and "pygmy form" have been separated into subspecies (Ichihara 1966; Rice 1998). It is possible that the substantial difference in mean size between sperm whales in the Gulf of Mexico and in the Pacific Ocean is the first indication that two distinct groupings of sperm whales exist. Another indication supporting this hypothesis is that one first-year calf (but not new born) was measured while it floated alongside the vessel, and was found to be about 3.3 meters in total length. This is substantially smaller than the expected size of calves as, according to whaling data, calves are born at a mean length of 4 meters (Rice 1989).

During leg 4 in 2004, we took measuring photographs of three presumed lone males (on 5, 6 and 9 August). They ranged in length from 10.6 to 13.3 meters. We also took measuring photographs of two individuals from what we believed might be a bachelor group and found their lengths to be 10.9 and 9.0 m. The length distribution of males is shown in Figure 4.1.19. For comparison purposes, the length distribution of large breeding males encountered in the Gulf of California (Mexico) and bachelor males measured in Kaikoura (New Zealand) are also presented.

As expected, males encountered in the Gulf of Mexico are substantially larger than females/immatures from the Gulf of Mexico (Figure 4.1.19). However, these males were significantly smaller than breeding males found in the Gulf of California. In the Gulf of California, no males smaller than 14.5 m, except immatures within groups of females and offsprings, were encountered. The lone males in the Gulf of Mexico were significantly smaller (10.6 m, 10.6 m, and 13.3 m), and no large males were ever encountered. Bachelor males from Kaikoura had a size intermediate between those of the Gulf of Mexico and Gulf of California (Jaquet 2006). It is likely that no breeding males have yet been encountered by us in the Gulf of Mexico and that all the males photo-identified and measured were bachelor males. The observations that none of these males were found in the proximity to groups of females/immatures and that no slow clicks (Weilgart and Whitehead 1988; Whitehead 1993) were heard during any of the acoustic monitoring stations in 2004 also support this suggestion.

In all other areas of the world where sperm whales have been studied in detail, breeding males are occasionally found with mixed groups year round, although in the northern hemisphere there seems to be a peak in frequency of observation during the spring months (Whitehead 2003; Jaquet 2004). It is therefore surprising that no breeding males have been encountered during our three field seasons. As first year calves were frequently sighted in 2004, and S-tagging data suggest that the range of females is restricted to the northern Gulf (Section 6.1), it is likely that breeding males must visit groups of females in the Gulf of Mexico. These findings suggest that the population of sperm whales in the Gulf of Mexico is somewhat different from well-studied populations from the Pacific Ocean and that either 1) males breed at a younger age or at least as smaller individuals than in the Pacific; 2) the breeding season is much shorter than in the Pacific, with few or no breeding males from late May to late August; or 3) breeding does not occur every year (rather unlikely). If hypothesis 1 were true, we would expect to find at least a few males with groups of females and to hear slow clicks at some acoustic monitoring stations, which we do not. We do not yet have enough data to discriminate between the other two hypotheses, and further field work would help to resolve this issue.

Resightings of Tagged Animals

During the three years of our photo-identification work in the Gulf of Mexico, we photographically identified 16 sperm whales that had been tagged by Bruce Mate and colleagues. For seven of these individuals, we also have a good picture of the tag (Table 4.1.5). Furthermore, we have one good picture of a tag for which we have no photo-identification as the whale did not fluke. During previous years we did not obtain good-quality photos of tags together with identification photographs. Tags were color-coded and, whenever possible, we approached the tagged individuals slightly on the side in order to determine the band colors. However, we found the determination of colors to be difficult, and observers seldom agreed. Yellow and white, or blue and black were especially difficult to separate in the field and thus the colors noted in Table 4.1.5 are indicative only.

The ability to identify tagged whales through photo-identification is very valuable, even allowing evaluation of the animal some time after a tag has detached. It provides data on the state of the tag and the animal's response and recovery after tagging. More importantly, the combined dataset of detailed satellite tracks from individual whales and photo-id data on its associates and their movements and associations is unique, and we anticipate gaining even more valuable insights as we bring the two SWSS datasets together in analysis.

Table 4.1.5

Information on Tagged Individuals

ID	Year Tagged	Tag Number	Photo of tag	Side	Date of tag photo	Possible Colors of tag	Callus	Length in meters
MTB 3	2002	2002-5719	n/a	n/a	n/a	n/a	Yes	n/a
LNB 2	2002	n/a	n/a	n/a	n/a	n/a	n/a	8.9
HR 2	2002	2002-5678	n/a	n/a	n/a	n/a	n/a	8.8
NN 1	2002	2002-5670?	n/a	n/a	n/a	n/a	n/a	9.5
HR 5	2003	2003-0843	n/a	n/a	n/a	n/a	n/a	n/a
LNL 2	2003	2003-0833	n/a	n/a	n/a	n/a	n/a	n/a
MTL 10	2003	2003-0828	n/a	n/a	n/a	n/a	n/a	n/a
MTR 2	2003	2003-0820	n/a	n/a	n/a	n/a	n/a	n/a
MTB 36	n/a	n/a	photo # 9	Right	25-Jul-04	All Blue?	No	n/a
SNB 10	n/a	n/a	Photo # 3	Right	4 July 04	White stopper, rest yellow?	n/a	8.9
SNB 31	n/a	n/a	photo # 7	Right	11 July 04	White base and blue tip	No	n/a
SNB 34	n/a	n/a	Photo # 2	Left	4 July 04		n/a	7.6
SNL 11	n/a	n/a	Photo # 4	Right	5-Jul-04	Blue base and yellow tip	n/a	8.6
SSB 32	n/a	n/a	Photo # 8	Left	19 July 04	Black base and white tip	n/a	n/a
SSR 33	n/a	n/a	Photo # 5	Left	10-Jul-04	Yellow base and red tip	n/a	n/a
?	n/a	n/a	Photo # 6	Left	10 July 04	Black base and white tip	n/a	n/a

4.1.3 Conclusions

Our study has shown that sperm whales can be easily found and studied in the northern Gulf of Mexico using the traditional techniques that have been utilized in many other areas. Using a quiet motor sailing vessel in 2004, an average of only 7.4 hours was needed to find a new group of whales. Sperm whales were found along the continental slope from the longitude of Galveston, TX, to the longitude of Florida. However, sperm whales seemed more abundant in the Mississippi area (including the area south of the Mississippi River Delta and the Mississippi Canyon) than elsewhere in the study area. We found a strong segregation between groups of female/immature sperm whales and bachelor groups or lone males. The former were mainly found in the Mississippi area and in the western part of the study area while the later were mainly found in the DeSoto Canyon and along the Florida slope. The reason for this segregation, which has not been described before, is puzzling. Mark-recapture analysis suggests that about 400 individual sperm whales utilize the northern Gulf of Mexico. This result suggests that a rather small population of sperm whales utilizes the northern Gulf of Mexico, in comparison to populations of sperm whales in the Pacific Ocean.

Groups of females and immature sperm whales have a high site fidelity for the Mississippi area, south of the River Delta and Canyon area. In 2004, some had a residency time of at least two weeks and about 40 individuals were present at any one time. Most resightings between years were observed from this area despite substantial effort in the western part of the study area and the DeSoto-Florida slope in both 2003 and 2004. Groups of female/immature sperm whales usually have a home range of about 800-1000 n.miles and move extensively within this home range (Whitehead 2003). To date, high site fidelity for a relatively small area (tens of n.miles) has been described in other areas only for bachelor males (Jaquet et al. 2000; Lettevall et al. 2002); this is the first time that it is described for female/immature sperm whales.

Comparisons within the NAMSC database have revealed no matches between Gulf of Mexico whales and identified animals in other parts of the North Atlantic and Mediterranean. However, the NAMSC catalogue is quite limited both in terms of spatial coverage and overall number of high quality images. Several other parameters suggest that the population of sperm whales of the northern Gulf of Mexico is different from other known sperm whale populations: group size is about half the size of groups encountered in the Pacific Ocean; individuals are significantly smaller than in other populations; their flukes are more heavily marked than populations from the Pacific Ocean; breeding males have either different behavior or different seasonality than in the Pacific Ocean.

Analysis of sperm whale movement patterns and defecation rates in the Mississippi area are consistent with the proposition that patches of prey here may be dense but rather small in size. Overall feeding conditions appear to be good for sperm whales. Sperm whales share their habitats with humans, but we have not found that their spatial organization is strongly affected by platforms. However, this population of sperm whales appears from our data to be so different from other known populations that more information is needed before more firm conclusions can be drawn.

4.2 Distributions and Relative Density of Sperm Whales in the Gulf of Mexico

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Introduction

During all the cruises undertaken as part of SWSS the immediate goals were to find groups of sperm whales and close with them so that research on individuals animals could take place. Such research might be photo-id, biopsy, or S-tag or D-tag telemetry. The cruises were not designed to provide population surveys with broad unbiased coverage. However, there were elements of searching both visually and acoustically on the cruises that used techniques very similar to those used for population surveys. By standardizing the way the search data were collected and distinguishing between periods when we were searching for whales in a pre-determined manner, periods when we were searching in a manner directed by existing or assumed knowledge of whale distributions, and periods when we were in contact with whales and following them, we have attempted to glean as much information as possible on population densities and distribution from these data.

Methods

Cruises normally started with a plan based on a set of pre-determined survey tracks designed to provide a fairly even and predictable coverage of the survey area. As cruises progressed, however, the plans usually had to be modified due to a number of factors including weather, logistic considerations, a requirement to avoid any potential for interference with other research groups or a desire to make use of recent or historical information on the likely distribution of whales to find groups for research purposes. Although predetermined survey designs were often soon abandoned rules similar in terms of survey areas, orientation of tracks and turning angles when the edge of survey areas were reached were usually applied, except when surveys tracks were directed towards areas of assumed whale density.

At all times, the vessel's activity was classified as being

- Monitoring survey – following predermined survey tracks or tracks determined using similar rules without knowledge of whale distributions,
- Passage – making a transit between two points which were not determined by whale locations; e.g., returning to port,
- Hunch Survey – moving to an area because there were reasons to believe that there were whales there, or
- Tracking – in contact with a group and following it so that whales could be approached for research.

This allowed any section of searching effort to be included or excluded from an analysis depending on the vessel activity. For example, monitoring and passage data might be considered appropriate data for investigating distributions but hunch surveys and tracking clearly would not.

Searching effort was both visual and acoustic. On the R/V *Gyre* visual and acoustic teams worked independently until detections had been made and the detected animals had come abeam. Because of the nature of the boat and of the research team, effective search effort on the sailboat was only acoustic. The acoustic teams monitored hydrophones carefully for one minute every 15 minutes. On the sailboat the engine would be slowed to tick-over during monitoring sessions to reduce noise and improve efficiency. Data from both the visual and acoustic teams were recorded in a standardized manner using the Logger database program.

Typically, once whales were heard the vessel would go into "tracking mode" and there would be no further survey effort until a decision was made to leave the group. The vessel would then steam away for at least an hour before survey continued.

To be able to understand whale distribution in terms of habitat parameters a GIS database was assembled incorporating information on bathymetry (depth, slope aspect) from the NGDC Coastal Relief Model (Volume 3-5), bottom type, and offshore structures (from MMS web site). Predictive variables for each survey point (listening station) were extracted from the GIS and General Additive Models (GAMS) were used to compare monitoring stations at which whales were not heard and those stations at which they were first heard.

Results and Discussion

GAMS models using data from 2002 and 2003 indicate a significant relationship between probability of detection (density) and both slope (Figure 4.2.1a), with angles in the mid range of 5-10 degrees having the greatest densities, and water depth (Figure 4.2.1b), where density plateaus between 1400 and 800 m (the higher values shown at depths of 600 m may be an artifact of very low samples size in this region). Once these factors were included in the model there were no additional effects related to range to platforms. The results so far must be considered very preliminary. They serve mainly to encourage us to pursue this approach. We hope, in collaboration with our oceanographer colleagues within SWSS, to include more predictor variables (including oceanographic variables) into our models in the near future and to repeat the analysis with input from specialist statisticians to advise on analysis of a somewhat non-standard dataset and address concerns about autocorrelation in monitoring data. It is encouraging though to find results that broadly agree with our own experience of sperm whale distributions in the area.

Within SWSS the S-tags will provide a very rich dataset on habitat usage by tagged sperm whales (Section 6; see in particular Section 6.2 that also examined slope and water depth on distributions). Thus one might question whether the type of analysis suggested here can contribute anything extra to that from telemetry. In fact it can be difficult to determine habitat preferences from telemetry data, as, by definition, they can only provide information on where a relatively small number of tagged whales went. Thus one must address the question of whether the data from a relatively small number of whales can be generalized to a larger population and whether relationships observed within the areas visited by these whales can be applied outside these areas. Thus a dataset such as this, which provides a more general perspective on where whales were and were not encountered within the study area is essential for confirming distributions patterns seen in telemetry data.

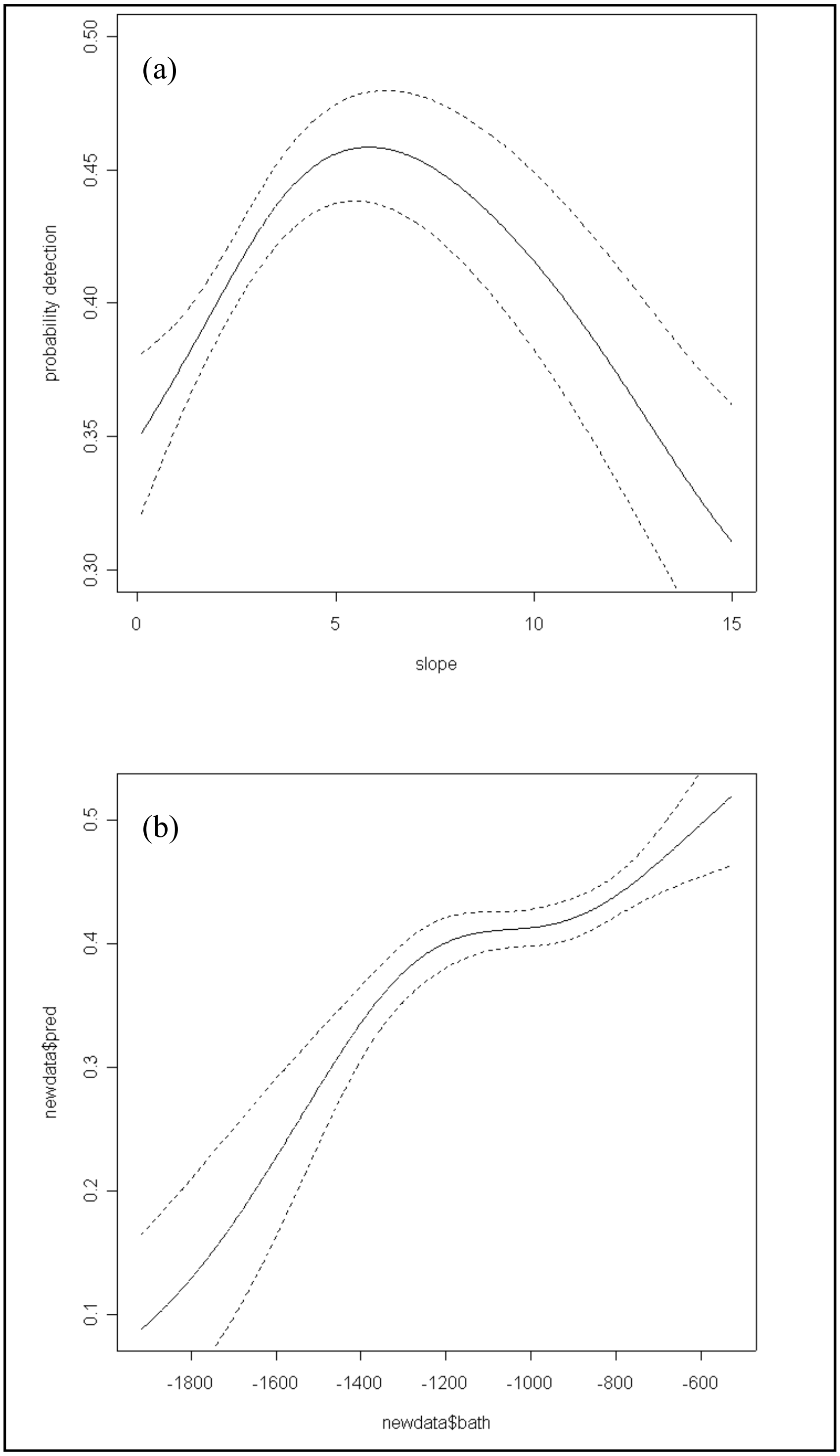

Figure 4.2.1. Output from GAMS models, using data from 2002 S-tag and 2003 WSHC cruises, showing relation between predicted density and (a) slope and (b) water depth.

4.3 Analysis of Codas from the Gulf of Mexico and Implications for Management

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Introduction

Sperm whale coda vocalizations consist of bursts of 3-20 broadband clicks, produced in stereotyped patterns, typically lasting for less than 3 seconds and often produced in repeated sequences. Codas were first described by Watkins and Schevill (1977) who reported that they often occurred at the end of sequences of regular clicks, hence their name. Most codas, however, are heard from members of mixed groups as they interact or "socialize" in large clusters at the surface. A typical behavioral pattern, reported from many regions, including the Gulf of Mexico, is for mixed groups to cease foraging and form such larger "socializing" clusters for an hour or so about once a day. An analysis of codas recorded in the Gulf of Mexico during GulfCet cruises between 1991 and 1997 identified 17 different types of coda and found no evidence of changes within coda types over this period (Apple 2002). Codas are thought to function as communication signals, and there is a rich field of fascinating research relating to the way in which sperm whales used codas to communicate. Here though, we focus on the important information that analysis of codas can provide for management and the insights this provides into population structure.

Within the Pacific, Weilgart and Whitehead (1997) found evidence of both group-specific dialects and geographical variation in coda repertoires. Whitehead et al. (1998) showed that variation in coda repertoire also correlated with differences in mtDNA. Most recently, Rendell and Whitehead (2003a) have shown that sperm whale social groups can themselves be organized into larger units which they called clans. Members of clans preferentially associate with groups in the same clans even though the spatial ranges of clans do overlap. It is clear that codas are learnt behaviors, thus the existence of clans has been taken as evidence of culturally-based organization in sperm whales. (Note: culture is an emotionally charged word and a great deal of rather fruitless discussion can be generated between groups applying their own different definitions. Here we use the word in the most straight forward sense suggested by Rendell and Whitehead (2001) "information or behavior – shared by a population or sub-population- which is acquired from conspecifics through some form of social learning".) Other types of behaviors which may significantly affect the fitness of individuals also seem to vary between clans. For example, Whitehead and Rendell (2004) showed that two clans encountered in the Galápagos appeared to differ in their foraging behavior, and in the way that they adapted their foraging behavior to an El Niño event. Clans were first identified through coda analysis and this remains the most effective way of determining clan membership and structure but the significance of clans from the perspective of management may go far beyond the fact that they make similar vocalizations.

The recognition of biological diversity within a species and the realization that this may be an important component of a species' evolutionary potential has led to an understanding that it is important in conservation to consider units at a lower level than that of the sub-species. The appropriate unit is often called the Evolutionary Significant Unit (ESU) but there is, as yet, no consensus on a definition for an ESU. Fundamentally though, it should be a subset of the species which, were it to be depleted, would represent the loss of a significant part of the species' overall biological diversity and evolutionary legacy. In most cases, biodiversity is thought of in terms of genetics and this is reflected in most definitions of ESU. For example, Waples (1995) suggests a population or group of populations that is (a) substantially reproductively isolated and (b) represents an important component of the evolutionary legacy of the species. However, long lived species with a complex social organization and overlapping generations may carry and pass on some of their evolutionary legacy, and information which is important for the survival and wellbeing of individuals, culturally and for these species, cultural as well as genetic subdivisions might sensibly be used to define ESUs. Weilgart et al. (1996) and Whitehead and Weilgart (2000) drew attention to the similarities in life history and social organizations between sperm whales and elephants. They present sperm whales as an extreme k selected animal living in an environment which can show large annual and decadal fluctuations. They suggest that information on how to best respond to different rarely encountered situations (major oceanographic changes such as El Niño for example) may be held within social groups in the memories of older individuals and transferred culturally between generations within groups and clans. In such a situation, maintaining diversity of knowledge and learned behavior should become an important goal for conservation. In the case of sperm whales it may then be argued that conservation management should be considered at the level of the clan and, as we have seen, these can be most readily distinguished through analysis of coda repertories. The argument here isn't that conserving codas is important per-se but rather that codas are indicators of a level of diversity of other learned behaviors which are likely to have survival significance. These may include a collective experience and learned responses to anthropogenic activities such as seismic surveys and other offshore activities.

Managers will often have more immediate concerns in addition to that of conserving biological diversity. Often animals will be managed as "populations" but the concept of population structure is a broad, and often poorly defined concept. In essence it's a description of differential association between animals but the temporal and spatial scales on which this association occurs, and the nature of the association, for example whether it is breeding or simply "being in the same area", can vary from example to example. From a management perspective, animals should be considered in separate populations if there is a reason for applying different management rules to each population group. Thus, for management, the levels and scales at which populations should be defined are really determined by the management questions that need to be answered. Animals that differentially associate to breed may, over many generations, develop genetic differences which can be identified as differences in genetic material (DNA), in proteins or in morphological traits. In animals with long generation times, such as whales, such differences may take thousands or millions of years to develop. Populations defined on this scale are relevant to management concerns relating to loss of genetic diversity (see above) and the extinction or recovery of populations over time periods of centuries. Typically though, management concerns and goals are orders of magnitude more immediate than this. Thus, even where no genetic differences are evident it may be appropriate to manage portions of the population as independent units. For example, western North Atlantic humpback whales share a common breeding ground in the Caribbean but sub-groups of the population are faithful to particular feeding grounds, which they are introduced to by following their mothers as calves. Management in feeding areas should consider feeding populations not just the larger breeding one indicated by genetics. Conversely, genetically distinct populations may share common feeding grounds where they may compete for food or be vulnerable to the same human impacts.

The conservation implications of cultural learning and organization in non-humans are discussed in a recent paper (Whitehead et al. 2004) which draws most of its examples from cetacea. These authors point out that the existence and nature of cultural organization can affect the way in which animals learn to adapt to or even exploit human activities. Where culture is horizontally structured newly learned traits can spread quickly through a population. Where cultural organization is vertical or oblique (as in sperm whales) different cultural units may develop different strategies to new situations. Because it can tend to favor conformity, culture can also lead to the persistence of maladaptive behavior in a population.

As a contribution to an International Whaling Commission (IWC) workshop to plan a research program for a worldwide in depth assessment of sperm whales, Whitehead and Mesnick (2003) presented a comprehensive review of methods for determining population structure and movements in sperm whales. They considered the strengths and shortcomings of a number of methods including telemetry, photo-identification, various types of genetic analysis, contaminants, morphology, trace analysis and others. They pointed out that many of the methods were complimentary. Each gave a different perspective on population structure and different methods provided information at very different temporal scales. Telemetry can provide information at the most immediate scales of hours to months. Photo-identification could best provide data at scales of years, while genetic analysis gave information on population structure at temporal scales of 100s to millions of years. Analysis of coda repertoires provided information at the temporal level of generations (decades) and was the only sperm whale characteristic that reliably showed geographical variation at spatial scales of less than an ocean basin (~5,000 km). We suggest that these are the temporal and spatial scales at which many sperm whale management issues in the Gulf of Mexico must be addressed making insights from coda analysis particularly relevant to management.

Methods

Data for this study have come both from cruises in the Gulf of Mexico as part of SWSS and SWAMP and from recordings made during a variety of cruises in the Azores and the Caribbean funded by the International Fund for Animal Welfare (IFAW).

Most recordings were made close to socializing groups, and in most cases we had information from photo-id on the time and location in which individual whales had been photographically identified within a day or so of the recording. Field recordings were made on a variety of media including analogue tape, DAT digital tape and directly to computer hard drives. Usually recordings were made using stereo towed hydrophones with 3m separation between elements and a fairly flat response between 0.1 and 15 kHz. In the analysis applied here we are concerned only with the relative time of individual clicks in codas, and for this, details of the frequency sensitivity of the recordings systems and small differences between them are not relevant.

Analogue field recordings were digitized at 48 kHz and DAT tape recordings were transferred directly to computer sound files. These full-length files were edited into a series of shorter files of manageable size (< 2mins) containing codas on a personal computer using editing software, such as Cooledit.

Codas were identified within recordings using the computer program Rainbow Click (Gillespie and Leaper 1996). Rainbow click identifies transient "click like" sounds and displays these on a time-bearing display. With user intervention, clicks produced by particular individuals were identified on the basis of their bearing, their spectral content and how they sounded when played back at full or reduced speed. Sequences of clicks comprising a single coda were identified and linked. Once this stage of the analysis was complete and the clicks for all codas within the recording had been correctly assigned, Rainbow Click's Export function was used to export the time and identity of each coda within the file. Thus, at this stage, the relative time of each click within a coda was known.

Methods for comparing repertoires followed the techniques described by Rendell and Whitehead (2003b) using code written in MATLAB. Readers are referred to that paper for methodological details.

Entire repertories of codas analyzed from particular identified groups were compared using an average multivariate similarity method which compared sets of codas based on the infinity-norm distance between two coda vectors.

$$s_{\mathrm{AB}} = \frac{\displaystyle\sum_{i=1}^{n_{\mathrm{A}}} \sum_{\substack{j=1 \\ l_j = l_i}}^{n_{\mathrm{B}}} \frac{0.001}{0.001 + d_{ij}}}{n_{\mathrm{A}}.n_{\mathrm{B}}},$$

In the equation above, S_{AB} denotes the similarity between coda sets A and B. l_i is the number of clicks in coda i of set A. l_j is the number of clicks in coda j of set B and d_{ij} is the maximum absolute distance between the vectors containing the standardized inter-click intervals of the codas. Codas having different numbers of clicks were assumed to have no similarity.

Results and Discussion

The dataset used in this analysis were 8885 codas. 3129 of these were recorded in the Gulf of Mexico during 2001, 2002 and 2003; 5092 codas were from the Azores, recorded between 1998 and 1995, 121 codas were recorded in Caribbean in 1995 and 1996 and 543 from the Mediterranean Sea.

Figure 4.3.1 is a dendrogram of the similarity matrix between coda repertoires. Again, recordings from different areas tend to cluster together being linked only at low similarity levels. The Gulf of Mexico is markedly distinct, even from encounters in the Caribbean. While there are clearly two or more clans present in the Azores there is only evidence for one clan being present in the Gulf of Mexico, and that clan is distinct from those found elsewhere in the North Atlantic.

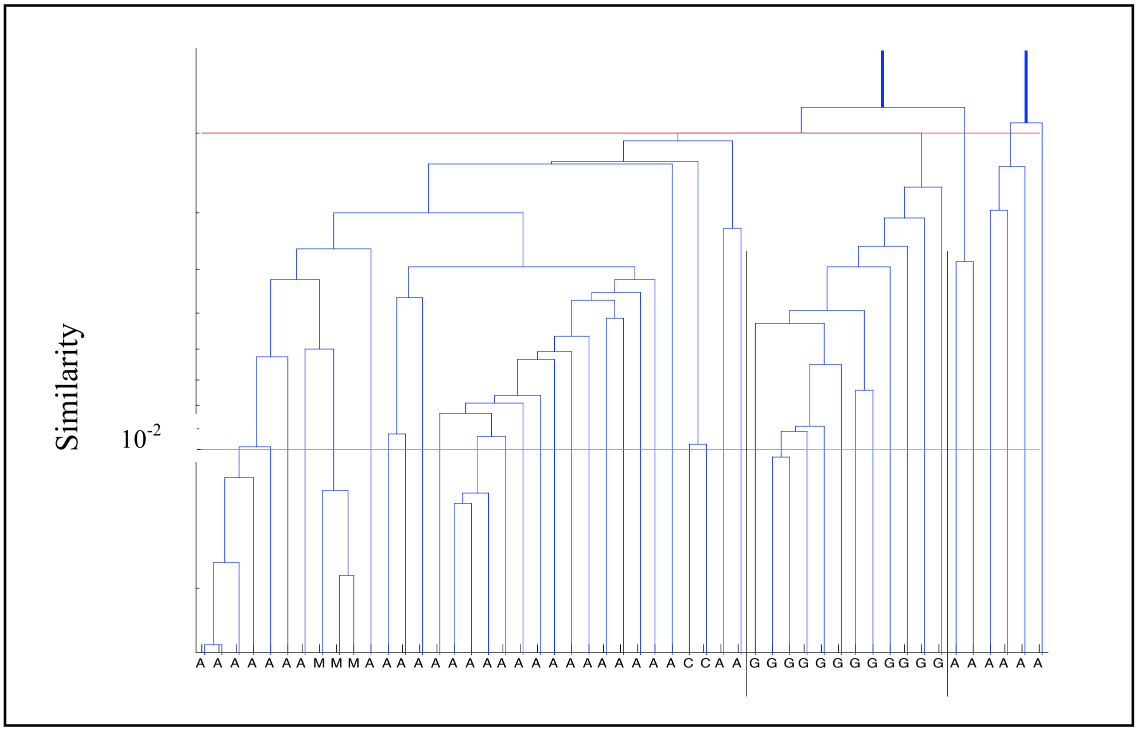

Figure 4.3.1. Dendrogram of the similarities matrix between the coda repertoires. G denotes Gulf of Mexico; A denotes Azores C, the Caribbean and M the Mediterranean. Only days when 25 or more codas were recorded are included. The red line represents the mean between clan similarity and the green the mean within clan similarity from independent studies in the Pacific (Rendell and Whitehead 2003a). Vertical black lines show how the Gulf codas represent a single discrete branch.

Conclusion

These preliminary results indicate that most of the mixed groups that have been encountered and recorded in the Gulf of Mexico belong to a single acoustic clan which was rarely encountered in other areas and that groups from other clans rarely enter the northern Gulf of Mexico. This can be taken as an indication of a degree of separation over scales of decades and suggests that for management questions at these temporal scales sperm whales in the Northern Gulf of Mexico should be treated as one population. This supports NMFS current designation of the Gulf of a distinct sperm whale stock in the Gulf of Mexico.

The existence of a distinct Northern Gulf of Mexico coda repertoire is most likely the result of learning within social groups. Members of these groups may also have learnt and share other behavioral traits which are important for their survival. They may have a shared experience of anthropogenic activities, which may be different to that of whales from other clans.

This work is preliminary, but paints a similar picture to that provided by many other lines of evidence from the SWSS project (photo-id, telemetry, genetics and body length) all indicating that the Northern Gulf of Mexico sperm whale population is reasonably discrete. It is interesting that among the recordings from the Caribbean, was one from just West of Cuba and yet should be so discrete. A research priority now should be to collect and analyze coda recordings from the wider Gulf of Mexico and adjacent regions in the Caribbean.

4.4 Acoustic Length Measurements from Gulf of Mexico Sperm Whales

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Introduction

The multipulsed structure of sperm whale clicks was noted in one of the very first publications describing the vocalizations of this species (Backus and Schevill 1966) and soon after, Norris and Harvey (1972) suggested a mechanism to explain this phenomenon. They proposed that clicks are produced by a structure called the museau de singe at the front of the whale's head and that this sound is then reflected between two air-filled sacs, which act as sound mirrors. One, at the front of the spermaceti organ is called the distal sac and a second running between the back of the spermaceti organ and the front of the cranium (the frontal sac) Each time the sound is projected forwards some passes out of the front of the whale's head into the sea and a proportion is reflected back again (Figure 4.4.1). Norris and Harvey realized that if this was the case the interpulse interval (IPI) should be twice the travel time between the air sacs at the front and back of the head. Later Møhl et al. (1981) proposed that measuring IPI could be a useful way of determining the body length of sperm whales in the field. Gordon (1991) analyzed IPIs from whales whose body lengths had been measured using an independent photogrammetric method. This provided support for Norris and Harvey's hypothesis and allowed an empirical formula relating IPI to body length to be derived. Recently, Rhinelander and Dawson (2004) have analyzed recordings made from photographically measured, moderate to large (13-15m) male sperm whales in New Zealand. This size class had not been well represented in Gordon's dataset and these new samples improve the reliability of the body length – IPI equation at these greater body lengths. Additional support for Norris and Harvey's proposed mechanism has come from experimental work by Mohl (2001). Working immediately post-mortem with a stranded sperm whale he was able to project impulsive sound into the head from close to the site of the museau de singe of and reproduce multi-pulsed clicks as predicted by the Norris and Harvey mechanism.

Acoustic length measuring can be a useful field technique in situations where it is difficult to measure body length in other ways. It also has the potential to provide very precise body length measurements, especially as IPIs from many tens or hundreds of clicks can be integrated to provide a single length estimate for an individual. For example, Pavan et al. (1998) were able to measure growth in individual sperm whales by comparing IPIs between years.

Different researchers have used a variety of methods to measure IPI. Gordon (1991) simply measured IPI directly from waveforms displayed on an oscilloscope, Goold (1996) and Pavan et al. (1998) recommended cepstrum analysis while Rhinelander and Dawson (2004) measured the time offset of a secondary peak in an autocorrelation of the entire waveform. In recent years (e.g., see in Jochens and Biggs 2004) we have used the IPI measurement tool within the Rainbow click program which performs a cross correlation between the first pulse in the click – which the user identifies and the waverform of the rest of the click. A difficulty when measuring IPI in typical field recordings is that additional pulses can appear between the "real" pulses, often increasing then decreasing in magnitude gradually over the course of a series of clicks. These can actually be bigger than the "real" secondary pulse and can lead to errors and bias when approaches such as full waveform correlation are used or involve a significant amount of interpretation and analyst input if the rainbow IPI length tool is employed. Such analyst input could introduce a subjective element to IPI measurement and also slows down the process of analyzing clicks.

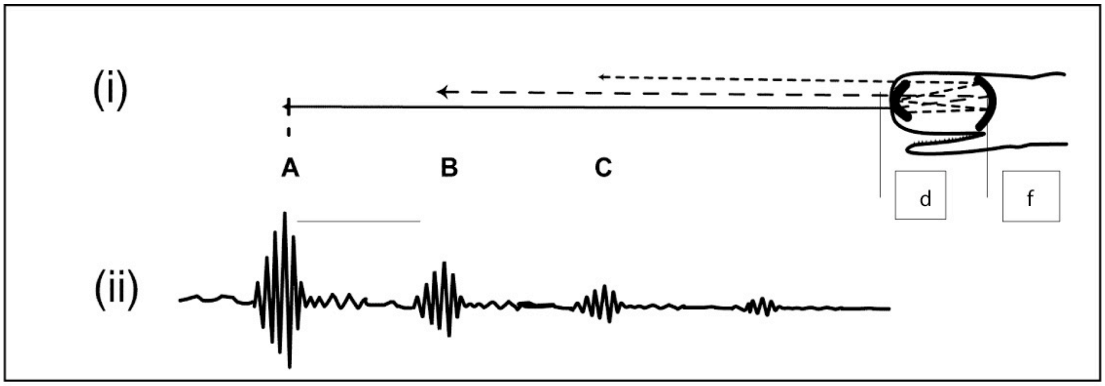

Figure 4.4.1. Mechanism for formation of pulsed clicks in sperm whales proposed by Norris and Harvey (1972). Sound produced at the front of the spermaceti organ reflects off the distal sac (*d*), passes back and is reflected by the frontal sac (*f*) and then passes forward. Some sound emerges as pulse A, some is reflected over the same pathway to eventually emerge as pulse B. The inter pulse interval (IPI) is twice the travel time between the distal and frontal sacs.

The mechanism for the production of multiple pulses in sperm whale clicks proposed by Norris and Harvey (1972), and now widely accepted, predicts that the "real" secondary and tertiary pulses should occur at a fixed time delay after the main pulse. With signals like this, temporal integration is a powerful signal processing technique for distinguishing a time invariant signal from noise and we have applied this approach to develop an automatic and robust method for measuring interpulse intervals in sperm whale clicks.

Methods

For this analysis only recordings made from the vessel *Summer Breeze* in 2004 have been analyzed. Field recordings were made after a whale fluked up using the sailing vessel's acoustic system (see Appendix for details). These recordings were analyzed using the Rainbow Click program. Typically, many whales could be heard vocalizing on such recordings but the clicks of the whale that had just fluked could be distinguished when it first started vocalizing and these could be recognized, tracked and labeled throughout the early part of the recording on the basis of their relative bearing and spectral characteristics. All clicks from the focal animal were labeled and the waveforms of all labeled clicks were extracted.

Temporal integration of click waveforms was implemented as a Matlab program. The program takes as input the waveforms (i.e., a series of sample values) of a sequence of clicks assigned to an individual whale. Each click waveform is rectified (all sample values are made positive), and added to the sum of the previous clicks in the sequence. Before integration each rectified waveform is time-aligned by finding the time delay between itself and the summed clicks. This is accomplished by using either a cross-correlation or maxima peak matching method.

For multi-channel recordings (e.g., stereo) each channel is added independently to the sum of previous clicks.

The IPI is estimated from the resulting integrated waveform by a peak finding routine and these measurements were also checked by eye (e.g., Figure 4.4.2). The quality of the integrated waveform and reliability with which IPI could be measured was assessed by eye and classified. Cases in which there was a single clear peak were allocated to category 1, less clear cases, where there was more than one peak for example, were classed as category 2 and cases where there was no clear peak were classified in category 3.

Results and Discussion

Ninety-three sound files (WAV PCM format) recorded immediately after whales fluked up in the Gulf of Mexico were analyzed to provide 119 individual whale IPI measurements (initial click trains from more than one whale could be distinguished in some recordings) which were based on integration of 26,262 click waveforms. Of these, 95 were in the highest category (1); 16 were in category 2 and eight were in category 3. The estimated lengths of the whales were calculated from the measured IPI values using the formula presented in Gordon (1991). Figure 4.4.3 shows data for 12 occasions on which a photographic and acoustic length measurement were obtained for the same individual whale. The two length measurements are well correlated although acoustically derived lengths tend to be greater than photographic lengths. Both methods are still being developed and we would hope that some variability will be reduced as the techniques are further refined. The distributions of acoustic length measurements for category 1 and 2 estimates and photographic length measurements made in 2004 are shown in Figure 4.4.4. Although the general distributions are quite similar some differences between photographic and acoustic length measurements are apparent. As would be expected from Figure 4.4.3, the modal class for acoustic estimates of length (9.0-9.5m) is greater than that for photographic length estimates (8.5-9.0 m). The disparity between the photographic and acoustic length estimates, evident here and in Figure 4.4.3, could well be due to inaccuracies in the equations used to derive body length from fluke span and/or from inter-pulse interval. The latter equation is probably rather less reliable than the former at the moment because it is based on a smaller number of reliable records. We can confidently look forward to more reliable equations being developed in the future; in addition, either length measurement technique can still be reliably used to measure growth and make comparisons between regions or between components of a population. There is a second small peak at around 12m in the acoustic data which is less prominent in the photographic distribution. This represents the larger animals encountered in the DeSoto Canyon area in the eastern portion of the study area. These have been excluded from the photographic dataset.

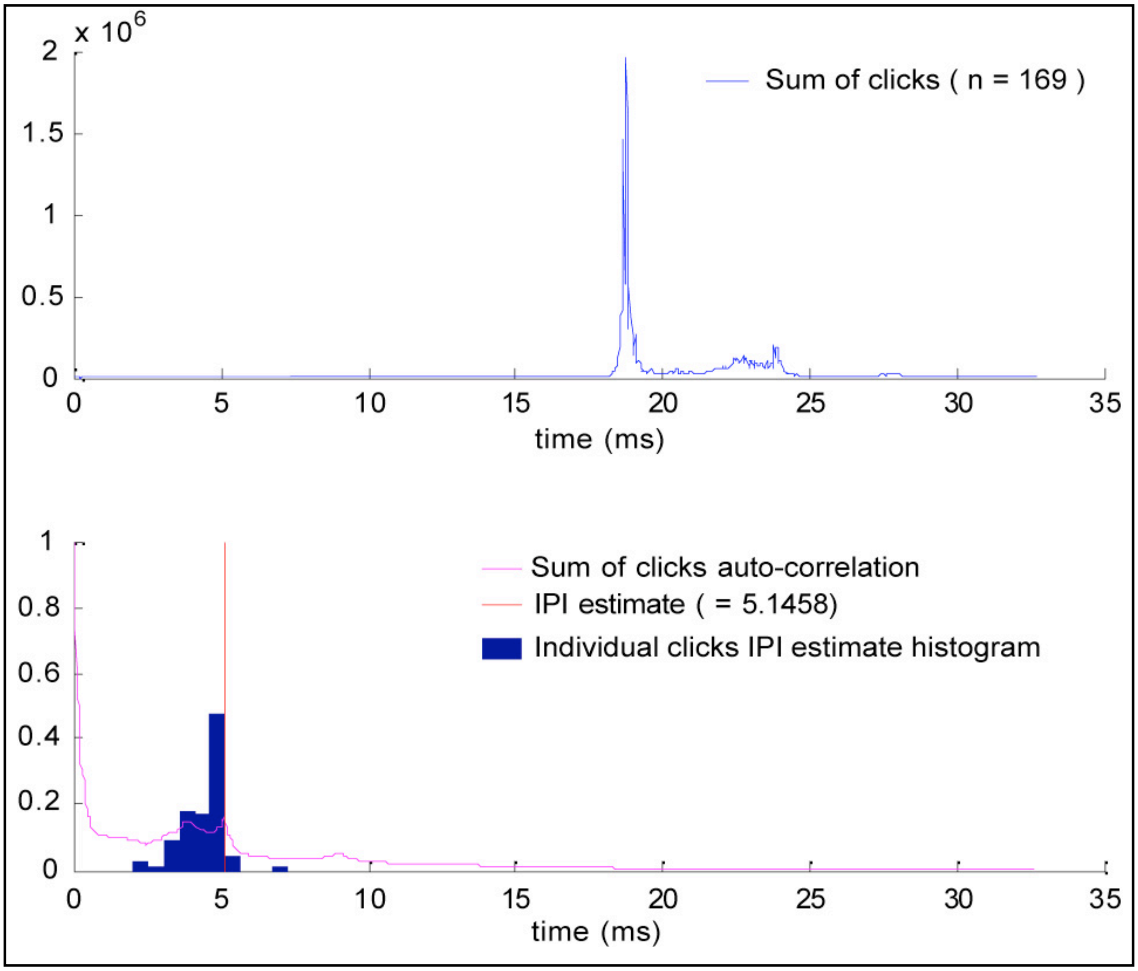

Figure 4.4.2 Example of application of the automatic IPI measurement by temporal integration. The top graphic shows the waveform resulting from the integration of 169 rectified clicks and shows two peaks corresponding to main and second pulses (A and B in Figure 4.4.1). The autocorrelation function of the integration waveform is shown in the lower pane with the IPI estimate value (red line) and the histogram from individual IPI click measurements.

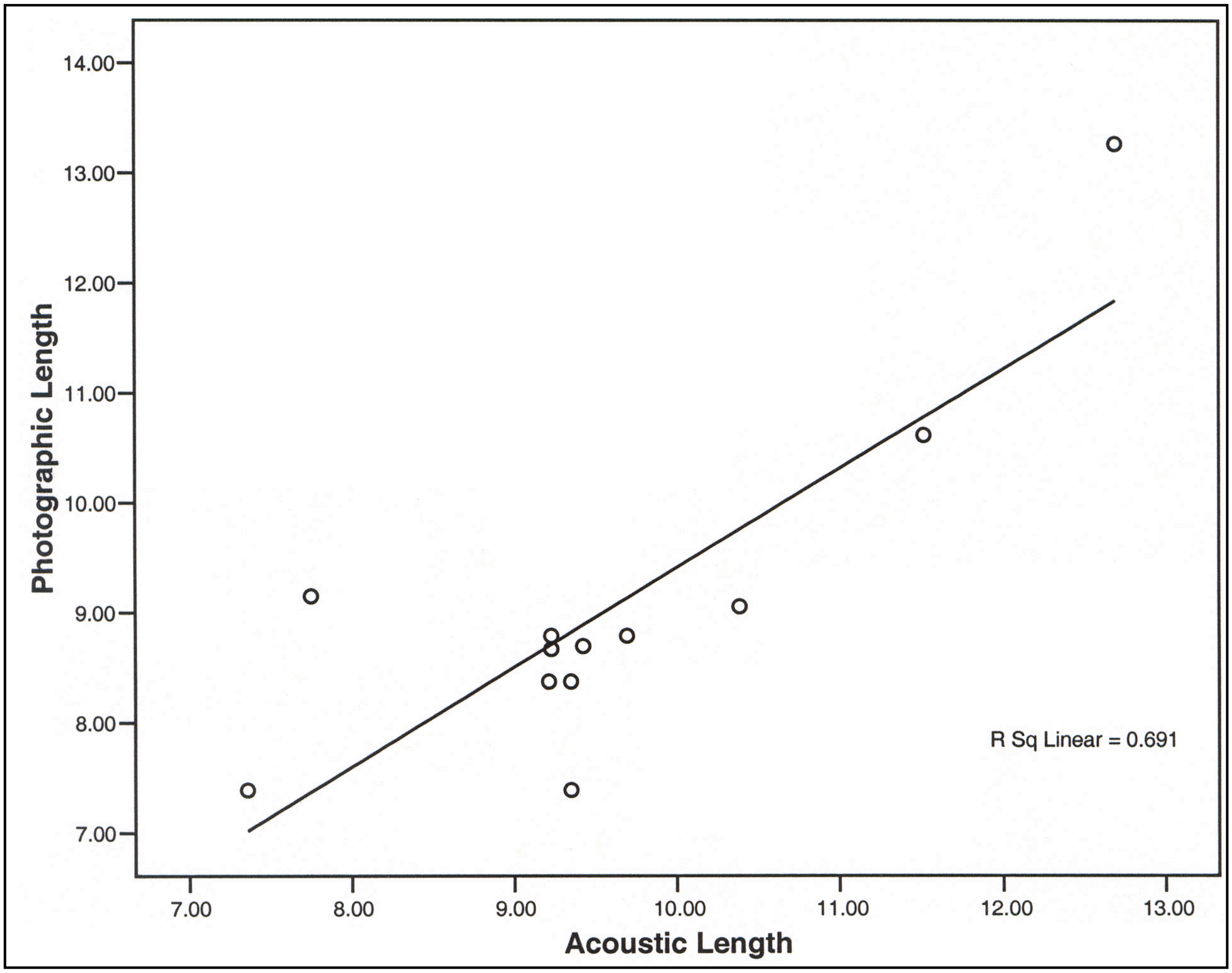

Figure 4.4.3. Photographic and acoustic measurements for 12 sperm whales made in the Gulf of Mexico in 2004.

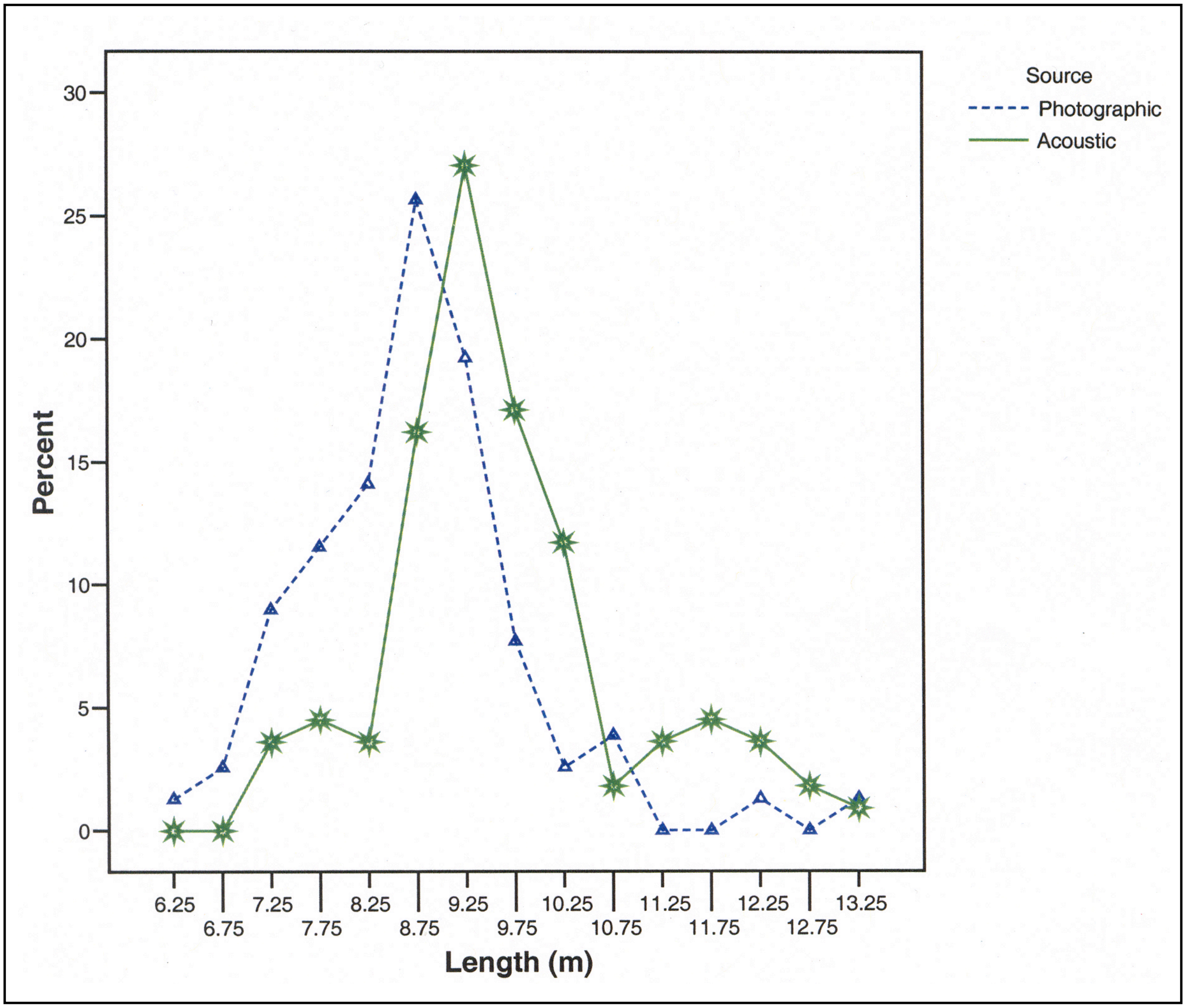

Figure 4.4.4. Photographic and acoustic measurements of sperm whales made in the Gulf of Mexico. Photographic measurements are only for members of mixed groups; acoustic measurements include solitary males.

Conclusions

The new algorithm, utilized here for the first time, shows promise as part of an automated method for reliably measuring IPIs from sequences of clicks. Development of this method is still in an early stage and further work needs to be done to reduce variability. Avenues to be explored will include filtering and windowing of the click waveforms prior to integration and alternative methods from peak detection.

The data from both the acoustic and photographic length estimates indicate that sperm whales in the Gulf of Mexico have shorter body lengths than populations in other areas such as the Pacific and Gulf of California. See Section 4.1.6 for a more detailed discussion of this finding and its implications.

If the acoustic method can be developed to deliver the accuracy that it promises to be capable of and provide length estimates with sufficient precision to allow yearly growth of identified animals to be measured directly, as Pavan et al. (1998) suggests, then it will have considerable significance as a source of useful information on vital parameters for managers. For example, long term impacts of anthropogenic activity might be detected first as a decrease in growth rate in certain age classes.

5 GULF OF MEXICO SPERM WHALES – A GENETIC PERSPECTIVE

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The molecular ecology for sperm whales (*Physeter macrocephalus*) in the northern Gulf of Mexico (GOM) was investigated in detail using a suite of molecular markers. In addition, several genetic related aspects for the Mediterranean Sea (MED), North Sea (NSEA) and the North Atlantic Ocean (NAO) putative sperm whale populations were also described. These analyses have provided new insights requiring proper management to ensure the survival of the northern Gulf of Mexico sperm whale stock in an area of increasing industrial activity.

Population structuring between the four putative populations, with respect to mtDNA, was highly significant and warrants the classification of each putative population as a unique stock for management purposes. The majority of Gulf of Mexico samples were from females and young males believed to be sexually immature based on rough size estimates. Incidental resampling of a few individuals over periods of days, months and years adds support for site-fidelity to the northern Gulf of Mexico exhibited by at least some whales. Although our sample set compares a more restricted geographic area than previous studies, the lack of significant nuclear differentiation between neighboring populations suggests that sexually mature males disperse from their natal populations and spread their genes to the more philopatric females.

The genetic composition of Gulf of Mexico sperm whale groups fits the mixed sex and bachelor group type so common in other areas of the world. Relatedness within the Gulf of Mexico female-dominated groups was significantly greater than that found between groups, but still surprisingly low and composed of both single and multiple matrilines. Highly related whales (i.e. parent-offspring) were present within groups, but infrequent. The most common relationship found was that of half-siblings. The all-male bachelor groups were comprised of multiple matrilines and members were generally unrelated, although cases for half-sibling pairs were present.

5.1 General Introduction

Several species of cetaceans are notoriously difficult to study as they spend the majority of their time underwater and inhabit deepwater offshore areas that require high-cost means to gain even a glimpse into their rather secretive lives. While data gathered by researchers aboard whaling vessels primarily between 1950 and 1980 did provide basic information with regards to reproduction, morphology and movement patterns through the use of discovery tag recaptures, an accurate assessment of social and population structure among free-ranging sperm whales (*Physeter macrocephalus*) proved illusive. Pioneering efforts by Jonathan Gordon and Hal Whitehead that began in the 1980s provided the initial non-lethal steps towards unraveling fine-scale social and population structure details for free-ranging whales. Whitehead's long-term study of sperm whales found off the Galapagos Islands and Ecuador provides one of the most significant contributions towards understanding how free-ranging sperm whales live.

The incorporation of molecular markers is a relatively young technique that has the potential to provide a wealth of information with respect to both social and population structure for 'difficult to study' species. With the advent of the polymerase chain reaction, minute amounts of DNA collected from sources ranging from skin to bone can be replicated to produce a viable sample for analysis. The analysis of nuclear DNA, mtDNA and sex-specific genetic markers provides information on identity (Paetkau and Strobeck 1994), gender (Berube and Palsboll 1996), kinship (Blouin et al. 1996; Richard et al. 1996; Ralls et al. 2001), mating systems (Girman et al. 1997; Fabiani 2002), reproductive success (Gemmell et al. 2001), philopatry and dispersal (Lyrholm and Gyllensten 1998; Lyrholm et al. 1999; Fabiani et al. 2003).

5.1.1 The Use of Molecular Techniques To Study Cetaceans

Population Structure
The allocation of endangered species into particular 'stocks' or populations based solely on geographic boundaries seems illogical for most marine mammals given their huge potential for movement. Genetic analyses provide a more suitable means of assessing biologically significant population subdivisions. Significant subdivisions within and among populations seen via an examination of gene frequencies provides a fundamental tool for the management of exploited and protected species. The differentiation of gene frequencies within and among populations can be a result of gene flow via migration of individuals or their gametes, random genetic drift, natural and sexual selection modes, mutations, and genetic recombination opportunities that have been mediated by the mating system (Avise 1994).

Female philopatry and male dispersal are the expected patterns of dispersion for mammalian species based on theoretical considerations (Greenwood 1980). The differences in dispersal between males and females may influence how populations are structured from a genetic perspective. Population structure affected by gender-based dispersal is particularly visible when one compares the haploid and maternally inherited mtDNA with the bi-parental nuclear genome (Avise 1994). If females are philopatric and males disperse, then one expects to find more variation between putative populations with respect to mtDNA and less variation with respect to nuclear DNA. Previous cetacean studies on humpback whales (*Megaptera novaeangliae*: Palumbi and Baker 1994; Baker et al. 1998), fin whales (*Balaenoptera physalus*: Berube et al. 1998) and sperm whales (Lyrholm et al. 1999) using genetic techniques based on mtDNA and nuclear DNA provide valid support for this sex-biased dispersal scenario. Lyrholm et al.'s (1999) sperm whale study examined population structure on a very broad global scale by comparing a collective set of samples from the North Pacific, North Atlantic and Southern hemisphere oceanic populations. Whether geographic structuring was present within geographic areas of the North Atlantic Ocean was untested and thus deemed a priority for sperm whale management related issues.

Group Composition
Sperm whale mixed groups tend to be found in low latitude warmer waters while young all-male bachelor groups and solitary males tend to frequent higher latitudes (Rice 1989). Upon reaching sexual and physical maturity, males return to lower latitudes to breed with females (Best 1979; Rice 1989; Whitehead 1993). Berzin's (1972) idea of sperm whales forming a 'harem band' mating system, with a male dominating a group of females, has since been replaced with a widely accepted polygynous system where sexually mature males only temporarily associate with groups of females in estrous (Best 1979; Rice 1989; Whitehead 1993; Christal and Whitehead 1997; Lyrholm et al. 1999; Whitehead and Weilgart 2000). The early studies that identified long-term relationships between females (Ohsumi 1971), the presence of juveniles and

calves of both sexes and adult females (Best 1979) and what appeared to be cooperation among individuals within groups (Caldwell and Caldwell 1966) led several researchers towards the premature conclusion that sperm whale groups were strictly matrilineal in structure. While it has been noted that the banding together of females into groups may indeed support cooperative foraging, communal care of calves, and provide a collective defense mechanism to defend against predators (Best 1979; Arnbom et al. 1987; Whitehead et al. 1991; Whitehead 1996b); a purely matrilineal group structure where females remain with their mothers has since been rejected (Richard et al. 1996; Lyrholm and Gyllensten 1998; Christal 1998). The stable social unit appears to present the most probable case for highly related members, although transfers of unrelated whales between units does exist (Christal 1998). In addition to avoiding inbreeding with one another, close kin in vertebrates tend to cooperate and associate more than unrelated individuals (Emlen 1997). The extent of kinship structure that underlies the observed social behavior of sperm whale groups is fundamental towards understanding the evolution of social organization and may have important implications as to how to best manage putative populations (Pamilo 1989; Queller and Goodnight 1989).

5.1.2 Study Aims

As a result of the lack of required information available for management to base decisions on, the primary objective of this research is to describe the genetic structure for the northern Gulf of Mexico stock of endangered sperm whales with respect to both group composition and population structure. In particular, group and cluster compositions were examined from both a gender and genetic relatedness perspective, while the assessment of mtDNA and nuclear DNA genotypes within and between putative populations were analyzed to provide resolution with respect to how stocks are structured.

This study aimed to describe the following aspects:

1. Genetic structure of four putative geographic sperm whale populations: Previous results for sperm whale population structuring on a global scale based on both matrilineal and bi-parental genetic markers are consistent with the expectation of greater female than male philopatry in this species (Lyrholm and Gyllensten 1998; Bond 1999; Lyrholm et al. 1999). A sufficient sample size allowed for an examination of structuring within sub-areas of the North Pacific (Lyrholm et al. 1999), however, genetic structuring within areas of the North Atlantic and Southern hemisphere was not possible due to the lack of sample material.

This study quantifies the level of geographic structuring and genetic variation among four putative sperm whale populations located in the Gulf of Mexico, Mediterranean Sea, North Sea and the North Atlantic by examining the maternally inherited mtDNA and multiple polymorphic microsatellite loci from the bi-parental nuclear genome. This comparison provides a genetic perspective towards understanding how male and female patterns of dispersal influence population structure within this species. Finally, this study provides an important insight as to what extent sexually mature males may be distributing their genes to multiple geographic populations. If sexually mature roving males spread their genes to multiple geographic populations, then this should have consequences on the level of nuclear DNA variation that is present within and between populations.

2. Composition of sperm whale groups and clusters in the northern Gulf of Mexico and the North Sea: Sperm whales exhibit a cosmopolitan distribution with females and young males remaining in more tropical and subtropical waters, while larger males increase their range into more polar latitudes as they age and grow (Best 1979; Leatherwood and Reeves 1983; Rice 1989). Apart from the solitary or occasionally paired sexually and physically mature males, sperm whales are most often found in mixed sex and all male (bachelor) groups (Best 1979; Whitehead and Arnbom 1987; Rice 1989; Childerhouse et al. 1995). Previous genetic-based findings suggest a significant level of relatedness among female dominated mixed sex social group members (Richard et al. 1996; Lyrholm et al. 1996, 1999; Christal 1998; Bond 1999). A better comprehension of the relatively unstudied groups found in the northern Gulf of Mexico stock was deemed an important and necessary step towards understanding the extent of group structure for these speculated 'resident' whales.

This study utilizes molecular markers to combine gender information, maternal lineages and genetic relatedness among individuals sampled from both clusters and groups to provide a more detailed assessment of how groups and clusters of sperm whales within the northern Gulf of Mexico are composed. Relatedness values were tested for members found both within and between groups and clusters to assess whether genetic patterns influence social structure (pending long-term association analyses). This was particularly important with respect to multiple whales that were biopsy sampled and tagged with OSU's satellite-monitored radio transmitters.

5.2 Materials and Methods

The collection of tissue samples from free-ranging and stranded sperm whales was conducted under Marine Mammal Protection Act / Endangered Species Act permit #909-1465. Tissue collection for free-ranging and stranded sperm whales, DNA extraction, DNA processing and data analysis methods are described in extensive detail in Engelhaupt (2004).

5.3 Results

5.3.1 Sampling Locations and Duplicate Samples

A total of 212 tissue samples comprised of biopsies (N = 152) and sloughed skin (N = 60) were collected from free-ranging sperm whales located in the northern GOM during one 2000 NMFS cruise (Figure 5.3.1) and six SWAMP and SWSS research cruises conducted during 2000 – 2004 (Figures 5.3.2 – 5.3.7). Of these, 24 samples were collected from sloughed skin that had opportunistically adhered to the WHOI Dtag suction cups and 37 samples were of whales sampled by biopsy dart or sloughed skin collection after OSU satellite-monitored tags had been attached. A further four samples were collected from dead stranded whales in the GOM (Texas: N = 2, Louisiana: N = 1, Florida: N = 1).

Of the 212 free-ranging sperm whales tissue samples, at least 92 samples (this number does not account for the 2004 samples still being processed) were determined to be genetic duplicates as per the criteria outlined in Engelhaupt (2004), leaving us with a total of 120 unique free-ranging individual whales sampled within the northern Gulf of Mexico.

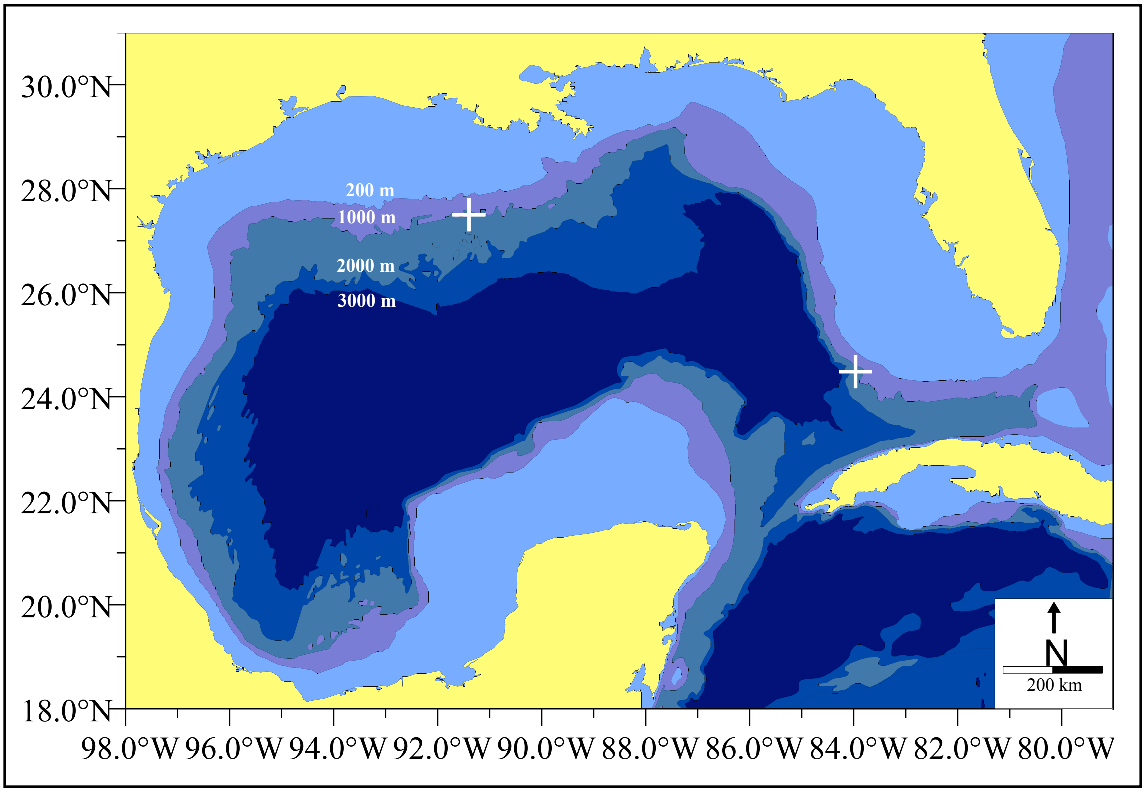

Figure 5.3.1. GOM biopsy sampling locations during the May 2000 NMFS marine mammal survey cruise are depicted as white crosses. Depth contours of 200m, 1000m, 2000m and 3000m are illustrated in shades of blue.

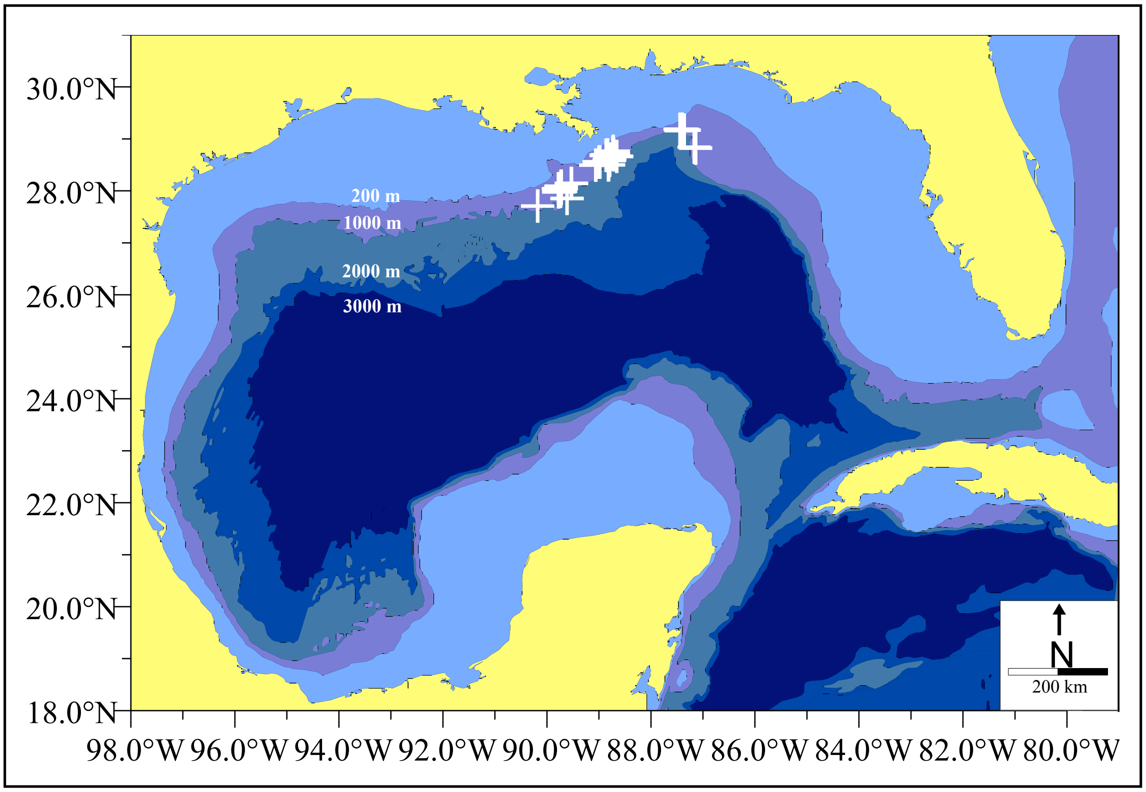

Figure 5.3.2. GOM biopsy and sloughed skin sampling locations during the SW2K July – August 2000 SWAMP cruises are depicted as white crosses. Depth contours of 200m, 1000m, 2000m and 3000m are illustrated in shades of blue.

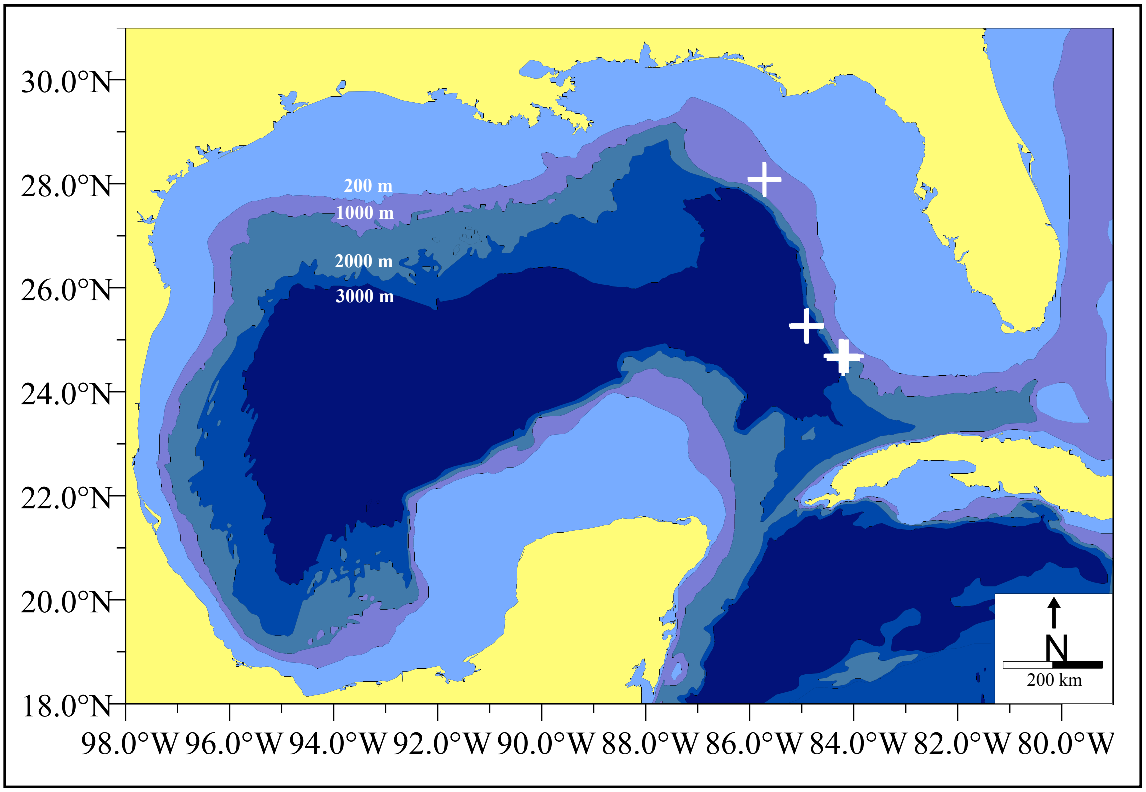

Figure 5.3.3. GOM biopsy and sloughed skin sampling locations during the SW2K1 March – April 2001 SWAMP spring cruise are depicted as white crosses. Depth contours of 200m, 1000m, 2000m and 3000m are illustrated in shades of blue.

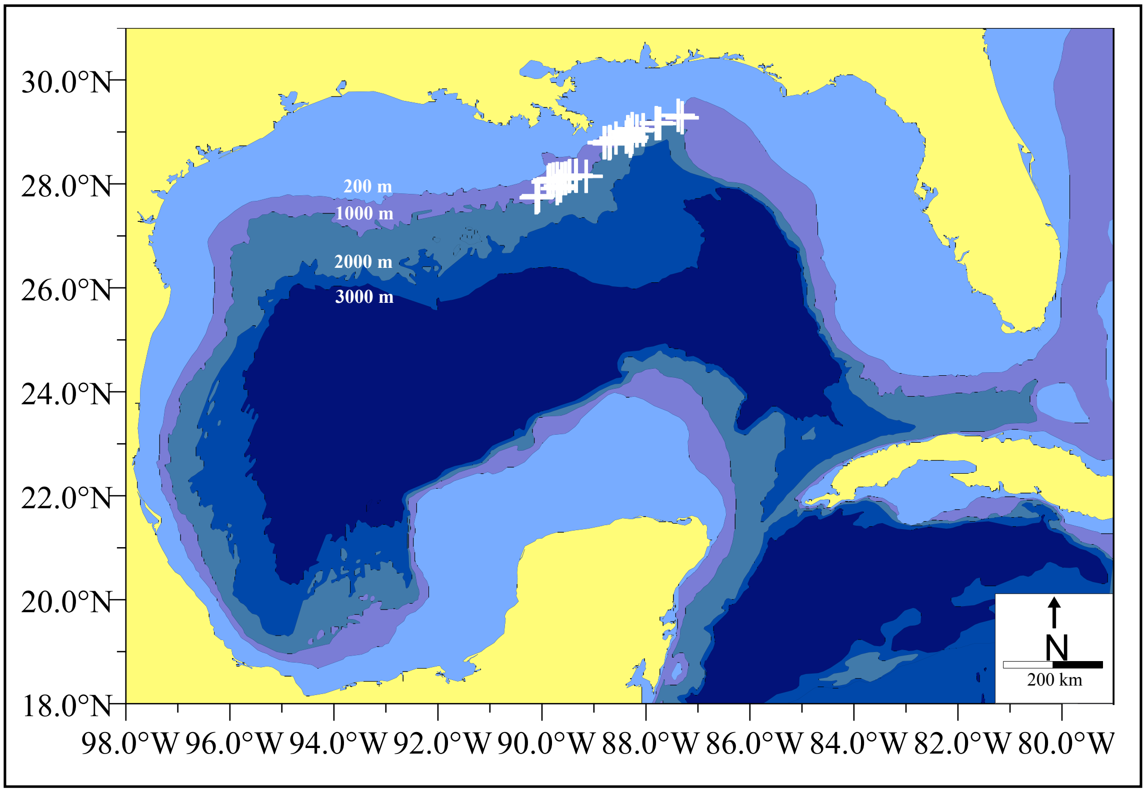

Figure 5.3.4. GOM biopsy and sloughed skin sampling locations during the SW2K1 July to August 2001 SWAMP summer cruise are depicted as white crosses. Depth contours of 200m, 1000m, 2000m and 3000m are illustrated in shades of blue.

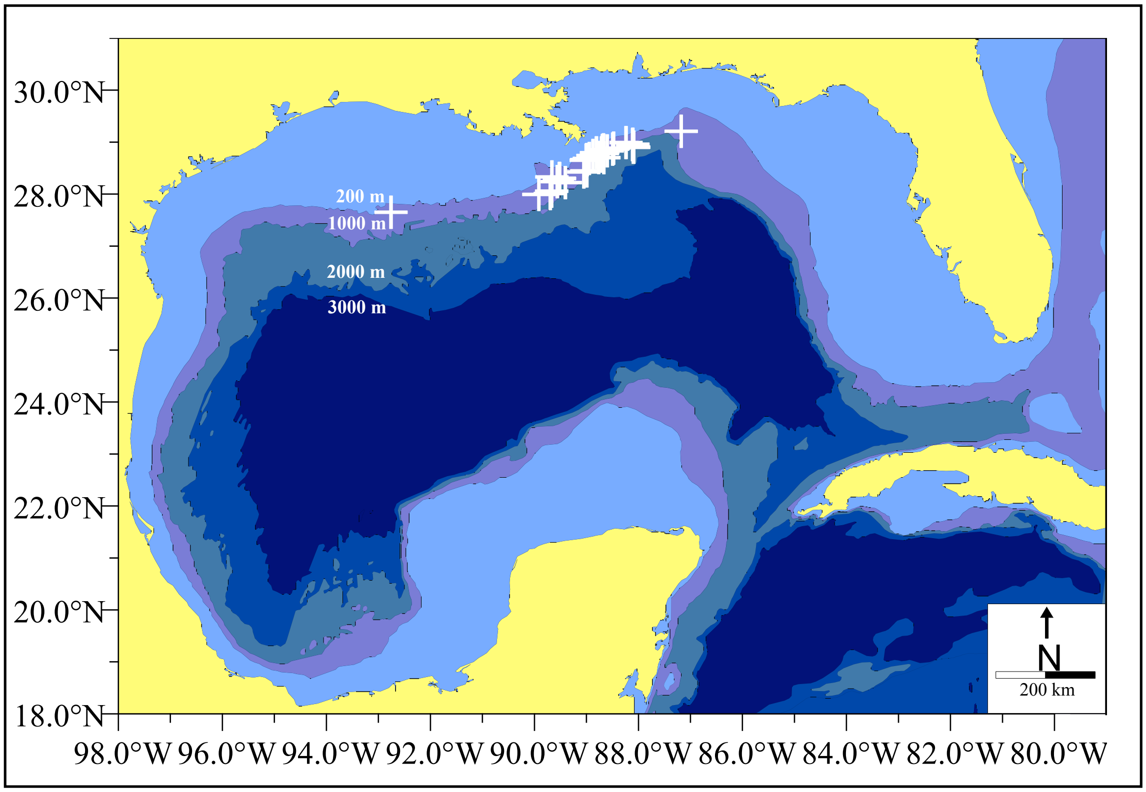

Figure 5.3.5. GOM biopsy and sloughed skin sampling locations during the SWSS 2002 summer cruises are depicted as white crosses. Depth contours of 200m, 1000m, 2000m and 3000m are illustrated in shades of blue.

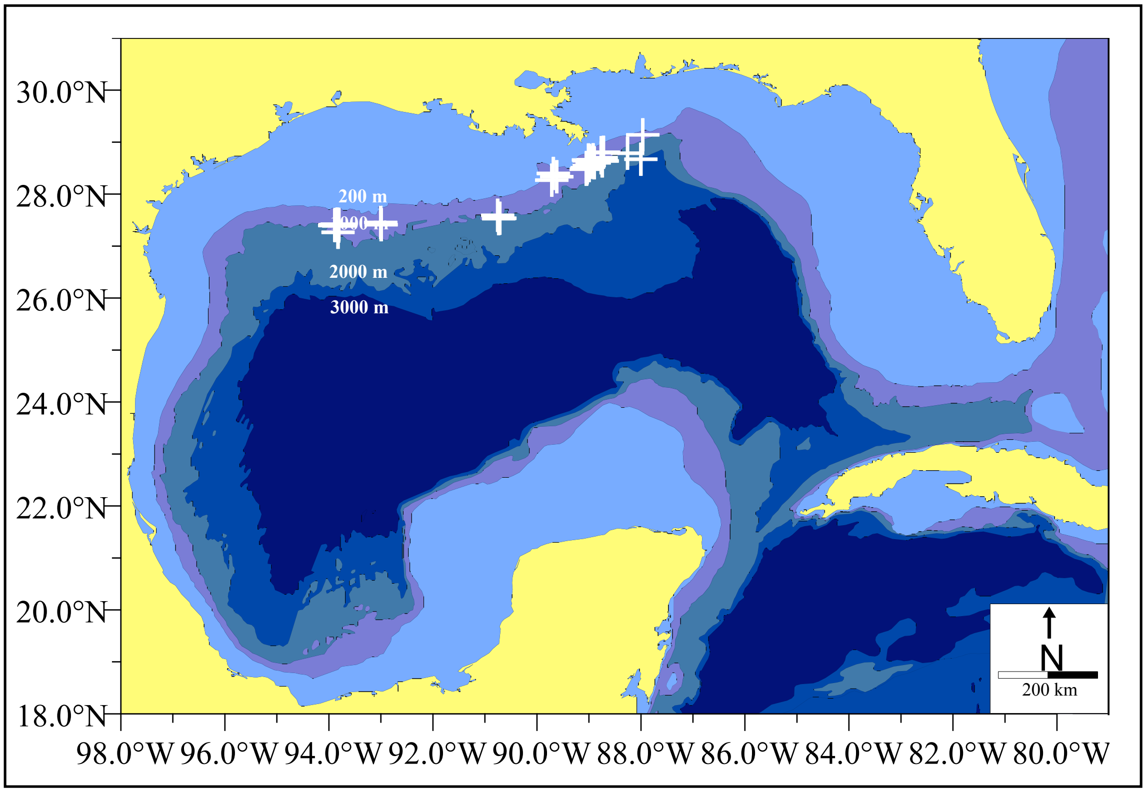

Figure 5.3.6. GOM biopsy and sloughed skin sampling locations during the SWSS May – June 2003 summer cruises are depicted as white crosses. Depth contours of 200m, 1000m, 2000m and 3000m are illustrated in shades of blue.

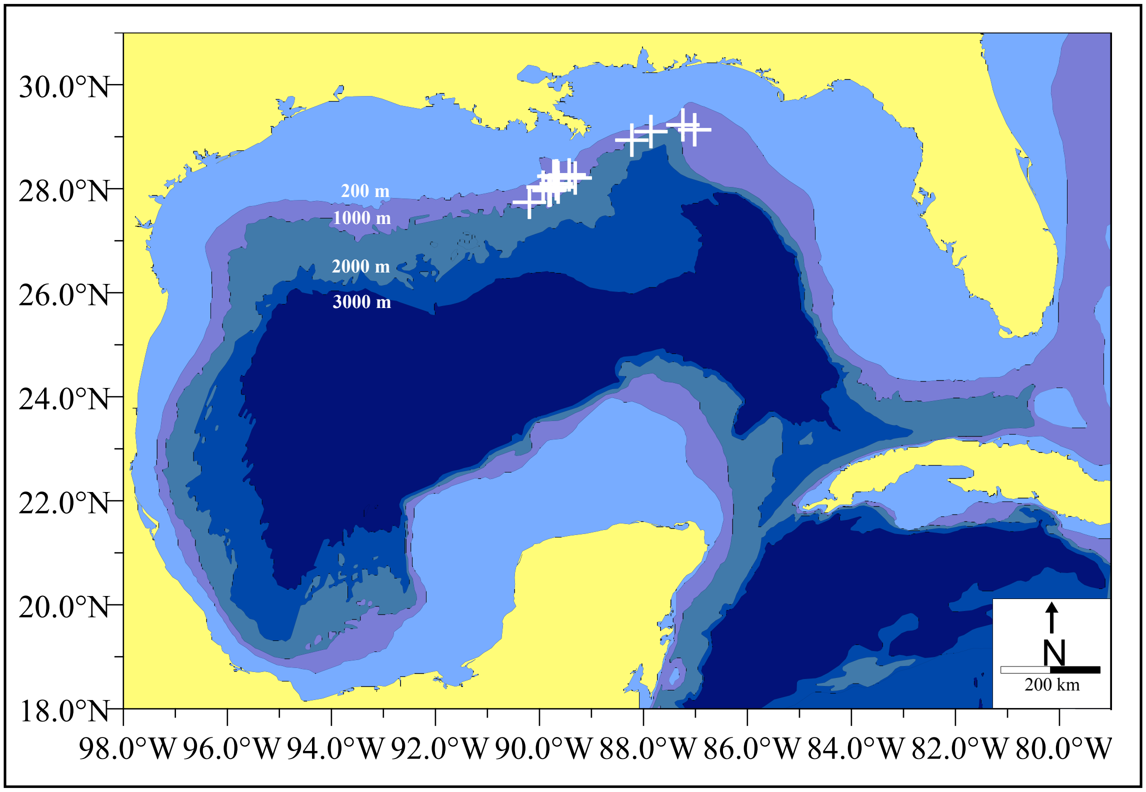

Figure 5.3.7. GOM biopsy and sloughed skin sampling locations during the SWSS May – June and June – August 2004 summer cruises are depicted as white crosses. Depth contours of 200m, 1000m, 2000m and 3000m are illustrated in shades of blue.

5.3.2 Surface Reactions to Biopsy Sampling

An assessment of behavioral reactions to biopsy sampling showed that the majority of reactions were generally mild and short-term "startle" responses similar to those described by Whitehead et al. (1990) (Engelhaupt and Hoelzel, in preparation A). No significant difference in behavioral reactions was observed between males and females. Although my sample size was small, no visible reactions to biopsy darting of the flukes were noticed and repeat biopsy events on the same individuals did not lead to increasing responses. Overall, these results are in agreement with previous studies performed on numerous cetacean species including sperm whales.

5.3.3 Gender Determination

Gulf of Mexico: For each of the 120 free-ranging GOM sperm whales, gender was determined for 119 samples using the ZFX/ZFY technique described by Berube and Palsboll (1996). Male and female strandings with known gender from the GOM and NSEA were included as a means of confirmation for PCR amplifications and yielded expected results. In the GOM, the sex ratio of females to males was 2.61:1, which is significantly different than an expected ratio of 1:1

(X^2=23.61, p<0.001) (Figure 5.3.8). This is not unexpected though given what appears to be a preference for lower-latitude waters by female mixed groups (Best 1979; Rice 1989). None of the males that were sampled appeared to be both physically and sexually mature based on very rough length estimates compared to the RHIB and morphological characteristics (e.g. pronounced heads: heads that appear swollen with a distinct ridge behind the base of the skull). However, several of these 'young' males may be either in or nearing sexual maturity based on these same rough size estimates and compared to Best's (1979) sexual maturity estimates.

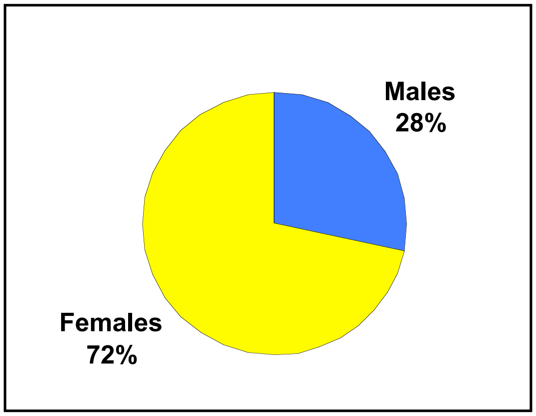

Figure 5.3.8. Gender composition of whales sampled in the northern GOM during 2000-2003.

5.3.4 Population Comparisons

Sample Size Reductions ('All' and 'Restricted' Sample Sets)

Population comparisons – sample numbers and parameters. Previous studies suggest that high levels of relatedness found within sperm whale groups could potentially bias statistical testing when examining geographic population structuring (Richard et al. 1996; Lyrholm et al. 1999; Bond 1999). As a result, population comparisons using mtDNA and microsatellite DNA (msatDNA) loci were performed using two datasets – 'all' and '*restricted*'. Two methods used to eliminate close kin from the *restricted* population structure estimates are described in detail in Engelhaupt (2004).

The 'all' dataset included all sampled individuals within each of three geographic areas (mtDNA: GOM: N = 117, MED: N = 19, NSEA: N = 18; msatDNA: GOM: N = 83, MED: N = 22, NSEA: N = 20). The '*restricted*' dataset consisted of individuals that were 'pruned' to eliminate close kin (mtDNA: GOM: N = 40, MED: N = 7, NSEA: N = 16; msatDNA: GOM: N = 40, MED: N = 8, NSEA: N = 18). Sample sizes differed from the original collected numbers due to failure of poor quality and quantity samples to be sequenced for the control region, failure for the majority of the 16 microsatellites to amplify correctly or samples still undergoing processing and analysis (ex. 2004 SWSS samples).

An additional analysis for mtDNA sequence results was set up that compared the GOM and MED 'all' and '*restricted*' populations against an overall NAO population. The NAO population was a compilation of data from published studies including samples distributed throughout the western and eastern NAO and the NSEA. The NAO incorporated my 'all' and '*restricted*' sequences from the NSEA (N = 18, *N = 16*), Caribbean Sea (N = 3, *N = 3*), and the western NAO (N = 1, *N = 1*) with those of Sarah Mesnick's (SWFSC) western North Atlantic sequences (N = 17, *N = 5*) and Lyrholm and Gyllensten's (1998) published NAO sequences (N = 47, *N = 42*). NAO sequences from SWFSC were taken from biopsy samples in the North Atlantic (N = 4, *N = 1*), and stranding events in the Bahamas (N = 7, *N = 1*), North Carolina (N = 2, *N = 2*), and Florida (N = 4, *N = 1*). NAO published sequences from Lyrholm and Gyllensten (1998) were incorporated into the population structure analyses from free-ranging and stranded whales located in the following areas: North Atlantic (NAO) N = 47: Azores N = 13, Denmark N = 15, Norway N = 8, Iceland N = 8, Sweden N = 1, Florida N = 1 and the Dominican Republic N = 1 (restricted numbers by specific region were not available). Unfortunately, Lyrholm and Gyllensten's (1998) published haplotypes by region were unobtainable at this time so the NAO can not be split into the western and eastern NAO for a more detailed comparison of geographic areas. The total number of samples used to represent the 'all' and '*restricted*' NAO was 86 and *67* respectively.

While a sufficient number of samples remained for the GOM, NSEA and NAO '*restricted*' datasets, the reduction of possible relatives within the putative MED population significantly reduced the number of individuals used for mtDNA analyses from 19 to *7* and for microsatellite analyses from 22 to *8*. Although the MED '*restricted*' data set was included in population comparisons, caution should be taken when interpreting results obtained from small sample sizes.

Mitochondrial DNA

Genetic diversity estimates: Sequences from this study for 222 (does not include 2002 DTAG samples & 2004 samples still being processed) individual sperm whales from the GOM, MED, NSEA and NAO were compared at the 399bp segment from the 5' control region with twenty-three sperm whale haplotypes (organized as letters A through W and Lyr. 4) provided by Sarah Mesnick (SWFSC) using the program Mega 2.0 (http://www.megasoftware.net/) to determine unique haplotypes within the three geographic regions. The SWFSC data include Lyrholm and Gyllensten's (1998) forty-seven previously sequenced samples and resulting haplotypes collected in areas throughout the NAO as well as all other haplotypes discovered to date that occur for sperm whales on a global scale.

For this study, six (1.5%) polymorphic nucleotide sites defining a total of only seven unique lineages were found between the GOM, MED, NSEA and NAO (Table 5.3.1). All nucleotide substitutions between haplotypes were transitions.

Shared haplotypes, distribution of haplotypes and haplotype frequencies are provided in Table 5.3.2. On a global scale, the three most common haplotypes were 'A', 'B', and 'C' (Lyrholm and Gyllensten 1998). While these three haplotypes clearly dominated the NAO (Lyrholm and Gyllensten 1998), two haplotypes ('X' and 'Y') were unique to the GOM with 'X' being the most common (65.0%). A total of five haplotypes ('A', 'B', 'C', 'X' and 'Y') occurred in the GOM, all samples collected from the MED were represented by a single haplotype ('C'), three haplotypes ('A', 'B' and 'C') occurred in the NSEA samples and five haplotypes ('A', 'B', 'C', ‘Lyr4’ and ‘N’) were present in the NAO data. Although ‘A’ and ‘B’ do occur in the GOM, NSEA and the NAO, only the ‘C’ haplotype was distributed across all geographic regions.

Table 5.3.1

Haplotypes with Corresponding Variable Sites
(For 399 base pairs of the mtDNA control region for sperm whales distributed throughout the GOM, MED, NSEA and NAO. Dots indicate nucleotide equivalence with the reference sequence (HapA) above.)

Haplotype	**Variable Sites**					
	62	121	207	272	288	319
Hap A	C	C	A	A	A	G
Hap B	T	.	.	.	.	.
Hap C	T	.	.	.	G	.
Hap Lyr4	.	T	.	.	.	.
Hap N	T	.	.	.	.	A
Hap X	T	.	G	.	G	.
Hap Y	T	.	G	G	G	.

Table 5.3.2
Haplotype Frequencies for Four Geographic Putative Populations
(The left number indicates the ‘all’ data set and the right italicized number indicates the ‘*restricted*’ subset.)

Haplotype	**Gulf of Mexico**	**Mediterranean Sea**	**North Sea**	**[*]North Atlantic Ocean**
A	0.017 / *0.000*	0.000 / *0.000*	0.444 / *0.438*	0.395 / *0.388*
B	0.179 / *0.225*	0.000 / *0.000*	0.111 / *0.125*	0.151 / *0.194*
C	0.077 / *0.100*	1.000 / *1.000*	0.444 / *0.438*	0.419 / *0.373*
Lyr4	0.000 / *0.000*	0.000 / *0.000*	0.000 / *0.000*	0.012 / *0.015*
N	0.000 / *0.000*	0.000 / *0.000*	0.000 / *0.000*	0.023 / *0.030*
X	0.650 / *0.575*	0.000 / *0.000*	0.000 / *0.000*	0.000 / *0.000*
Y	0.077 / *0.100*	0.000 / *0.000*	0.000 / *0.000*	0.000 / *0.000*
Total	117 / *40*	19 / *7*	18/*16*	86 / *67*

[*] Includes published haplotypes from Lyrholm and Gyllensten (1998), sequences from SWFSC and the NSEA sample set.

Gene (or haplotype) diversity (*h*) and nucleotide diversity (π) for each population were unusually low across each of the four 'all' and '*restricted*' populations datasets (Table 5.3.3). Very similar results were reported by Lyrholm et al. (1996) and Lyrholm and Gyllensten (1998). The GOM, NSEA and the NAO populations all possessed similar low levels of gene diversity. Nucleotide diversity was also extremely low and constant across the GOM, NSEA and NAO populations (0.2% to 0.3% ± 0.2).

The results of Tajima's *D* for each 'all' and 'restricted' population (excluding the MED due to total lack of polymorphism) were non-significant ($p > 0.05$), suggesting that this locus is not under selection. Fu's F_S test confirmed these results ($p > 0.10$ for each population).

Genetic differentiation between populations: An exact test of population subdivision revealed significant differentiation between all populations for comparisons done for both the all and *restricted* datasets (*p*-value = 0.000 ± 0.000), with the exception of the MED-NSEA (*p*-value = 0.049 ± 0.001) '*restricted*' comparisons (Table 5.3.4). After correction with sequential Bonferroni, the MED-NSEA and the MED-NAO '*restricted*' datasets were non-significant, suggesting no differentiation between the two. This result may be a consequence of the '*restricted*' dataset's small sample size (N=7) for the MED.

Table 5.3.3

Haplotype Diversity (*h*), Nucleotide Diversity (π) ± Standard Deviation and the Mean Number of Pairwise Differences ± Standard Deviation Within Four Geographic Populations
(*Restricted* dataset numbers are in italics.)

Location	**Dataset**	***n***	**Haplotype Diversity (*h*)**	**Nucleotide Diversity (π)**
GOM	all	117	0.538	0.002 ± 0.002
	restricted	*40*	*0.614*	*0.003 ± 0.002*
MED	all	19	0.000	0.000 ± 0.000
	restricted	*7*	*0.000*	*0.000 ± 0.000*
NSEA	all	18	0.628	0.003 ± 0.002
	restricted	*16*	*0.642*	*0.003 ± 0.002*
NAO	all	86	0.653	0.003 ± 0.002
	restricted	*67*	*0.682*	*0.003 ± 0.002*
Total	all	222	0.752	0.003 ± 0.002
	restricted	*130*	*0.776*	*0.003 ± 0.002*

Table 5.3.4

Exact Test *P*-values for Population Comparisons
(Datasets are divided into all and *restricted* material. *P*-values significant at the 0.05 level after sequential Bonferroni correction are in bold type and marked with an ‘*’.)

	Dataset	***N***	**GOM**	**MED**	**NSEA**
GOM	all	117	—		
	restricted	*40*			
MED	all	19	0.000 ± 0.000	—	
	restricted	*7*	*0.000 ± 0.000*		
NSEA	all	18	0.000 ± 0.000	0.000 ± 0.000	—
	restricted	*16*	*0.000 ± 0.000*	***0.049 ± 0.001****	
NAO	all	86	0.000 ± 0.000	0.000 ± 0.000	—
	restricted	*67*	*0.000 ± 0.000*	***0.041 ± 0.002****	

F_{ST} and Φ_{ST} measures of genetic differentiation were calculated for the sequenced fragment based on conventional *F*-statistics and the Tamura-Nei distance measures respectively. A comparison between the GOM, MED and NSEA populations was performed first. A second comparison between the GOM, MED and NAO (which combines the sequences from the NSEA and whales throughout the NAO into an overall NAO population) was then performed.

AMOVA results, incorporating Φ_{ST}, suggest that the primary source of variation (55.04% / *59.55%*) for the GOM, MED and NSEA ‘all’ and ‘*restricted*’ samples originates within populations and 44.96% / *40.55%* of the variation is attributed to among population variation. As expected, similar results were obtained when we examined the within population variation (54.25% / *57.77%*) and among population variation (45.75% / *42.33%*) for both datasets in the GOM, MED and NAO comparison. All pairwise calculated values, apart from for the MED-NSEA ‘*restricted*’ population comparison, proved highly significant ($p < 0.01$) for both F_{ST} and Φ_{ST} genetic differentiation measures (Table 5.3.5). After correcting for multiple comparisons using the sequential Bonferroni correction, the MED-NSEA ‘*restricted*’ comparison was no longer significant at $p < 0.05$. Overall, rather high F_{ST} and Φ_{ST} values showed extensive differentiation between the GOM, NSEA, MED and NAO with respect to both the ‘all’ and ‘*restricted*’ population comparisons.

Table 5.3.5

mtDNA Population Comparison Among Three Geographic Areas of GOM, MED, and NAO (F_{ST} values are presented in the lower left matrix and Φ_{ST} values for are presented in the upper right matrix. '*Restricted*' dataset values are in italics and provided below the 'all' dataset values. Statistically significant p-values based on 10,000 permutations of the data and after Bonferroni corrections are marked with an asterisk ($p < 0.05$ = *; $p < 0.01$ = **; $p < 0.001$***).

	GOM	**MED**	**NSEA**	**NAO**
GOM	—	0.408*** *0.334***	0.471*** *0.420****	0.464*** *0.432****
MED	0.579*** *0.511****	—	0.485*** *0.365*	0.355*** *0.333***
NSEA	0.394*** *0.326****	0.443*** *0.319*	—	—
NAO	0.366*** *0.292****	0.310*** *0.279***	—	—

Microsatellite Results

All population differentiation analyses using nuclear DNA 'microsatellite' markers between the GOM, MED and the NSEA were conducted on two sets of data – 'all' and '*restricted*'.

Microsatellite Genetic Diversity Within Populations:

1. Linkage Disequilibrium & Hardy Weinberg Equilibrium (HWE) Deviation. Sixteen microsatellite loci were analyzed for 125 individuals from three different geographic locations. Linkage disequilibrium was tested for each pair of loci within each of the three putative geographic populations and across the data as a whole to ensure that loci were independent of one another. Eleven locus pairs in the 'all' dataset (GOM = 9, MED = 1, NSEA = 1) showed linkage disequilibrium with a *p*-value < 0.05. After correcting the given *p*-values with the sequential Bonferroni adjustment for multiple comparisons, the resulting *p*-values were non-significant for the 'all' population; therefore no association between alleles at different loci was assumed in subsequent analyses.

Estimations of HWE deviation were performed for each population at each locus by testing for heterozygote deficiency and excess within populations and on a global scale. After sequential Bonferroni adjustments were made to the existing *p*-values, significant deviation ($p < 0.05$) from HWE with respect to heterozygosity deficiency remained at locus EV37 (GOM '*restricted*', MED 'all' and MED '*restricted*' datasets) and EV104 for the GOM 'all' and the MED 'all' and '*restricted*' datasets.

2. Microsatellite allele frequency variation among geographic populations. Under HWE, the observed and expected heterozygosity should be similar in value. Discrepancy between the two

may be a result of non-random mating or inbreeding, null alleles or the Wahlund effect. Mean observed and expected levels of heterozygosity over all 16 loci across all 6 datasets are shown in Table 5.3.6.

Total alleles across all three populations for both the 'all' and '*restricted*' datasets was 174 and *163* respectively. The GOM 'all' and '*restricted*' datasets contained the largest number of scored alleles (total alleles = 164 and *151* respectively), while the MED showed the lowest amount (total alleles = 100 and *78* respectively). This result is most likely directly attributed to the difference in sample sizes between geographic areas. Allele sizes didn't appear to differ drastically between populations and were similar to values produced by both Lyrholm et al. (1999) and Bond (1999). Several loci exhibited higher levels of polymorphism than others in both the 'all' (allele range = 3–24 alleles/locus) and '*restricted*' (allele range = *3–21* alleles/locus) datasets and the mean number of alleles/locus over all sixteen loci across all individuals in all populations for each dataset was 10.88 and *10.19* respectively. The percentage of private alleles (*pa*) observed per population and per dataset was as follows: GOM (*pa* = 19.0%, *15.3%*); MED (*pa* = 0.5%, *0.0%*); and NSEA (*pa* = 5.2%, *4.9%*). Overall, private alleles occurred more frequently within the GOM population, but at rather low frequencies across all three populations and both datasets ($pa \leq 0.078$ and $pa \leq 0.075$ respectively).

Table 5.3.6

Mean Observed and Expected Heterozygosity Levels for Each Population's Respective Dataset

Heterozygosity	**Gulf of Mexico**		**Mediterranean Sea**		**North Sea**	
	All	*Restricted*	All	*Restricted*	All	*Restricted*
H_O	0.742	*0.750*	0.651	*0.648*	0.742	*0.741*
	±0.162	*±0.186*	±0.240	*±0.314*	±0.158	*±0.155*
H_E	0.752	*0.759*	0.687	*0.671*	0.762	*0.766*
	±0.133	*±0.143*	±0.211	*±0.258*	±0.142	*±0.145*

Population Genetic Differentiation:

1. Allelic and Genotypic Distributions. An exact test used to test allelic distribution in different populations (null hypothesis: that allelic distribution is identical across populations) yielded interesting results with respect to population differentiation. However, results may be due to low power at some loci. The extent of significant genetic differentiation between putative populations depended on the locus that was screened. Comparisons for each 'all' dataset population pair across all loci using Fisher's method revealed highly significant *p*-values ($p < 0.001$) for both the GOM-MED and the MED-NSEA. Comparisons for each '*restricted*' dataset population pair across all loci using Fisher's method revealed significant *p*-values ($p < 0.01$) for both the GOM-MED and the MED-NSEA.

Tests of genotypic differentiation (null hypothesis: the genotypic distribution is identical across populations) were also performed and the results confirmed several of the previous genetic results. Several loci that differentiated pairs of populations in both datasets continued to differentiate them at significant levels ($p < 0.05$ after seq. Bonferroni correction). Comparisons for each 'all' dataset population pairs across all loci using Fisher's method revealed highly significant p-values ($p < 0.001$) for both the GOM-MED and the MED-NSEA before and after sequential Bonferroni corrections. Comparisons for each '*restricted*' dataset population pair across all loci using Fisher's method revealed significant p-values ($p < 0.01$) for both the GOM-MED and the MED-NSEA before and after sequential Bonferroni corrections.

2. <u>Population Structure</u>. The extent of genetic differences that lead to genetic structuring between populations was tested using F_{ST}, theta (θ), R_{ST} and Rho_{ST} statistical measures. Each measures the extent of genetic variation that can be attributed to the genetic differences between each population pair. R_{ST} (Slatkin 1995) and Rho_{ST}, the latter being an unbiased analogue to R_{ST} developed by Goodman (1997), were developed specifically for microsatellites and take the SMM model into account when calculating differentiation. Based on previous sperm whale genetic and behavioral findings, our null hypothesis was that variation observed in nuclear markers (i.e. microsatellites) between putative populations would be low or non-existent, a result that is suggestive of male dispersal between populations.

F_{ST} and θ estimates for the GOM-MED and the MED-NSEA comparisons each showed low, but significant ($p < 0.01$), differentiation between populations in the 'all' and '*restricted*' datasets before and after sequential Bonferroni corrections were implemented (Table 5.3.7). Pairwise results for R_{ST} and Rho_{ST} are also provided in Table 5.3.7. Rho_{ST} over all populations was 0.020 (95% CI: 0.018 – 0.058; $p < 0.01$) and *0.014* (95% CI: 0.013 – 0.083; $p > 0.05$) for the 'all' and '*restricted*' datasets respectively.

Testing for a recent bottleneck event using the Wilcoxon test in the program BOTTLENECK 1.2.02 also showed some evidence of heterozygosity excess within the GOM population ($p = 0.007$), but not the MED or NSEA populations ($p = 0.058$).

3. <u>Sex-biased dispersal</u>. As previously described, genetic differentiation was highly significant among the GOM, MED, NSEA, and NAO samples for the mtDNA control region sequences, but only the MED population showed significant differentiation for the microsatellite DNA loci. Sex-biased dispersal results are in agreement with females being the more philopatric sex and males dispersing from their natal populations (Table 5.3.8). Although F_{ST} was slightly higher among females than males, it was non-significant ($p > 0.05$). However, sperm whale population comparisons using nuclear markers show little to no significant differentiation with respect to nuclear DNA and this may have a direct effect on F_{ST} testing for sex-biased dispersal. The variance assignment test provided an expected higher value for males (the dispersers) than for the females (the more philopatric sex), although values were slightly above the non-significant threshold ($p = 0.081$). The mean assignment test, F_{IS} and H_S were all highly significant ($p < 0.01$) and provided values in accordance with males dispersing.

Table 5.3.7

Pairwise Comparisons and Distance Measurements for the GOM, MED and NSEA Populations using F_{ST}, θ, $R_{ST}(S)$, Rho_{ST}
('*Restricted*' dataset values are in italics and provided below the 'all' dataset values. Statistically significant p-values after Bonferroni corrections are marked with an asterisk ($0.01 < p < 0.05$ = *; $0.001 < p < 0.01$ = **; $p < 0.001$***.)

	F_{ST}	θ	$R_{ST}S$	Rho_{ST}
GOM-MED	0.033*** *0.032****	0.035** *0.037***	0.052*** *0.078***	0.037*** *0.047*
GOM-NSEA	0.000 *-0.005*	0.000 *-0.005*	0.009 *0.015*	0.004 *0.004*
MED-NSEA	0.030*** *0.031***	0.030** *0.033***	0.030 *0.047*	0.031 *0.038*

Table 5.3.8

Sex-biased Dispersal Results for Males and Females with Respect to F_{IS}, F_{ST}, H_O, H_S, Mean Assignment and Variance Assignment

	n	F_{IS}	F_{ST}	H_O	H_S	Mean Assignment	Variance Assignment
Females	66	-0.004*	0.043	0.738	0.735*	0.785*	14.278
Males	59	0.049*	0.016	0.713	0.750*	-0.878*	16.010

*p-value < 0.01

5.3.5 Genetic Composition of GOM Groups

Composition of Groups Without Satellite-monitored Tags

Members from nineteen groups of whales (G0 – G18) were sampled throughout the Mississippi River Canyon, DeSoto Canyon and Dry Tortugas areas during the spring and summer 2000 and 2001 field seasons (Figure 5.3.9). The boundaries of the specified areas are quite arbitrary given the enormous potential for large-scale movement possessed by individual sperm whales (Best

1979; Ivashin 1981; Kasuya and Miyashita 1988; Rice 1989; Dufault and Whitehead 1998). No distinctively 'large' whales were found within the study area, giving the impression that physically mature adult males were not present during the study periods. Additional details on group composition are provided in Engelhaupt (2004).

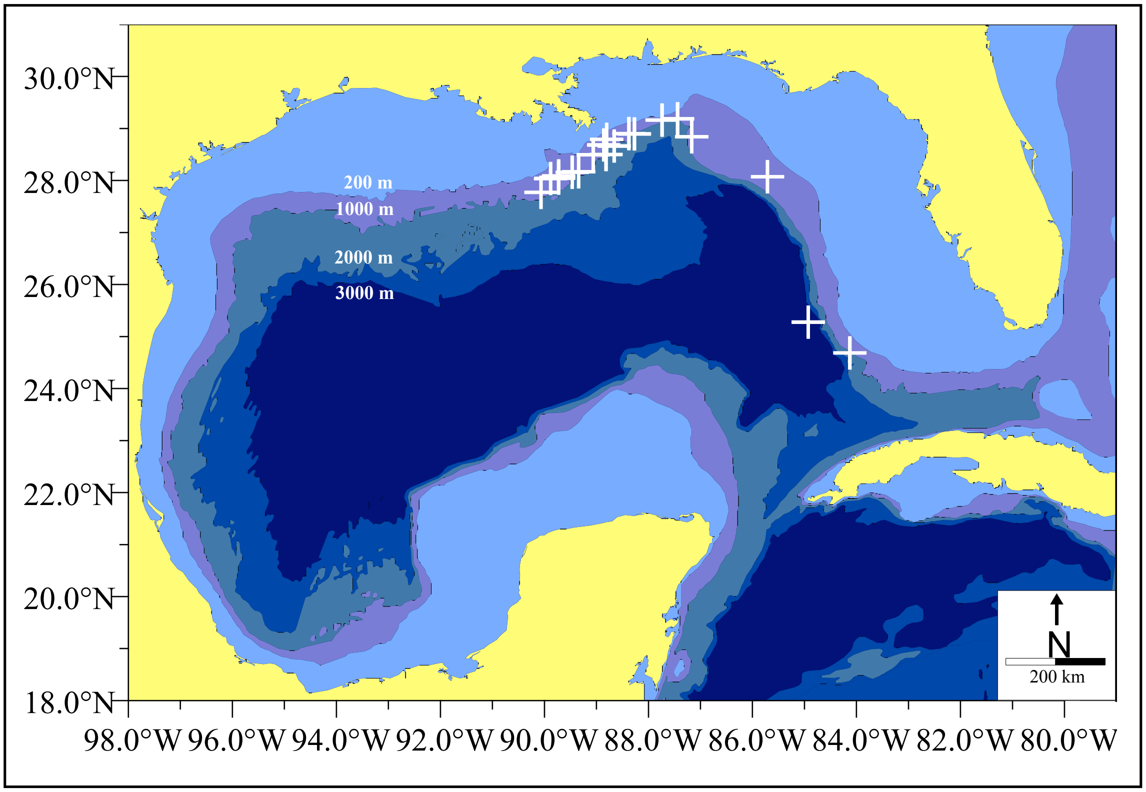

Figure 5.3.9. Locations of 19 groups (G0-G18) sampled in the northern GOM during 2000-2001 are represented by white crosses. Depth contours of 200m, 1000m, 2000m and 3000m are illustrated in shades of blue.

Composition of Satellite-Tagged Groups: The combination of satellite-monitored tagging and biopsy sampling allows for an in-depth examination of how related and un-related individuals within a group maintain associations through time and space. During the summer of 2002, 20 whales in the northern GOM were biopsy sampled in association with satellite-monitored tag deployments (Figure 5.3.10). Estimated group sizes for six groups (G19 – G24) were determined at the time of tagging. Group size estimates ranged from seven to 18 whales. Genetic relatedness among group members was tested for all sampled whales (including whales with and without satellite-monitored tags). A detailed comparison of genetic relatedness with extremely fine-scale association and movement patterns over days to years are pending Oregon State University's final analyses of the tag data (Ortega-Ortiz et al., in preparation).

Gender composition of groups: The sexual composition of groups G0 to G18 was examined using molecular techniques. The majority (72.3%) of whales sampled in these groups were sexed as females. The males were generally scattered throughout, although there were three cases of all male groups (G6, G7 and G8). These males were thought to be sexually immature based on their estimated sizes. By limiting the dataset to include only groups that have ≥ 50% of their estimated group size sampled, only groups G0, G1, G3, G4, G5, G6, G7, G8 and G18 were retained. This more conservative approach results in 66.6% of the nine groups fitting a mixed sex social group scenario and 33.3% fitting the bachelor group scenario. Of these nine groups, 67.5% of all individuals were females and 32.5% were males.

Gender composition of satellite-tagged groups. The gender composition of satellite-monitored tag groups was examined to provide an understanding of group type (mixed sex or bachelor) encountered in the northern GOM. Of the twenty whales from groups G19-G24 that were biopsy sampled after tag attachment, 15 (75%) were sexed as females and five (25%) were sexed as males. All whales identified as males were believed to be sexually immature based on estimated sizes. While a broader examination of the gender data continues to provide support for the previous unequal sex ratio results for whales located in the northern GOM, only group G22 contained a sufficient percentage (66.7%) of samples from the estimated group size to be used in further analyses of group composition by gender.

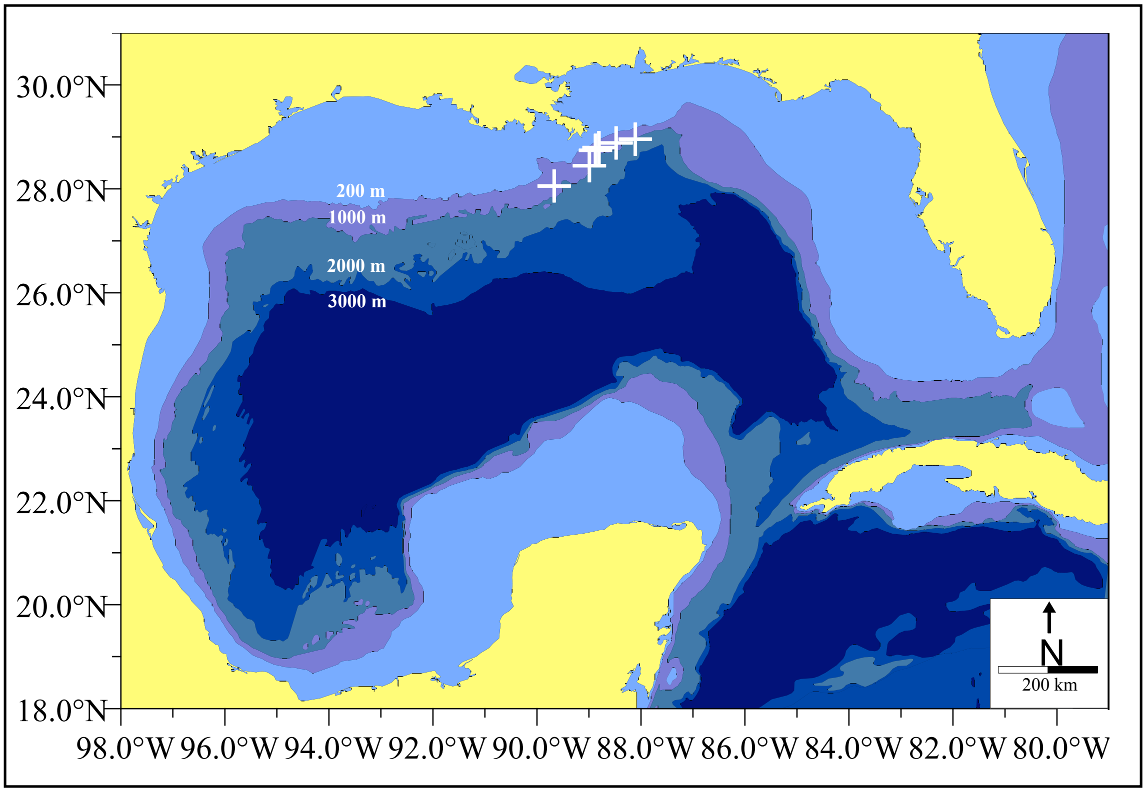

Figure 5.3.10. Locations of six satellite-monitored tagged groups (G19-G24) sampled in the northern GOM during 2002 are represented by white crosses. Depth contours of 200m, 1000m, 2000m and 3000m are illustrated in shades of blue.

Pairwise and group relatedness estimates: All groups were tested as separate entities to provide estimates of relatedness. Estimates of relatedness were determined based on *restricted* and all allele frequency datasets as previously described. Incorporating both datasets allowed a means to assess the extent that background alleles may or may not have when calculating R-values. Relatedness measurements ranged from -1.0 to +1.0 with positive values signifying two individuals sharing more alleles that were identical by descent than expected by chance, whereas negative R-values were indicative of two individuals sharing fewer such alleles than expected by chance. When populations are in Hardy-Weinberg equilibrium, relatedness coefficients should average 0.50 for first-order relatives (e.g., parent-offspring and full-sibling pairs), 0.25 for second-order relatives (e.g., half-sibs, grandparent-grandchild, and aunt/uncle-niece/nephew) and 0.00 for pairs of randomly chosen individuals that are not related. Relatedness values among all nineteen groups ranged from *-0.130* to *0.278* for the restricted dataset and -0.155 to 0.270 for the all dataset. The mean group relatedness estimate among all 19 groups was *0.067* (s*td. dev. 0.123*) and 0.073 (std. dev. = 0.113) for the *restricted* and all datasets respectively. Pairwise relatedness estimates were obtained for all individual members within their respective group. Estimates of relatedness for all (n=139) pairwise combinations found within each of the 19 groups ranged from *-0.284* to *0.675* and -0.285 to 0.666 with an overall mean of *0.063* (std. dev. = 0.193) and 0.054 (std. dev. = 0.192) for the *restricted* and all datasets respectively. Both the *restricted* and all means were not significantly different than an R-value of 0.000 (*restricted* Wilcoxon-Mann-Whitney: $U = 83.5$, $p = 0.813_{20,000}$ (where the subscript = Monte Carlo resampling size); all Wilcoxon-Mann-Whitney: $U = 76$, $p = 0.905_{20,000}$), which is indicative of non-relatedness among individuals. The distribution of group R-values was centered near zero and suggests individuals within groups are generally unrelated.

Relatedness values for whales found within groups were compared to relatedness levels for whales found between groups to determine whether relatedness is significantly higher within rather than between group members. The mean R-value for all (n=2,556) pairwise relatedness comparisons possible between groups G0-G18 was -0.013 (std. dev. = 0.138) and *-0.003* (*std. dev. = 0.137*) for the all and *restricted* datasets respectively. A highly significant difference (*restricted* Wilcoxon-Mann-Whitney: $U = 144863$, $p = 0.000_{20,000}$; all Wilcoxon-Mann-Whitney: $U = 143977$, $p = 0.000_{20,000}$) in mean relatedness values was found for whales within vs. between groups with respect to both the *restricted* and all datasets suggesting that whales within a group are more related to one another than whales found between groups.

Pairwise and group relatedness estimates – satellite-tagged groups. Levels of relatedness from whales within the six satellite-monitored tagging groups were determined based on 12 polymorphic microsatellite loci. No groups were sampled in their entirety. All groups were tested for relatedness within and between groups. Between group relatedness ranged from -*0.014* to *0.032* for the restricted dataset and -0.042 to 0.019 for the all dataset with a mean of *0.005* (*std. dev. = 0.020*) and -0.020 (std. dev. = 0.024) for the *restricted* and all datasets respectively. Estimates of relatedness for 35 pairwise combinations within each of the six groups ranged from *-0.328* to *0.390* and -0.364 to 0.353 with an overall mean of *-0.011* (*std. dev. = 0.141*) and -0.033 (std. dev. = 0.144) for the *restricted* and all datasets respectively. These means were not statistically different than an R-value of 0.000 (*restricted* Wilcoxon-Mann-Whitney: $U = 17.5$, $p = 1.000_{20,000}$; all Wilcoxon-Mann-Whitney: $U = 12$, $p = 0.723_{20,000}$), which is indicative of non-relatedness among individuals. The distribution of all group R-values was centred near zero and suggests that the majority of individuals within groups were not highly related.

No significant difference (*restricted* Wilcoxon-Mann-Whitney: U = 2588, p = *0.765*$_{20,000}$; all Wilcoxon-Mann-Whitney: U = 2595, p = 0.777$_{20,000}$) in relatedness levels was detected when whales found within S-tagged groups were compared to whales found between S-tagged groups with respect to both the all and *restricted* dataset.

The following relatedness estimate data describes two groups of whales where > 2 members of the group were both sampled and tagged with OSU satellite-monitored tags (Ortega-Ortiz et al., in preparation). Age-classes (immature and adult) were estimated based on visual observations only. No young calves were sampled or tagged during this study.

> *Group G20* contained approximately 18 whales, of which four immature males and one adult female were sampled. Two individual males (02070103 and 02070104) within the group shared the same haplotype (C), while the other three whales carried the A, B and X haplotypes. The group estimates of relatedness were *-0.011* (*restricted*) and -0.025 (all). Pairwise relatedness estimates among group individuals ranged from *-0.242* to *0.110* (*restricted*) and -0.279 to 0.110 (all). The female (02070105) shared neither a haplotype nor a strong relatedness value with any of the young males.
>
> *Group G22* contained approximately eleven whales, of which seven adult females were sampled. All whales within the group shared the same 'X' haplotype. The group estimates of relatedness were *-0.014* (*restricted*) and -0.040 (all). Pairwise relatedness estimates among group individuals ranged from *-0.327* to *0.390* (*restricted*) and -0.364 to 0.353 (all). Interestingly, four whales (00071904, 00071907, 00071908 and 00071909) were previously sampled two years earlier in July 2000 when they were members of group G3.

Matriline composition within groups: All sperm whales sampled in the northern GOM contained one of five haplotypes (A, B, C, X and Y). To date, no additional lineages have been found in samples throughout the GOM. Figure 5.3.11 represents the percentage of sampled members haplotypes (B, C, X and Y) within each of the GOM groups.

Matriline composition within s-tagged groups: Sperm whales sampled in the northern GOM during satellite-monitored tagging operations contained one of five haplotypes (A, B, C, X and Y). Figure 5.3.12 represents the haplotype percentage for members of each of the satellite-monitored tag groups.

Putative highly related pairs within groups: Highly related pairs (e.g. mother-offspring, full-siblings, half-siblings and grandparent-grandchild) within groups were identified via an examination of R-values determined with Relatedness 5.0.2 and Kinship 1.3.1 software. Alleles shared across 16 polymorphic loci between possible pairs were examined by eye. Out of 76 individuals comprising 19 groups, only nineteen potential highly related pairs were identified within 12 of the 19 groups. Of the nine groups with ≥ 50% of their members sampled, six groups contained highly related pairs within their respective group. Degrees of relatedness between relations were tested for three scenarios – parent-offspring, full-siblings and half-siblings using the likelihood method previously described. Due to the lack of additional long-term behavioural information, relatedness values could not provide further clarification about which relationship between individuals was the correct one. Certain relationships that tested positive for mother-offspring or full-siblings pairs were discarded after comparing mtDNA haplotypes. For example, the female pair 01032602 / 01032603 that passes for a full-sibling pair ($p < 0.01$) cannot be correct as they come from two different maternal lineages ('B' and 'C' respectively). However, the likelihood of this pair being half-sisters that are related via paternal lines remains plausible ($p < 0.001$).

Nine pairs show R-values that represent parent-offspring, full-siblings or half-siblings based on log-likelihood testing. Interestingly, two of the all male groups (G6 and G8) contained potential full-sibling pairs. None of the members of the two sampled pairs were deemed large enough to be considered sexually mature. Given the similar estimated length observed in the field, gestation period and growth curve data presented by Best (1979), the most likely scenario would be that these two whales are related at the half-sibling level (sharing a common mother or father – either is possible in this case).

Potential relative pairs within satellite-tagged groups. Following an examination of R-values, two highly related pairs were identified within only one of the six groups containing whales tagged with satellite-monitored transmitters. Group G22 was thought to have the majority (66%) of its members sampled. Neither of the pairs tested positive for parent-offspring relationships. Full-sib relationship was positive, but only for the *restricted* dataset. A half-sibling relationship via maternal or paternal lines was likely for both pairs.

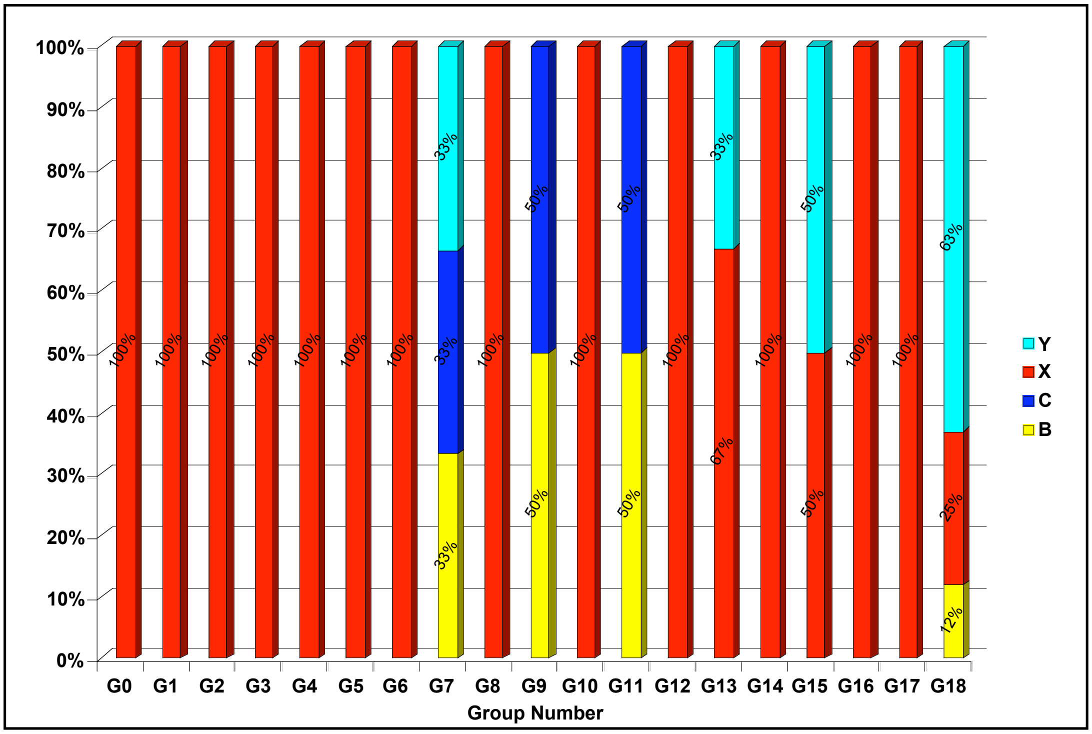

Figure 5.3.11. Percentage of haplotypes B, C, X and Y within the 19 GOM groups.

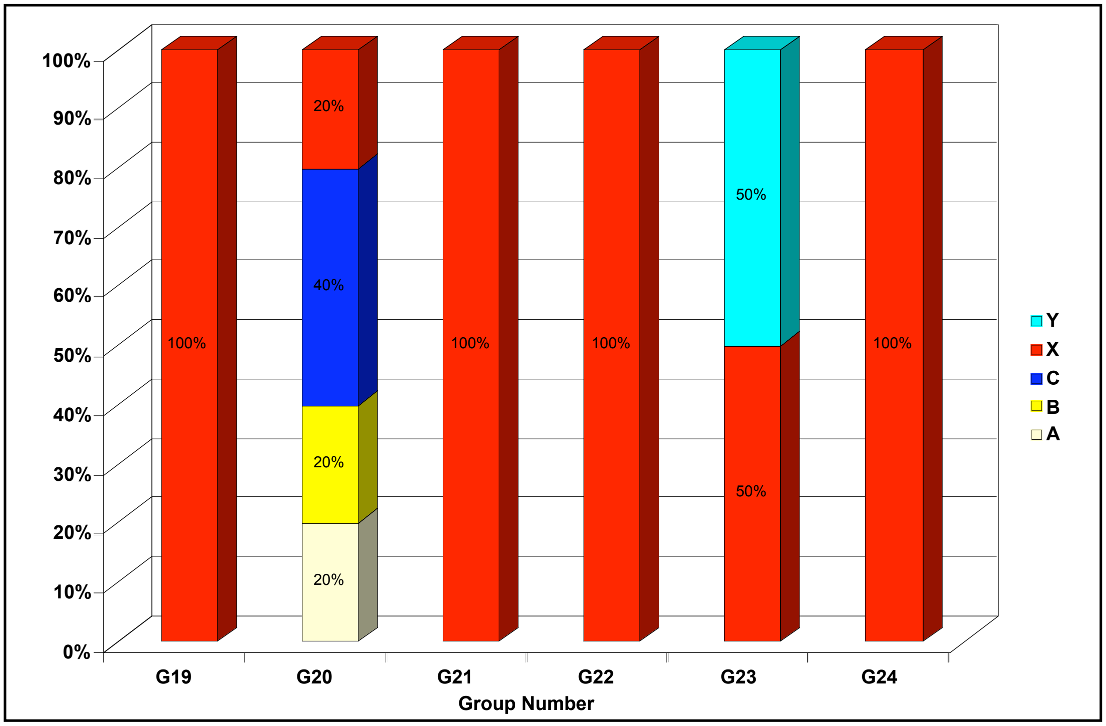

Figure 5.3.12. Percentage of haplotypes A, B, C, X and Y within the six satellite-monitored tagged groups.

<u>Genetic Composition of Clusters</u>

Clusters vary from groups mainly with respect to the behavior exhibited and the distance separating whales at the surface. Two individuals from each of six clusters (A, B, C, E, F and G), three from cluster D and four from cluster I were sampled using biopsy and sloughed skin collection methods. All clusters described here were imbedded within groups and therefore share the same locations as six of the 19 groups seen in Figure 5.3.9. Additional information such as cluster sizes, number of samples/cluster, gender, haplotype and relatedness values are provided in Engelhaupt (2004). Given the cluster size range of two to ten whales, it is clear that not all clusters were sampled in their entirety and caution should be taken when interpreting the results. However, clusters C, F and G were sampled in full.

Genetic Composition of Satellite-Monitored Tagging Clusters: Satellite-monitored tagged whales with accompanying genetic material were collected from four clusters (J, K, L and M). All S-tag clusters described here were embedded within S-tag groups and therefore share two of the six locations seen in Figure 5.3.10. Additional information such as cluster sizes, number of samples/cluster, gender, haplotype and relatedness values are provided in Engelhaupt (2004). Only clusters K and L contained ≥ 50% of the cluster size at the time of sampling.

Gender composition of clusters: Fifteen females (78.9%) and four males (21.1%) sampled from eight free-ranging clusters in the northern GOM were confirmed using molecular sexing methods. Females within a given cluster varied from juveniles to adults (based on approximate sizes estimated from small boat personnel), while all males within a cluster were considered sexually immature based on estimated sizes. If we limit our dataset to incorporate only clusters that have ≥ 50% or more of their estimated cluster size sampled, then we retain clusters A through G. Only three of these seven clusters were sampled in their entirety. This more conservative approach results in four clusters comprised of females only, two clusters including males and females and only one containing all males. Of these seven clusters, 73.3% of all individuals sampled while in a cluster formation were females and 26.6% were males. Although it would appear that clusters in the northern GOM are primarily composed of females and/or female-young male combinations, this may simply be a result of the full GOM sample set being dominated by females.

Gender composition of satellite-tagged clusters. Four females (44.4%) and five males (55.6%) were sampled from four free-ranging clusters in the northern GOM during 2002. Both females and males found within a given cluster ranged in size (based on approximate sizes estimated from small boat personnel) and thus varied in estimated age-class. If we limit our dataset to incorporate only clusters that have ≥ 50% of their estimated cluster size sampled, then we retain clusters K and L only. Cluster L contained two whales, both of which were sampled. Of these two clusters, 50% of all individuals sampled while in a cluster formation were females and 50% were young/immature males. This more conservative approach results in 100% mixed sex makeup for satellite-tagged clusters.

Pairwise and cluster relatedness estimates: All clusters were tested as separate entities to provide estimates of relatedness. Individual cluster relatedness values over all eight clusters ranged from *-0.119* to *0.585* for the *restricted* dataset and -0.135 to 0.584 for the all dataset. The mean cluster relatedness estimate over all eight clusters was *0.206* (s*td. dev. = 0.289*) and 0.193 (std. dev. = 0.293) for the *restricted* and all datasets respectively. Pairwise relatedness estimates were obtained for all individual members within their respective cluster. Estimates of relatedness for all 15 pairwise combinations within each of the nine clusters ranged from *-0.224* to *0.585* and -0.241 to 0.584 with an overall mean of *0.100* (std. dev. = 0.263) and 0.084 (std. dev. = 0.266) for the *restricted* and all datasets respectively. These means were not statistically different than an R-value of 0.000 (*restricted* Wilcoxon-Mann-Whitney: $U = 8$, $p = 1.000_{20,000}$; all Wilcoxon-Mann-Whitney: $U = 7$, $p = 1.000_{20,000}$), which is indicative of non-relatedness among individuals. The distribution of all cluster R-values was centred near zero, which suggests that individuals within clusters were not highly related.

Pairwise and cluster relatedness estimates – satellite-tagged clusters. All clusters were tested separately and together to provide estimates of relatedness. The mean cluster relatedness estimate over all four S-tagged clusters was *0.002* (s*td. dev. = 0.037*) and -0.020 (std. dev. = 0.023) for the *restricted* and all datasets respectively. Pairwise relatedness estimates were obtained for all individual members within their respective cluster. Estimates of relatedness for all six pairwise combinations within each of the four clusters ranged from *-0.127* to *0.094* and -0.153 to 0.072 with an overall mean of *-0.002* (std. dev. = 0.085) and -0.015 (std. dev. = 0.084) for the *restricted* and all datasets respectively. These means were not statistically different than an R-value of 0.000 (*restricted* Wilcoxon-Mann-Whitney: $U = 3$, $p = 1.000_{20,000}$; all Wilcoxon-Mann-Whitney: $U = 2$, $p = 0.858_{20,000}$), which is indicative of non-relatedness among individuals. The distribution of all group R-values was centered near zero and suggests that individuals within clusters were not highly related.

Potential relative pairs within clusters: First order relative pairs within clusters were identified upon an examination of R-values determined with Relatedness 5.0.2 and Kinship 1.3.1 software. Out of 19 individuals comprising eight clusters, only three potential highly related pairs were identified within three separate clusters (C, F and G). One pair was from the male only cluster G. Potential parent-offspring relationships were only possible within clusters C and F as cluster G was composed of two young males. Both pairs in clusters C and F shared alleles at 16 of 16 loci and provided significant likelihood results for each relationship tested. The male sampled in cluster F was deemed immature based on estimated size. Cluster G could be composed of either full or half-sibs. The two males sampled in cluster G were believed to be immature based on estimated size.

Potential relative pairs within satellite-tagged clusters. No potential first order relative pairs were identified within any of the four clusters containing whales that were tagged with satellite-monitored tags.

Cluster vs. group comparisons: The mean relatedness value for whales found within clusters was compared to the mean relatedness level for whales found within groups to determine whether relatedness is higher within clusters rather than groups. No significant difference (*restricted* Wilcoxon-Mann-Whitney: $U = 1030$, $p = 0.942_{20,000}$; all Wilcoxon-Mann-Whitney: $U = 1051$, $p = 0.959_{20,000}$) was found when clusters A-I were compared with the mean relatedness values of whales found within groups G0-G18. This suggests that clusters and groups share a low level of relatedness among members.

Satellite-tagged clusters vs. satellite-tagged groups. The mean relatedness value for whales found within S-tagged clusters was compared to the mean relatedness level for whales found within S-tagged groups to determine whether relatedness is higher within S-tagged clusters rather than within and between S-tagged groups. The mean R-value for all (N = 6) pairwise relatedness comparisons found within each of the four clusters was *-0.002* (*std. dev. = 0.085*) and -0.015 (std. dev. = 0.084) for the *restricted* and all datasets respectively. No significant difference (*restricted* Wilcoxon-Mann-Whitney: $U = 97.5$, $p = 0.794_{20,000}$; all Wilcoxon-Mann-Whitney: $U = 91.5$, $p = 0.633_{20,000}$) was found when S-tagged clusters were compared with the mean relatedness values for whales found within S-tagged groups.

5.4 Summary of Results and Recommendations for Future Research

The research conducted during both the SWAMP and SWSS projects provides a detailed understanding of the molecular ecology for sperm whales occupying the northern Gulf of Mexico (GOM) in addition to describing genetic details for the putative populations located in the Mediterranean Sea (MED), North Sea (NSEA) and North Atlantic Ocean (NAO). Population structuring between geographic locations, with respect to mtDNA, was highly significant and warrants the classification of each putative population as unique stocks for management purposes. The genetic composition of GOM sperm whale groups fits the previously described scenarios for both mixed sex and bachelor groups located in other areas of the world.

5.4.1 Genetic Structure of Four Putative Geographic Sperm Whale Populations

The northern GOM stock is currently listed as a separate stock from that of the western NAO (Waring et al. 2001). At present, this appears to be based solely on geographic boundaries. Prior to this research, distribution and abundance surveys found sperm whales present year-round throughout the northern GOM which may be an indication of philopatry by some whales to an area (Davis et al. 1998). Molecular sexing results indicate that the majority of samples obtained from the Gulf were from immature and adult female whales. If the expected pattern for mammalian dispersion (Greenwood 1980) holds true and females are philopatric to particular geographic areas as indicated by surveys and resightings of individuals within an area over time (Weller et al. 2000), then population structuring with respect to the maternally inherited mtDNA genome may be visible between putative populations (barring extensive emigration and immigration between geographic locations). Although variation and diversity between locations were low, the highly significant level of structuring with respect to this examination of 399 bp of the mtDNA control region supports previous genetic results suggesting a significant degree of female philopatry between ocean basins (Lyrholm and Gyllensten 1998). This study's comparison of mtDNA haplotypes between regions proved highly significant with respect to genetic differentiation measures (F_{ST} range = *0.279* (*restricted*) to 0.579 (all); Φ_{ST} range = *0.333* (*restricted*) to 0.485 (all)) and was consistent with Lyrholm and Gyllensten (1998) results which provided evidence of mitochondrial genetic differentiation on a world-wide scale. This is not specific to sperm whales though and has been described for a variety of other marine mammals (see Hoelzel et al. 2002b for a comparative review). While Lyrholm's global-scale study found low mtDNA variation between oceans, this study provides a novel finding in the form of two unique haplotypes ('X' and 'Y') only found among whales sampled in the northern GOM. The majority of whales sampled in the GOM carry Haplotype 'X'. Also unique was the fact that all samples sequenced from the MED contained only one haplotype ('C'). Although haplotype 'C' was the most common haplotype among all the NAO samples, the total lack of haplotype and nucleotide diversity within the MED sample set may be an indication of population isolation, small effective population size or bottleneck event that has reduced maternal lineages (Baker et al. 1999; Hoelzel et al. 2002a; Lyrholm et al. 1996).

Also in agreement with Greenwood (1980), the lack of strong significant nuclear differentiation between neighboring populations suggests that sexually mature males disperse from their natal populations and spread their genes to the more philopatric females. F_{ST}, R_{ST} and Rho_{ST} values ($<$ 0.08), although significant, indicated minimal genetic differentiation between the GOM-MED and the MED-NSEA (significant for F_{ST} only) populations with respect to nuclear differentiation. By testing for sex-biased dispersal, our F_{IS}, H_S and mean assignment results were all in agreement with males being the dispersers and females being the more site-faithful of the sexes. However, larger sample sizes are required to increase the power of these tests (Goudet et al. 2002). While Lyrholm et al. (1999) has already provided evidence for sex-biased dispersal occurring on a global scale, our sample set compares a more restricted geographic area and only includes populations that border the NAO.

Overall, our population structure results support the delineation of the northern GOM into a female-dominated stock that is genetically distinct from the NAO, MED and NSEA putative populations (Engelhaupt et al., in preparation). As such, the GOM population requires proper management to ensure stock survival. While the putative population in the MED lacks any mtDNA variation among sampled members, only further sampling in conjunction with additional studies focusing on contaminant analysis, site-fidelity, movement patterns and habitat use will provide a more thorough understanding with regards to questions of isolation.

Recommendations for Future Research – Population Structure

A continuation and extension of multi-faceted research techniques in multiple locations (e.g. the southern Gulf of Mexico, the Caribbean Sea, the MED, throughout the western and eastern NAO and NSEA) would provide further support needed to accurately describe levels of both population and possibly subpopulation structuring. Movement among female sperm whales appears to be limited resulting in population structuring with respect to the mtDNA genome. The ability to 'bridge the gaps' between geographic areas would provide valuable information as to the extent of gene flow within and among geographic locations as well as provide manageable stock boundaries. The development and incorporation of Y-chromosome genetic markers would allow for an assessment of whether genetic variation between males from different geographic populations exists in addition to quantifying levels of relatedness between males from multiple geographic locations. Dedicated efforts to sample large physically and sexually mature males generally found at higher latitudes as well as at lower latitudes during the breeding season would provide further clues as to how males disperse from their natal populations and spread their genes to the more philopatric females. The compilation of genetic studies via collaboration amongst researchers around the globe provides important answers with regards to previously unknown questions. Calibrations are currently underway to combine our microsatellite allele size results with those of published data (i.e., Lyrholm et al. 1999) on sperm whale microsatellites to provide a more detailed picture as to how these three putative populations fit into the global sperm whale nuclear DNA picture. Further sampling in conjunction with additional studies focusing on contaminant analysis, site-fidelity, movement patterns, habitat use and coda structure among clans will provide a proper understanding of how to properly manage existing sperm whale populations.

5.4.2 Composition of Sperm Whale Groups and Clusters in the Northern Gulf of Mexico

Based on preliminary length estimates and group size estimates conducted during the GulfCet I and GulfCet II cruises, sperm whale groups encountered in the northern GOM were assumed to contain adult females, immatures and calves of both sexes (Davis et al. 1998; Weller et al. 2000; Würsig et al. 2000). In order to accurately assess group type and relatedness among whales within and between groups, this study compared a greater number of polymorphic microsatellites (N = 16) than previous sperm whale studies, analyzed the highly variable mtDNA control region to describe maternal lineages and incorporated gender results based on molecular sexing techniques. Although our assessment of group composition lacks the required long-term association data and total group sampling to fully understand social structure within GOM groups, both poorly and well-sampled (≥ 50%) group results were quite comparable with gender and relatedness findings suggesting that the majority of groups encountered in the GOM fit the mixed-sex group scenario comprised of both related and unrelated adult females and young of both sexes (Engelhaupt and Hoelzel, in preparation B). The occurrence of what seems to be all-male bachelor groups utilizing the same low-latitude feeding grounds as the female mixed-sex groups in the GOM was unexpected.

Relatedness within groups was surprisingly low, but significantly greater than relatedness found between groups. This result is consistent with other sperm whale studies that have focused on both groups and units (Richard et al. 1996; Christal 1998; Bond 1999). There were instances of first-order kin pairs present among sampled group members; however, they were not as frequent as one would expect within a previously described matrilineal species where females show high levels of care for their offspring (Whitehead and Weilgart 2000). Interestingly, groups were composed of both single and multiple (up to 3 in some instances) matrilines. Individuals that shared numerous alleles across multiple loci, but carried different mtDNA haplotypes were assumed to be related at the level of half-siblings via a common paternal line or perhaps grandmother/grandchild (no large males that could be grandfathers were present in the study site) if they shared the same haplotype. Bond (1999) described half-sibling relationships as the most common for mixed sex groups in the Azores and our findings for the GOM appear quite similar. However, the Azores groups were predominantly composed of related individuals (Bond 1999) while the GOM group relatedness values imply that groups are primarily composed of unrelated members.

The sampling of clusters was undertaken on an opportunistic basis. Clusters contained both single and multiple (up to 3) haplotypes and relatedness results among clustered members indicated that clustered whales were no different than whales found within groups.

Recommendations for Future Research – Group Composition

Unfortunately, the GOM lacks long-term (i.e. multi-year) association data required to accurately describe social affiliations among group members. Aside from OSU's satellite-monitored tagging results, our data on group composition is currently unable to imply whether whales sampled within groups are constant companions or simply casual acquaintances that mix with permanent group members on a temporary basis (Whitehead et al. 1991). Future work must build on the integration of photoID, photogrammetry and biopsy sampling in order to combine relatedness issues with association patterns between whales of an accurately known age class over long durations. The combination of satellite-monitored tagging and biopsy sampling will continue to provide one of the most in-depth examinations of how related and non-related whales sampled within a group either move apart or stay together through space and time. This combination of techniques promises an extremely fine-scale assessment into the daily lives of sperm whales utilizing the northern GOM.

6 SATELLITE-TRACKED TAGGING OF SPERM WHALES IN THE GULF OF MEXICO

Section 6 presents preliminary results from the satellite-tracking of sperm whales in the Gulf of Mexico. The movements of tagged whales and their seasonal distributions are presented in Section 6.1. In Section 6.2 the locations of the tagged sperm whales are considered relative to habitat characteristics.

6.1 Movements and Seasonal Distribution of Satellite-Tracked Sperm Whales

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Abstract

Movements and home range were studied for 39 sperm whales tagged with satellite-monitored implantable radio tags in the Gulf of Mexico. A total of 2,826 locations were received from 8 August 2001 to 15 October 2004. Quality of satellite-estimated locations was very good: 45.5% of them were classified as Argos standard locations classes (LC3, LC2, and LC1, which are predicted to be within 50 m, 350 m, and 1000 m of the actual location respectively). To 5 November 2004, the active life of tags (number of days between deployment and last satellite location) ranged from 17 to 607 days and the number of locations per tag ranged from three to 183. Whales were tracked for at least 106,743 km during 6,477 whale-tracking days with individual and yearly average distances up to 17,068 km and 3,719 km, respectively, and travel speeds ranging from 0.2 - 2.3 km/hr (average 0.7 km/hr). Tagged female whales tend to more routinely occupy the upper slope edge with far less representation over deep water than males. Only two tagged females actually moved out over deep water, while several males and individuals of unknown sex moved offshore and traveled to the southwestern reaches of the Gulf (Bay of Campeche). One of the male whales moved into the north Atlantic and, after getting near the path of Hurricane Isabel, turned around and went back into the Gulf of Mexico. Our data indicate that males have a larger individual range than females, with emphasis over deeper waters. Moreover, home range estimates for each month indicate the year round importance of the Mississippi River Delta region. No significant negative effect was observed on resighted tagged whales; none of them appeared emaciated and all observed behavior was normal.

Methodology

Forty-five sperm whales were tagged with four types of Argos Satellite-monitored implantable radio transmitters between 2001 and 2004. The 2001 tags were applied with a Barnett 150-pound crossbow during a 1-8 August 2001 National Marine Fisheries Service cruise sponsored by the Minerals Management Service. The 2002-2004 tags (N = 18, 15 and 8, respectively) were applied as part of the Sperm Whale Seismic Study sponsored by the Minerals Management Service. The latter tags were applied with an air-powered applicator modified from an air-powered line throwing device (Heide-Jørgensen et al. 2001). The tags were similar in design to those used on right whales, humpbacks, blue whales, and fin whales and were coated with a long-term release antibiotic (Gentomycin sulfate in a methacrylate compound) to reduce the possibility of infection. Whales were typically tagged at a range of 2 - 3 meters from a rigid hulled inflatable boat launched from the NOAA ship *Gordon Gunter* (2001) and the Texas A&M

research vessel *Gyre* (2002-2004). Although the survey cruises covered a wide area in the central and eastern northern Gulf of Mexico, most whales were tagged off the Mississippi River Delta (see Sections 3.1 and 3.2 and Appendix A.1).

In general, tags transmitted for selected hours of each day during 2001. In subsequent years, the same daily transmission cycle was used for the first 90 days. On the 91st day, a new cycle took effect, in which each transmission day was followed by either 3 days or 4 days without transmission. This resulted in most locations beyond the 90th day being 3 to 4 days apart. Straight-line distance between locations most likely underestimated the distance traveled and hence calculated speed, both of which therefore should be considered minimums.

Location Quality and Screening Criteria

A total of 2,826 locations were received from 39 tagged whales from 2001 to 15 October 2004 (Figure 6.1.1). Argos locations were assigned one of seven levels of accuracy by Service Argos, depending on satellite/transmitter geometry, number of messages received during a pass, and transmitter frequency stability (Table 6.1.1). Most of the sperm whale locations were of LC0 quality or better (Figure 6.1.2). We applied a series of screening criteria to identify locations to be used in subsequent analyses. In this criteria process, we added a “radial buffer” of 11.5 km to locations with Argos quality less than LC1, 1 km to LC1 locations, and none to LC2 and LC3. This buffer represents the area within which the true location should be most of the time (Mate et al. 1997).

Removal of locations to minimize errors then proceeded in several steps:

1. Locations with buffer areas entirely on land were removed.

2. Locations with speeds <15 k/h between them were retained. If speeds were greater than 15 k/h, the sum of the two location buffer values was subtracted from the total distance between them and the speed recalculated. If the new value was less than 15 k/h, both locations were retained; otherwise one location was removed. The location with the lower LC quality was removed. If the locations had the same quality, the one whose removal minimized distance traveled was edited out.

3. Locations were also edited on a temporal basis. When a location with an assigned quality of less than LC1 was less than 1 hour apart from another location, only one was retained. The location with the higher LC quality was chosen or, if they were both less than LC1, the one whose removal minimized distance traveled was edited out.

4. When an LC1 location was less than 10 minutes apart from an LC2 or LC3, the LC1 location was removed. If an LC1 location was less than 10 minutes apart from another LC1, the location whose removal minimized distance traveled is edited out.

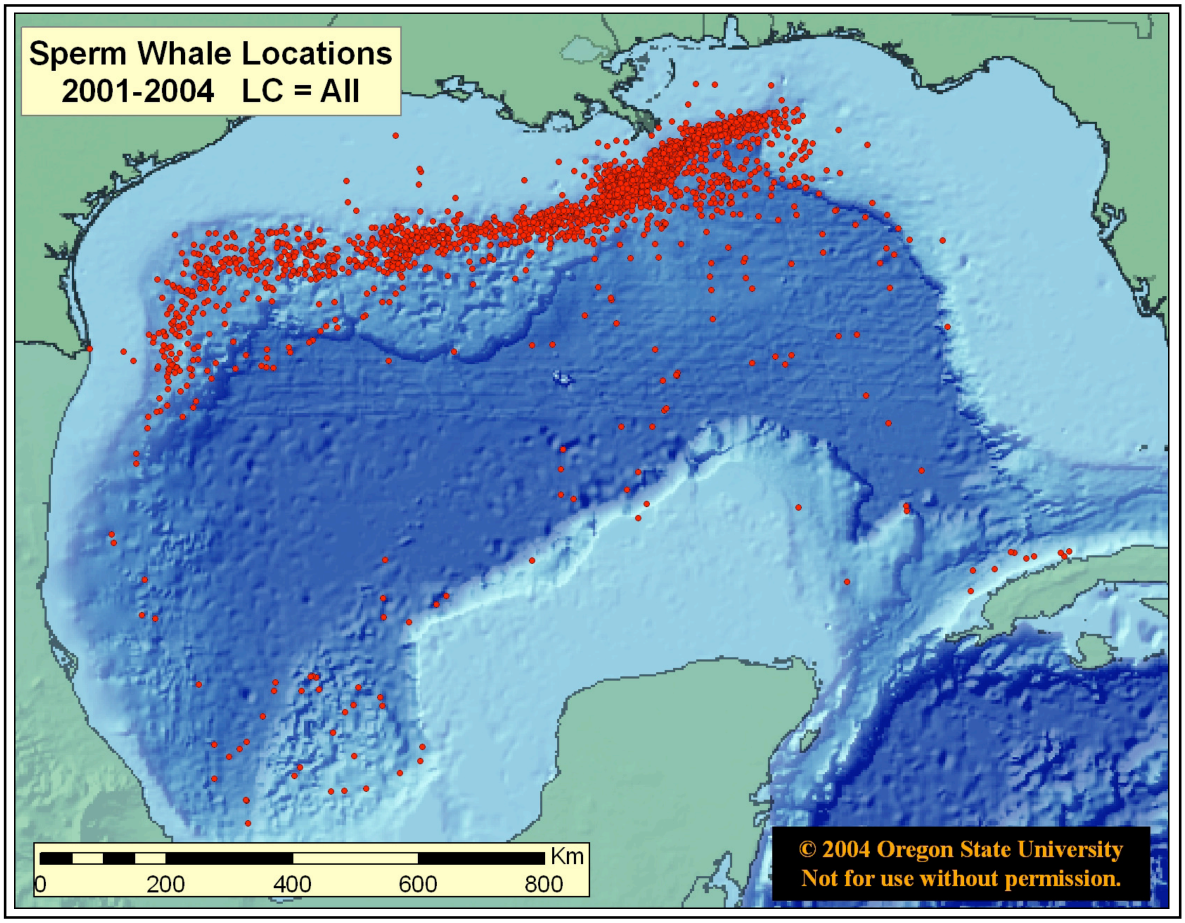

Figure 6.1.1. Locations of sperm whales tagged in 2001-2004. All ARGOS location classes are included.

Table 6.1.1

Argos Estimates of Location Accuracy for Each Location Class

Location Class	Accuracy	Number of Messages
0	Over 1000m	4 +
1	350m to 1000m	4 +
2	150m to 350m	4 +
3	Under 150m	4 +
A	No Estimate	3
B	No Estimate	2
Z	Invalid	N/A

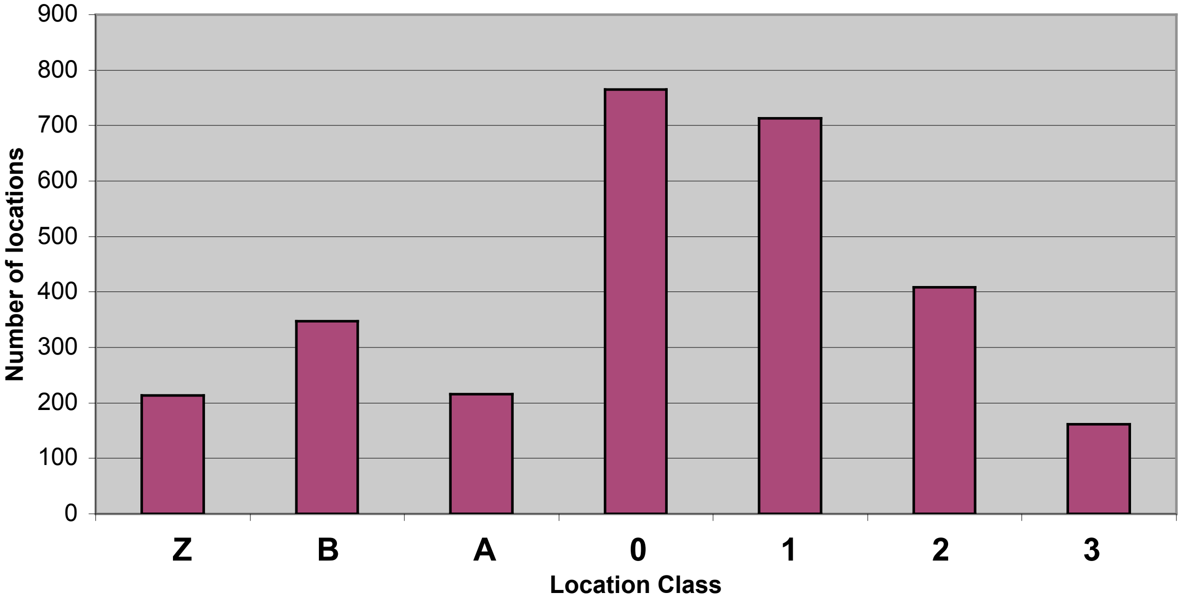

Figure 6.1.2. Summary of location quality for 2826 sperm whale satellite-determined locations.

Home Range Analysis

A practical and commonly used definition of home range is "utilization distribution" (UD), which is the bivariate probability density function of finding an animal at a particular location on a plane (Anderson 1982). We estimated home range of satellite-tracked sperm whales through calculation of the 50% UD. The Animal Movement Extension (version 2.0) for Arcview (Hooge and Eichenlaub 2000) was used to calculate UD by kernel method with the smoothing parameter (*H*) calculated by least-squares cross-validation (Worton 1989).

Results

General Distributions

Following this filtering process, 2,047 locations were retained with accuracies from LC 0-3 (Figure 6.1.3). This composite of filtered locations from all years for both sexes provided a general pattern of distribution for sperm whales, emphasizing the upper Gulf along the continental slope edge. By connecting the locations in chronological order for each individual whale, the minimum estimate of whale movements could be calculated (Figure 6.1.4). Caution should be exercised in interpreting these "movements", as they do not represent the true route of movement. Instead, they are the shortest distance between chronological locations and are thus a very conservative estimate of distance and speed traveled. The emphasis of locations off the Mississippi River Delta may be a bias of having tagged the animals in that general region.

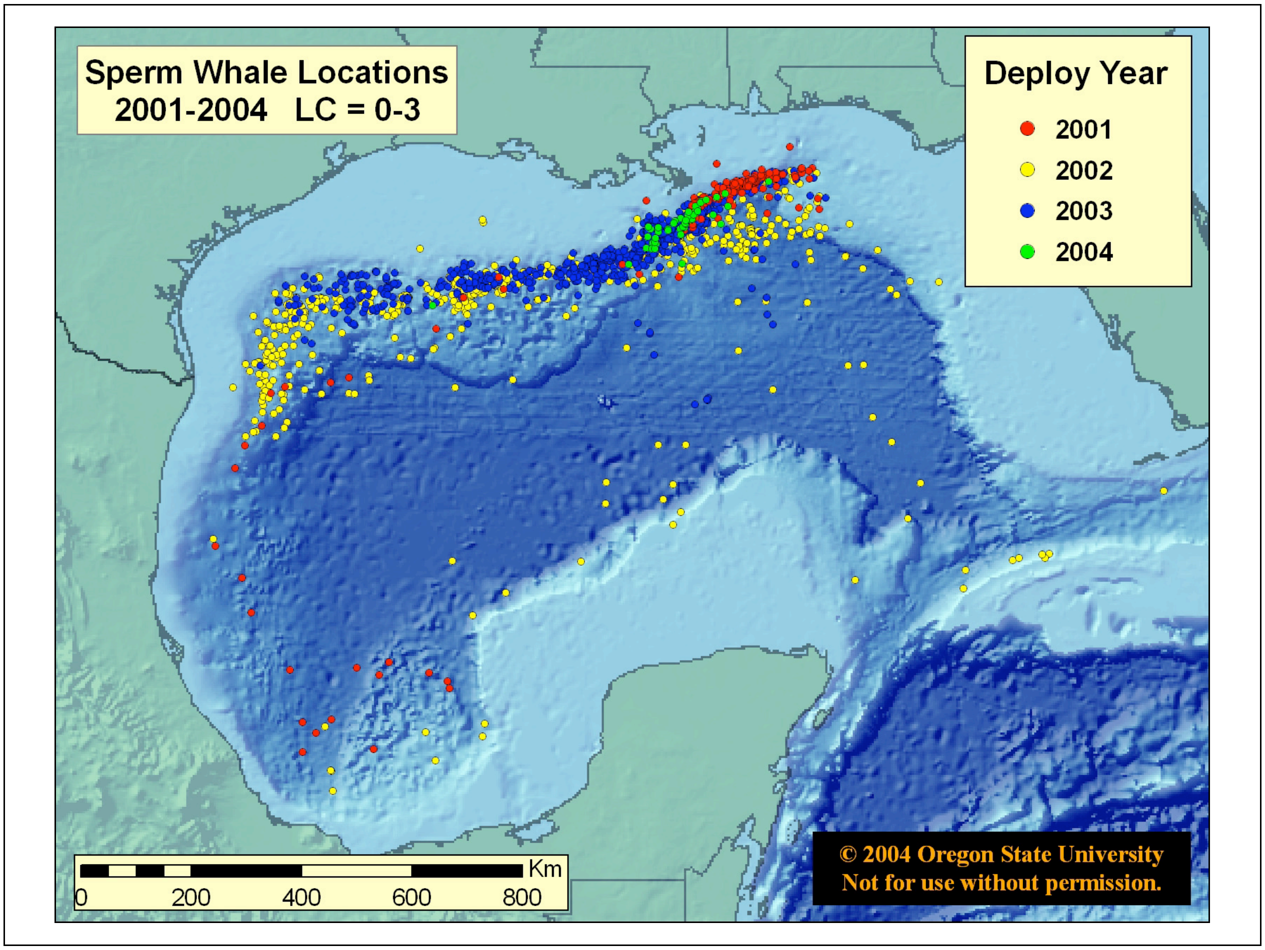

Figure 6.1.3. Locations of classes 0-3 from sperm whales tagged in 2001-2004.

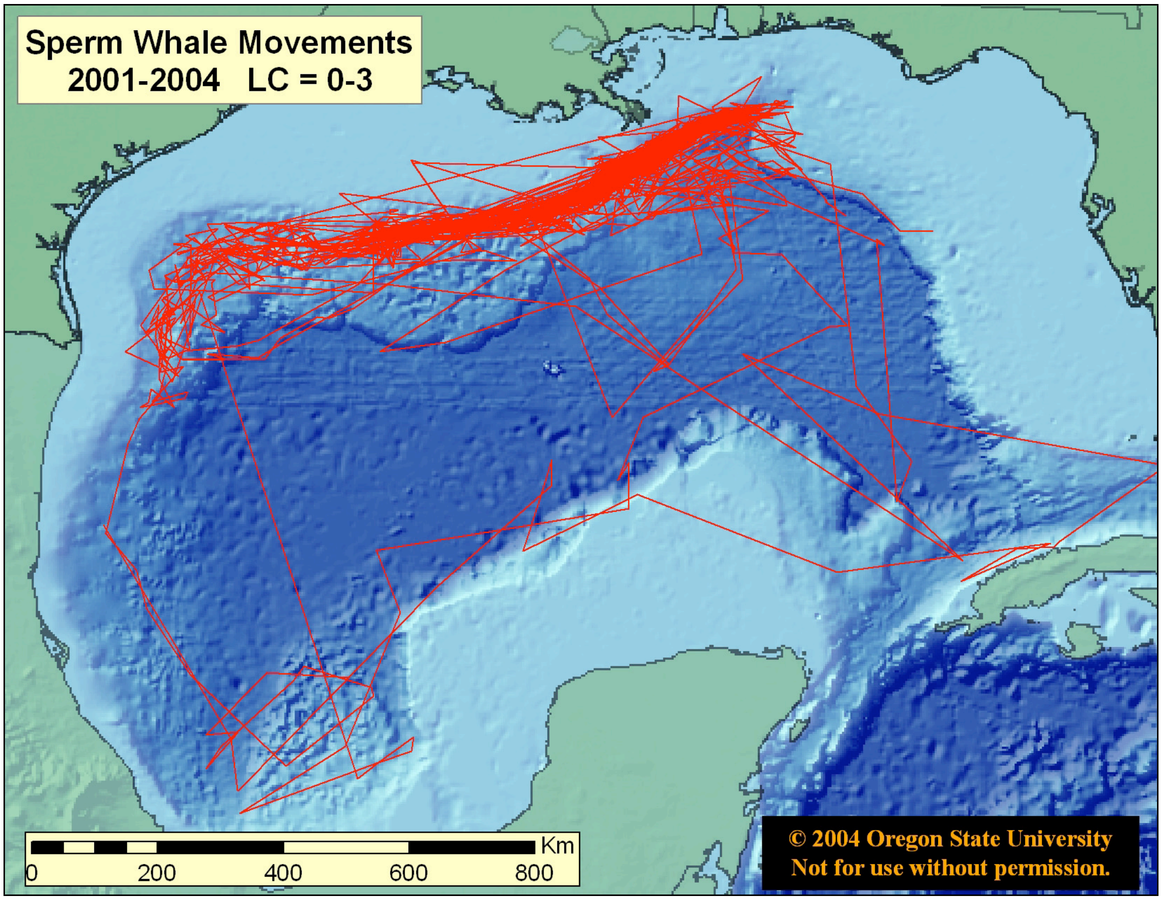

Figure 6.1.4. Tracklines of the 39 sperm whales tracked by satellite in 2001-2004; LC = 0-3.

In total, whales tagged during 2001 - 2004 were tracked for at least 106,743 km during 6,477 whale-tracking days (Figures 6.1.5-6.1.8), with individual and yearly average distances up to 17,068 km and 3,719 km, respectively, and travel speeds ranging from 0.2 - 2.3 (average 0.7 km/hr, Table 6.1.2-6.1.5). Movements were characterized as meandering or linear (for more details see section by Ortega-Ortiz et al. in this report). About 95% of the speed calculations for consecutive pairs of locations of class 0-3 were less than 6 km/h. As a result, we are presently re-evaluating our screening criteria and the effects of a more conservative speed filter.

A depiction of travel speeds between chronological locations does not show any area of consistently higher-speed travel, which might be indicative of a movement corridor between high-use areas (Figure 6.1.9). Instead, generally slow speed travel appears to be a consistent feature along the entire upper Northern Gulf. Some of the speeds are undoubtedly the result of long periods between locations, underestimating true distance travel and speed.

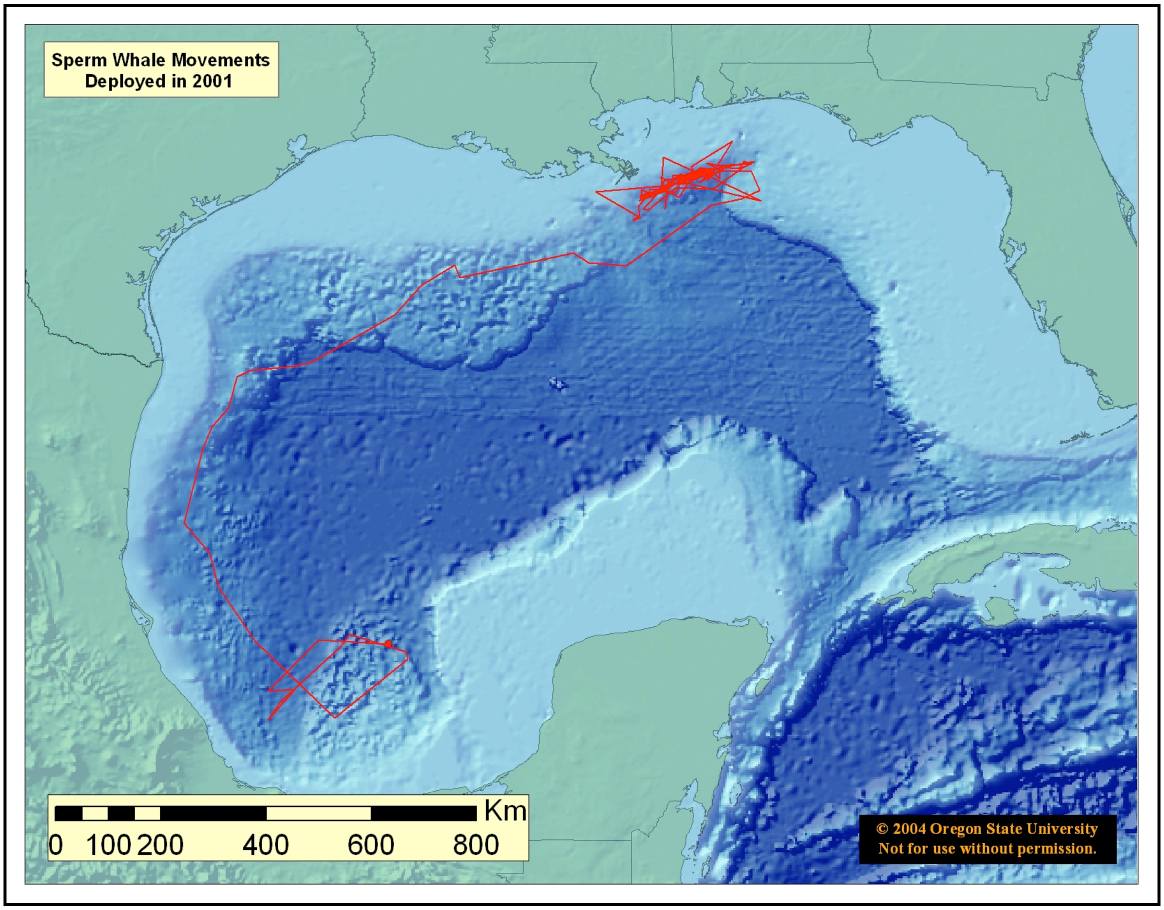

Figure 6.1.5. Trackline of the sperm whale tagged in 2001.

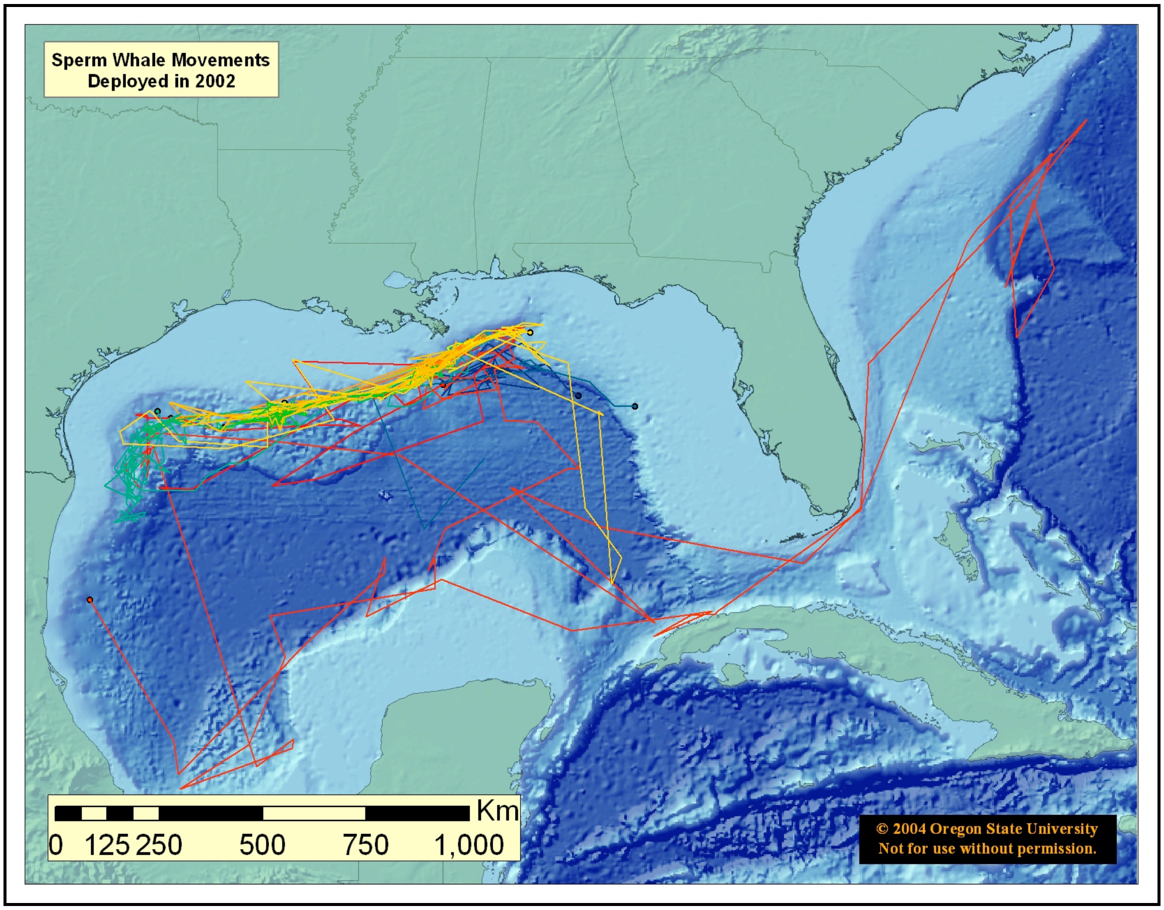

Figure 6.1.6. Tracklines of sperm whales tagged in 2002.

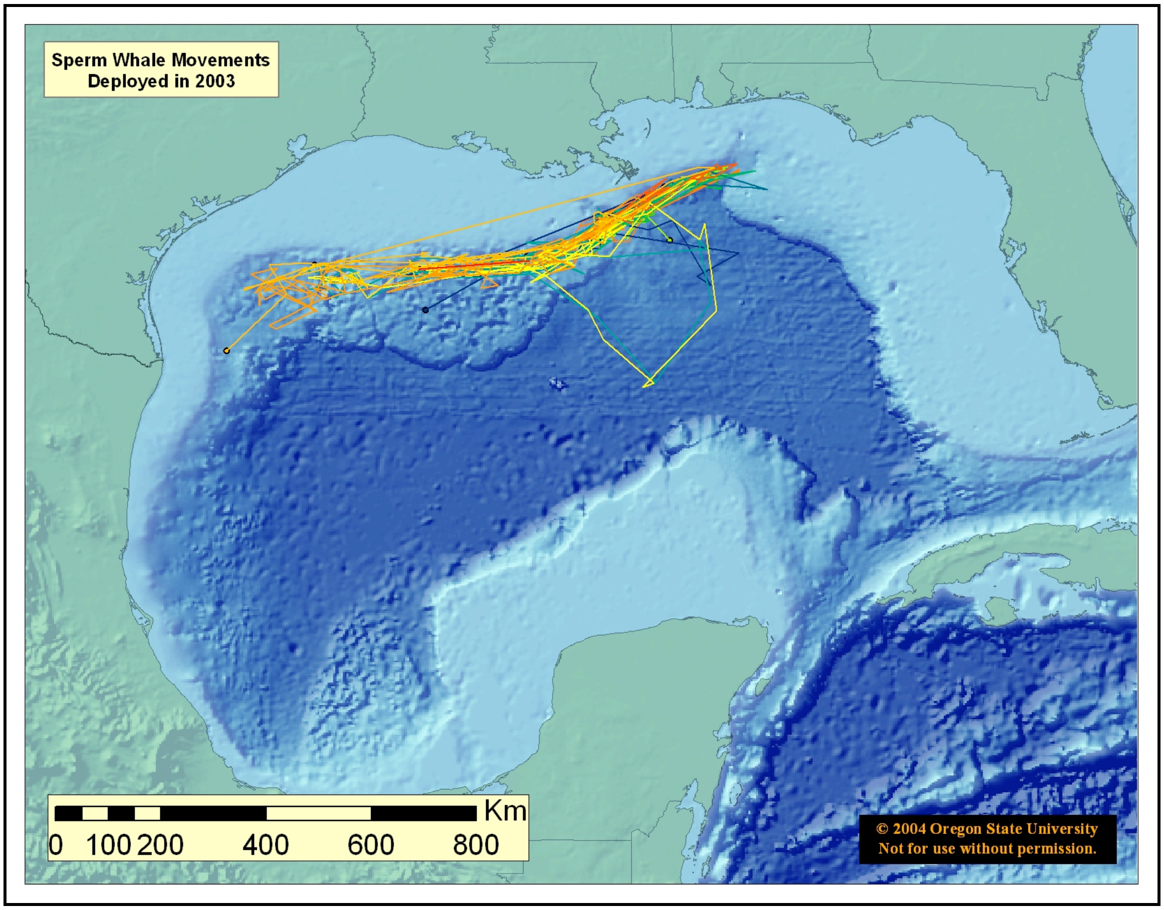

Figure 6.1.7. Tracklines of sperm whales tagged in 2003.

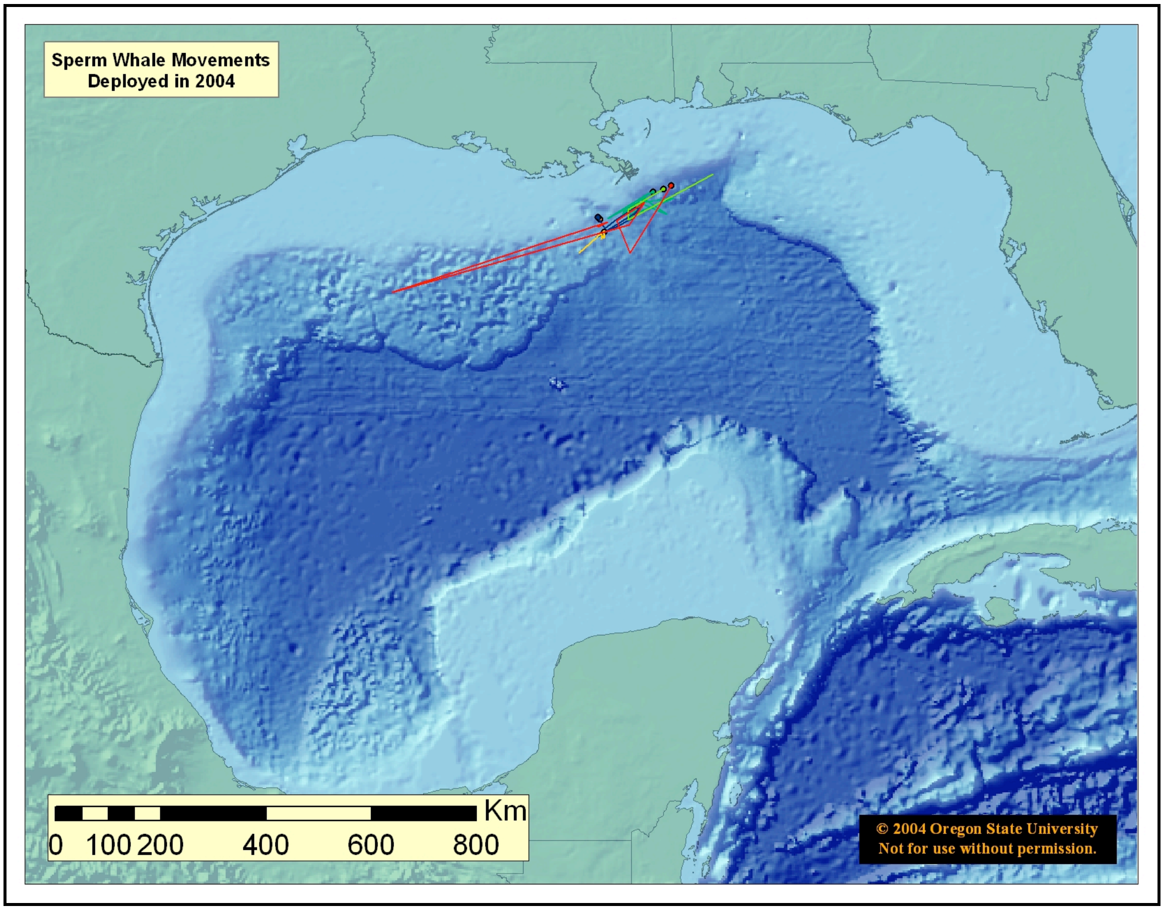

Figure 6.1.8. Tracklines of sperm whales tagged in 2004.

Table 6.1.2

Summary of Tracking Data for Whales Tagged in 2001
(PTT = Platform Transmitter Terminal number or tag number, Deployed = date tag was deployed, LocDays = time (days) from tag deployment until last location was received, MsgDays = time (days) from tag deployment until last message was received, Dist = summation of straight-line distance between all pairs of consecutive locations, Spd = average speed of straight-line travel between pairs of consecutive locations.)

PTT	Deployed	LocDays	MsgDays	Dist (km)	Spd(km/h)
02083	8/8/01	136.6	136.6	7624	2.3
10820	8/1/01	0.0	1.2		
23030	8/7/01	0.0	0.0		
23032	8/8/01	0.0	0.0		
Totals		136.6	137.7	7624	
AVERAGES		34.1	34.4	1906	2.3

Table 6.1.3

Summary of Tracking Data for Whales Tagged in 2002
(Abbreviation of column headers is the same as Table 6.1.2.)

PTT	Deployed	LocDays	MsgDays	Dist(k)	Spd(k/h)
05647	7/1/02	135.7	135.7	3523	1.1
05648	6/28/02	73.0	73.0	3134	1.8
05649	7/7/02	371.8	376.9	5106	0.6
05650	7/1/02	268.0	272.4	5875	0.9
05654	6/24/02	122.6	122.6	1840	0.6
05655	7/3/02	74.6	74.6	2130	1.2
05660	6/24/02	63.7	63.7	978	0.6
05669	7/3/02	454.7	486.2	5426	0.5
05670	7/3/02	286.0	286.0	2609	0.4
05678	7/2/02	17.1	17.1	196	0.5
05685	7/1/02	567.0	567.0	8196	0.6
05701	7/3/02	247.2	247.2	5138	0.9
05709	7/3/02	372.9	388.0	5006	0.5
05710	7/7/02	82.4	85.8	1278	0.6
05719	7/3/02	70.7	70.7	1683	1.0
05720	7/3/02	30.8	30.8	329	0.4
05725	7/1/02	607.3	607.3	17068	1.2
05726	7/1/02	275.8	280.6	6482	1.0
Totals		4121.3	4185.5	75997	
AVERAGES		229.0	232.5	4222	0.8

Table 6.1.4

Summary of Tracking Data for Whales Tagged in 2003
(Abbreviation of column headers is the same as Table 6.1.2.)

PTT	Deployed	LocDays	MsgDays	Dist(k)	Spd(k/h)	Dives/h
00826	7/11/03	243.5	243.5	4507	0.8	N/A
00827	7/11/03	179.1	179.1	1032	0.2	3.6
00828	7/4/03	304.0	304.0	6474	0.9	3.8
00829	7/9/03	298.9	298.9	4127	0.6	3.8
00833	7/5/03	155.8	155.8	2281	0.6	3.2
00839	7/8/03	48.1	50.2	252	0.2	25.4
00843	7/5/03	361.0	361.0	6871	0.8	3.2
01385	7/3/03	391.4	391.4	6293	0.7	4.1
05654	7/4/03	79.9	79.9	1672	0.9	2.9
05678	7/11/03	218.1	230.1	4504	0.9	7.6
05710	7/7/03	408.7	411.2	6338	0.6	4.1
05719	7/6/03	341.0	344.4	8409	1.0	5.3
05720	7/6/03	130.4	130.4	1930	0.6	4.5
10820	7/9/03	61.8	81.4	525	0.4	7.0
23038	7/11/03	95.6	95.6	564	0.2	18.1
Totals		3317.2	3356.8	55778		
AVERAGES		221.1	223.8	3719	0.6	6.9

PTT 00826 sensor malfunctioned

Table 6.1.5

Summary of Tracking Data for Whales Tagged in 2004
(Abbreviation of column headers is the same as Table 6.1.2.)

PTT	Deployed	LocDays	MsgDays	Dist(k)	Spd(k/h)	Dives/h
00838	6/10/04	0.0	0.6	0		
00841	6/17/04	0.0	0.0	0		
00845	6/10/04	91.3	91.7	473	0.2	22.3
1387	6/10/04	139.2	139.2	933	0.3	4.6
01390	6/10/04	95.2	95.2	837	0.4	22.3
02083	6/6/04	39.5	39.5	230	0.2	9.0
05660	6/6/04	71.9	71.9	75	0.0	19.3
05670**	6/6/04	151.9	151.9	1783	0.5	24.7
Totals		588.9	589.9	4329		
AVERAGES		73.6	73.7	541	0.3	17.0
Totals > 5 days		588.9	589.3	4329		
AVERAGES > 5 days		98.1	98.2	722	0.3	17.0

**Still transmitting 11-5-04

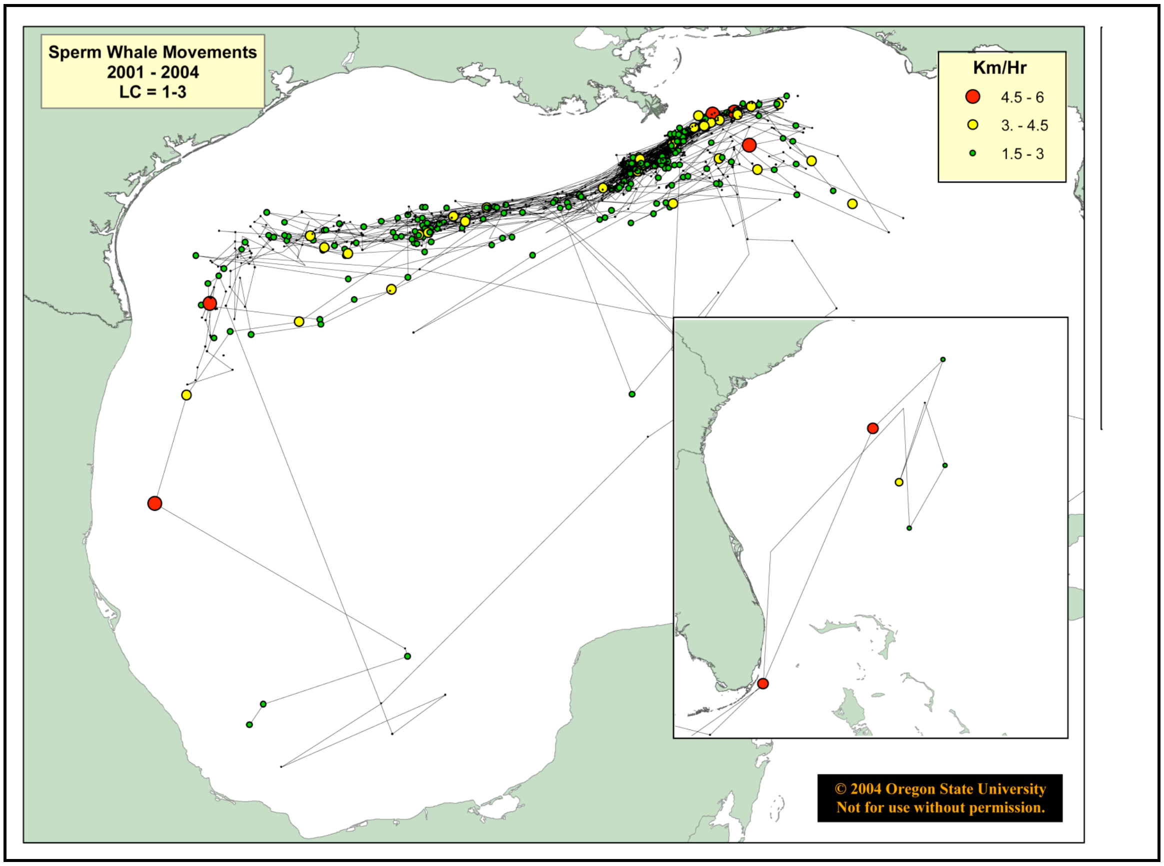

Figure 6.1.9. Travel speeds by segment. The color and size of each dot represent the speed of a tagged whale's previous travel segment.

The seasonal movements of all tagged whales are shown as a set of composite figures (Figures 6.1.10-6.1.13) and as a set of individual seasons by year (data for tags beyond 12 months are shown with the following year's tagged animals): 2001 (Figures 6.1.14-6.1.16), 2002 (Figures 6.1.17-6.1.20), 2003 (Figures 6.1.21-6.1.24), and 2004 (Figures 6.1.25 and 6.1.26). Because tagging was done in summer months, there are obviously more individuals being tracked during those months than in other parts of the year. Furthermore, the summer tagging locations bias the view of sperm whale distribution throughout the northern Gulf in the summer. Sperm whales are known to inhabit other areas of the Gulf besides the tagging area. Had animals been tagged elsewhere, their summer movements may have taken place in other areas. This provides a compelling rationale for proposed SWSS II studies to tag sperm whales in other regions of the Gulf.

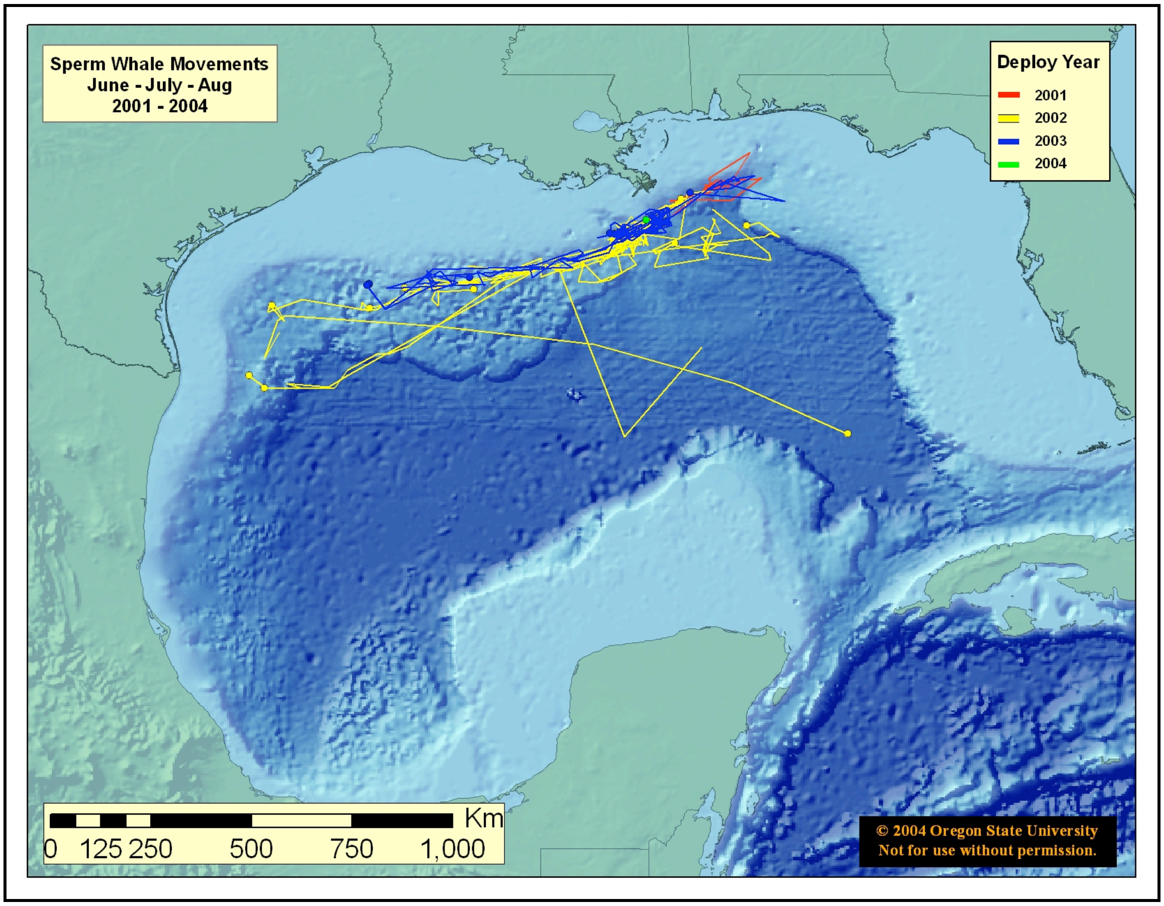

Figure 6.1.10. Tracklines of tagged sperm whales for the period June-July-August 2001-2004.

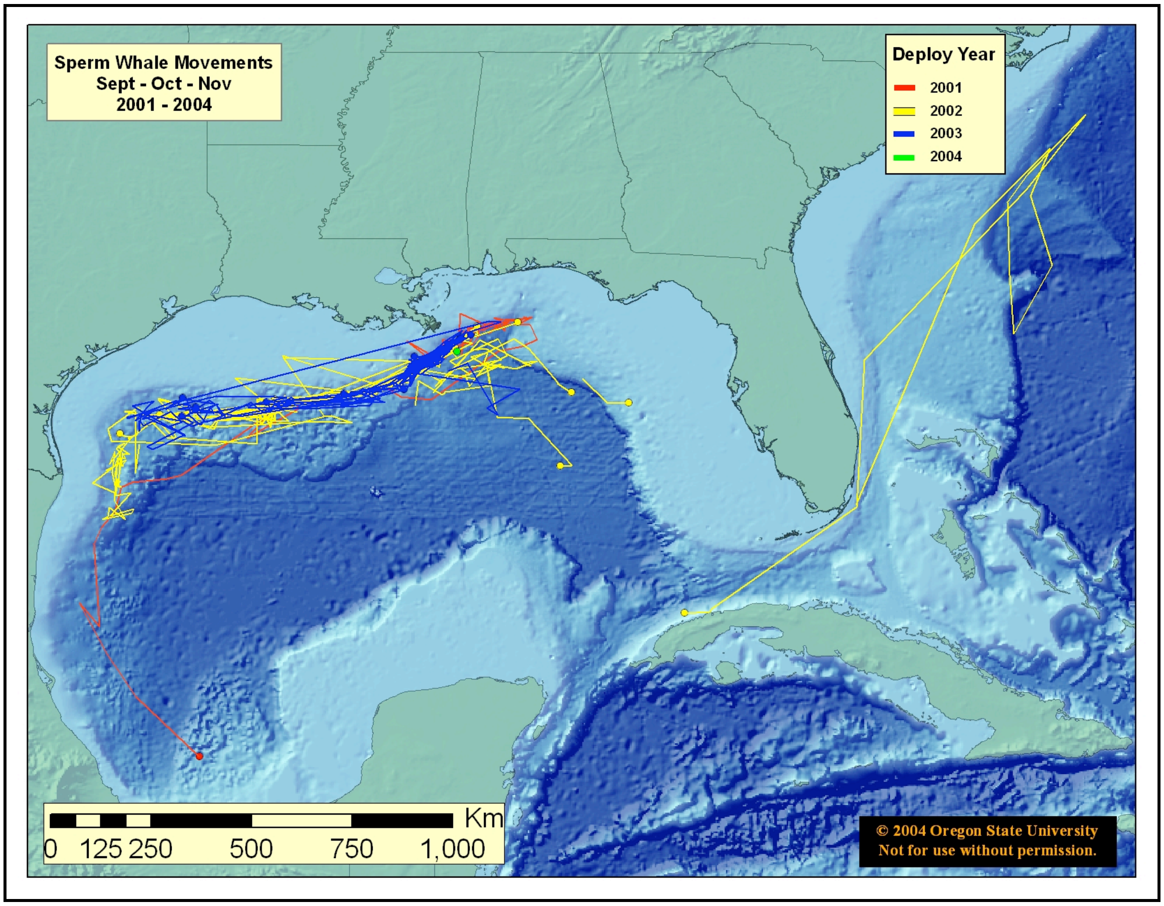

Figure 6.1.11. Tracklines of tagged sperm whales for the period Sept-Oct-Nov 2001-2004.

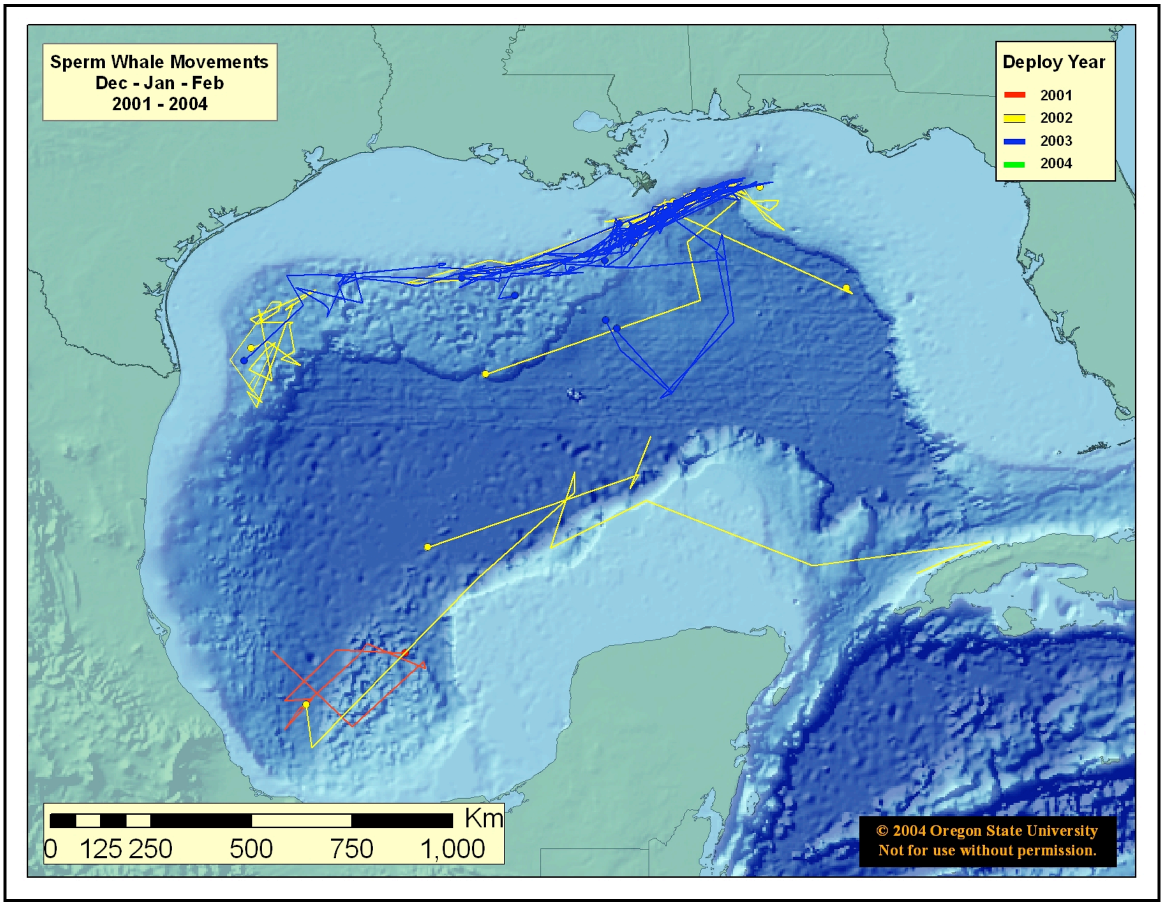

Figure 6.1.12. Tracklines of tagged sperm whales for the period Dec-Jan-Feb 2001-2004.

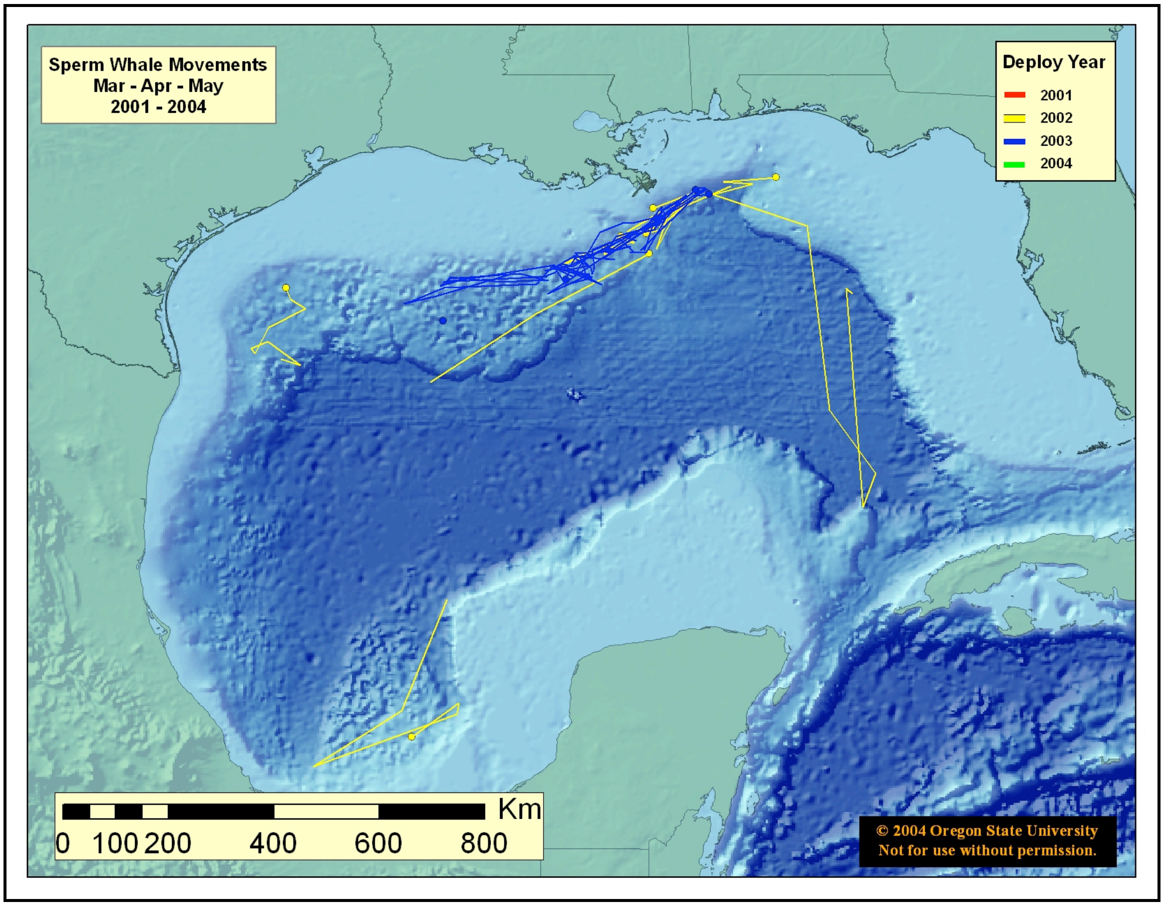

Figure 6.1.13. Tracklines of tagged sperm whales for the period Mar-Apr-May 2001-2004.

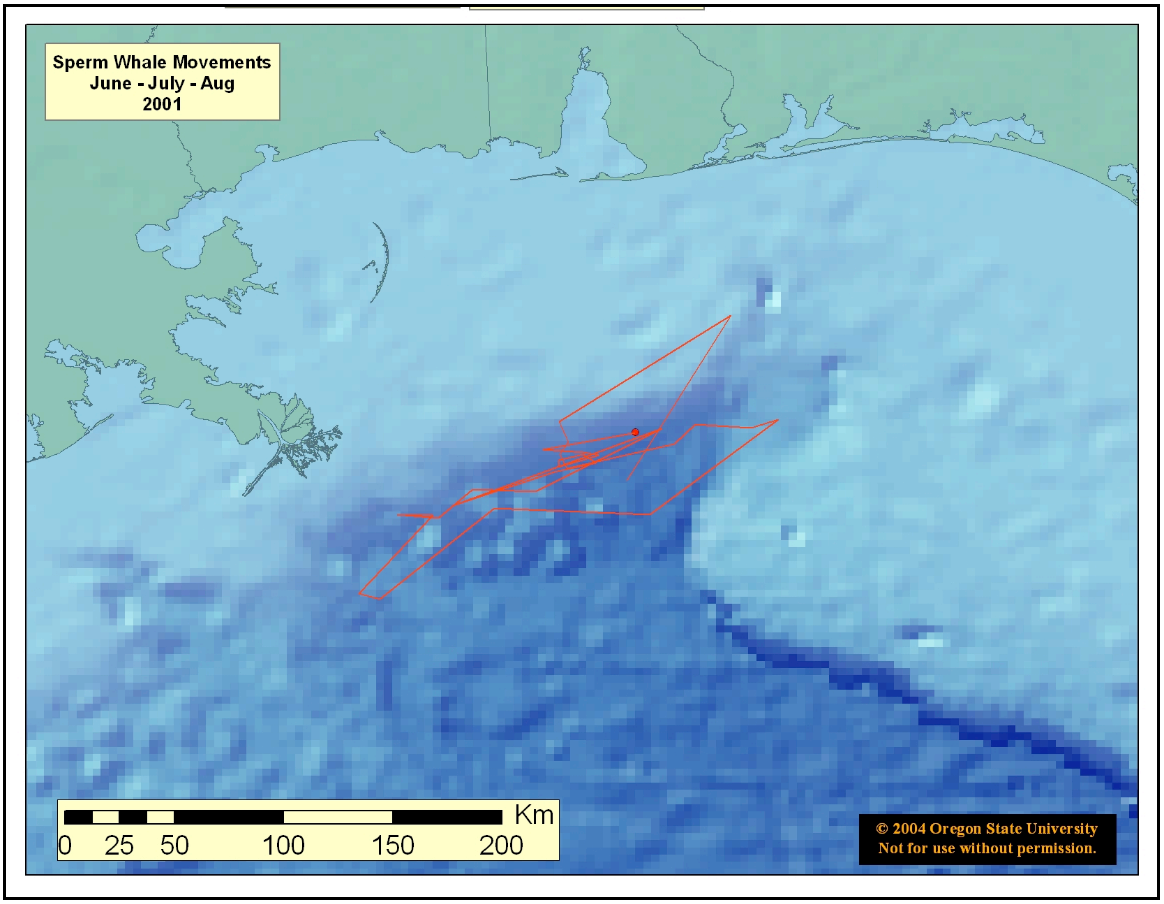

Figure 6.1.14. Tracklines of tagged sperm whales for the period June-July-Aug 2001.

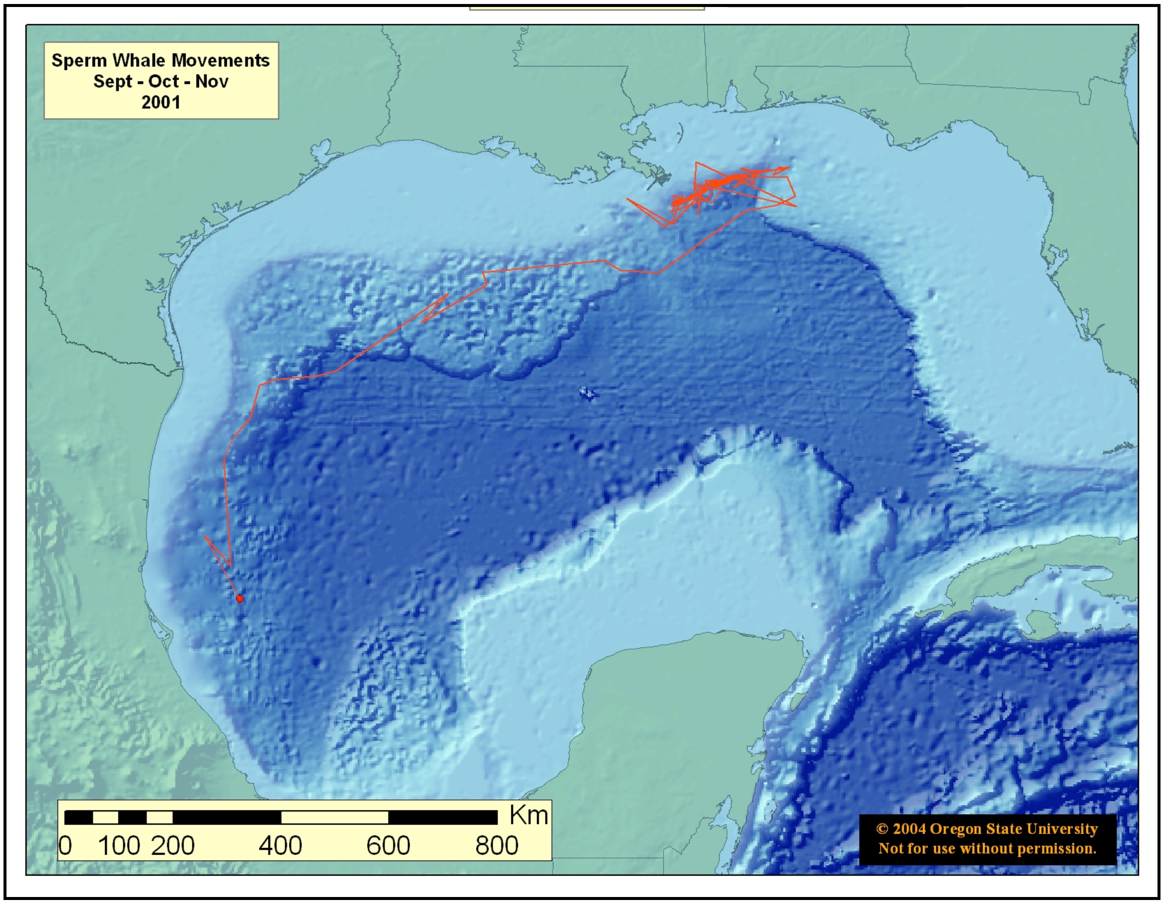

Figure 6.1.15. Tracklines of tagged sperm whales for the period Sept-Oct-Nov 2001.

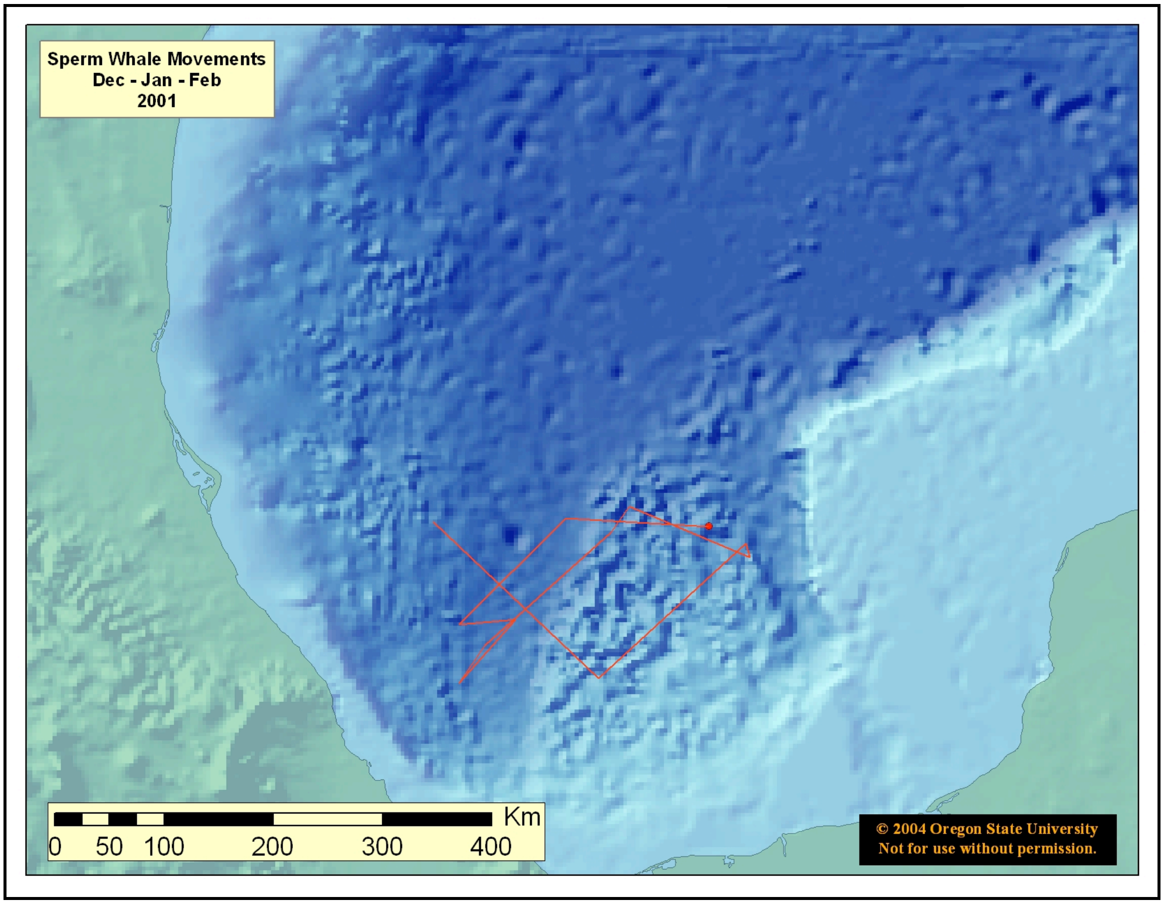

Figure 6.1.16. Tracklines of tagged sperm whales for the period Dec-Jan-Feb 2001.

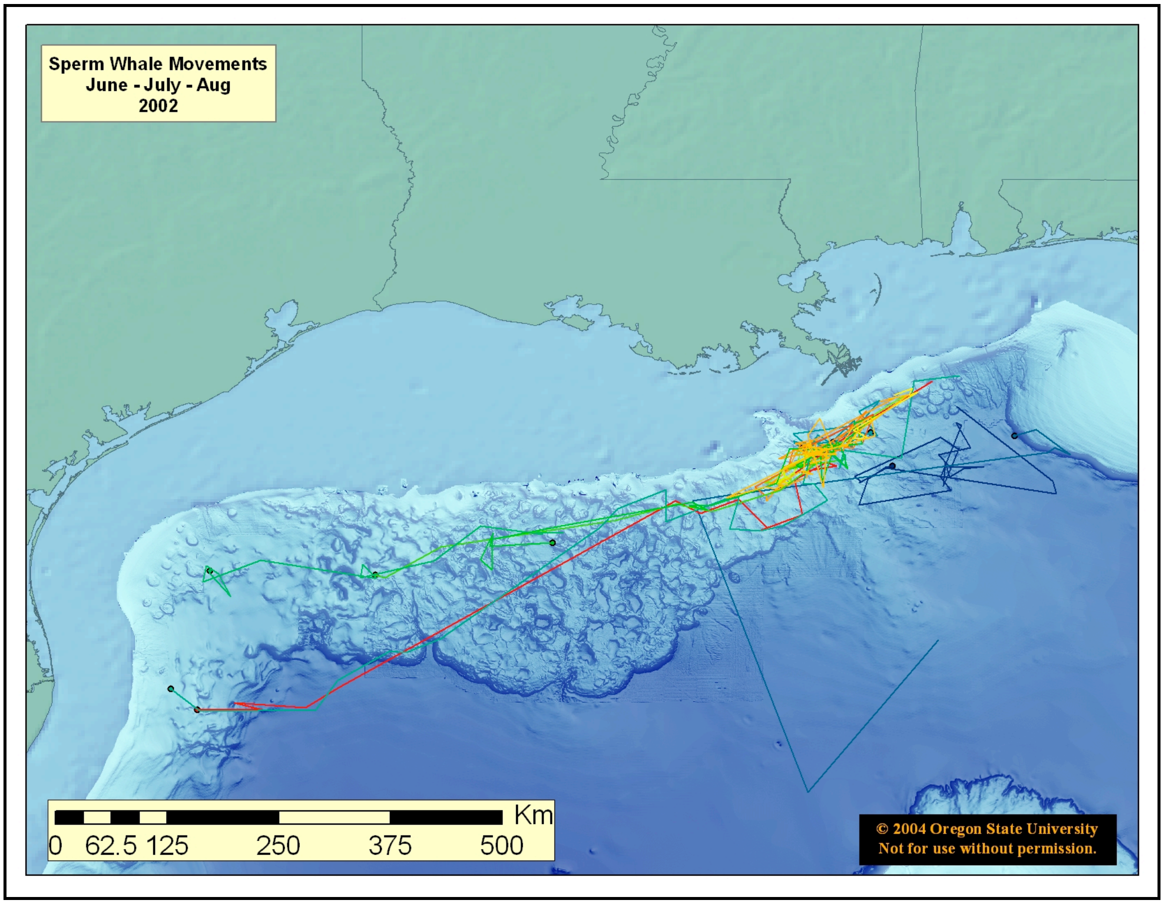

Figure 6.1.17. Tracklines of tagged sperm whales for the period June-Jul-Aug 2002.

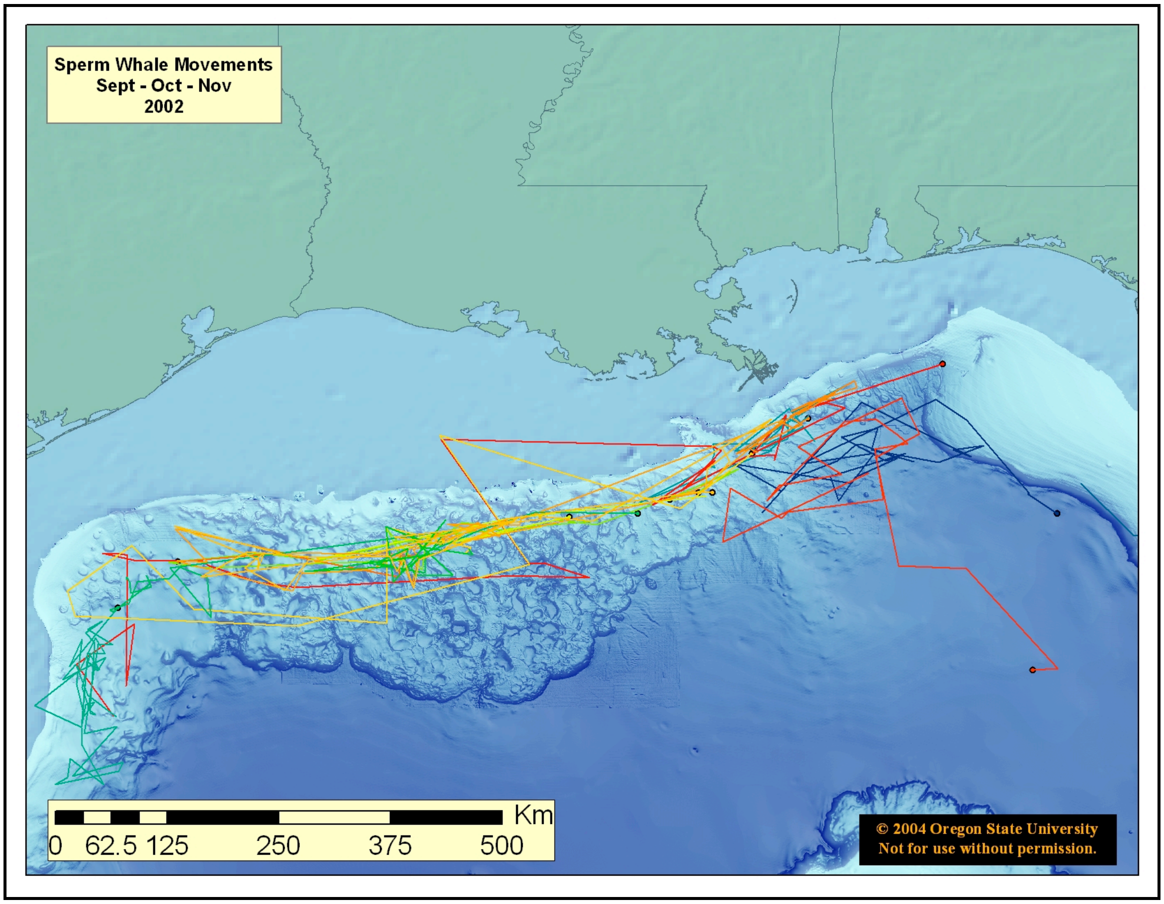

Figure 6.1.18. Tracklines of tagged sperm whales for the period Sept-Oct-Nov 2002.

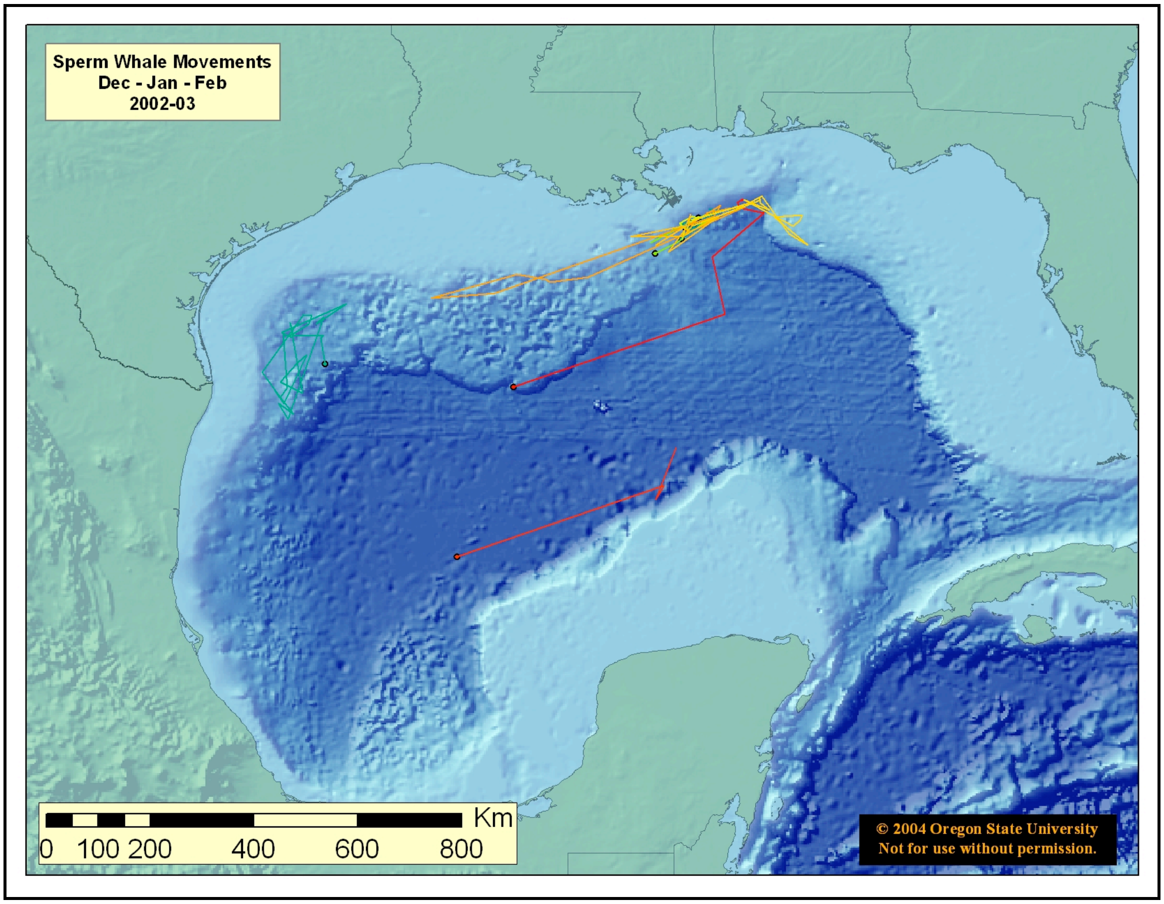

Figure 6.1.19. Tracklines of tagged sperm whales for the period Dec-Jan-Feb 2002-03.

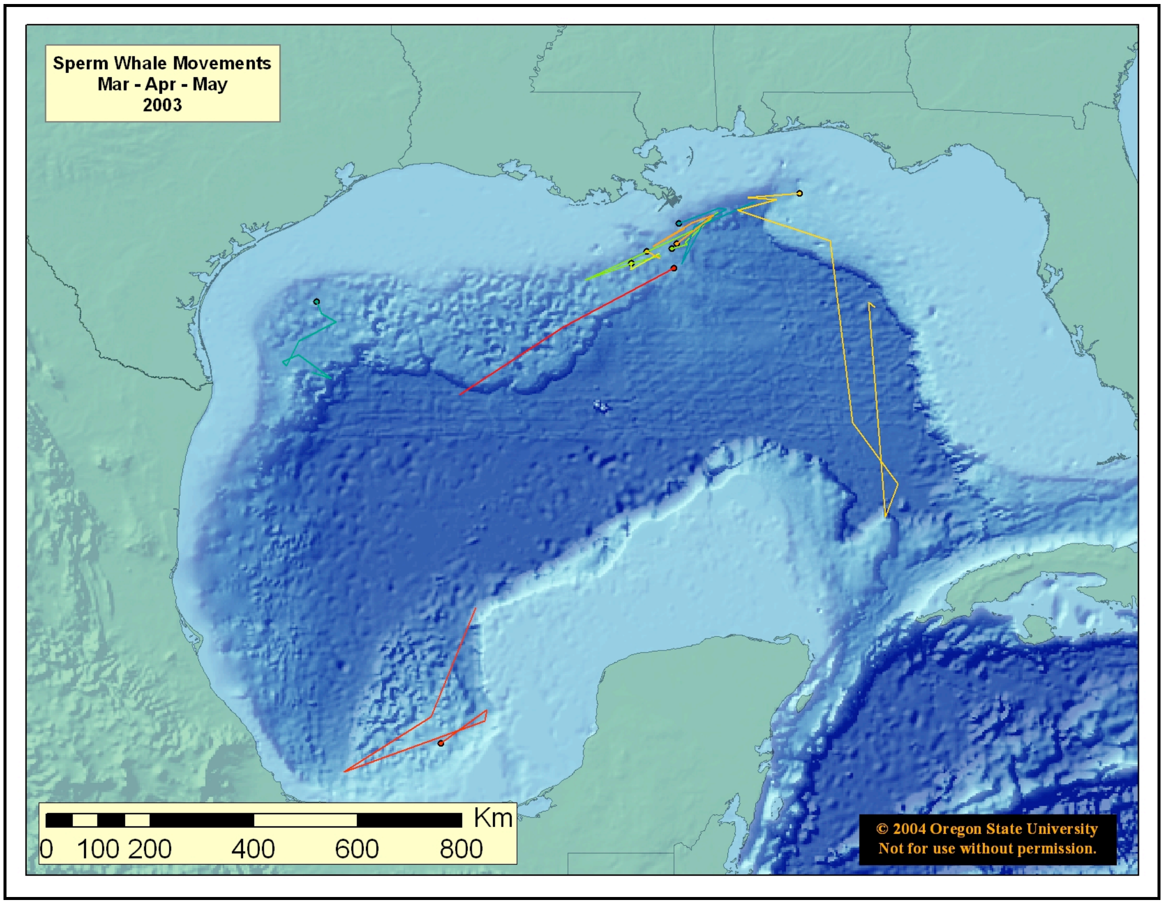

Figure 6.1.20. Tracklines of tagged sperm whales for the period Mar-Apr-May 2003.

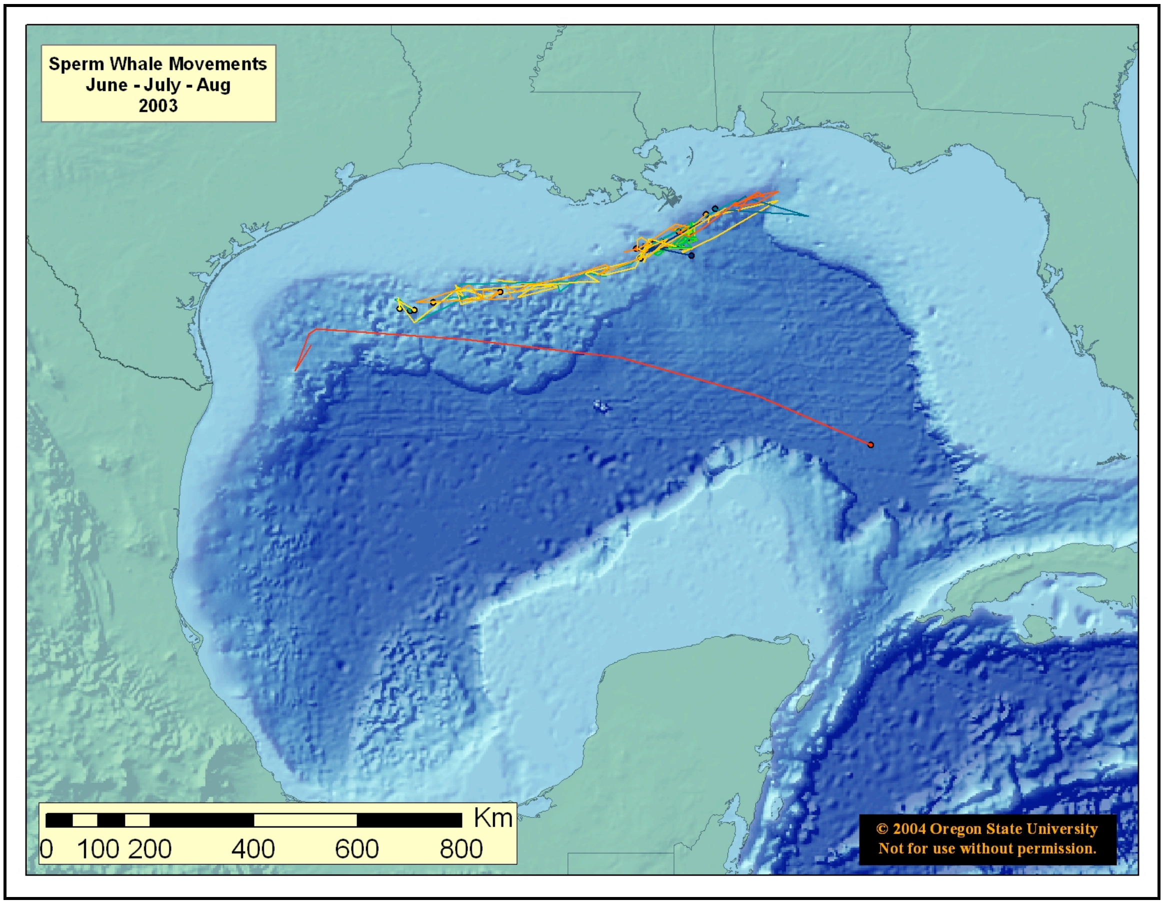

Figure 6.1.21. Tracklines of tagged sperm whales for the period June-Jul-Aug 2003.

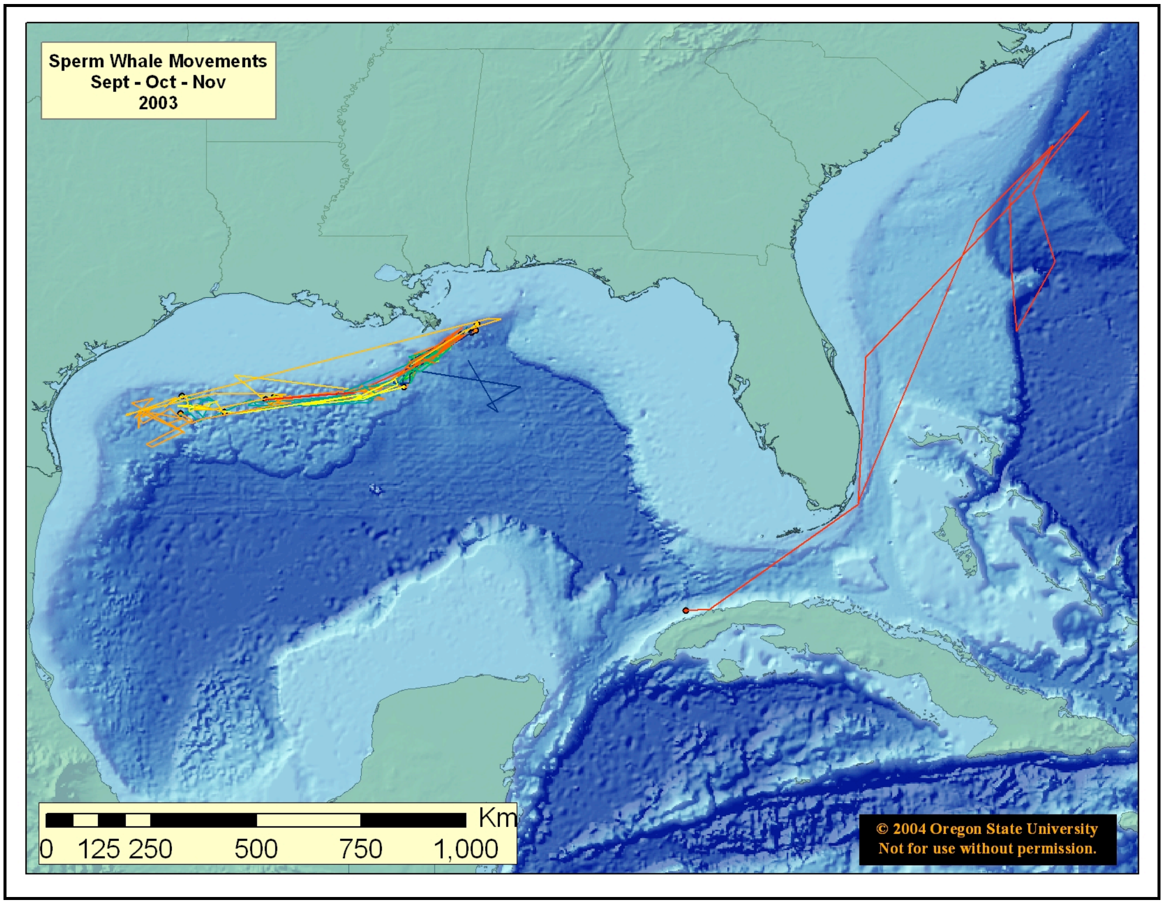

Figure 6.1.22. Tracklines of tagged sperm whales for the period Sep-Oct-Nov 2003.

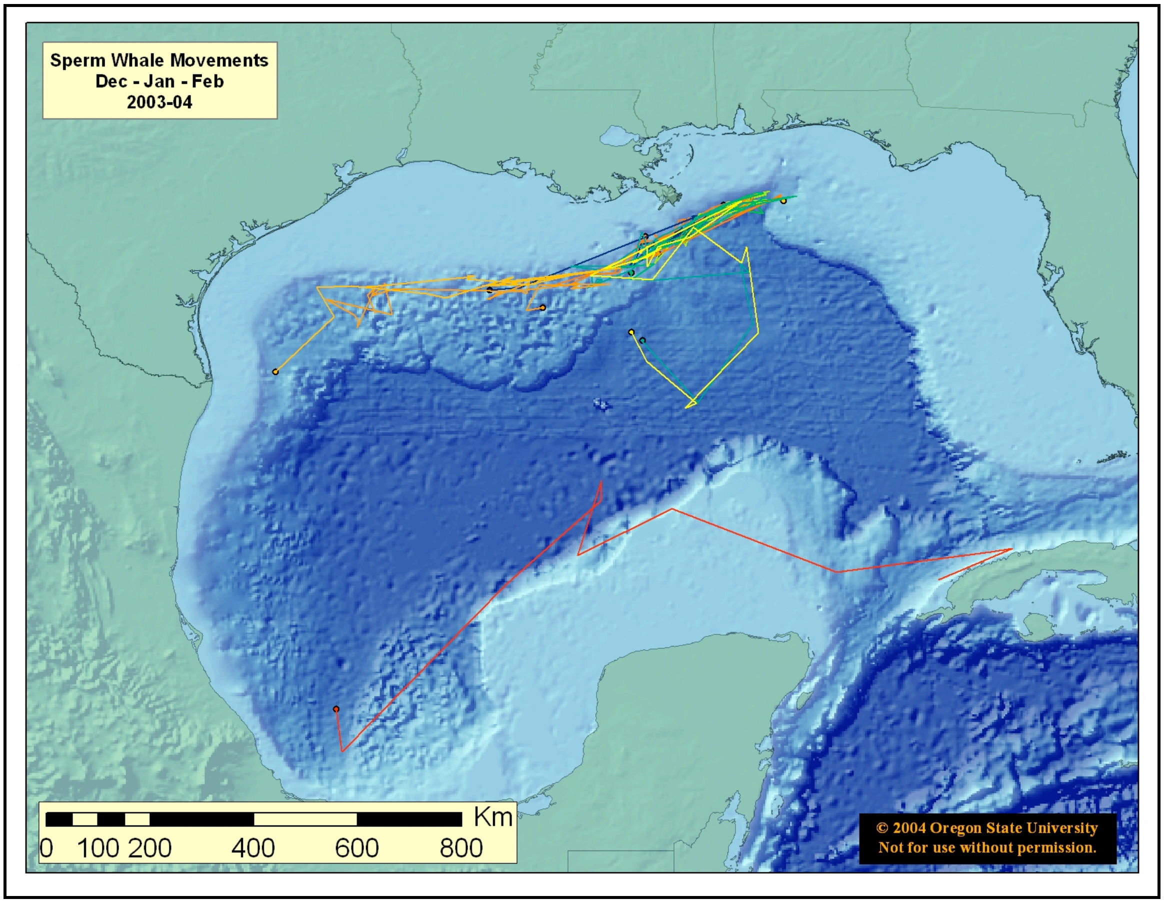

Figure 6.1.23. Tracklines of tagged sperm whales for the period Dec-Jan-Feb 2003-04.

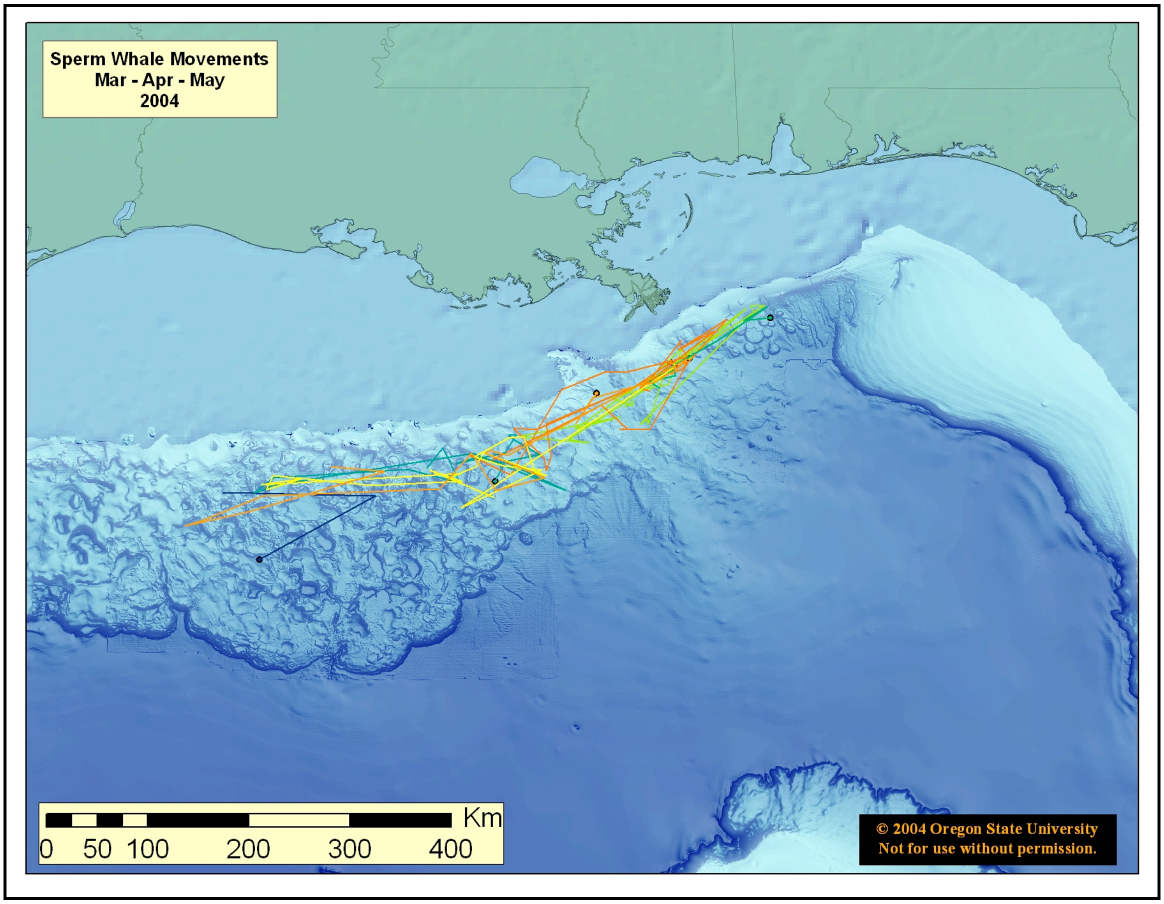

Figure 6.1.24. Tracklines of tagged sperm whales for the period Mar-Apr-May 2004.

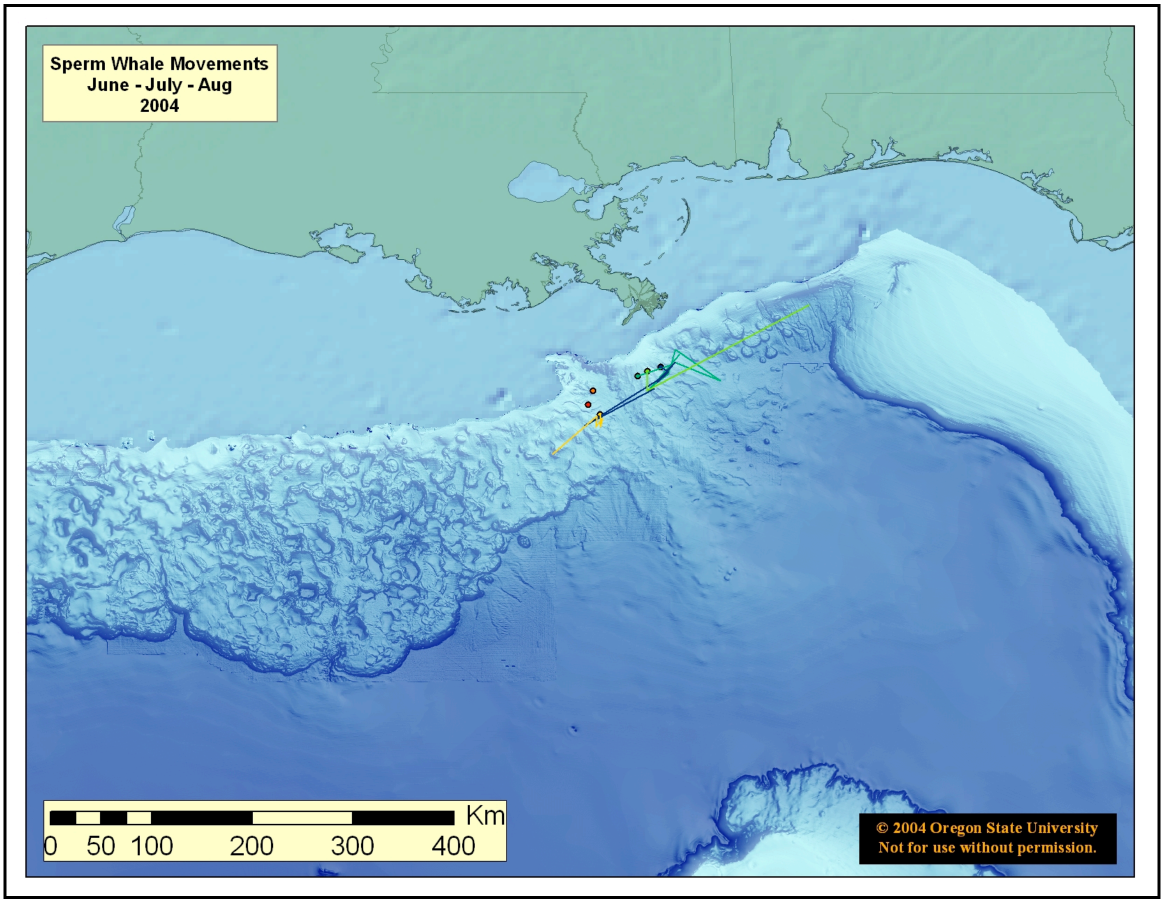

Figure 6.1.25. Tracklines of tagged sperm whales for the period June-Jul-Aug 2004.

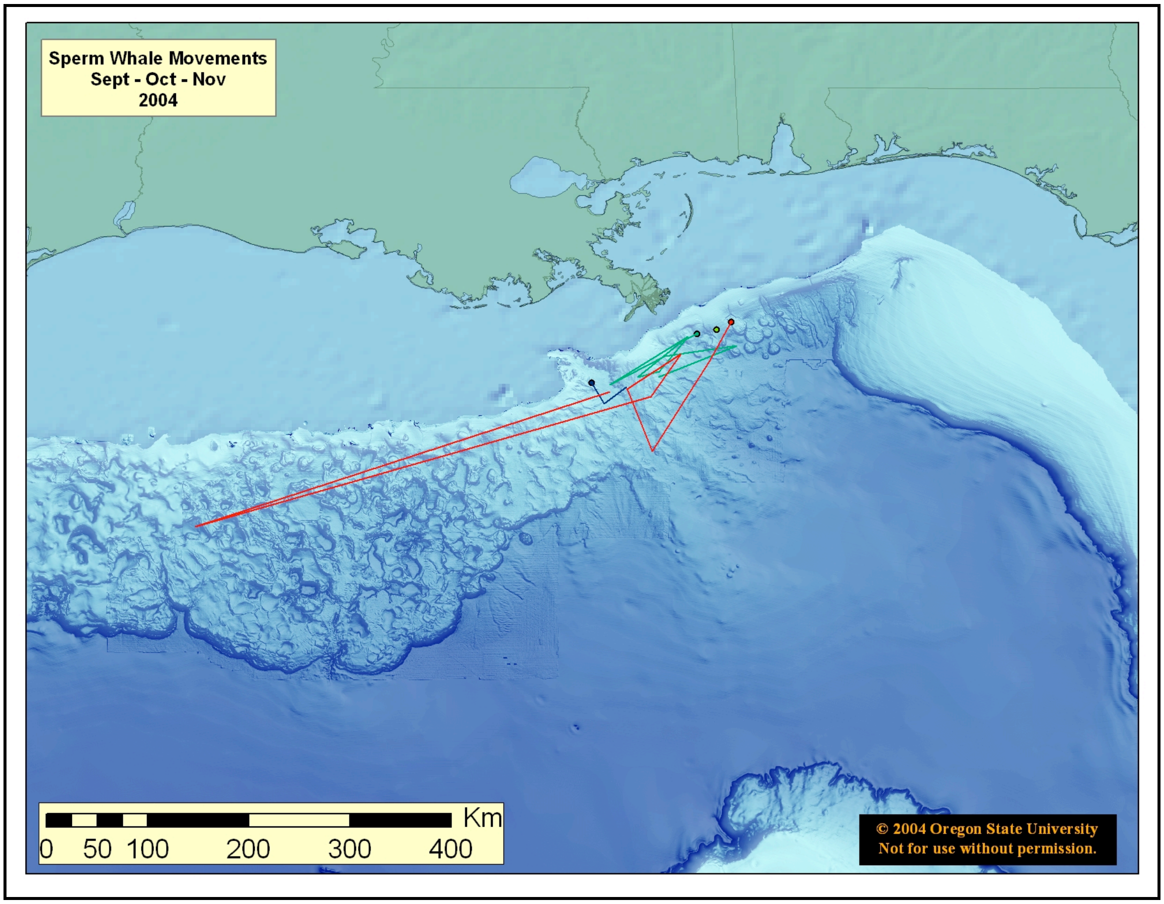

Figure 6.1.26. Tracklines of tagged sperm whales for the period Sept-Oct-Nov 2004.

Year-to-Year and Gender Variation

Sperm whales tagged in 2002 ranged over a larger area than animals tagged in any other year (Figure 6.1.27). However, the 2001 season is represented by only a single animal (Figure 6.1.5), which shows much of the dynamic range exhibited by 2002 animals (Figure 6.1.6) for both the northern and western Gulf, albeit transiting the upper and western Gulf without stopping. Movement of whales tagged in 2003 (Figure 6.1.7) were limited to the northern Gulf slope edge and a few offshore locations in the central Gulf, while the smaller number of whales tagged in 2004 (Figure 6.1.8) had a very restricted range in the central northern Gulf.

Females tend to more routinely occupy the upper slope edge with far less representation over deep water than males, especially considering the bias of how many more known females were tagged in comparison to males (Figure 6.1.28). Only two females actually moved out over deep water, while several males and individuals of unknown sex moved offshore (Figure 6.1.29) and traveled to the southern reaches of the Gulf (Bay of Campeche). One of these whales also moved into the north Atlantic (see below).

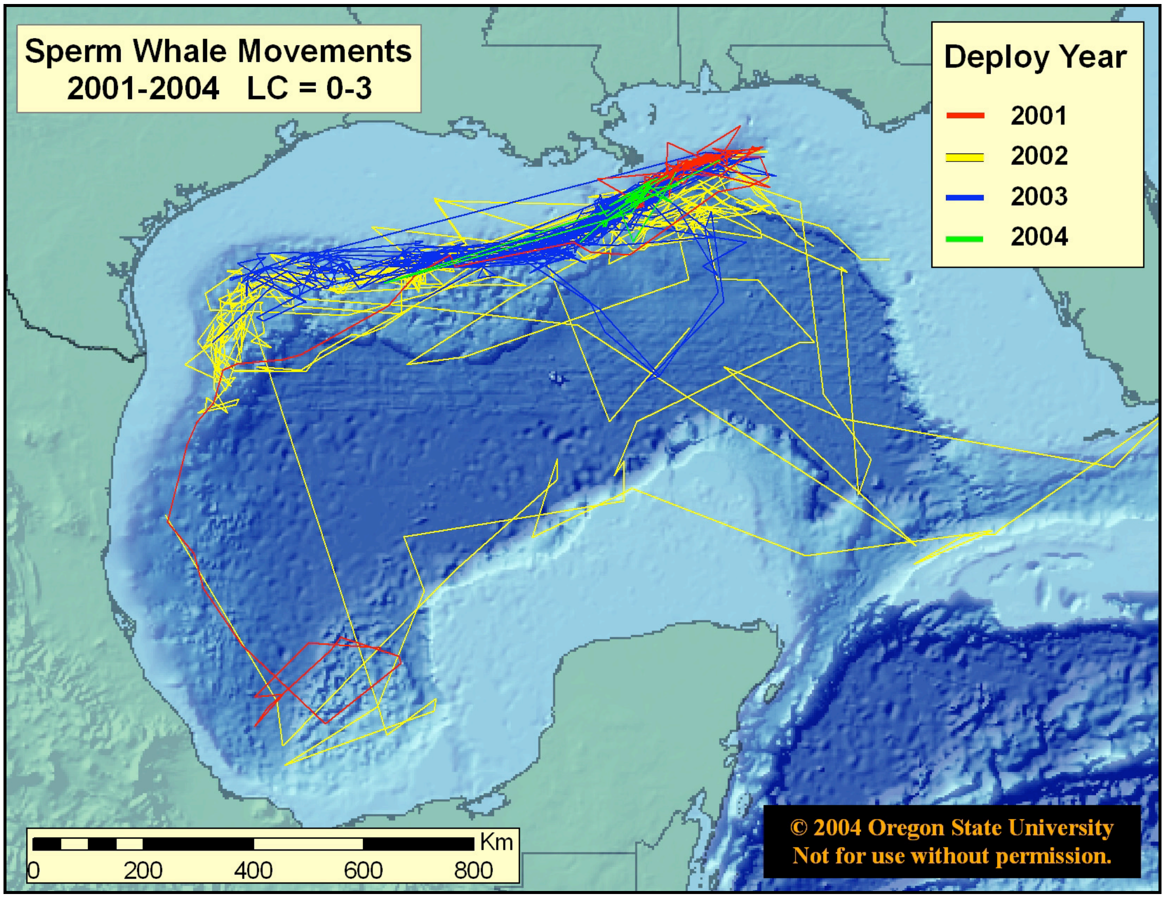

Figure 6.1.27. Sperm whale movements, 2001-2004; LC = 0-3, showing deployment year.

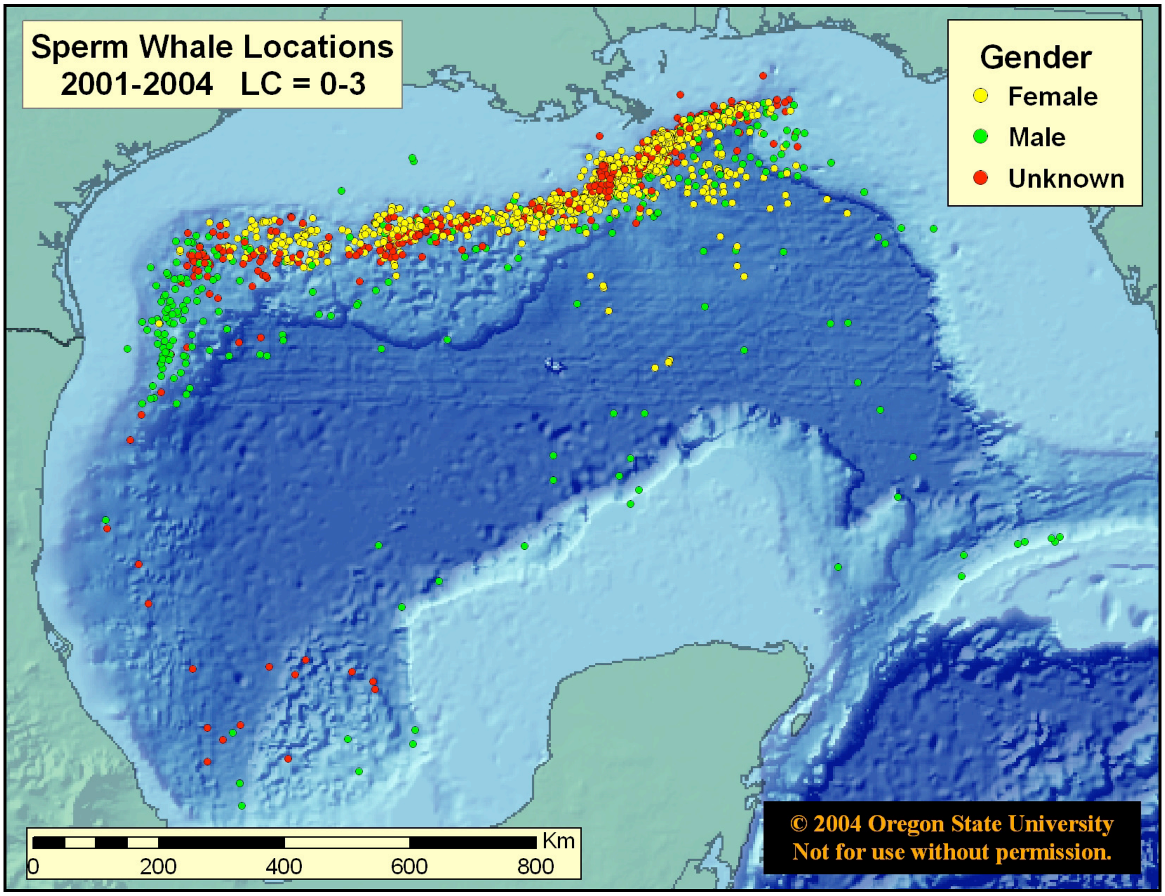

Figure 6.1.28. Sperm whale locations by gender, 2001-2004; LC = 0-3.

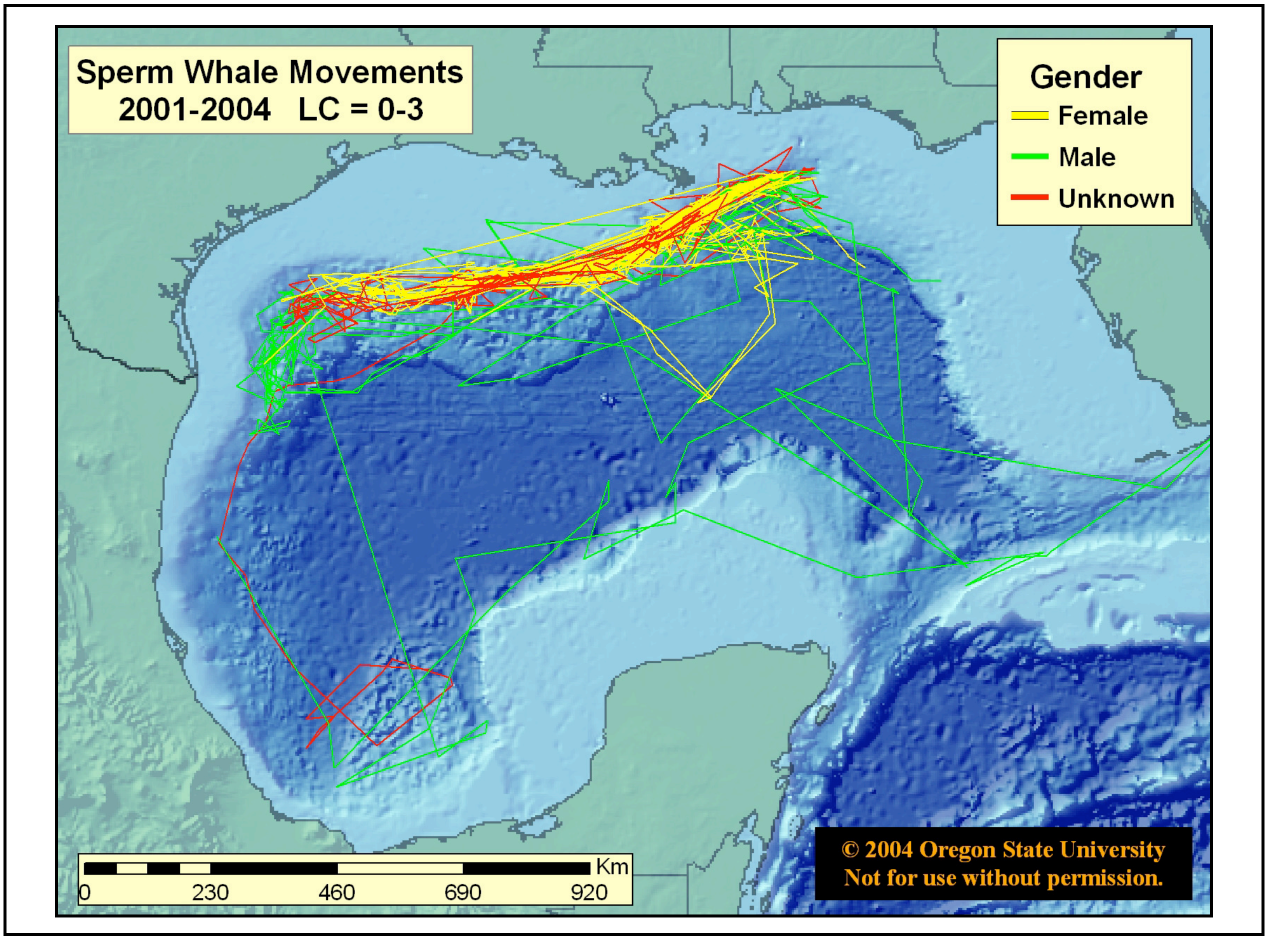

Figure 6.1.29. Movements of sperm whales tagged in 2001-2004 (LC=0-3).

The individuals tagged in 2002 had more offshore movement than those of any other year due to the larger numbers of males tagged. On average, 2002 males traveled faster than females of any year (Table 6.1.6). The summary maps provided here do not contain sufficient information to evaluate the movements of individual animals seasonally, or how they move with respect to one another. The latter is covered in Section 6.2.

Table 6.1.6

Average Speed of Tagged Whales by Sex and Tagging Year

	Year tagged			
Sex	**2001**	**2002**	**2003**	**2004**
Females	NA	0.65	0.72	0.27
Males	NA	1.10	0.20	NA
Unknown	2.3	0.75	0.33	0.25

Movement into the North Atlantic

The longest and most dramatic track of any individual whale was a male tagged in 2002 whose tag provided locations up to 610 days after tagging (Figure 6.1.30). This individual provided four important insights.

1. Did not spend the summers of 2002 and 2003 in the exact same area of the upper Gulf. Conversely, the entire upper Gulf may have been its summer feeding habitat, as suggested by the observed wide-ranging east-west movements of other individual whales along the northern slope edge. One might speculate that this male found sufficient food in the region of the western Gulf in 2003 to maintain its continued feeding effort and did not need to move elsewhere. Perhaps, had prey levels been lower in the west, the tagged whale may have moved on to another area.

2. Moved out into the North Atlantic for a period of 2 months, demonstrating for the very first time that such movements occur. That other males did not conduct such excursions may be a matter of maturity or just individual variation. Large breeding male sperm whales are considered to be more widely ranging than sub-adult males. Based on data from other areas (Best 1979), this tagged whale was potentially large enough to be considered sexually mature, but not large enough to be considered a successful breeding bull.

3. Used the Bay of Campeche as winter/spring range during two consecutive years.

4. May have detected and avoided the severe weather resulting from Hurricane Isabel (Figure 6.1.31). Sperm whales dive for more than 45 minutes and are obliged to rest at the surface for 7 to 10 minutes recovering their oxygen debt before undertaking another long dive. Surface respiration is logically more difficult in high swells and spray associated with hurricane force winds. Because 90 percent of the noise on stormy days comes from rain and breaking swells, it may be possible for acoustically adept sperm whales to passively acquire information about the direction and severity of surface weather conditions and then avoid them.

For comparison purposes, we applied the following more conservative screening criteria to this whale's location record: 1) maximum speed of 6 k/h used for locations <12 h apart; 2) maximum speed of 3.5 k/h used for locations >12 h apart; 3) "redundant" locations eliminated for <LC1 less than 4 h apart (instead of 1 h), and 4) "redundant" LC1 locations eliminated for those less than 20 min apart (instead of 10 min). Under these criteria, six locations were eliminated (Figure 6.1.30). It can be seen that none of the major conclusions drawn on the basis of the more liberal filter are changed. The major difference is the deletion of some locations on the shelf north of the Yucatan Peninsula, where the water depths seem inconsistent with the rest of the available records.

It must be noted that the use of conservative screening parameters reduces the chances of making discoveries that are outside the prevailing "current wisdom." Thus, conservative filtering parameters can become self-fulfilling prophesies and preclude the "discovery" of higher speeds and subsequently new habitats. However, owing to the level of debate over sperm whale movements with regard to seismic issues, we feel the conservative criteria are more appropriate at this time. While this conservative analysis has not been applied yet to this entire report, it will be part of our overall evaluation prior to submission of peer-reviewed publications. Therefore, those wishing to reference this report in any authoritative way should contact the authors to determine whether their conclusions from this report remain valid after the more conservative criteria are applied.

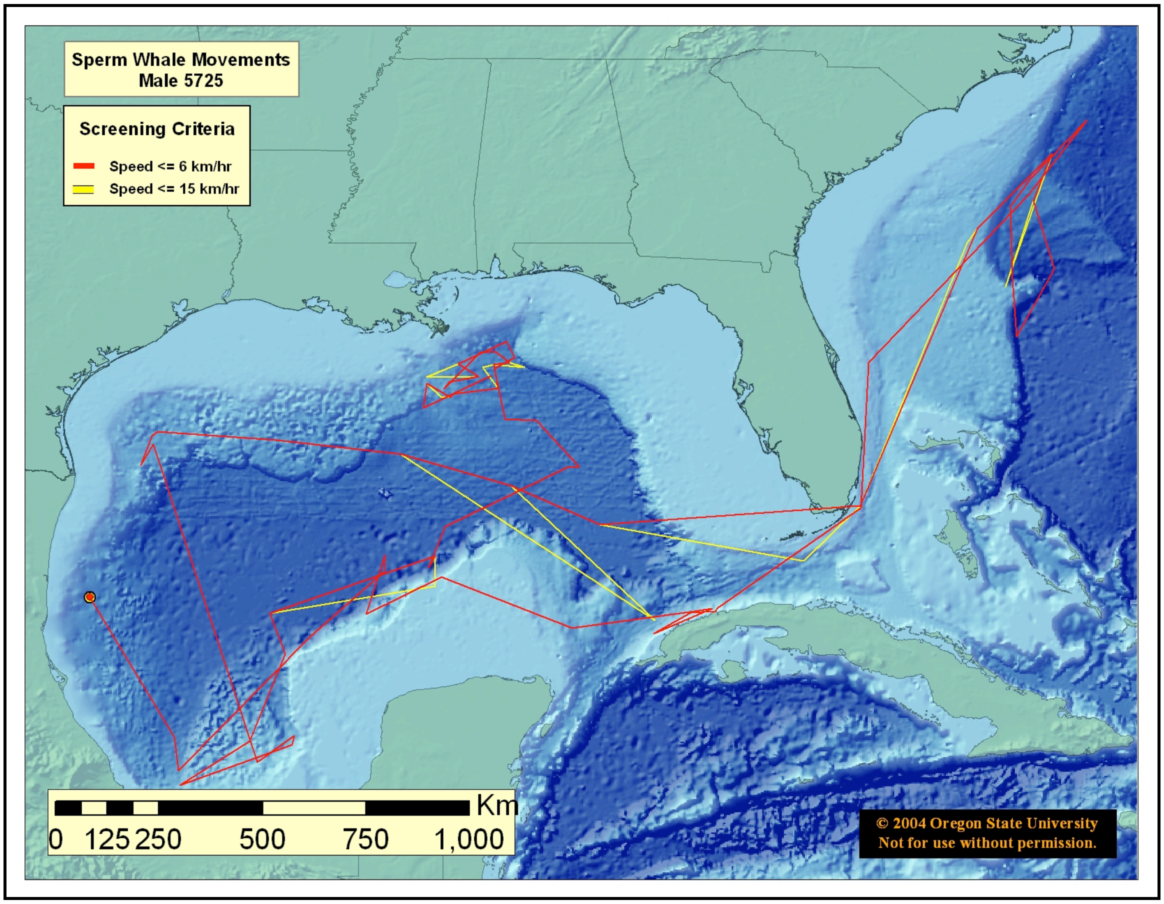

Figure 6.1.30. Male sperm whale, tag number 5725, provided locations up to 610 days after tagging.

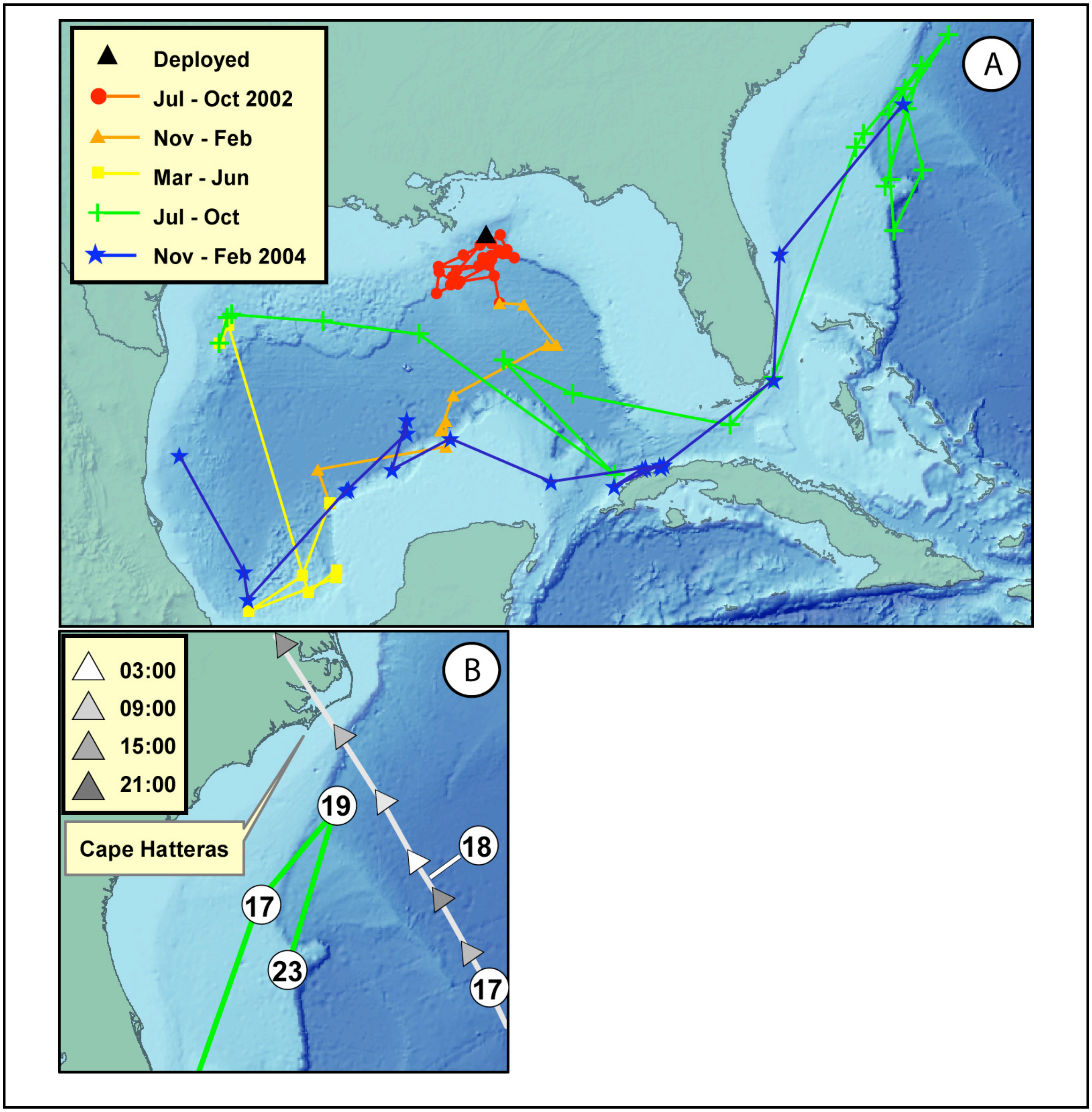

Figure 6.1.31. Path of sperm whale Male 5725. Figure 6.1.31A shows the route of sperm whale Male 5725 from 2002-2004; Figure 6.1.31B shows the path of Hurricane Isabel in September 2003 along with Male 5725's possible detection and avoidance of this severe weather.

Home Ranges and Hot Spots

The overlapping home ranges of individual tagged whales for 2001 (N=1), 2002 (N=9), 2003 (N=14), and 2004 (N=4) are shown in Figure 6.1.32. The highest overlap between all these years is the area in and around the Mississippi River Delta, where the bulk of tagging efforts occurred. The broader westerly distribution observed in 2003 is due to a few individuals who spent time off the Texas coast around Alaminos Canyon. Examining the overlapping home ranges further by gender required a change in "scales" to evaluate the 2002 movements (Figures 6.1.33-6.1.35). Aside from the obvious concentration area in the region of tagging, there is also observable overlap between sexes in each of the other major aggregation areas (overlapping of home ranges). Despite a limited sample size in individual years and an incomplete assessment of sexual identity, it is apparent that males have a larger range than females and also use deeper waters. Home range estimates for each month (Figures 6.1.36-6.1.47) indicate the year round importance of the Mississippi River Delta region.

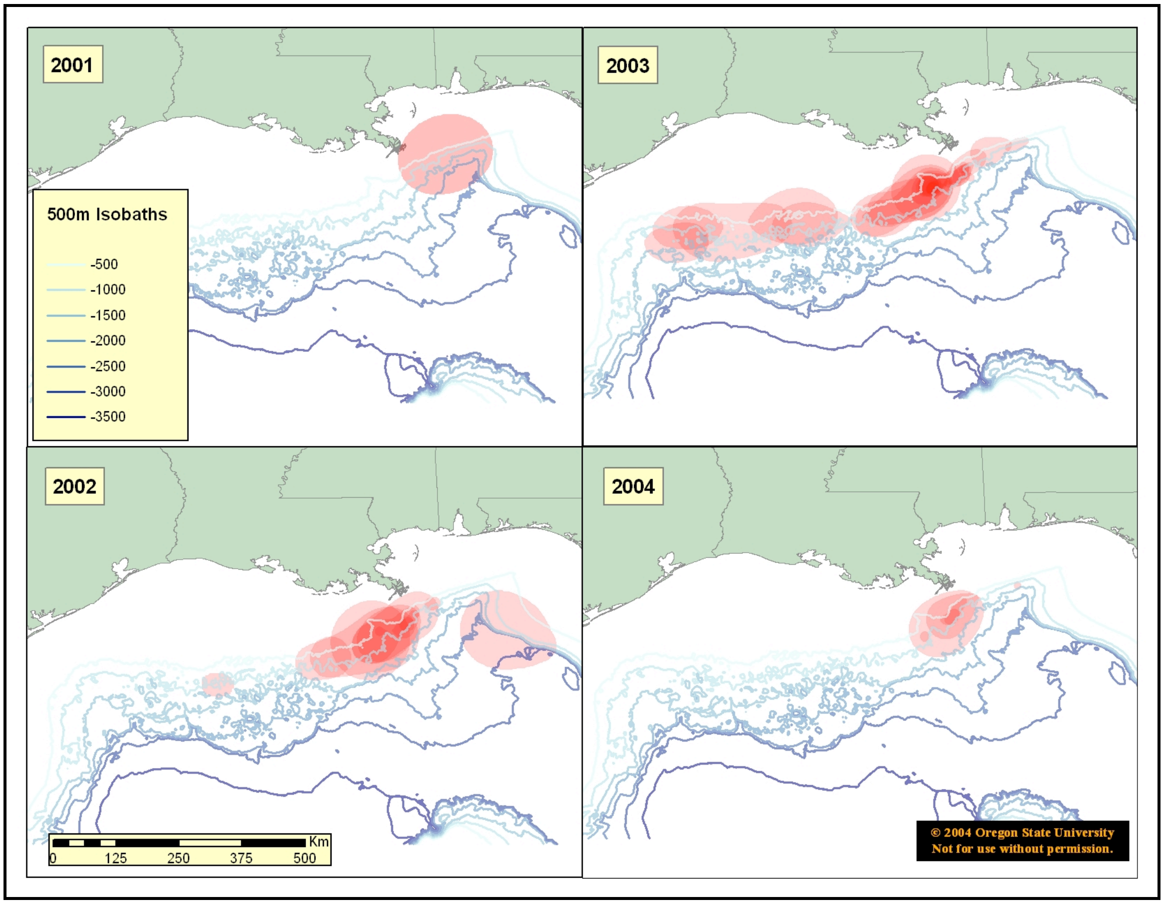

Figure 6.1.32. Overlapping home ranges of individual tagged whales for 2001, 2002, 2003, and 2004.

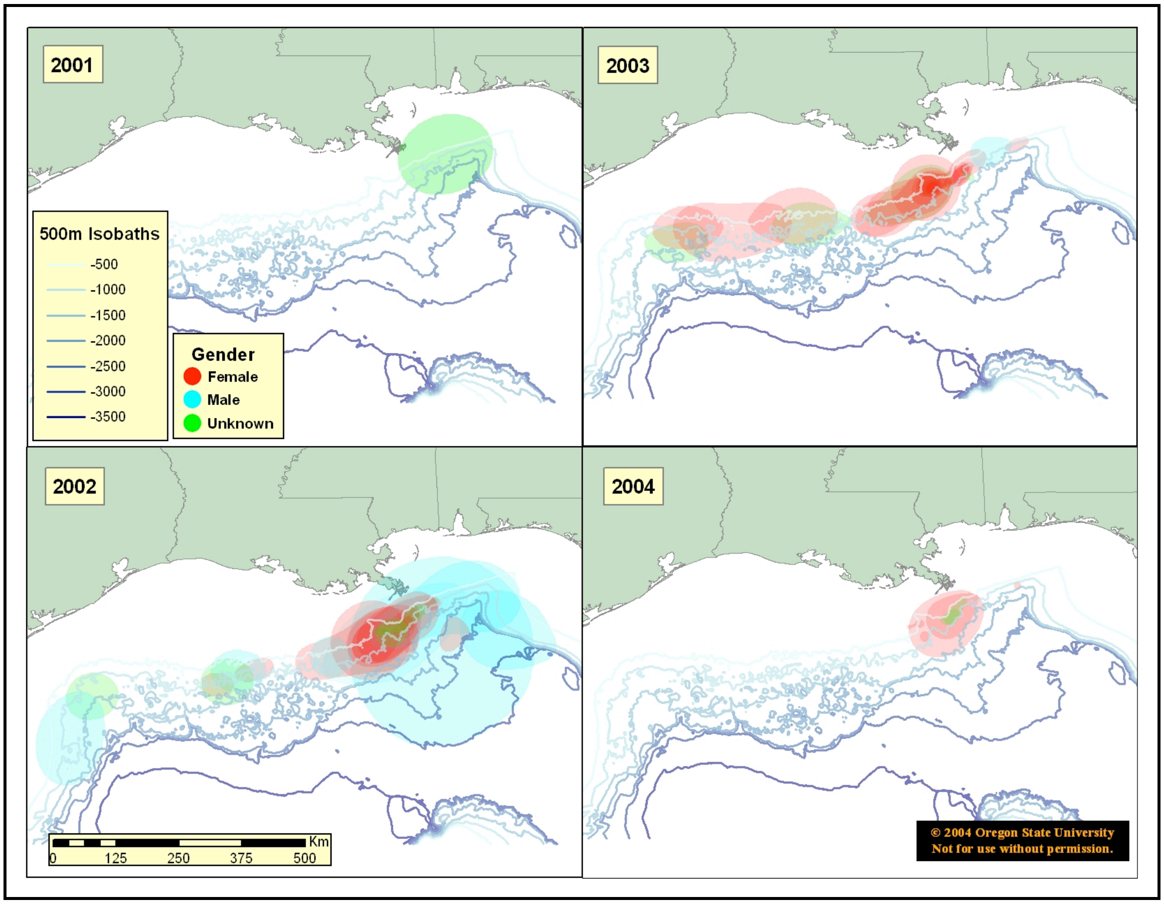

Figure 6.1.33. Overlapping home ranges of individual tagged whales by gender for 2001, 2002, 2003, and 2004.

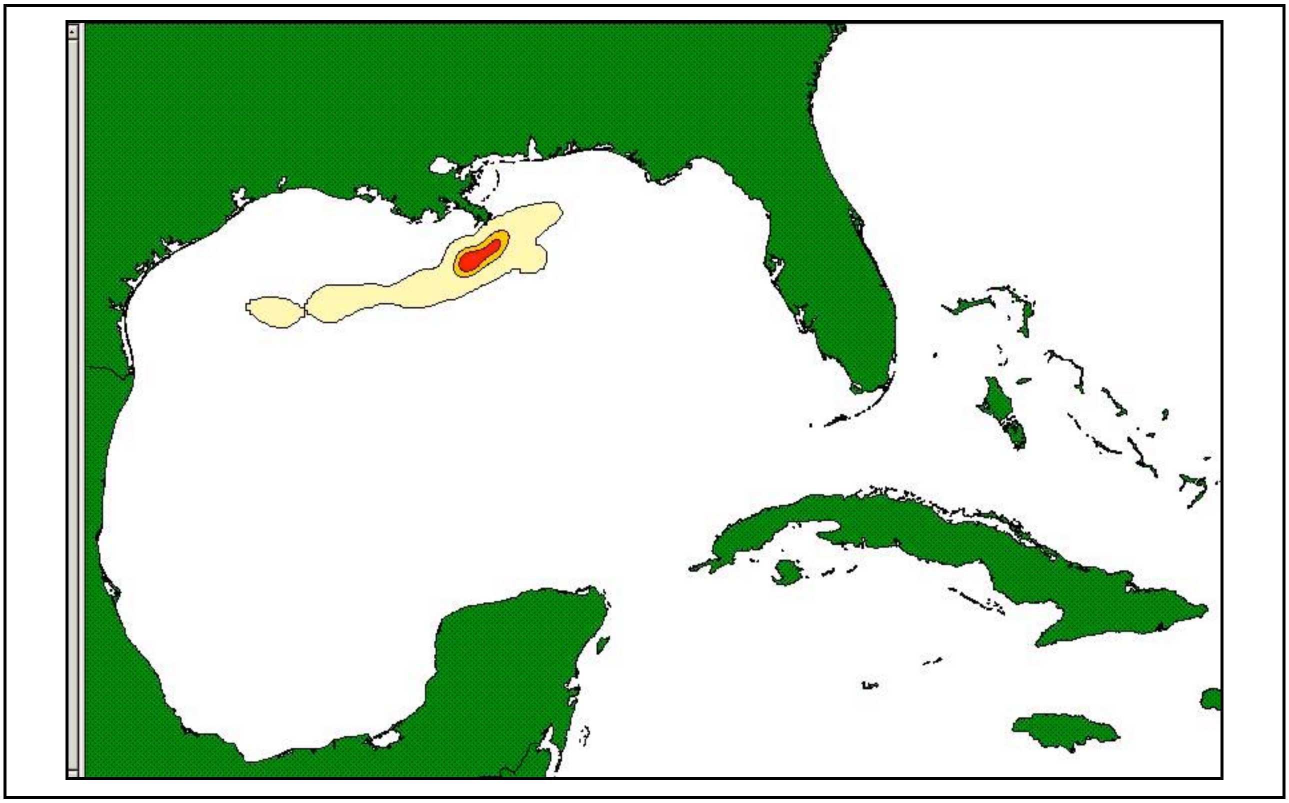

Figure 6.1.34. Density estimates of the utilization distribution (UD) for all the satellite locations of female sperm whales. The 95% UD is in light yellow, 50% UD in orange and 25% UD in red.

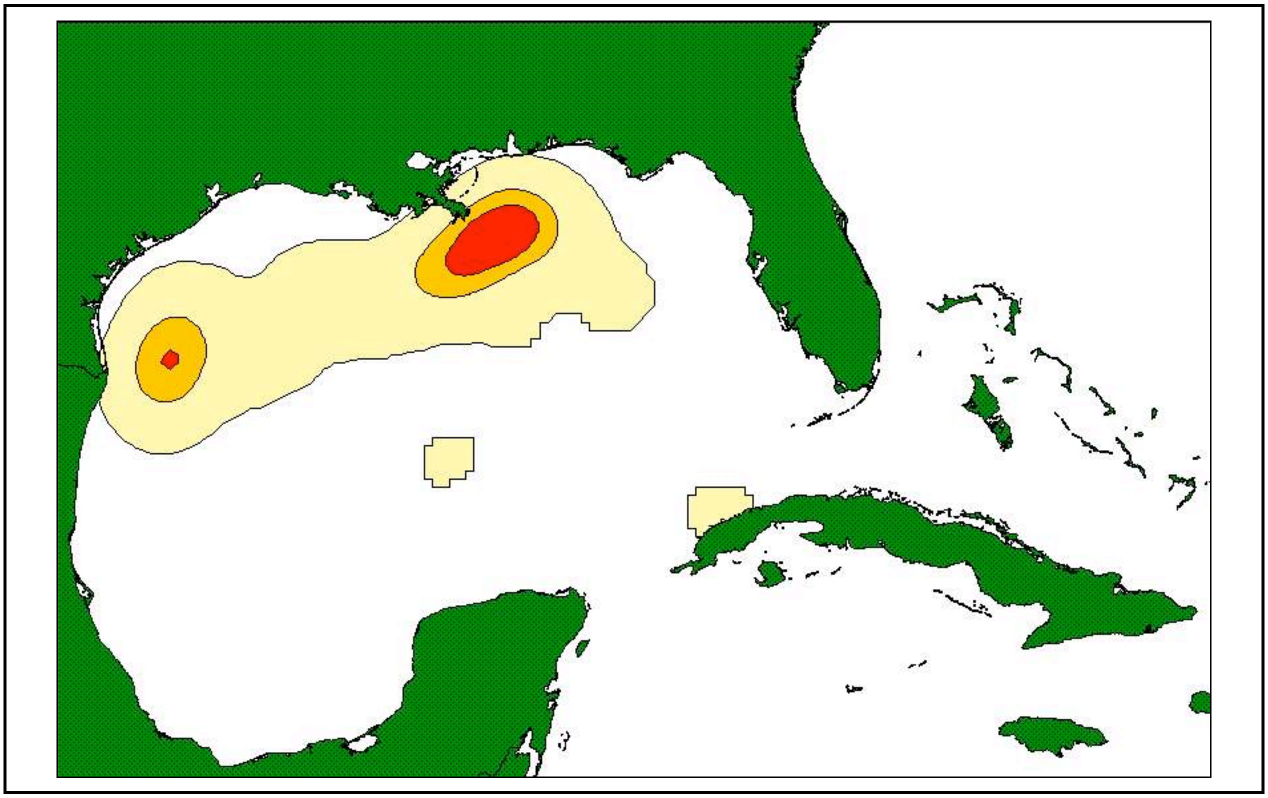

Figure 6.1.35. Density estimates of the utilization distribution (UD) for all the satellite locations of male sperm whales. UD levels and color code are the same as in Figure 6.1.34.

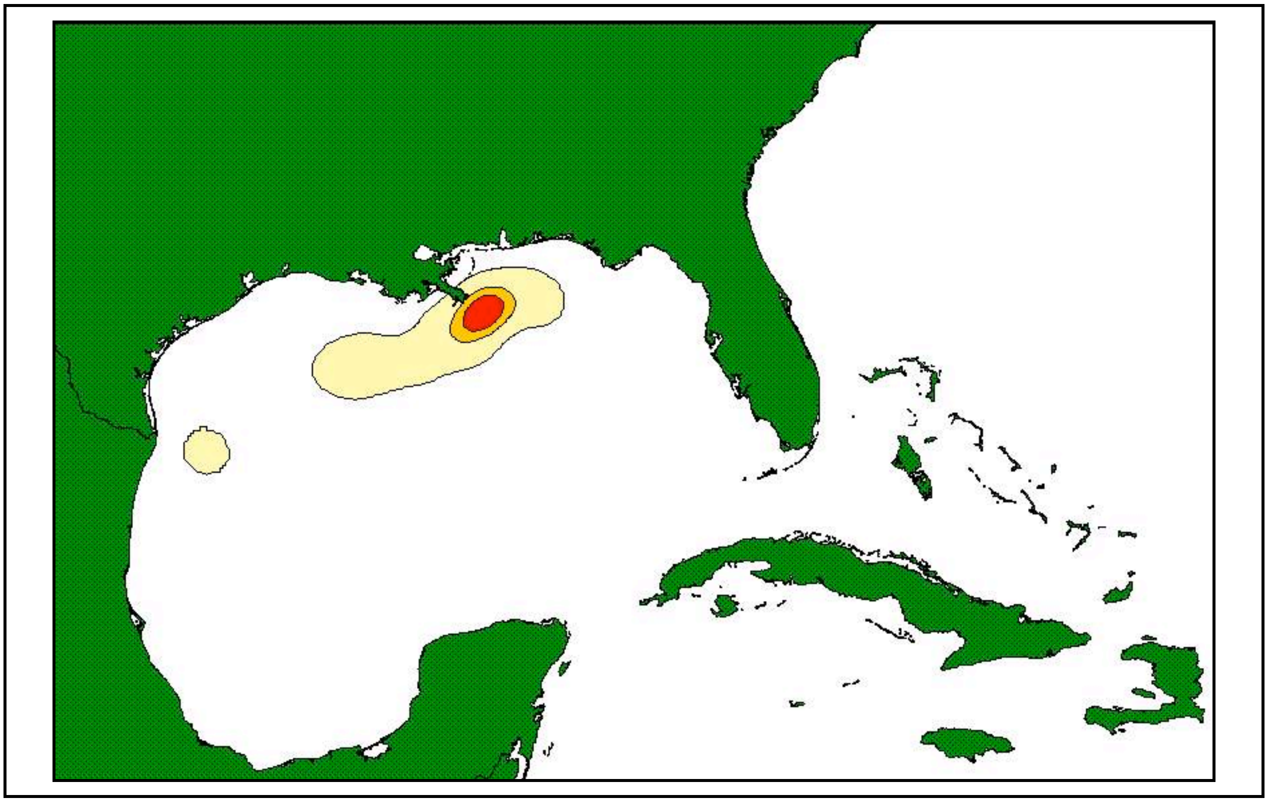

Figure 6.1.36. Density estimates of the utilization distribution (UD) for satellite locations received during the month of January. UD levels and color code are the same as in Figure 6.1.34.

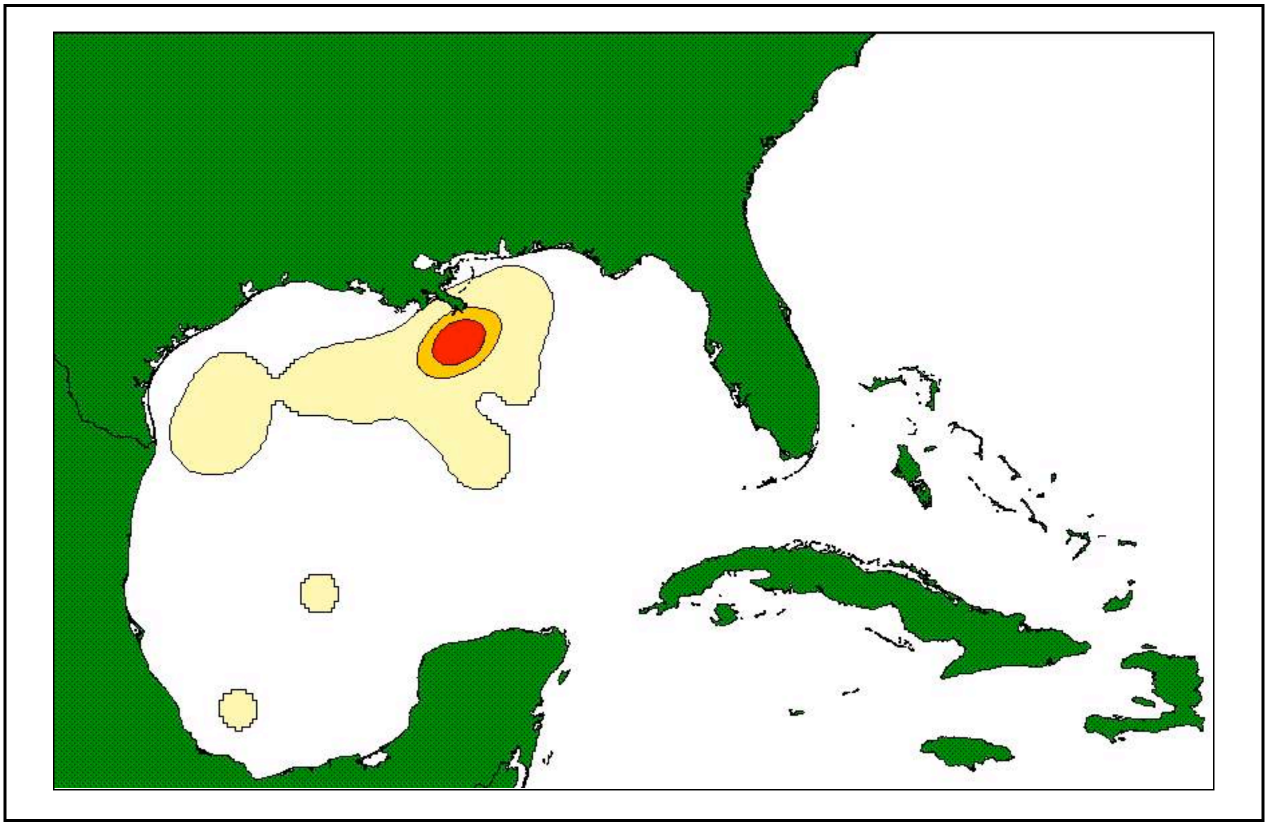

Figure 6.1.37. Density estimates of the utilization distribution (UD) for satellite locations received during the month of February. UD levels and color code are the same as in Figure 6.1.34.

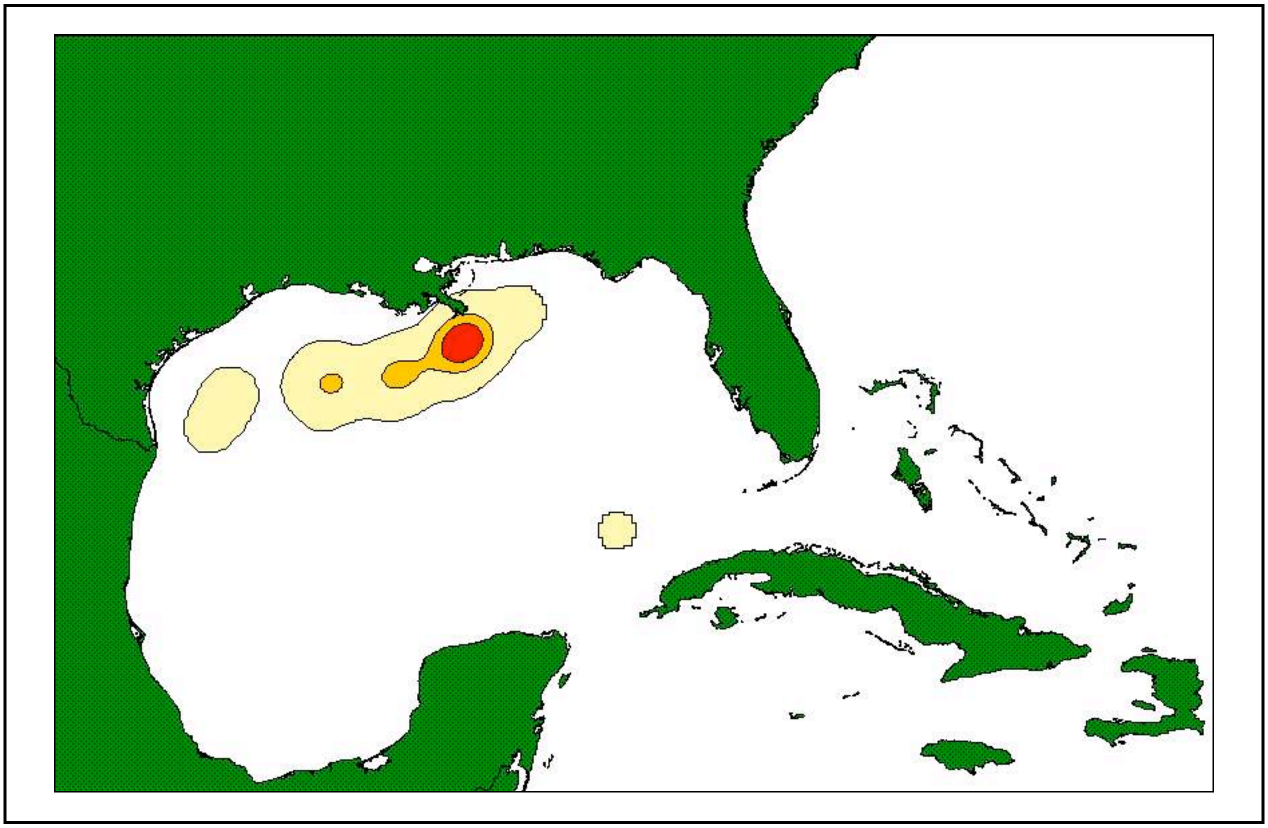

Figure 6.1.38. Density estimates of the utilization distribution (UD) for satellite locations received during the month of March. UD levels and color code are the same as in Figure 6.1.34.

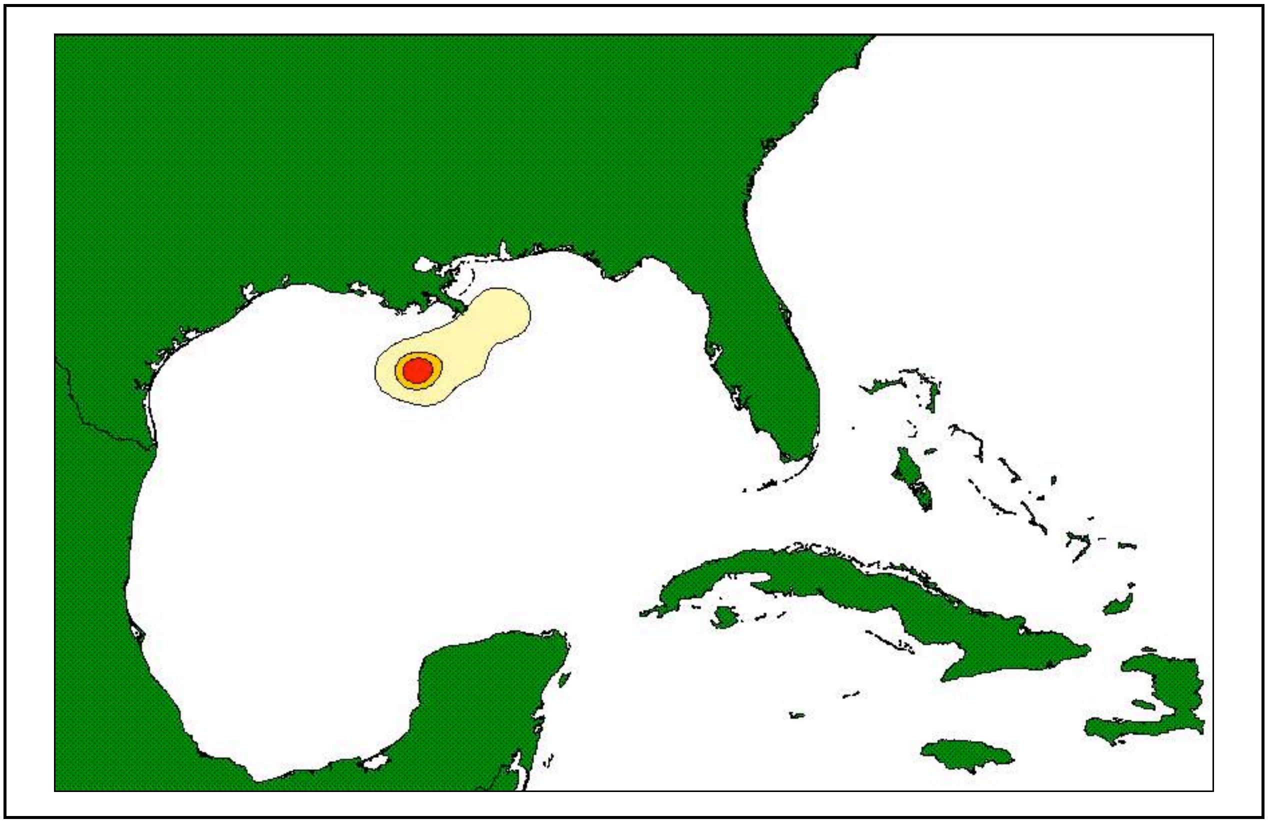

Figure 6.1.39. Density estimates of the utilization distribution (UD) for satellite locations received during the month of April. UD levels and color code are the same as in Figure 6.1.34.

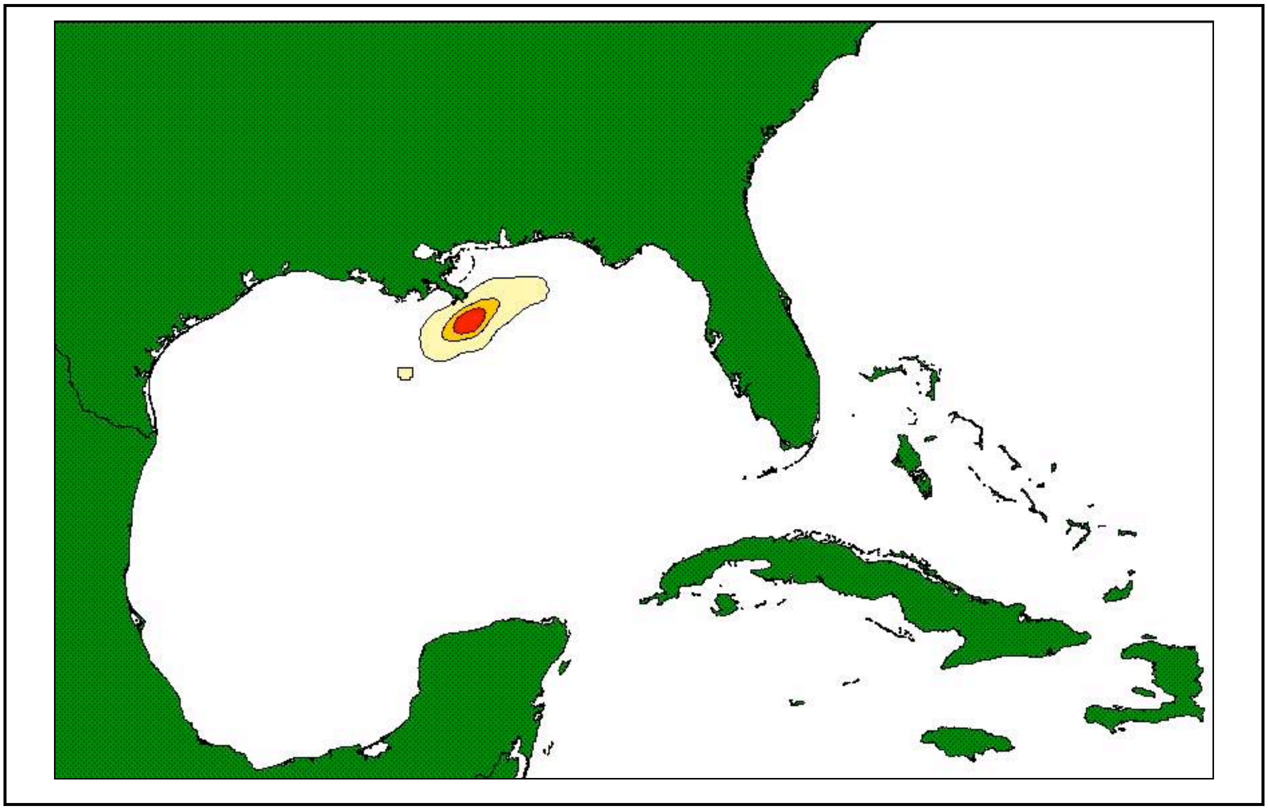

Figure 6.1.40. Density estimates of the utilization distribution (UD) for satellite locations received during the month of May. UD levels and color code are the same as in Figure 6.1.34.

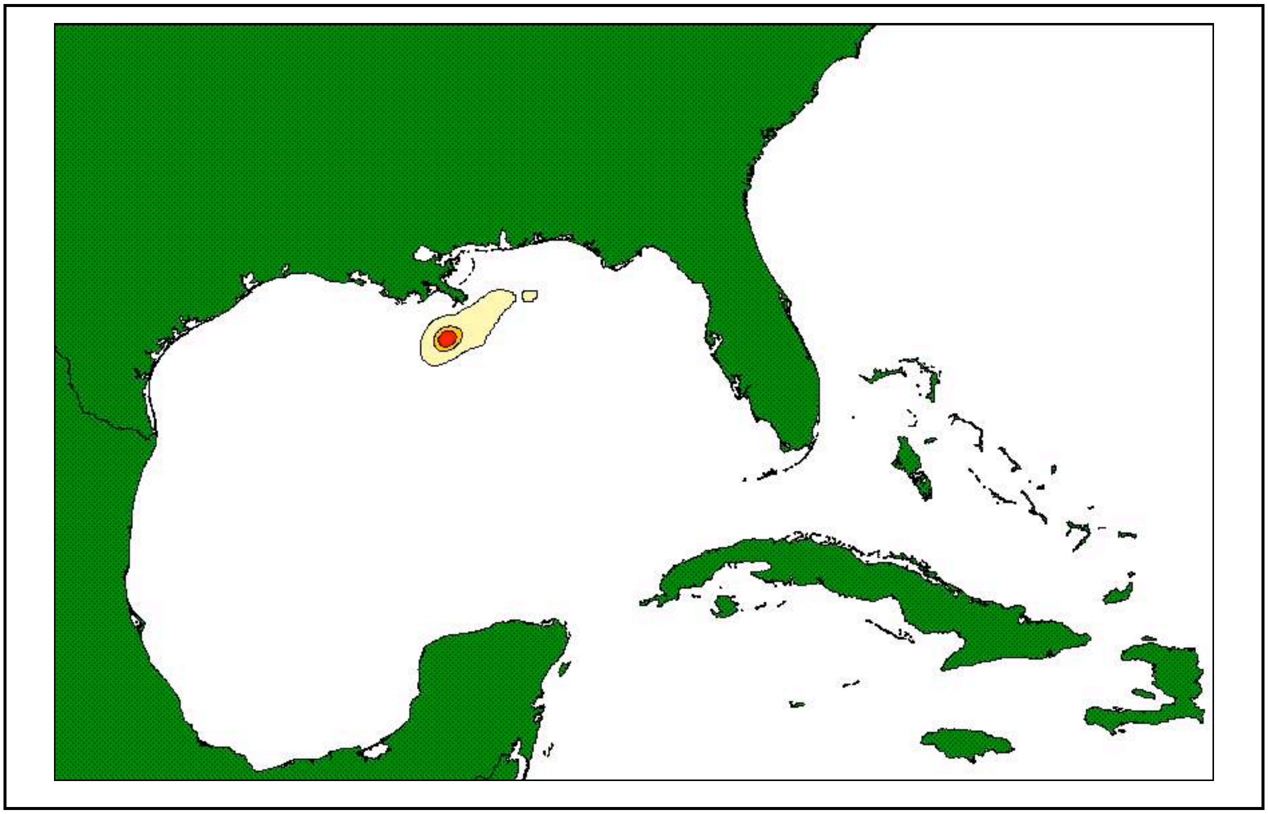

Figure 6.1.41. Density estimates of the utilization distribution (UD) for satellite locations received during the month of June. UD levels and color code are the same as in Figure 6.1.34.

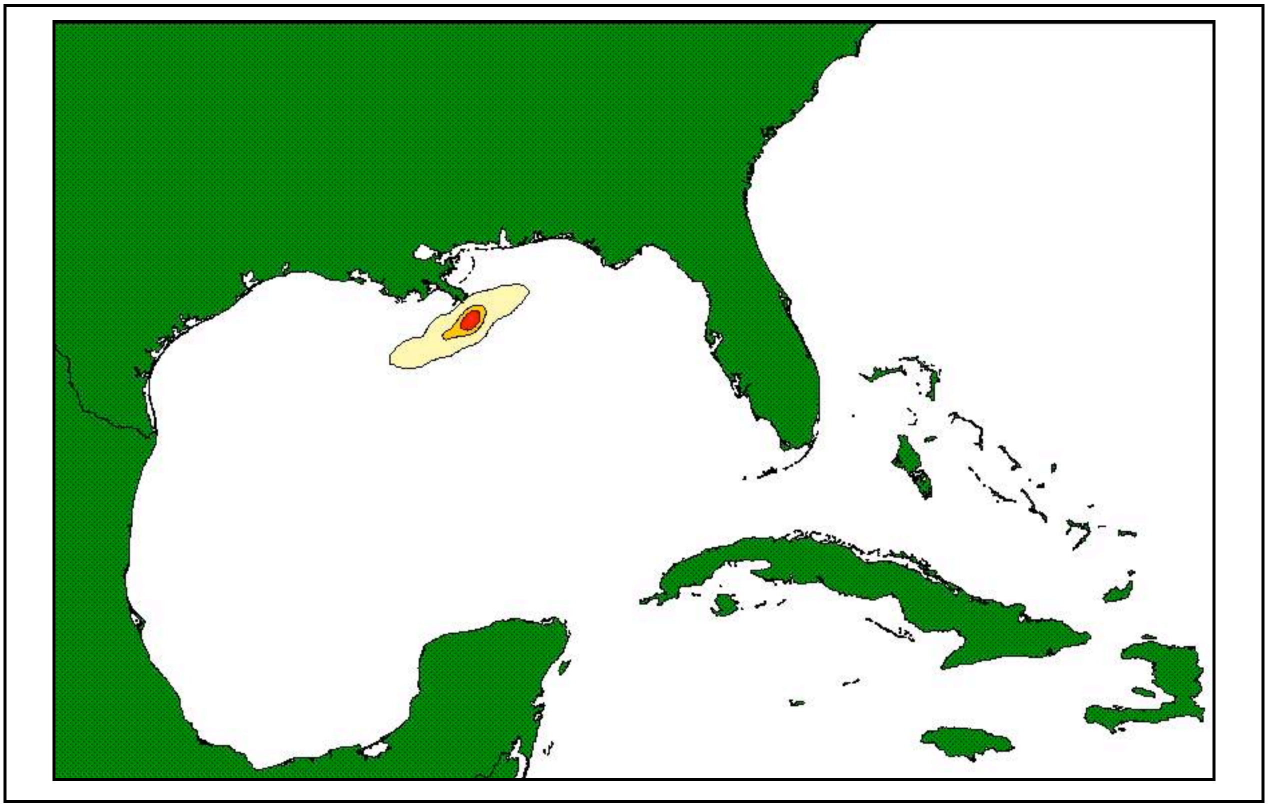

Figure 6.1.42. Density estimates of the utilization distribution (UD) for satellite locations received during the month of July. UD levels and color code are the same as in Figure 6.1.34.

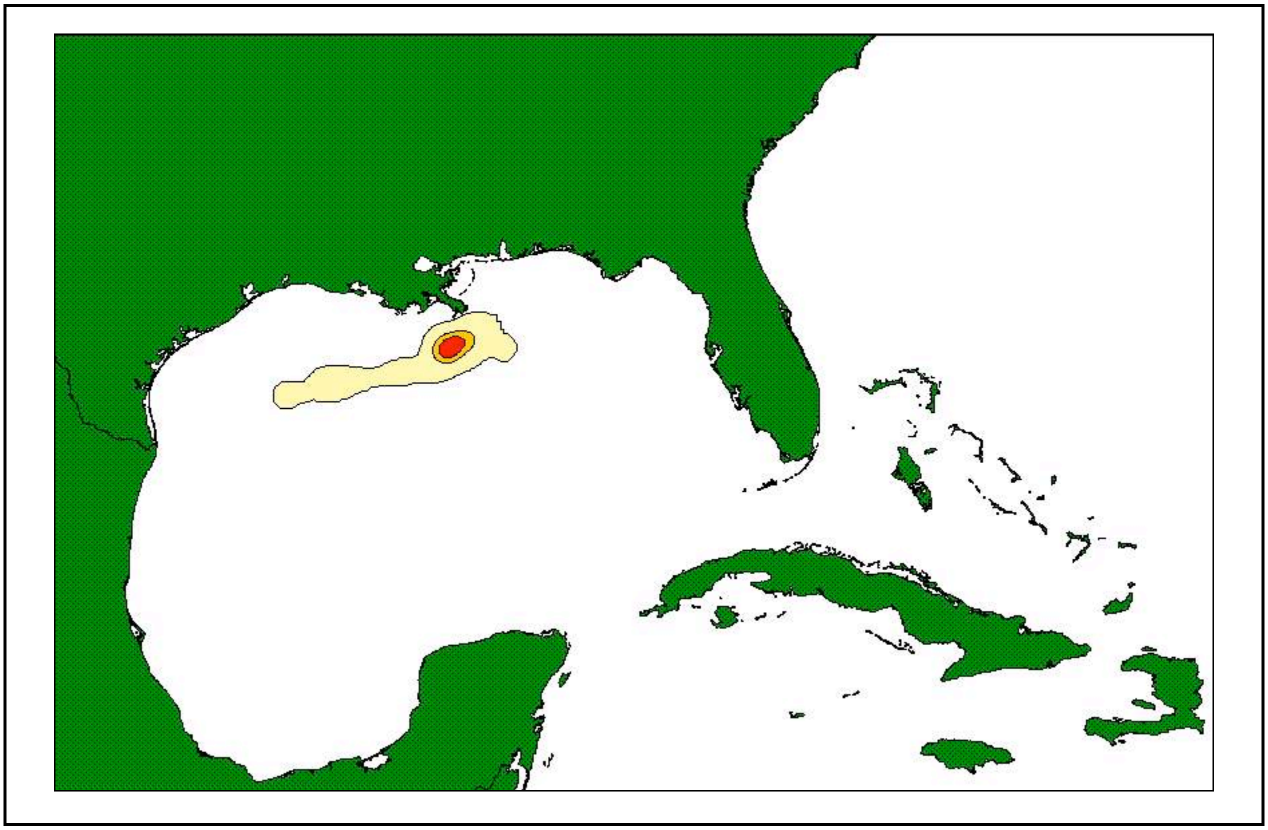

Figure 6.1.43. Density estimates of the utilization distribution (UD) for satellite locations received during the month of August. UD levels and color code are the same as in Figure 6.1.34.

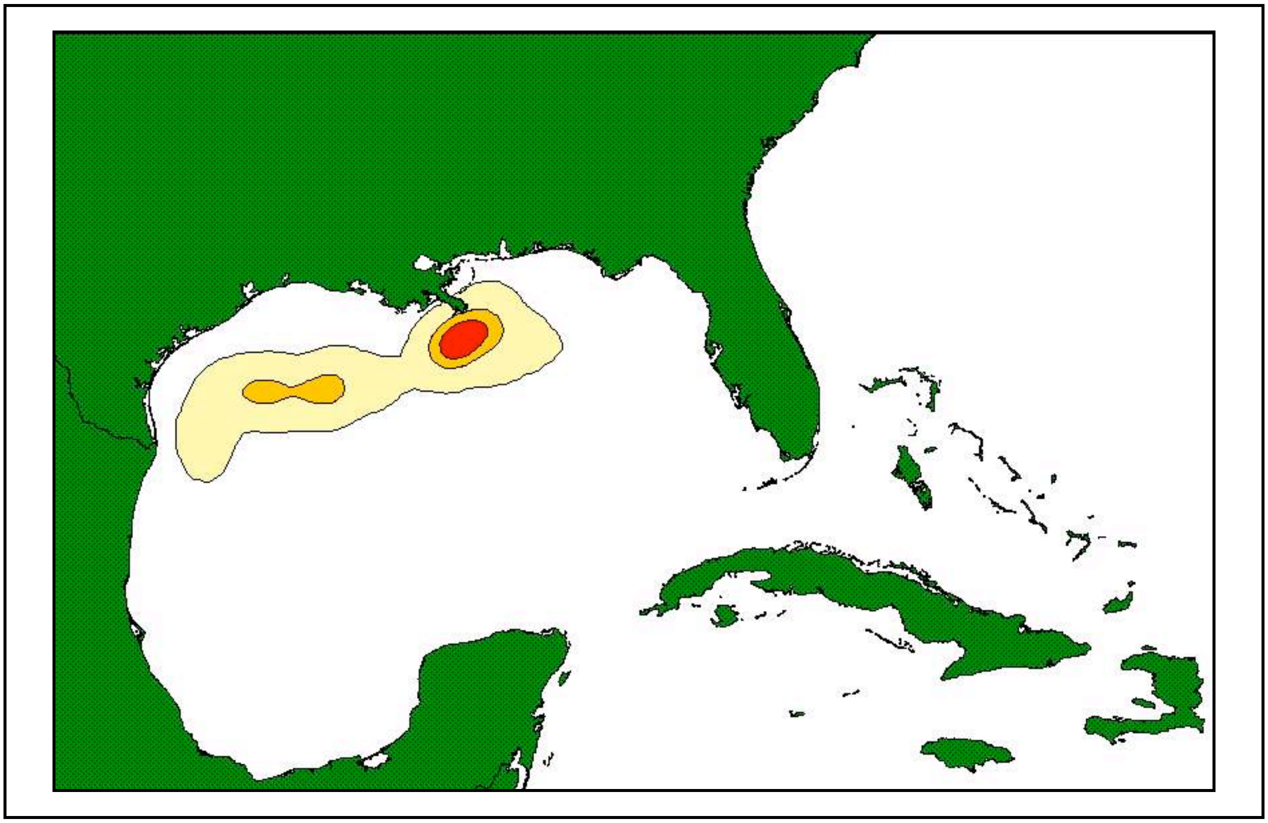

Figure 6.1.44. Density estimates of the utilization distribution (UD) for satellite locations received during the month of September. UD levels and color code are the same as in Figure 6.1.34.

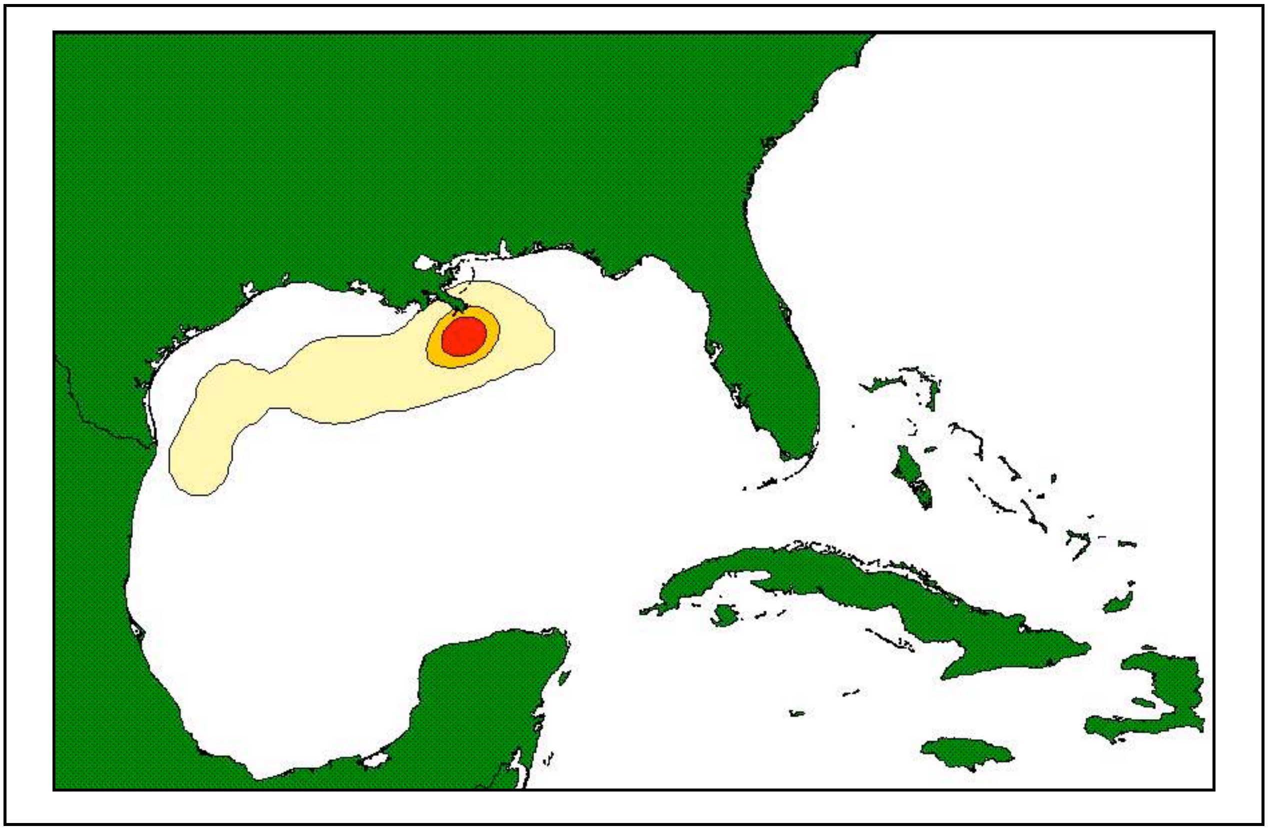

Figure 6.1.45. Density estimates of the utilization distribution (UD) for satellite locations received during the month of October. UD levels and color code are the same as in Figure 6.1.34.

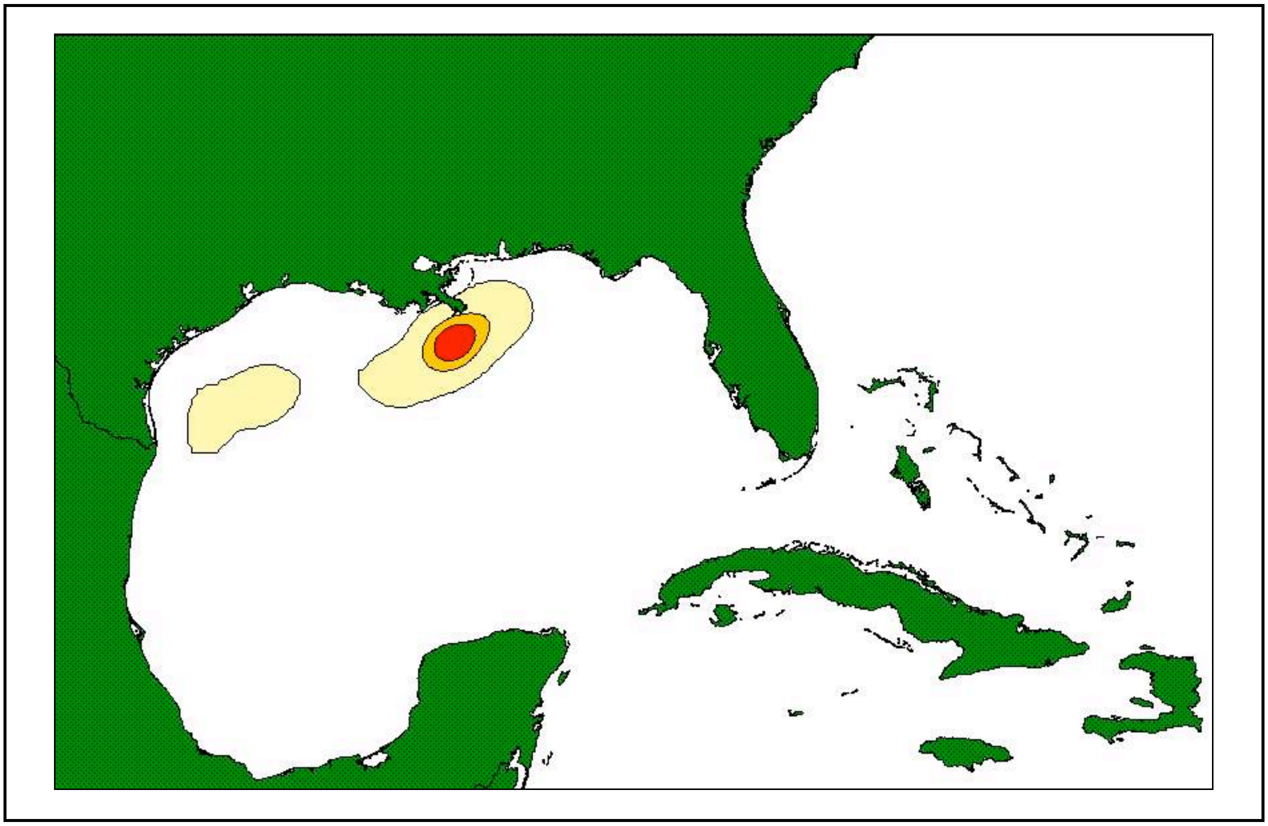

Figure 6.1.46. Density estimates of the utilization distribution (UD) for satellite locations received during the month of November. UD levels and color code are the same as in Figure 6.1.34.

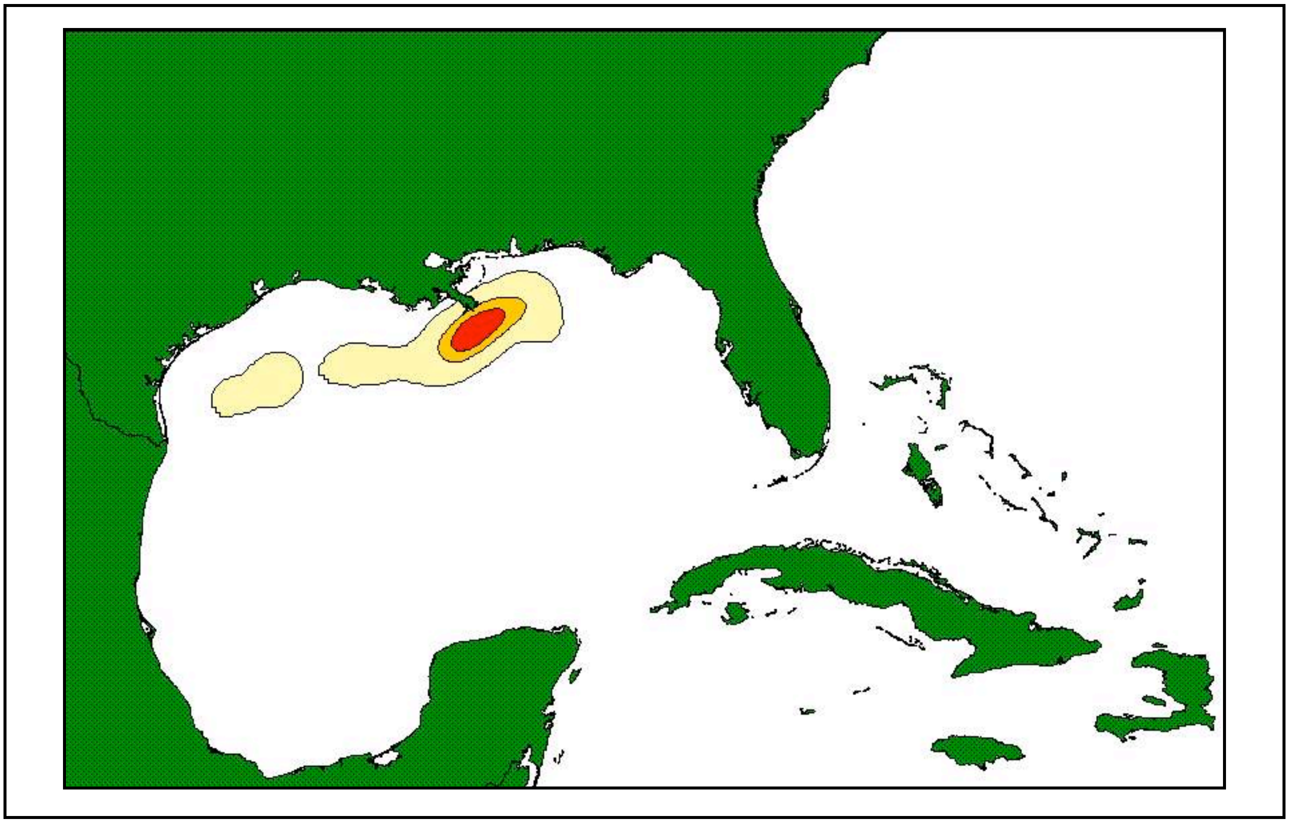

Figure 6.1.47. Density estimates of the utilization distribution (UD) for satellite locations received during the month of December. UD levels and color code are the same as in Figure 6.1.34.

Tag Longevity and Possible Effects

Satellite monitored radio tags performed better on sperm whales (205.8 days of average attachment duration) than on any baleen whale species (Figure 6.1.48). Sperm whales have tougher skin and subdermal connective tissue than baleen whales, which resulted in many tags not being fully deployed and being lost prematurely. However, it may be because of this tougher skin and connective tissue (leading to better tag holding retention once the tags were fully deployed) that our longest tracking time, as of mid-October 2004, has been with a sperm whale. Every effort was made to resight tagged whales during cruises (both original and subsequent tagging cruises) to examine the effects of tag attachment. At least 6 of the 39 tracked whales have been resighted to mid-October 2004, and three of these still had operational tags one year after tagging. None of the resighted whales appeared emaciated and all observed behavior was normal. Two whales were seen that had lost their tags and there was no evidence of infection or tissue sloughage at the tag site. One tag that was in the process of working its way out was exposed at least 70% of the tag's length and had three gooseneck barnacles attached to it (one to the stainless steel housing and two to the antenna/salt water switch area). The attachments were partially exposed and the tag was horizontal (parallel to the whale's major axis). Despite this extensive exposure and some additional drag, the tag site looked excellent and the tag was still providing useful data.

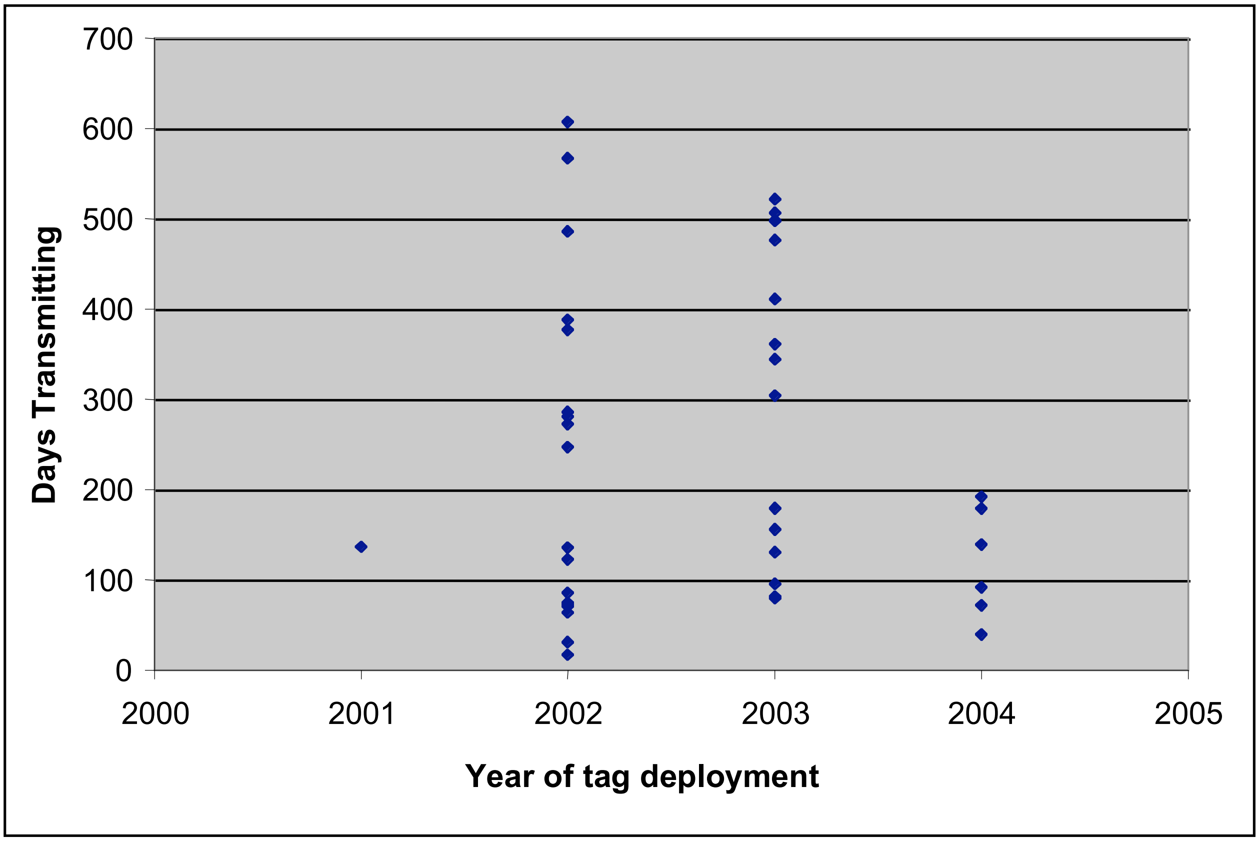

Figure 6.1.48. Satellite monitored radio tags performed better on sperm whales than on any baleen whale species, with 205.8 days of average attachment duration.

6.2 Habitat Characterization of Satellite-tracked Sperm Whales

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Abstract

Physical habitat of sperm whales (*Physeter macrocephalus*) in the northern Gulf of Mexico was studied by analyzing environmental variables for locations of 39 whales tagged with satellite transmitters. Movement paths of satellite-tracked whales were characterized and each location was assigned to one of two categories: meandering or transit. Ocean bottom depth and slope were determined for each satellite-determined whale location and comparisons were made between sex classes and movement types. None of the environmental variables analyzed had a normal distribution or equal variances among compared groups (even after transformation); therefore, non-parametric statistics were applied. Statistically significant differences were observed in the median values of bottom depth at locations for females and males (Mann-Whitney – Wilcoxon test statistic $W = 50930$, p-value < 0.01, $n = 798$ and 214, Median = 884 and 1171 meters, respectively). Median values of bottom slope were also different between females and males ($W = 68546.5$ p-value $= 0.013$, Median = 3.06 and 2.39 degrees, respectively). Significant differences were observed in the median depth for locations assigned to meandering and transit move types ($W = 119942$, p-value < 0.01, $n = 853$ and 338, Median = 895 and 968 meters, respectively). Median bottom slope was not different between meandering and transit. No significant differences were found in sea surface height (SSH) values between females and males. However, the median value of SSH was different between meandering and transit locations ($W = 98475$, p-value < 0.01, Median = -3.86 and -7.12 dynamic centimeters, $n = 818$ and 326, respectively). Satellite-tracked female sperm whales were located more frequently on the upper continental slope of the northern Gulf of Mexico. Males were also located in this last region, but some tracked males moved into the central Gulf or over deeper waters with less steep bottom slope (i.e. lower continental slope and abyssal plain). The statistical differences observed in SSH at locations of meandering and transit move types could indicate that sperm whales have differential use for areas of the Gulf. Moreover, movements of tracked whales showed that, although most individuals frequented the Mississippi Canyon (MC) and the Mississippi River Delta (MRD), there are differences between males and females, as well as among individuals, in the specific areas frequented during the year. A trend was observed for satellite-tracked whales to aggregate near the MC and MRD in the summer. While some individuals may spend several months in those areas, others disperse in different directions the rest of the year.

Introduction

Several factors affect cetacean distribution, such as food availability, predation avoidance, interspecific and intraspecific competition, and reproductive strategies. Prey abundance and availability have been suggested as factors with great influence on the distribution of cetaceans

(Kenney et al. 1985, Kenney and Winn 1986, Croll et al. 1999). We hypothesize that distribution of sperm whales in the Gulf of Mexico is driven by prey availability. However, it is difficult to obtain concurrent prey abundance estimates during cetacean surveys, particularly for species that feed in deep waters, like sperm whales. For this reason, previous studies of cetacean distribution have focused on characterizing the environmental conditions of the areas frequented by cetaceans. Several studies have compared distribution of cetaceans to oceanographic variables and bottom physiography (e.g., Hui 1979; Au and Perryman 1982; Kenney and Winn 1986; Smith et al. 1986; Reilly and Thayer 1990; Davis et al. 1998; Griffin 1999; Croll et al. 1999, Baumgartner et al. 2001; Davis et al. 2002). With the exception of studies that measured acoustic backscatter either with an echo sounder or an ADCP (Croll et al. 1999, Baumgartner et al. 2001; Davis et al. 2002; Baumgartner et al. 2003; Benoit-Bird and Au 2003), the variables included in the analyses do not have an apparent direct effect on cetaceans and they are rather proxies for more important factors such as prey abundance.

Waring et al. (1993) reported that distribution of sperm whales in the northeast coast of the U.S. is associated with the occurrence of Gulf Stream warm-core rings near the continental shelf edge. More recently, Griffin (1999) reported that concentration of sperm whales was higher in the vicinity of a thermal front on the eastern boundary of a Gulf Stream warm-core ring off Georges bank. In the Gulf of Mexico, most sightings of sperm whales have been made over the middle continental slope (mean bottom depth = 1104.9 m, median = 1009.3 m, Davis et al. 1998), over the lower continental slope and deep Gulf (depth >1000 m, Baumgartner et al. 2001), and areas of steep bottom slope on the lower slope in areas of cyclonic circulation or confluence between cyclone-anticyclone (Davis et al. 2002). Those studies have followed a synoptic, Eulerian, approach, similar to taking a picture of the cetaceans and the environmental conditions in the study area at the time of the shipboard survey. During ship surveys, the sex of the individuals cannot be determined and only the presence of mother-calf pairs can give indication of the composition of the groups. Moreover, the surveys were limited to specific seasons, mainly spring or summer (Baumgartner et al. 2001; Davis et al. 2002). Therefore, shipboard surveys previously conducted in the Gulf of Mexico cannot determine possible seasonal changes in habitat utilization. Indeed, Hansen et al. (1996) observed seasonal differences in cetacean abundance in the western and central regions of the northern Gulf of Mexico that may have been influenced by temporal changes in the local oceanography. In this paper, we use a Lagrangian approach to study distribution patterns of sperm whales by analyzing environmental conditions, at different times and locations, for individuals tracked by satellite-telemetry.

Materials and Methods

The Argos Data Location and Collection System was used to track 39 sperm whales in the Gulf of Mexico from 8 August 2001 to 15 October 2004 (Table 6.2.1). This technique is described more in more detail by Mate et al. (1997) and in Section 6.1. To 5 November 2004, the active life of tags (number of days between deployment and last satellite location) ranged from 17 to 607 days and the number of locations per tag ranged from three to 183.

Sex of tagged whales was determined from genetic analysis of skin biopsy samples. Genetic analysis is explained in more detail in Section 5. Sex was determined for 30 of the 39 tagged whales: 24 females and six males.

Table 6.2.1

Date and Location of S-tag Deployments and Active Life of Tags to 5 November 2004

PTT #	Sex	Date & Time	Latitude	Longitude	Days Tracked	Number of Locations
2505647	F	01-Jul-2002 21:58	28.903	-88.092	135.66	82
2505648	M	26-Jun-2002 23:03	29.207	-87.178	72.96	32
2505649	U	07-Jul-2002 20:20	28.708	-88.911	371.83	117
2505650	M	01-Jul-2002 19:48	28.956	-88.109	268.05	134
2505654	U	24-Jun-2002 23:06	27.993	-89.913	122.58	48
2505655	U	03-Jul-2002 20:47	28.839	-88.687	74.61	67
2505660	F	24-Jun-2002 18:36	28.011	-89.913	63.69	25
2505669	F	03-Jul-2002 23:07	28.804	-88.693	454.72	96
2505670	F	03-Jul-2002 19:48	28.840	-88.692	286.03	47
2505678	F	02-Jul-2002 23:10	28.860	-88.529	17.06	10
2505685	M	01-Jul-2002 19:35	28.958	-88.109	567.02	112
2505701	F	03-Jul-2002 23:42	28.805	-88.698	247.16	120
2505709	F	03-Jul-2002 16:49	28.788	-88.764	372.88	95
2505710	U	07-Jul-2002 19:25	28.732	-88.923	82.41	46
2505719	F	03-Jul-2002 15:24	28.793	-88.808	70.72	26
2505720	F	03-Jul-2002 20:09	28.850	-88.673	30.75	8
2505725	M	01-Jul-2002 21:40	28.903	-88.099	607.32	109
2505726	M	01-Jul-2002 20:16	28.950	-88.113	275.83	96
2800826	F	11-Jul-2003 23:15	28.805	-88.722	243.52	21
2800827	M	11-Jul-2003 20:43	28.796	-88.763	179.11	148
2800828	F	04-Jul-2003 00:06	28.657	-89.009	303.96	100
2800829	F	09-Jul-2003 23:38	28.482	-89.043	298.86	86
2800833	F	05-Jul-2003 17:41	28.731	-88.763	155.78	9
2800839	U	08-Jul-2003 19:03	28.521	-88.946	48.07	177
2800843	F	05-Jul-2003 15:49	28.725	-88.721	361.03	118
2801385	F	03-Jul-2003 23:42	28.651	-89.000	391.39	36
2805654	F	04-Jul-2003 00:21	28.666	-89.007	79.85	80
2805678	F	11-Jul-2003 20:17	28.787	-88.758	218.13	169
2805710	U	07-Jul-2003 20:15	28.652	-88.908	408.71	183
2805719	F	06-Jul-2003 00:08	28.698	-88.764	340.99	53
2805720	F	06-Jul-2003 23:54	29.140	-87.965	130.41	18
2810820	F	09-Jul-2003 16:18	28.506	-89.026	61.83	93
2823038	U	11-Jul-2003 23:35	28.794	-88.724	95.57	5
3200845	U	10-Jun-2004 17:05	28.332	-89.436	91.26	18
3201387	U	10-Jun-2004 19:45	28.300	-89.372	139.18	25
3201390	F	10-Jun-2004 17:46	28.311	-89.433	95.22	13
3202083	F	06-Jun-2004 23:00	28.247	-89.670	39.45	9
3205660	F	06-Jun-2004 14:30	28.266	-89.428	71.90	3
3205670	F	06-Jun-2004 15:51	28.271	-89.485	151.86	15

Squared displacement (Turchin 1998) was estimated for each one of the locations of the tracked whales. Move types defined in this analysis are based on the concepts explained by Stern (2002). We identified a movement type that corresponds to the move type defined by that author as "foraging"; however, since we do not have evidence that this movement pattern was related to feeding activity, we refer to it as "meandering". The move type we defined as "transit" corresponds to the types defined by Stern (2002) as "commuting" and "ranging". A satellite location (i) was considered to be of the meandering move type if three conditions were true:

a) Change of squared displacement (dD/dm) for the move between locations i and i+1 was less than the 99th percentile of the distribution of dD/dm (72829 km^2 for females and 14775 km^2 for males). All tagged whales of unknown sex had displacement values similar to those of females; therefore, the 99th percentile of the distribution of dD/dm for females (72829 km^2) was also used for individuals of unknown sex.

b) Distance between location i and location i+1 was less than or equal to the upper 99.9% confidence interval of the mean of move lengths (49.62 km for females and 94.90 km for males). The confidence interval of females was used for all the individuals of unknown sex.

c) Linearity between moves i and i+2 was less than 0.95. Linearity (l) was calculated as:

$$l = \frac{C}{A+B}$$

where,
A = distance between location i and location i+1
B = distance between location i+1 and location i+2
C = distance between location i and location i+2

Locations that did not meet all three criteria were considered to be transit moves. Figure 6.2.1 shows and example of move types characterized within the track of a tagged whale.

Bottom depth and bottom slope were obtained for each of the sperm whale satellite-determined locations from the Texas Sea Grant College Program high-resolution bathymetry of the Gulf of Mexico. This database has a 0.003-degree resolution and covers all the U.S. Exclusive Economic Zone. For locations that were not included within that grid, the ETOPO-2 (2 minute resolution) terrain elevation model was used.

Sea surface height (SSH) for each location was obtained from a database of daily grids with 0.25 x 0.25 degree resolution provided by the Colorado Center for Astrodynamic Research. The grids were derived from tandem sampling by altimeters aboard the TOPEX/Poseidon and ERS-2 satellites. A detailed description of the method used to compute SSH can be found in Leben et al. (2002).

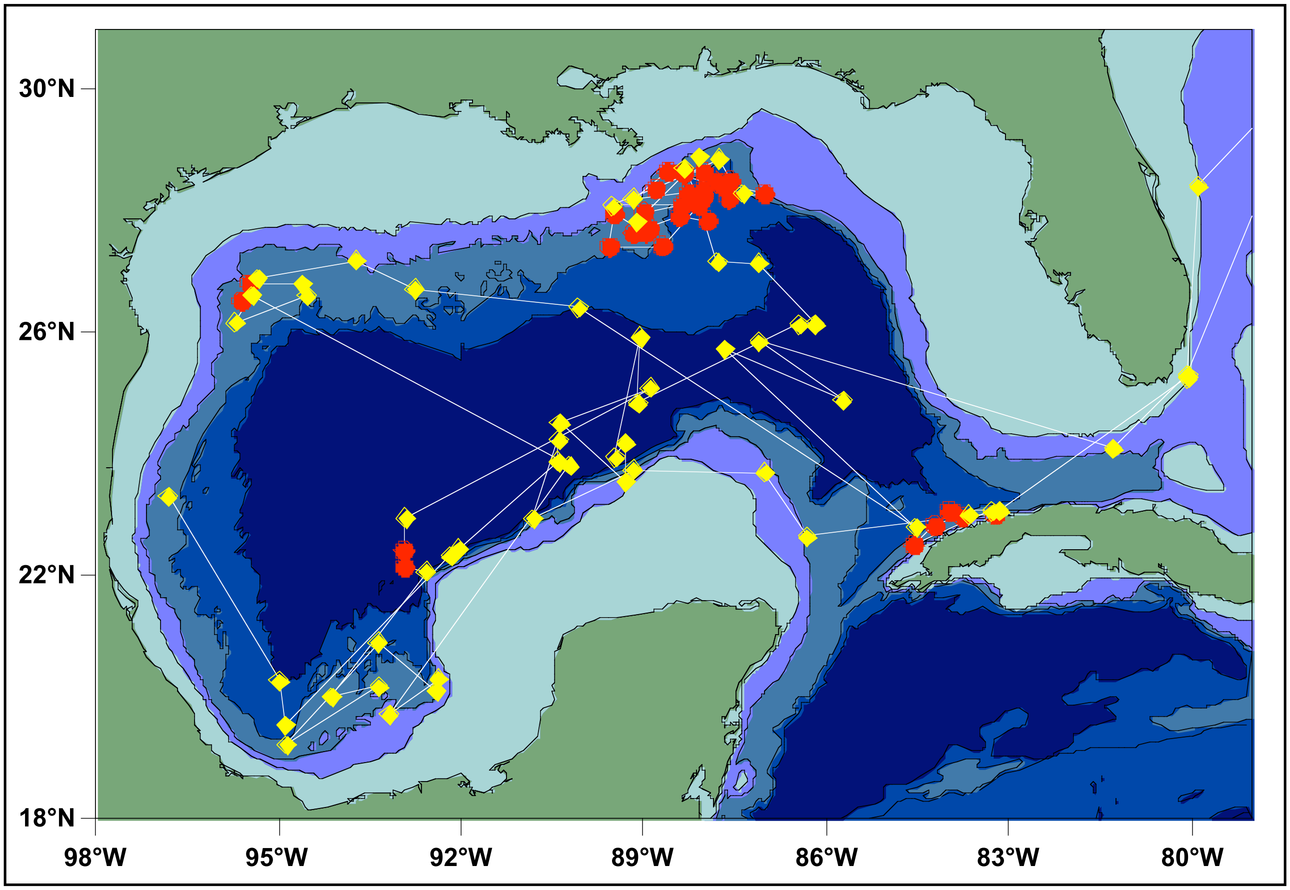

Figure 6.2.1. Trackline of tagged whale PTT#2505725 indicating the move type assigned to each satellite location. Circles are locations characterized as "meandering" and diamonds are "transit" locations. Contour lines indicate the 200, 500, 1000, 2000, and 3000 meter isobaths.

<u>Results</u>

None of the environmental variables analyzed had a normal distribution or equal variances among compared groups (even after transformation); therefore, non-parametric statistics were applied. Comparison of the environmental variables at locations for different move types and sex classes are presented in Tables 6.2.2 and 6.2.3 and Figures 6.2.2 through 6.2.11.

The median of water depth at satellite locations of female whales (884 m) was shallower than the median water depth for males (1171 m). Most of the locations of female whales were on the upper continental slope in a narrow water depth interval (Q_1 = 1011 m, Q_3 = 784 m). Locations for males occurred over a wider range of water depths (Q_1 = 1552 m, Q_3 = 866 m). Although male and female locations overlapped on the upper continental slope, less than 10% of locations from satellite-tracked females were in water deeper than 1300 m compared to 40% for males

(Figure 6.2.2). Median values of bottom slope were higher for females (3.06 degrees) than for males (2.39 degrees) (Figure 6.2.3). No significant differences were found in SSH values between females and males (Figure 6.2.4). However, the mean and median SSH for males and females (as well as the overall mean SSH) were all negative values, which indicates that sperm whales in the northern Gulf occur more frequently in cyclonic areas.

Locations classified as meandering move type occurred in shallower water than transit locations (Median = 895 m and 968 m, respectively) (Figure 6.2.5). Moreover, meandering locations occurred within a narrow depth range (Q_1 = 786 m, Q_3 = 1036 m) compared to transit locations (Q_1 = 804 m, Q_3 = 1252 m) (Figure 6.2.5). Although the difference in water depth at locations of the two movement types is small, it may reflect the patterns of prey distribution. No significant differences were observed for bottom slope between move types (Figure 6.2.6). However, the median value of SSH was significantly higher for meandering locations (-3.86 dyn. cm) than the median value for transit locations (-7.12 dyn. cm) (Figure 6.2.7). All of these findings appear to be the result of a few male excursions into deep water which were classified as transit.

Discussion

Sexual segregation of sperm whales has been well documented. Females and immature males are restricted to areas of latitude < 40º (50º in the North Pacific) while adult males spend most of their time in higher latitudes and only move to low latitudes to mate (Gulland 1974, Whitehead 2003). Moreover, differences in habitat use and movement patterns have been reported between sympatric groups of female and immature male sperm whales from different vocal clans (Whitehead and Rendell 2004). Our results indicate differences of habitat and movement patterns between females and males, as well as between individuals of the same sex. Future studies of vocal clans in the Gulf of Mexico will indicate if the differences between individuals or groups of individuals are related to vocal clan structure.

The majority of satellite-tracked whales were tagged in the MC and MRD in the summer. We also observed a tendency of satellite-tracked whales that transmitted over a year to return to that area next summer. This "aggregation" of whales in the MC and MRD could be related to annual cycles in the circulation patterns of the northern Gulf. In their circulation model for the continental shelf in the northern Gulf of Mexico, Cochrane and Kelly (1986) describe the occurrence of shift of currents in the summer months. Circulation on the continental shelf is cyclonic most of the year, so water moves from the MRD towards the western Gulf shelf during most of the year, except for the summer months (June-August), when the circulation is reversed.

The movement patterns of satellite-tracked female sperm whales indicate possible affinity for specific areas in the northern Gulf of Mexico. However, sightings of sperm whale groups with calves have also been reported in locations of the Gulf outside of the area where the tagged females were tracked. Therefore, it is possible that the different groups of females have affinity for different environmental conditions or locations within the Gulf. This hypothesis has significant implications for management purposes and can be tested by focusing future tagging efforts on female whales in areas other than the MC and MRD.

Table 6.2.2

Summary Statistics for Comparison of Selected Environmental Variables at Locations of Female and Male Satellite-tracked Sperm Whales

Descriptions		All data	Females	Males
Bottom depth (m)				
	Number of locations	2688	1600	446
	Mean	1052.84	978.3	1388.3
	Median	911.0	892.5	1169.0
	Standard deviation	544.01	419.09	732.66
	Minimum (shallowest)	5.0	151.0	365.0
	Maximum (deepest)	4650.0	3348.0	3682.0
Bottom slope (degrees)				
	Number of locations	2688	1600	446
	Mean	4.67	3.69	3.46
	Median	3.00	3.00	2.38
	Standard deviation	7.832	3.153	3.837
	Minimum	0.00	0.05	0.00
	Maximum	85.72	45.73	33.93
Sea surface height anomaly (dynamic centimeters)				
	Number of locations	2577	1600	446
	Mean	-4.64	-4.74	-4.70
	Median	-4.94	-4.59	-5.52
	Standard deviation	8.644	7.348	9.369
	Minimum	-29.05	-29.05	-27.98
	Maximum	64.95	26.97	63.24

Table 6.2.3

Summary Statistics for Comparison of Selected Environmental Variables at Locations of "Meandering" and "Transit" Move Types of Satellite-tracked Sperm Whales

Descriptions		**Meandering**	**Transit**
Bottom depth (m)			
	Number of locations	853	338
	Mean	997.26	1172.75
	Median	895.0	968.0
	Standard deviation	350.662	670.707
	Minimum (shallowest)	31.0	126.0
	Maximum (deepest)	3111.0	4650.0
Bottom slope (degrees)			
	Number of locations	851	320
	Mean	3.72	3.89
	Median	2.99	2.78
	Standard deviation	3.075	4.019
	Minimum	0.0	0.157
	Maximum	33.93	26.97
Sea surface height anomaly (dynamic centimeters)			
	Number of locations	818	326
	Mean	-3.78	-6.67
	Median	-3.85	-7.12
	Standard deviation	7.554	7.616
	Minimum	-28.32	-24.30
	Maximum	57.90	62.37

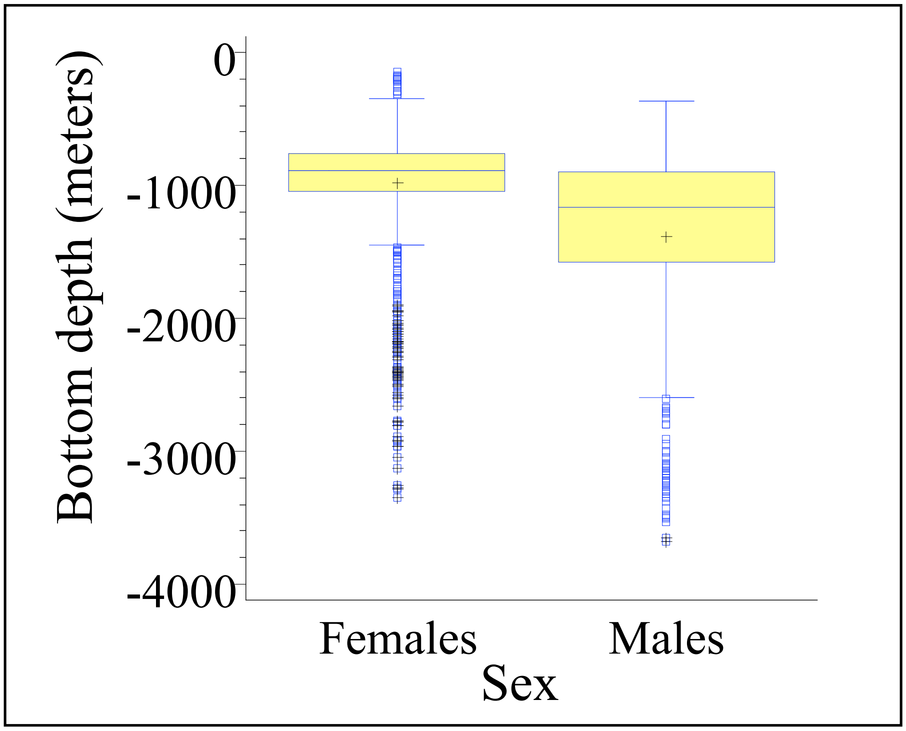

Figure 6.2.2. Box-and-whisker plot of bottom depth by sex class.

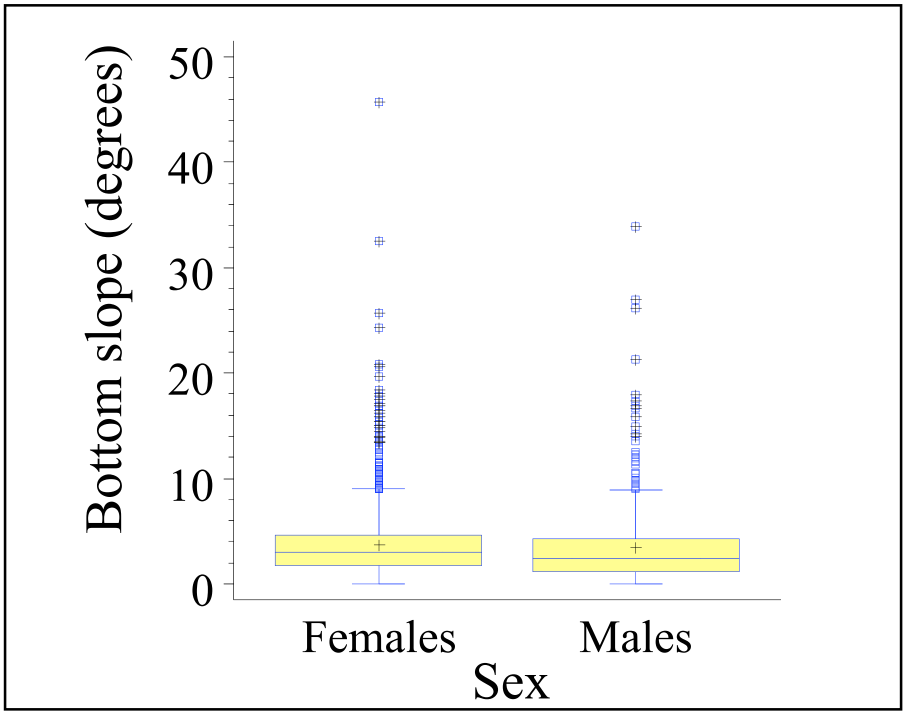

Figure 6.2.3. Box-and-whisker plot of bottom slope by sex class.

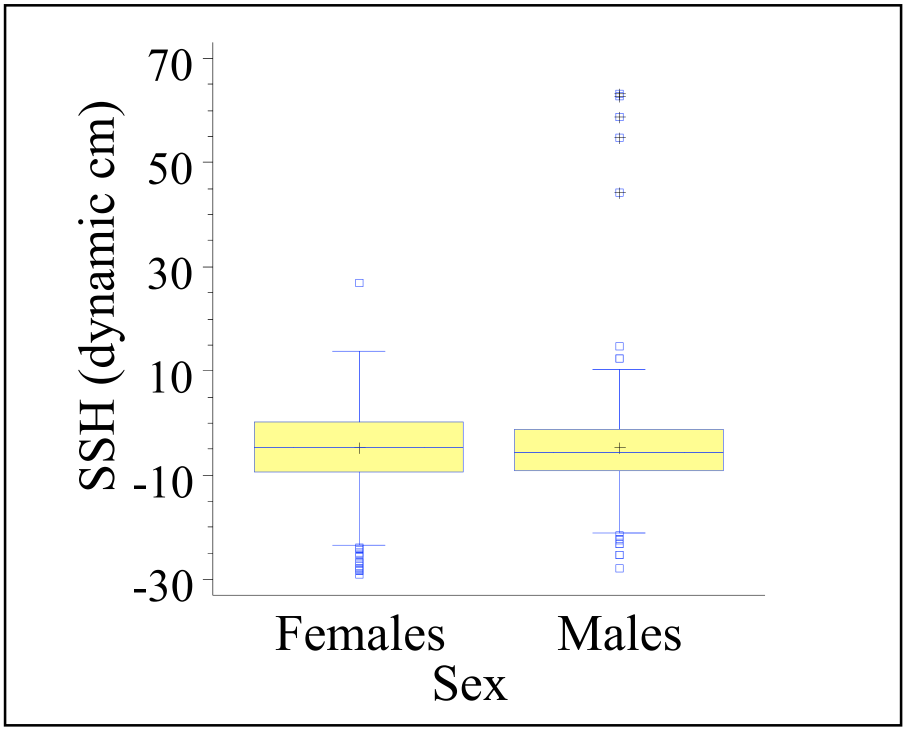

Figure 6.2.4. Box-and-whisker plot of sea surface height by sex class.

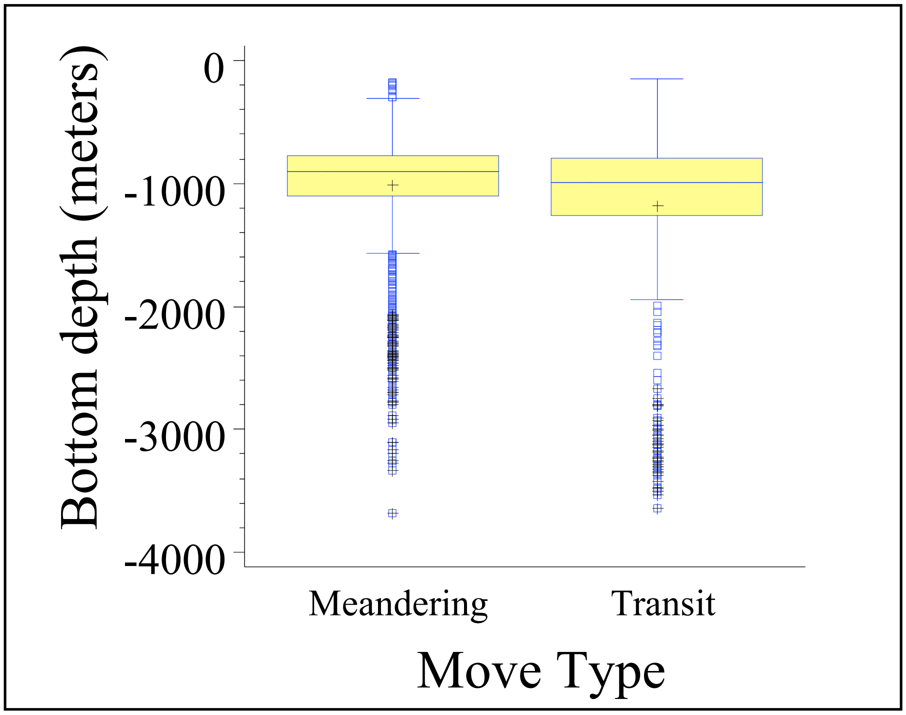

Figure 6.2.5. Box-and-whisker plot of bottom depth comparison by move type.

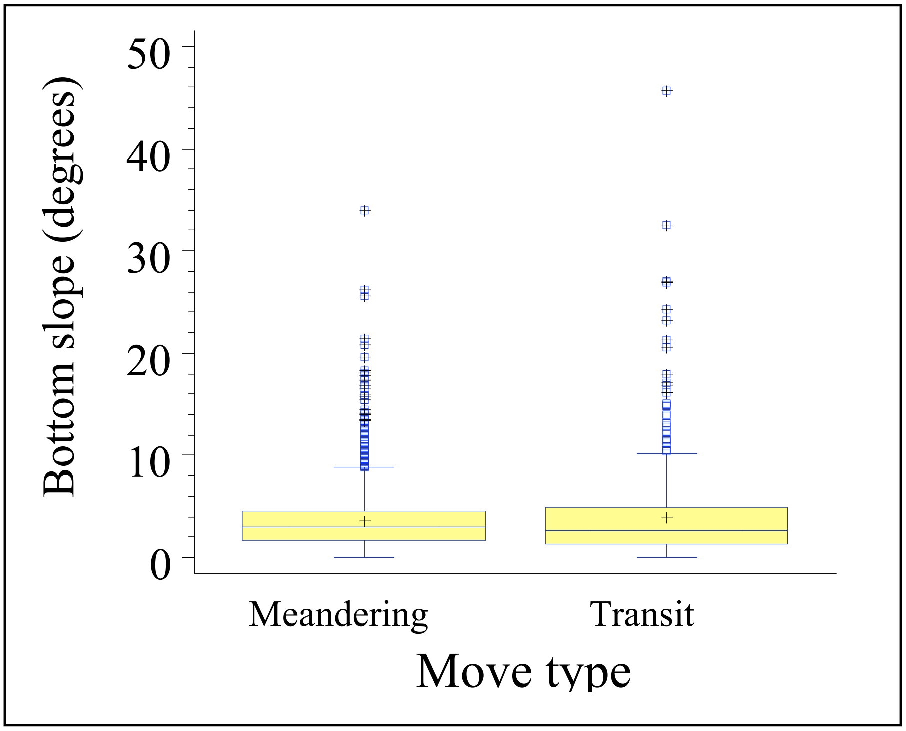

Figure 6.2.6. Box-and-whisker plot of bottom slope by move types.

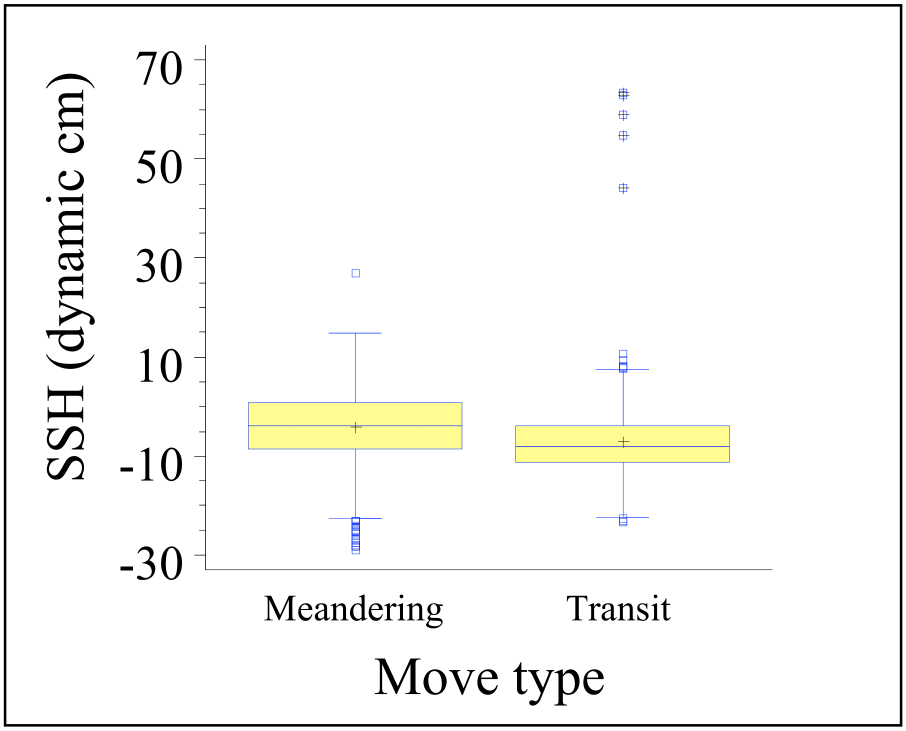

Figure 6.2.7. Box-and-whisker plot of sea surface height by move types.

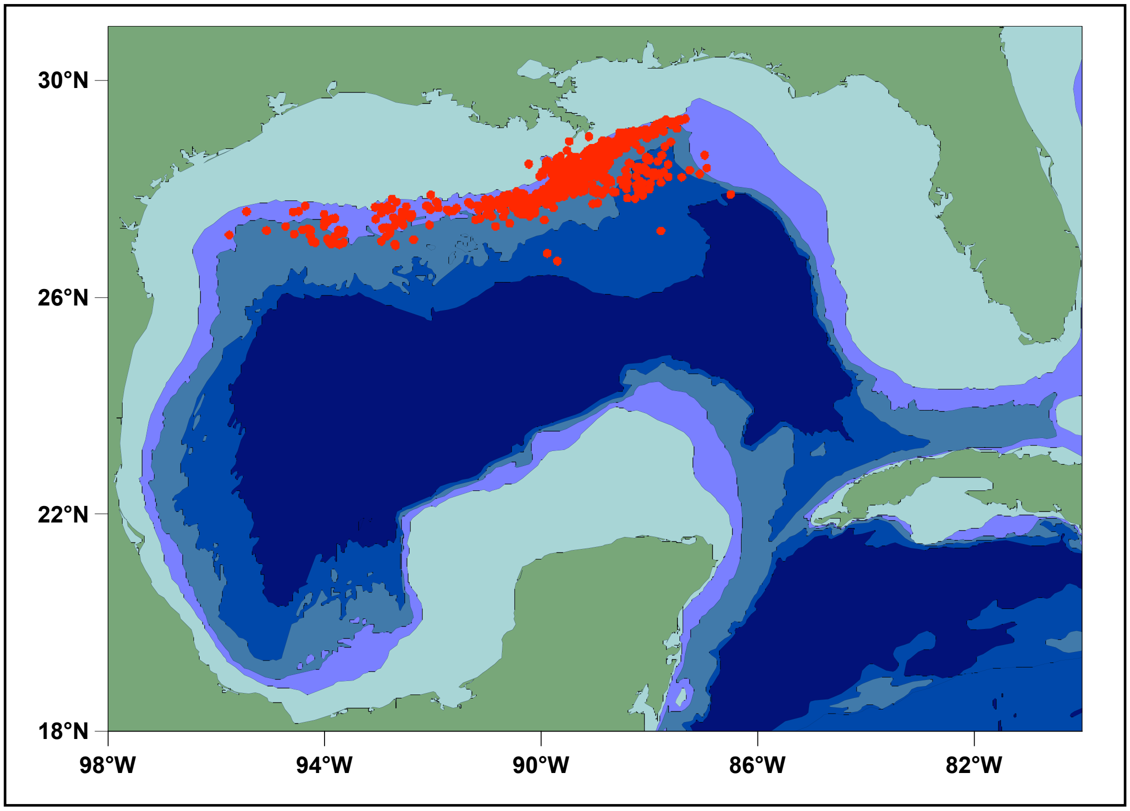

Figure 6.2.8. Locations of female whales classified as meandering move type. Contour lines indicate the 200, 500, 1000, 2000, and 3000 meter isobaths.

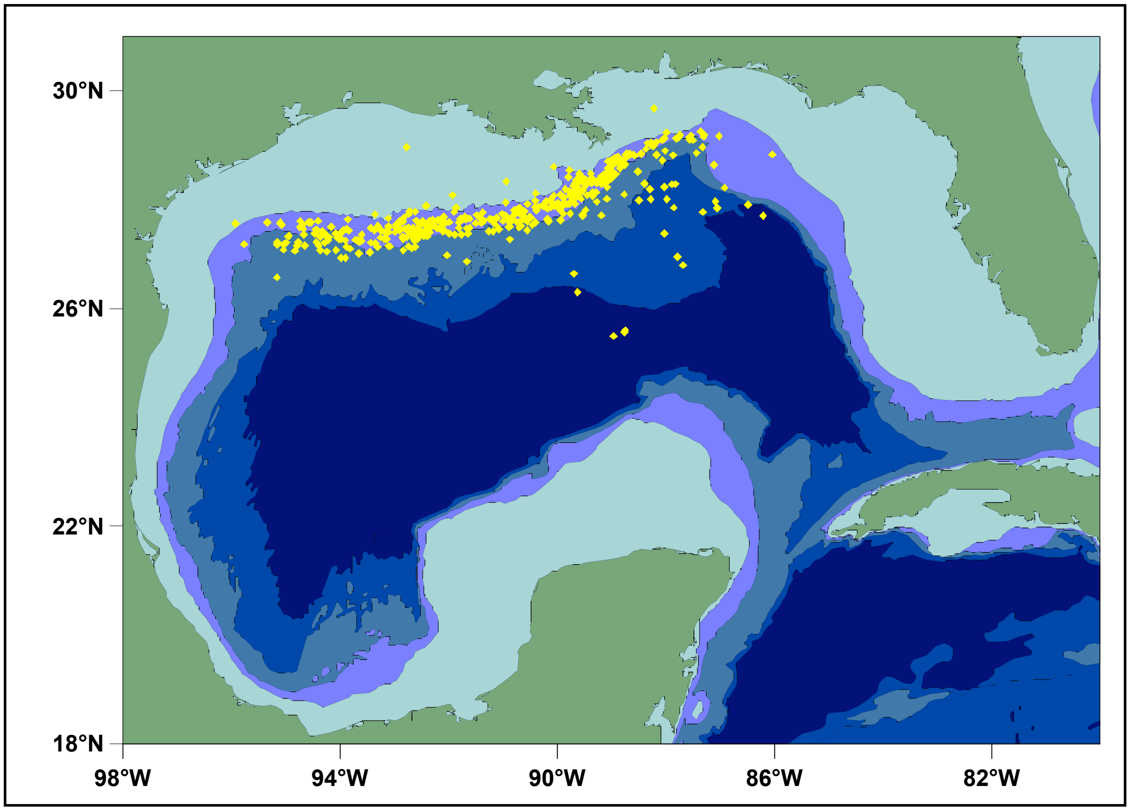

Figure 6.2.9. Locations of female whales classified as transit move type. Contour lines indicate the 200, 500, 1000, 2000, and 3000 meter isobaths.

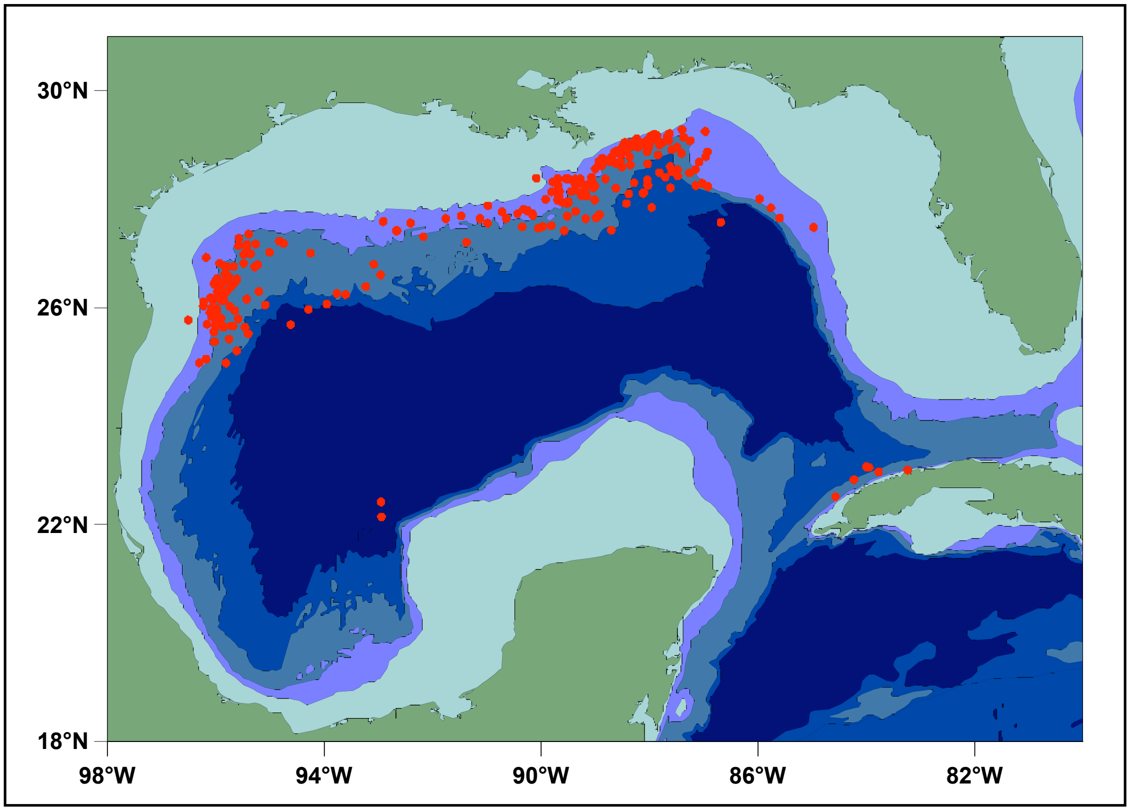

Figure 6.2.10. Locations of male whales classified as meandering move type. Contour lines indicate the 200, 500, 1000, 2000, and 3000 meter isobaths.

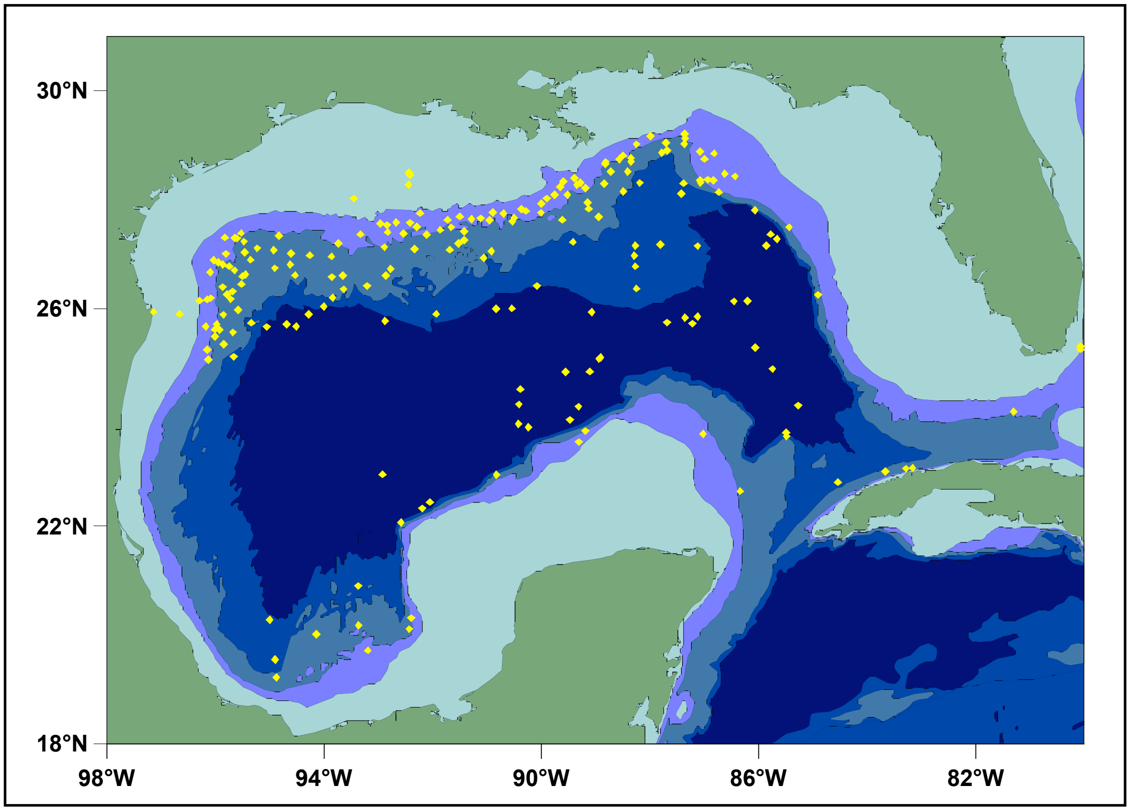

Figure 6.2.11. Locations of male whales classified as transit move type. Contour lines indicate the 200, 500, 1000, 2000, and 3000 meter isobaths.

7 RESPONSE OF SPERM WHALES TO AIR GUN SOUNDS IN THE GULF OF MEXICO

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7.1 Overview

As oil exploration and extraction activities in the northern Gulf of Mexico move into deep water, they overlap the habitat of the sperm whale, which is listed as endangered by the US Endangered Species Act. Loud underwater sound sources such as air guns are the primary tool for oil exploration and deep-diving sperm whales are inevitably exposed to air gun sound at levels shown in some anecdotal accounts to cause disturbance. However, conflicting scientific results on the effect of noise on sperm whales makes it difficult to determine whether air gun sounds cause a significant impact or not for this species. We proposed a 3-year program using a newly developed tag (the DTAG), in tandem with supporting visual and acoustic observations, to: (i) identify risk factors for noise disturbance in northern Gulf sperm whales and (ii) conduct controlled exposure experiments (CEEs) to measure reactions of these whales to airgun sounds. This research was conducted in collaboration with researchers from the Oregon State and Texas A&M universities with the seismic vessel provided by the seismic survey industry. This broad collaborative approach was designed to detect reactions of sperm whales to sound on multiple temporal and spatial scales, and relate those reactions to the ecology of sperm whales.

The non-invasive DTAG provides a detailed recording of both the sound field at a tagged animal and its movements throughout the dive cycle (Johnson and Tyack 2003), overcoming limitations of previous studies based only on surface visual observations and passive listening. The DTAG has been applied to 37 sperm whales during 2000 to 2003 in the Atlantic Ocean, Gulf of Mexico, and Ligurian Sea, producing a remarkable data set of 198 complete and partial foraging dives. For this project we have planned to analyze disturbance in terms of habitat avoidance, changes in foraging rate, and potential for auditory masking. As part of this project, Stephanie Watwood (Watwood et al. 2006) has submitted a paper describing the dive behavior of sperm whales, which provides additional control data against which to compare the behavior of exposed sperm whales.

At the time of this report, we are still in the process of publishing in peer reviewed scientific journals the results from the full SWSS data set detailing the reactions of sperm whales to controlled exposures from airgun sources at various ranges (and therefore received sound levels at the whale). Reaction of sperm whales to airgun sounds are compared to no-exposure controls to elucidate the biological context and significance of observed reactions. Two different kinds of control are used: non-exposure periods for each individual tagged whale, and a large corpus of whales tagged under baseline conditions. Each CEE subject was followed after tagging and before exposure to provide a pre-exposure control; exposure was stopped hours before the tag was programmed to release to provide a post-exposure control. Our extensive tagging of animals not exposed to CEE also provide data on animals that were not exposed or were exposed to low levels of airgun sounds.

The CEE cruises during the first two years of SWSS were successful both in controlling and measuring exposure during these experiments, and in assessing potential responses on a very fine scale. From experience with similar studies on right whales and on the effects of the SURTASS LFA sonar, we estimated for the initial proposal that three field seasons of at least 5 weeks each were required for a statistically powerful data set. The number of playbacks per time period of the research cruises reflects that estimated in the original proposal, but because of the halving of the field effort each year and the withdrawal of support for a research cruise during the third year, our full sample size is just 8 whales exposed to full CEEs. The 8 whales for which these seismic CEEs were conducted were all exposed to maximum sound levels between 130 and 160 dBp-p re 1 μPa at ranges of 1-12 nm (approx 3-23 km) from the sound source.

Background

The published literature on disturbance responses of sperm whales to airguns is mixed. Some researchers report responses to noise such as Mate et al. (1994) who reported that sperm whales in the Gulf of Mexico moved as far as 50 km away when seismic surveys began in the area. Bowles et al. (1994) suggested that Indian Ocean sperm whales decreased vocal activity when a 16-element seismic survey array was operated up to 300 km away. In contrast to these reports of disturbance at great distance from the source, Madsen et al. (2002c) reported that male sperm whales did not respond to nearby explosions of underwater detonators.

The high variability in reported responses may reflect a broad spread in sensitivity of sperm whales to sound, perhaps related to the age and sex of the subjects or their history of sound exposure. However, the above studies were limited to observations of group vocal output and surface movement. They were unable to observe sub-surface behavior or estimate the biological cost of disturbance when it occurred. In addition, none of these studies involved a well-controlled experimental design with unbiased selection of subject animals prior to sound exposure. Clearly more definitive research on the effects of noise is needed to aid management decisions and to set safe noise exposure levels for sperm whales.

One specific question of great interest to government regulators, industry, and environmental groups concerns the effectiveness of ramp-up of airgun arrays in mitigating the impact of seismic noise on sperm whales. In a ramp-up, or soft-start, airguns in an array are started from one to increasing numbers of guns over about a 30 minute period. The goal of soft-starts is to allow sperm whales nearby to move away from the airguns before full energy is transmitted into the water. However, no studies have directly investigated how sperm whales react to the onset of airguns nearby or whether ramp-up is an effective mitigation tool. A particularly important unexplored question is whether sperm whales react to a nearby ramp-up in a fashion that reduces the risk of harm or severe disturbance from the airgun sounds. For example, do sperm whales respond to lower received levels during the initial phases of a ramp-up to move away and avoid exposure to higher received levels as the full array is energized. Given the complex beam-pattern of a partially powered airgun array, a whale at a horizontal distance from the array may be exposed transiently to higher than expected sound levels during a ramp-up. For example, a full airgun array is designed to direct most of its sound energy downwards, but sound emitted during ramp-up is less directional, potentially creating higher levels horizontal to the array (Caldwell & Dragoset 2000). We proposed to use our DTAG to measure the exposure of tagged sperm whales during ramp-up and to document how they react to this exposure.

Research program to study responses of tagged whales to controlled exposures of airgun sounds

Opportunistic observations of how sperm whales react to noise, like those reviewed above, suffer from potential bias in selection of subjects, and lack of experimental control. In order to control for these problems for scaling animal responses to noise exposure we designed a carefully controlled experimental approach in which a tagged animal is followed pre-exposure, exposed to a test sound at a safe level and its reaction assessed during and after exposure (Tyack et al. 2004). We developed a 3-year program using a high performance tag (the DTAG), in tandem with ship-based visual and acoustic observations, to (i) identify risk factors for noise disturbance in northern Gulf of Mexico sperm whales, and (ii) to conduct replicated controlled exposure experiments (CEEs) to measure the sensitivity of sperm whales to disturbance from airgun sources. This approach was designed to ensure detailed and replicated measurements of response suitable for statistical treatment. Sounds from both a closing array during ramp-up and full power were used.

The DTAG, developed by Mark Johnson at WHOI in 1999, was used to measure the exposure level received by a target animal, and to document any behavioral reactions to exposure. This non-invasive tag records the sounds heard, and made, by the tagged whale together with its depth and orientation (i.e., pitch, roll, and heading), in a synchronized fashion throughout the dive cycle (Caldwell 2002; Johnson and Tyack 2003). The tag records data digitally for between 10 and 24 hours, depending on sampling rate, with enough resolution to track individual fluke strokes (e.g. Nowacek et al. 2001). The DTAG is attached to the whale with suction cups. A 13 m (40') long cantilevered-pole is used to deliver the tag to the whale, minimizing the impact of tagging. Intensive visual and acoustic observations from a nearby research vessel record the social and geographical context of the whales' behavior, before, during, and after tagging. The sensitivity and dynamic range of the DTAG allows a wide range of exposure levels to be tested: DTAGs on sperm whales in the northern Gulf have recorded sounds from a commercial seismic survey at a range of 24 km (15 nautical miles) with excellent fidelity.

Our team has extensive experience performing controlled exposure experiments on marine mammals (e.g., Miller et al. 2000; Zimmer et al. 2003). In parallel research projects involving northern right whales and manatees, clear responses to controlled sound playbacks and boat approaches have been found in DTAG data (Nowacek et al. 2004). Responses include cessation of fluking, brief re-orientation towards the sound source, and prolonged rapid fluking. Such responses, although invisible from the surface, entail an energetic expense for the disturbed animal. The DTAG technology allows us to examine natural underwater behavior and quantify responses to noise at a measured received level. Detail is sufficient to estimate the biological significance of an observed disruption in terms of habitat avoidance, energetic cost of locomotion, foraging attempts, and masking of communication.

The broad range of time scales over which reactions to airgun sounds are possible, from short-term distraction to long-term habitat avoidance, necessitate a multi-level study. The work proposed in this subcontract constitutes the fine-scale component of an omnibus of integrated proposals. Partners from Oregon State University and Texas A&M University studied, respectively, the long-term movements of satellite tagged sperm whales with respect to seismic survey activity and the oceanography associated with sperm whale habitats in the Gulf of Mexico. The seismic industry provided material support to the program in the form of a survey vessel and airgun array to be used in the controlled exposure experiments. The unique combination of fine- and large-scale tagging efforts linked to physical and biological mapping were designed to improve our understanding of sperm whale ecology in the Gulf of Mexico, and the significance of potential disturbance due to exposure to airgun sounds.

Scope-of-work

The proposed research was planned as a series of cruises over several years for the following reasons: (i) controlled exposure experiments ideally require a pause to analyze data before increasing target received level; (ii) repeat cruises make it easier to avoid repeat playbacks to the same recently exposed animals, and (iii) pauses between cruises allow for presentation of in-progress data in workshops, followed by mid-course corrections if necessary. From experience gained on prior controlled exposure studies and on the 2000-2001 SWAMP sperm whale cruises, we estimated that a three-year study with 5-6 weeks of fieldwork per year would provide a statistically-powerful data set.

Field experiments were scheduled in the Mississippi Delta and DeSoto Canyon areas of the northern Gulf of Mexico where sperm whales have been reliably sighted in large numbers, and during summer months when weather was expected to be calm enough to allow tagging of whales. In year 1 we proposed a single 6-week cruise to be split between potential deep-diving habitat in DeSoto Canyon, and the Mississippi Delta where we expected to encounter larger social groups. In years 2-3, we planned one or two cruises per year. Each D-tag cruise was designed to be dedicated to performing a number of very precisely defined controlled exposure experiments (CEEs) on sperm whales tagged with the DTAG.

Detailed visual observations and passive acoustic monitoring were planned to complement the DTAG data. Our previous research with sperm whales highlights the need to follow tagged whales, and other whales nearby, both visually and with passive acoustics before a controlled exposure is attempted. It is critical to know in real-time where whales are in order to predict the received level at the whales for a sound exposure. In addition, merging data from the tag with visual observations and passive acoustic monitoring yields much more valuable data than would any single approach alone (Zimmer et al. 2003). The study design involved performing observations before, during, and immediately after each CEE, and then, when possible, a second observation effort (partner proposal by Gordon, Jaquet, and Würsig) was planned to continue to track the behavior of exposed sperm whales for one or more days. This would be of especial value when a seismic vessel is in attendance, allowing the D-tag/CEE team to continue with CEEs without compromising longer-scale data collection. In another partner study, Texas A&M University proposed to sample the physical oceanographic context whenever sperm whales were encountered to establish parameters of sperm whale habitat.

All research that might "harass" marine mammals requires a Federal permit from the National Marine Fisheries Service. Tyack's group at WHOI has such a permit (NMFS Scientific Research Permit 981-1578-01 and 981-1578-02 for year 1 and Permit 981-1707 for year 2 & 3) enabling airgun playbacks at received levels up to 180 dB re 1 μPa valid until 30 September 2005. Should the program have developed in a way that suggested exposure to received levels > 180 dB, an amendment to the permit would have been required.

The procedure during the field study can be divided into 5 distinct phases: search, tagging, pre-exposure, exposure, and post-exposure.

Search: We located sperm whales using visual and acoustic techniques. Visual observers scan for whales using big-eye binoculars, and acoustic observers detect and locate sperm whales by listening for their vocalizations on a towed hydrophone array. Oceanographic sampling was also conducted during the search phase under the direction of Texas A&M researchers. The search pattern was informed by remote sensing data (e.g., the presence of gyres), and by the positions of whales tagged on a prior cruise with satellite tags. Once whales were detected, the acoustic monitors then tracked submerged whales in preparation for tagging and recorded array signals to multi-channel digital recorders. The R/V was steered toward the whales, and visual observers recorded the numbers and distribution of the group of animals.

Tagging: Once whales were located, and the R/V had moved close to the animals, a RHIB was deployed with a 4-person tagging team to attach DTAGs to whales. The choice of RHIB is crucial as it controls our ability to draw close to sperm whales with as little disturbance as possible. Once the RHIB was deployed, a directional hydrophone was used on the RHIB to locate and close on sperm whales. Visual and acoustic observers on the R/V supported the tagging effort by providing surfacing positions and acoustic bearings of whales to the RHIB team. Where possible, we tagged multiple animals prior to each CEE to increase the sample size of subjects while minimizing habituation. After attaching a tag, we measured the length of the whale using photogrammetry and took photographs of the fluke and other distinguishing features for photo-identification if this had not already been accomplished. We inspected the whale's surfacing location to search for and collect feces or skin. Once a whale had been tagged and photographed, the RHIB either returned to the R/V or attempted to tag another whale. The number of whales tagged before each CEE depends on the likely attachment duration, the group composition, and our ability to adequately observe multiple animals. No more than three whales were tagged at one time.

Pre-exposure: Once a suitable number of tags was deployed, we planned a pre-exposure period of approximately 2 hours to record baseline behavior of the tagged whales and to move the source vessel into the appropriate position. For deep-diving animals, a 2 hour baseline period amounts to about 2 dives (3 surfacings), sufficient to establish some parameters of foraging activity and to predict swim speed and heading. Visual observers on the R/V tracked the tagged whale(s) from a distance and noted the positions of other animals in the group. Range from the ship to each surfacing whale was determined by measuring the declination from the horizon using big-eye binoculars. All visual data were entered in real-time into Logger, a data gathering program, and displayed to aid positioning of the source vessel relative to the whales. Acoustic observers coordinated with the visual team to continue tracking whales while underwater. During this project, we wrote a computer program to integrate the ship's navigation data, visual and acoustic monitoring, and tag data. By combining all of these data sources, we built up a detailed real-time track of each tagged animal from which we could predict exposure level and so control the CEE.

Exposure: After the prescribed pre-exposure period, and when the source vessel was in the appropriate position, we proceeded to present one of three sounds to the tagged whale(s): no sound (baseline), coda playbacks (biologically-relevant control), or transmissions from an airgun array as described below. Transmission duration was up to 2 hours, sufficient to document whale reactions during 2 deep-dives. The choice of sound to transmit was determined by the availability of the seismic source vessel and by the need for a statistically significant number of trials of each exposure. Visual and acoustic observations continued during exposure both to qualify the tag data and to ensure mitigation in the event of a strong reaction. In year 1, our primary goal was to measure the behavior of sperm whales during the ramp-up onset of an airgun array relative to base-line. Since this involves relatively low levels at the whale, and following the protocol outlined in our application for a Federal permit to conduct this research, we targeted a received level (RL) at the whale of 120-140 dB re 1μPa in the first year. The target RL was increased during the course of the study as little response was detected in preliminary analyses of trials at the initial level. The conditions of the Federal permit under which this research will be conducted limit the exposure of whales to an RL <180dB re 1μPa. The protocol called for halting transmissions if any whale was detected visually or acoustically in areas where they might be exposed to levels above those allowed by the permit. To this end visual observers were stationed on the source vessel in cooperation with our IAGC/IRFC collaboration partners. For the biologically-relevant control sound, a broadband underwater source was deployed off the R/V or tagging vessel to play coda sounds to tagged whales. In year 1, we conducted one coda playback but these biologically-relevant control sound playbacks were not conducted in the second year in order to maximize the number of seismic CEEs.

The choice of target RL throughout the program was made as follows. We proposed to start with an RL known to be safe in terms of injury, but where disturbance was possible. Preliminary observations of sperm whales exposed to seismic survey show contradictory results, with some animals silencing or avoiding a source and others showing little obvious reaction to RLs in the 120-140rms dB range. This suggested an initial target RL of 120-140 dBrms for airgun sounds, which is the initial target level specified in our Federal permit. The source level for a single airgun is around 215-230 dBpeak implying that, under expected propagation conditions, the source vessel should maintain a range to the tagged whale(s) of some 10s of km. A similar range would be needed for horizontal propagation of a seismic array. We attempted to tag sperm whales in both Delta and Canyon areas and include members of family groups and lone males, if found. In year 1, we hoped to test reactions of 3-5 whales. If the responses to the exposure were consistently weak, our plan was to consider raising the target RL (to say 140-160 dBrms) during the next cruise. If we were to see predictable responses within the target range of RLs, we would continue playbacks at that level until we had enough data to estimate the biological significance of the responses. To assist us in interpreting results and in making decisions concerning further increases in exposure level above 160 dBrms, we sought input from workshops to be held in conjunction with the annual MMS Information Transfer meeting. In fact, little response was obvious in the first year data, so our target received level for the second year was increased to 140-160 dBrms.

Post-exposure: After the nominal 2-hour sound transmission period, visual and acoustic observations continued. The tagged whale(s) were tracked and the positions of animals nearby recorded. Post-exposure observations continued until all DTAGs detached from the subject whales. DTAGs were then recovered using the RHIB, and data downloaded from the tags in preparation for the next experiment. Skin samples were occasionally collected on the tag suction cups and these were treated and stored for genetic analysis. If analysis of the first year's data suggested that the subjects had not returned to baseline behavior by the time tags have detached, our plan was to increase the attachment duration for following years.

Data analysis

The entire data set from the tag and supporting visual and acoustic observations were analyzed to determine the sound level to which the tagged animal was exposed and are being analyzed to determine the reaction of the sperm whale to sound transmissions. Raw tag sensor data were converted to the pitch, roll, and heading of the tagged whale, and detailed 3-dimensional tracks were created by linking whale orientation data from the DTAG with visual observations of surfacing position. Behavior during exposures to airgun sounds are being compared to responses to baseline behavior collected from the tags. Metrics for behavior include: direction-of-movement, fluking rate, whale position, diving behavior and duration, surfacing durations, and vocal behavior (foraging clicks, buzzes, codas).

The critical issue for disturbance is not just to detect how responses scale to exposure; one must also develop a framework to evaluate whether the impact of disturbance is biologically significant or not. We are evaluating the following potential impacts: avoidance of habitat, decreased energetic efficiency during foraging, and masking of acoustic behaviors.

Avoidance of habitat: Most sperm whales range over many hundreds of kilometers a week as they forage. This movement pattern may reduce the potential for negative impact if a group is able to move away from a seismic survey without disruption of foraging. However, DTAG data collected in the northern Gulf in 2000 and 2001 have revealed a previously unknown foraging habit among northern Gulf animals. While most of the tagged whales foraged in open water with motions suggesting chasing and capturing of prey in the water column, one animal foraged at the bottom with distinctly different motions. Such bottom-foraging may entail particular risks, for example, foraging habitat may be limited to specific locations or bottom features where prey aggregate, and a whale may need to develop local knowledge to exploit the prey efficiently.

If other research partners can provide us with environmental observations of habitat quality we can analyze tracks of the movement of tagged animals to assess whether animals move away from desirable habitat.

Decreased energetic efficiency: DTAG data also allow us to model the energetic costs and benefits of foraging dives. Before this proposed work, the DTAG had been applied to 15 sperm whales in the northern Gulf of Mexico and in the Mediterranean Sea, yielding detailed information on diving energetics and foraging behavior that help expose potential risk factors. The DTAG records rapidly accelerating clicks (buzzes) when the whale is foraging and these are linked with a transient increase in motion (Miller et al. 2004a); we are treating these periods as a potential measure of feeding success as the animal appears to be closing on prey. Buzz rates have been planned as one measure used to quantify the impact of seismic exposure on foraging since the beginning of this project. We cannot be sure that sperm whales actually catch a prey item during each buzz, nor do we know the caloric value of prey, but the buzz rate is the best proxy available to assess foraging attempts for sperm whale dives.

We are also working to develop an energy budget for the energetic cost of diving based upon drag and buoyancy forces measured indirectly by the tag (Miller et al. 2004b). Deep-diving animals must gain enough energy through foraging to pay the expense of diving: the tighter this energy budget is, the greater the cost of a disturbance. For example, the bottom-feeding animals discussed above may be more energetically constrained than open water feeders: the expense of diving to the bottom must be countered through increased foraging efficiency (Costa and Gales 2003). Nursery groups in the northern Gulf in which females provide maternal care to young sperm whales may be another group with heightened energy demands. In the latter case, the net energetic cost of a disturbance may be an especially important indicator of population-level disruption.

The tagging program allows us to quantify elements of the energy budget of diving sperm whales and to establish proxies for the relative energetic expense of observed reactions to noise as a function of behavior and habitat use. We are developing metrics for locomotion expense from DTAG data (3-D tracks and accelerometer data) to estimate the impact of sound playback on energetic expenditure, and relate relative energetic expenditure to foraging attempts as described above.

Masking of acoustic behaviors: Manmade noise may interfere with a whale's ability to forage or socialize. For example, a man-made sound could mask a weak echo from prey resulting in decreased foraging success. Masking may be less likely for intermittent sounds, such as those from airguns, than for more continuous noise such as the propulsion noise of ships, but it remains an important potential impact to measure. The impact of masking may be measurable by comparing rates of coda production in response to distant codas or buzz rates (or other features of foraging behavior) during exposure to sounds relative to pre-exposure periods or control exposures.

7.2 Review of Evidence that Buzzes Correspond to Attempts to Capture Prey

During the 1950s, Donald Griffin pioneered the study of echolocation in bats. Not only was the very concept of animal echolocation controversial, but Griffin's discovery that bats can use echolocation to search for, select, and capture prey, was met with initial skepticism (Griffin 1958; Griffin et al. 1960). Griffin (1958, p. 200) describes in detail the studies he used to develop "strong evidence that the bats which I have been describing depend to a very large extent on echolocation in their feeding activities. Certainly the sound pattern shown in Fig. 8 and Plate 8 [slow regular clicks developing into a buzz] is a unique one which seems to occur only during the pursuit of insect prey." Similarly, Griffin et al. (1960, p. 141) state "When bats are hunting insects they adjust the pattern and tempo of their high frequency orientation sounds in a way that seems quite appropriate for active echolocation of small moving targets …. The most obvious change is a marked rise in the pulse repetition rate just as the bat closes on its prey. For example, *Eptesicus fuscus* often emits only four or five pulses per second in straight cruising flight; but during insect pursuit, the same bat may shift to a 'buzz' in which the pulses are separated by only five milliseconds." This pattern is remarkably similar to that of the sperm whale, which emits regular clicks at rates of 0.5-2/sec and buzzes with inter-click-intervals of about 20 msec (Madsen et al. 2002a). Since that time, neurophysiological studies have verified that "brain maps of mustache bats help them identify the distance to a flying insect (target range) and the speed with which the prey is moving (target velocity), vital information if the bat is to intercept the prey. … Thus, the specialized sensory maps contained in the brains of mustache bats are indeed used by the animals to perform two different perceptual tasks needed for prey tracking and capture." (Alcock 1993, p. 131). The dominant model, now well accepted, is that some bats use regular clicks in the search phase of foraging, switching to the buzz to capture prey.

Most biologists studying sperm whales have argued that sperm whale clicks are used for echolocation during foraging (summarized in Whitehead 2003). Fristrup and Harbison (2002) suggested two alternative hypotheses that sperm whales use vision to forage. Miller et al. (2004a) use D-tag data to show that the predictions of these vision hypotheses were not supported. Miller et al. (2004a) provide data supporting the hypothesis that buzzes in sperm whales are also an echolocation signal involved in the final attempt to capture prey, analogous to terminal buzzes in bats and several other species. Buzzes occur during the bottom phase of the dive, when sperm whales are thought to feed. The end of buzzes is marked by a pronounced increase in angular movement of the whale, a maneuvering likely to involve movement to capture the prey. There was also a strong positive correlation of buzz rate and bottom time for 12 of the 15 whales studied, suggesting that sperm whales spend longer feeding in better patches of prey. The total number of buzzes per day is consistent with estimated feeding requirements of sperm whales.

The interpretation that buzzes represent attempts to capture prey is strongly supported by D-tagging work with beaked whales. Johnson et al. (2004) demonstrated that *Ziphius cavirostris* and *Mesoplodon densirostris* also produce regular clicks during deep foraging dives. Interspersed among the regular clicks are buzzes similar to those of bats and sperm whales. Like sperm whales, beaked whales show a pronounced dynamic acceleration at the end of the buzz. The unique element of the beaked whale data is that we can detect echoes in the water column from these clicks. For about 10 sec before a buzz, it is possible to follow an echo from a target that the whale closes on. At about 3 m, the whale switches to the buzz, and just as the target closes to <1m, we often hear something soft hitting the tag. Our interpretation is that these targets represent prey, and as with bats and sperm whales, the rapid clicks of the buzz provide the rapid update used to actually capture the prey. Madsen et al. (2005) document details of the biosonar strategies used by beaked whales to capture their prey.

Miller et al. (2004a) summarize the conclusions that form the basis of the buzz analysis in this chapter "our results suggest that overall buzz rates are an indicator of feeding success across a series of successive dives, during which prey type should be fairly stable." Given the preceding analysis, we follow our initial proposal for this work to use buzz rates as a proxy for foraging attempts, which are likely to correlate with foraging rate during time intervals corresponding to the different phases of our CEEs. So long as the relationship between buzz rate and prey-intake rate is constant over the time-course of a single experiment, this is a justified proxy. Our interpretation does not require a precise one-to-one relationship between a buzz and prey capture event. In fact, given the trend we observed of reduced buzz rates during exposure, the only way reduced buzz rates could not represent reduced prey-intake would be if buzz-rate success *increased* during exposures, which seems to be unlikely during exposure to an anthropogenic noise source. Behavioral disruption would seem more likely to decrease capture success per buzz than to increase it.

7.3 In Progress Analysis

This section presents a discussion of the progress of the following analyses:

- In progress analysis of deep diving behavior of sperm whales
- In progress analysis of coda vocalizations of sperm whales
- Problems with RMS safety levels for transients
- Progress on quantitative measures of air gun pulses impinging on sperm whales (*Physeter macrocephalus*) using controlled exposures and onboard, acoustic tags
- Analysis of whale movement and behaviour in relation to controlled experimental exposures from a seismic array
- Measuring the distance between whales using acoustic recording tags

7.3.1 In Progress Analysis of Deep Diving Behavior of Sperm Whales

This analysis incorporated data from sperm whales tagged during the SWAMP and SWSS cruises.

Methods

Dive characteristics: Dive periods were divided into 4 phases based on the methods described in Miller et al. (2004b): surface time, descent phase of dive, bottom period of dive, and ascent phase of dive. The descent was the period of time from when the whale left the surface until the pitch first became positive (whale was no longer oriented downward). The ascent started when the whale was last oriented downward (pitch<0º) and ended when the whale reached the surface. The bottom phase of the dive contained the time between the end of the descent and the beginning of the ascent. Shallow dives were defined as dives with a maximum depth between 10 and 300 m.

For the descent and ascent phases, we calculated the duration and average vertical velocity. For the bottom phase, we recorded the start depth, end depth, minimum depth, and maximum depth, and calculated the duration. We calculated the duration and average depth for the inter-dive intervals (surface phases). Additionally, for each animal we calculated the time at the surface and the percent of time within 10 m of the surface. We compared for each animal the dive depth and dive duration vs. time of day.

Vocalizations: Sperm whales have a vocal repertoire that is dominated by four different click types: regular clicks, buzzes, slow clicks, and codas (Whitehead and Weilgart 1991; Madsen et al. 2002a). Regular clicks and buzzes have been implicated in echolocation-based foraging (Gordon 1987; Madsen et al. 2002a), whereas slow clicks and codas are used in social communication (Watkins and Schevill 1977; Whitehead and Weilgart 1991; Weilgart and Whitehead 1997). Clicks produced by the tagged animal were identified by their consistent waveforms and high amplitudes. We defined a search phase as the time between the first and last regular click produced by the focal animal. For the search phase of each dive, we recorded the depth at the start and end of the search phase and calculated the duration and percent of the total dive time in the search phase. We defined a foraging phase to be the time between the first and last buzz produced by the tagged whale. We determined the starting and ending depth of the foraging phase, the duration, and the number of buzzes produced for the foraging phase of each dive. Diving efficiency was calculated as the percent of the dive cycle spent actively foraging (foraging duration)/(dive duration + post-dive surface interval) (Ydenberg and Clark 1989).

Preliminary results are presented as mean standard deviation [mean (SD)].

Preliminary results and discussion

Figures 7.3.1 and 7.3.2 show dive profiles for two whales from the North Atlantic and two whales from the Gulf of Mexico, respectively. The results described here are derived from 7 and 23 successful D-tag deployments in the Atlantic Ocean and Gulf of Mexico, respectively. The dives made by sperm whales fell into two distinct categories: dives < 150 m and dives > 300 m. We will define deep dives as all dives > 300 m.

Two whales were tagged twice and the data were combined for each individual. Two whales did not perform any deep dives while wearing the D-tag. The structure of the deep dive cycle was highly stereotyped. There was considerable variation in dive parameters among individuals within a location. See Tables 7.3.1 and 7.3.2 for average dive and foraging parameter values for whales in the North Atlantic and Gulf of Mexico.

Dive duration: A typical sperm whale deep dive lasted 46 (7.0) minutes (range 14.2-63.9 min). Ninety-five percent of recorded deep dives lasted more than 30 minutes and less than 57 minutes. Dive duration was correlated with maximum dive depth for whales in the Gulf of Mexico. The dive durations reported here were similar to those described for whales in the Galapagos and Scotian Shelf (Mullins et al. 1988; Papastavrou et al. 1989).

Descent phase: Whales descended at an average vertical velocity of 1.2 (0.2) m/s. Whales began producing regular clicks (start of the search phase) at a depth of approximately 221 (84.1) m in the Atlantic and Gulf of Mexico. Whales in the Gulf of Mexico and Atlantic Ocean started producing regular clicks at depth similar to whales in the Galapagos (Papastavrou et al. 1989) and Papua New Guinea (Madsen et al. 2002b), between 200 and 300 m. Whales continued descending and producing regular clicks until they reached the depth of prey.

Bottom phase: Whales stopped descending and began the bottom phase of the dive, where they moved up and down through the prey layer. Whales dove to 966 (67.2) m in the Atlantic (range 830.3 - 1202.2 m) and 659 (133.6) m in the Gulf of Mexico (range 326.8 - 972.0 m). The deepest dive recorded was to a depth of 1202 m by a whale in the Atlantic Ocean. Whales started and ended the bottom phase at shallower depths in the Gulf of Mexico than in the Atlantic Ocean. Sperm whales in the Atlantic made regular dives to depths greater than 700 m, similar to sperm whales in other regions (Amano & Yoshioka 2003; Watkins 1980; Watkins et al. 1993), and other deep diving species such as bottlenose whales (Hooker & Baird 1999).

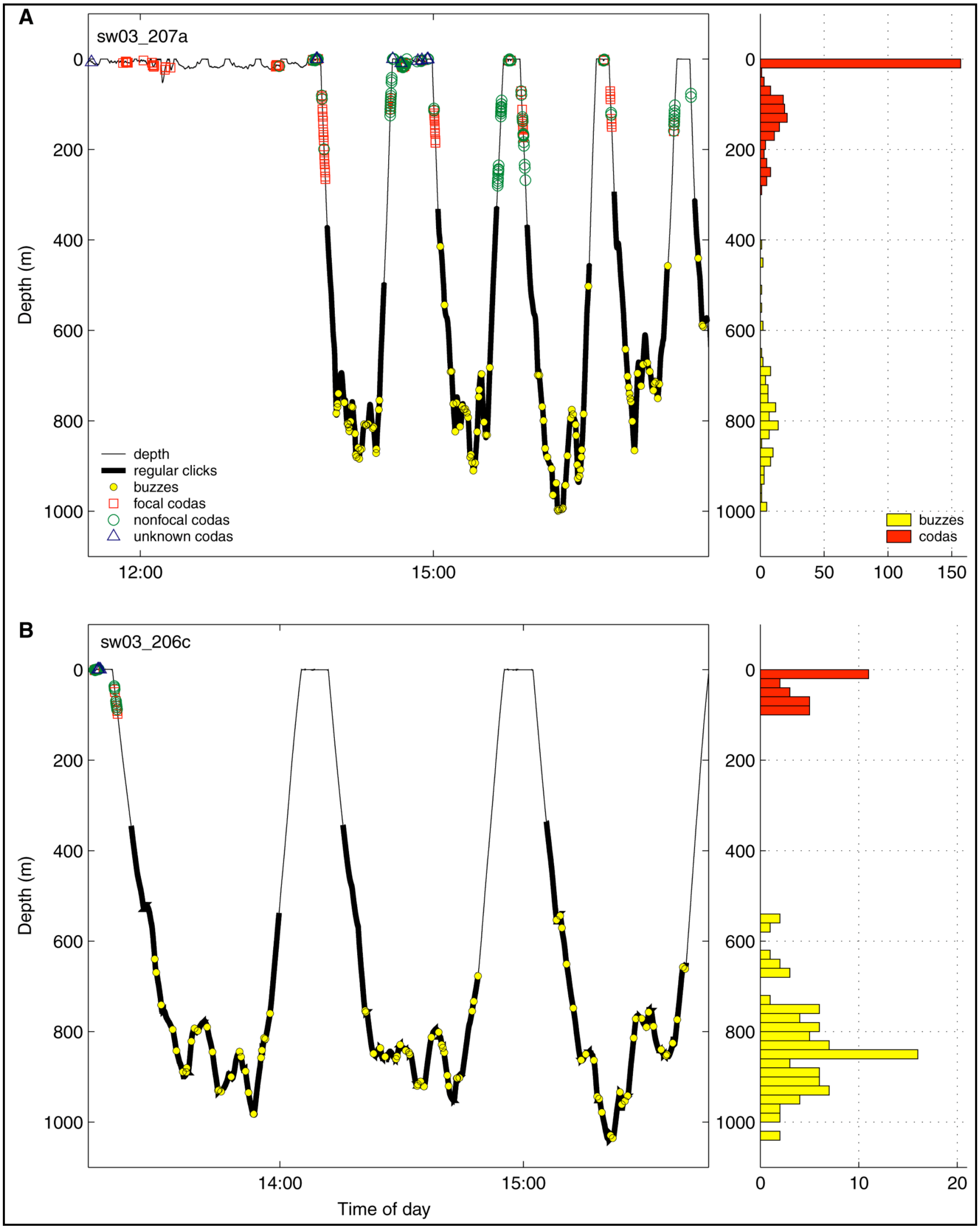

Figure 7.3.1. Dive profiles for **A** sw03_207a and **B** sw03_206c from the North Atlantic.

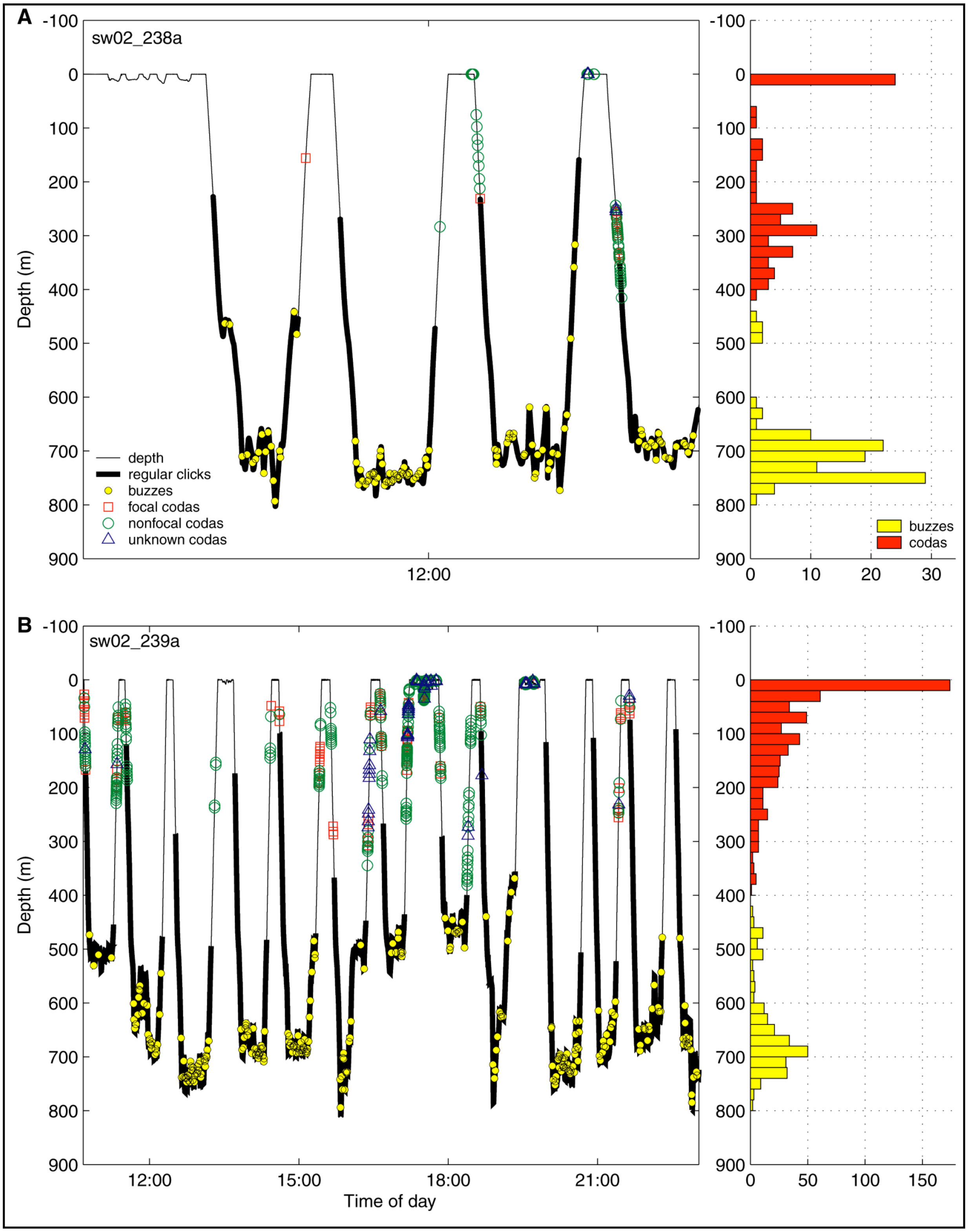

Figure 7.3.2. Dive profiles for **A** sw02_238a and **B** sw02_239a from the Gulf of Mexico.

Table 7.3.1

Mean (SD) of Dive Parameters for Whales from the North Atlantic and Gulf of Mexico

	Number of deep dives	Dive duration	Descent duration	Descent vertical velocity	Bottom duration	Bottom start depth	Bottom end depth	Minimum bottom depth	Maximum bottom depth	Ascent duration	Ascent vertical velocity	Post-dive surface duration
Atlantic Ocean	2.8	44.2	9.4	1.2	25.4	637.1	784.0	618.3	966.4	9.4	-1.4	9.6
	(1.5)	(5.6)	(1.7)	(0.2)	(6.8)	(70.1)	(47.9)	(63.1)	(67.2)	(0.6)	(0.2)	(2.2)
Gulf of Mexico	6.1	47.1	8.2	1.1	31.8	554.0	554.3	491.9	658.9	7.3	-1.3	12.8
	(6.4)	(7.6)	(1.7)	(0.1)	(6.1)	(123.0)	(123.0)	(101.9)	(133.6)	(1.4)	(0.2)	(6.8)

Table 7.3.2

Mean (SD) of Foraging Parameters for Whales from the North Atlantic and Gulf of Mexico

	Search phase start depth	Search phase end depth	Search phase duration	Foraging phase start depth	Foraging phase end depth	Foraging duration	Number of buzzes per foraging phase
Atlantic	263.9	533.6	35.1	613.2	656.9	27.2	22.7
	(89.3)	(124.8)	(7.2)	(45.7)	(131.8)	(8.8)	(8.6)
Gulf of Mexico	207.5	452.8	39.3	539.7	538.4	30.1	16.7
	(80.2)	(85.1)	(7.3)	(106.4)	(115.4)	(6.6)	(8.9)

The foraging phase began when the first buzz was produced, which was interpreted as indicating when whales were encountering or possibly capturing prey items. The first buzz was generally produced at the start of the bottom phase (mean: 4 (136.7) seconds after the start of the bottom phase, range: 8.5 min before – 6.4 min after).

The majority of active foraging occurred in the bottom phase of the dive cycle. Bottom duration was similar in both locations, although on average whales in the Gulf of Mexico stayed in the bottom phase longer. Foraging phase duration was also similar, averaging 29 (6.5) minutes, accounting for 60 (12.8) percent of the dive duration.

The foraging phase duration was significantly correlated with dive duration for whales in the Gulf of Mexico. Whales remained in the foraging phase longer in longer dives. The foraging phase was therefore a large component in determining overall dive duration.

Buzzes were produced in 99.9% of recorded deep dives. The number of buzzes per dive (which we treat as a proxy for the number of capture attempts; see section 7.2 above and Miller et al. 2004a) was similar in both regions and averaged 17.9 (8.0) buzzes per dive with whales producing between 5 and 44 buzzes in 95% of the dives. Whales in the Atlantic appeared to produce slightly more buzzes per dive than whales in the Gulf of Mexico, but the difference was not significant**.** Foraging phase duration was correlated with the number of buzzes produced per dive for whales in the Gulf of Mexico.

Ascent phase: Shortly after the last buzz, whales stopped regular clicking and returned to the surface. During the ascent, vertical velocities were higher than during the descent phase of the dive for whales in both locations. Whales in the Gulf of Mexico had shorter ascent durations, due to the shallower depths of their dives.

Surface phase: Whales spent on average 11 (5.3) minutes at the surface following a deep dive. There were no differences in surface duration between locations or among individuals within any location. Intervals between deep dives ranged 3-230 minutes. Intervals longer than 19 minutes were generally associated with shallow dives and social behavior (Whitehead and Weilgart 1991; Amano and Yoshioka 2003) and accounted for less than 5% of all inter-deep dive intervals. The whales spent 28 (17.5) percent of their time wearing the D-tag less than 10 m from the surface. Whales were within 10 m of the surface for 18 (12.3) min/hour tagged in the Atlantic and 14 (7.8) min/hour tagged in the Gulf of Mexico. Post-dive surface intervals were consistent with reported values from other regions (Amano & Yoshioka 2003; Gordon & Steiner 1992; Jaquet et al. 2000; Papastavrou et al. 1989).

Tagged whales spent 88 (17.0) percent of their time in foraging dive cycles. Over an average entire dive cycle (start of a deep dive to the start of the next dive), whales had a diving efficiency of 0.52 (0.1) (foraging phase duration/dive cycle duration). Thus, the whales spent half of their time during the dive cycle foraging. Over the course of the dive, whales spent approximately 82 (4.5) percent of their time submerged producing regular clicks, interspersed at times with buzzes. This amounted to 66 (7.1) percent of their dive cycle, or 40 (4.3) minutes out of every hour wearing the tag. A given whale spent a much larger percentage of its time at depth producing regular clicks than near the surface. Therefore, acoustic surveys would be more practical for abundance estimates of whales than visual surveys, since whales are clicking for 82% of the time they are submerged.

Combined data from the present study and previous studies (Amano & Yoshioka 2003; Gordon & Steiner 1992; Jaquet et al. 2000; Papastavrou et al. 1989) suggest an average sperm whale dive duration of 40-50 minutes and dive depths of 400-1200 m. Sperm whale dives are similar to U-shaped or square dives described for many diving predators (Schreer et al. 2001). Sperm whales did not produce V-shaped dives common to other species, which are thought to function in predator avoidance or exploration for prey patches (Schreer et al. 2001). U-shaped dives are associated with foraging behavior in several species (Lesage et al. 1999) and bottom time is often used as a proxy for a foraging phase.

7.3.2 In Progress Analysis of Coda Vocalizations of Sperm Whales

Since codas appear to be used for social communication, codas are frequently produced when animals are in close contact. Therefore, assigning codas to the tagged animal was not as straightforward as with regular clicks and buzzes. We used a combination of the received level on the tag and the interpulse interval (IPI) of the coda clicks to distinguish codas produced by the tagged focal animal from those produced by nonfocal animals. IPI has been used in several other studies to identify individuals, both with regular clicks (Rhinelander & Dawson 2004) and codas (Rendell & Whitehead 2004). Sufficiently loud codas with an IPI consistent with the IPI of regular clicks from the tagged animal were identified as "focal codas". Codas with IPIs that were inconsistent with the focal regular clicks and were at a low received level were identified as "nonfocal codas". Codas with consistent IPIs but low received level or high received level but more variable IPIs were marked as "unknown codas." The number of focal, nonfocal, and unknown codas were then determined for each of the five phases of the dive period.

Preliminary results and discussion

Codas were recorded from five of 11 tags examined in the North Atlantic, seven of nine tags examined in the Gulf of Mexico in 2003, and 14 of 16 tags examined from the Gulf of Mexico in 2002. Codas were assigned to the focal animal for four tags from the North Atlantic and 19 tags from the Gulf of Mexico. Codas were produced primarily in the first 300 m of the water column in both locations (Figures 7.3.1 and 7.3.2). There was considerable variation in number of codas produced by focal and nonfocal whales from one tag recording to the next, although no codas were recorded from the bottom phase of the dive (Table 7.3.3). On average, focal whales in the Atlantic Ocean produced more codas at the surface per tag than whales in the Gulf of Mexico. Whales produced about equal number of codas during dives in both regions. More nonfocal codas were recorded on average from the Gulf of Mexico than from the Atlantic Ocean. A larger percentage of codas assigned to the focal whale were produced during dives than while at the surface for whales in the Gulf of Mexico compared to the North Atlantic. However, codas were more difficult to assign to particular individuals when at the surface, since whales were often in close contact.

Table 7.3.4 lists the average number of dives with codas recorded per tagout and the percentage of dives with recorded codas on each tagout. Values are very similar in the two regions. On average, focal whales produced codas on about half of their dives, and hear nonfocal codas on a similar percentage. This is consistent with codas being social, and used during interactions with other whales. Therefore, focal whales would produce codas when they heard codas from other whales. A larger percentage of descents contained codas than ascents in general for both regions.

Table 7.3.3

Preliminary Average Total Number of Codas in Each Dive Phase and Percent of Total Codas in Each Dive Phase per Tag for Whales in the Atlantic Ocean and Gulf of Mexico.

	Total number of codas in each dive phase				Percent of codas in each dive phase			
	Surface	Dive	Descent	Ascent	Surface	Dive	Descent	Ascent
Focal codas								
Atlantic	24.0	19.0	14.8	4.3	53.3	46.7	20.1	26.5
Ocean	(32.5)	(27.6)	(25.1)	(4.9)	(41.0)	(41.0)	(23.3)	(49.1)
Gulf of	9.6	19.3	8.2	11.1	29.4	70.6	35.9	34.7
Mexico	(14.9)	(26.6)	(11.7)	(18.9)	(33.2)	(33.2)	(39.1)	(38.1)
Non-focal codas								
Atlantic	41.3	23.0	10.0	13.0	72.6	27.4	18.4	9.0
Ocean	(37.8)	(33.2)	(11.1)	(22.5)	(23.7)	(23.7)	(20.2)	(15.5)
Gulf of	74.8	39.4	15.8	23.6	59.8	40.2	18.5	21.7
Mexico	(83.5)	(57.3)	(22.6)	(38.7)	(34.4)	(34.4)	(25.7)	(31.6)

Table 7.3.4

Preliminary Average Number of Dives with Codas per Tag and Average Percent of Dives with Codas per Tag for Whales in the Atlantic Ocean and Gulf of Mexico

		Number of Dives with codas						Percent of Dives with codas					
		Focal codas			Nonfocal codas			Focal codas			Nonfocal codas		
	Total dives	Dives	Descents	Ascents	Dives	Descents	Ascents	Percent of dives	Percent of descents	Percent of ascents	Percent of dives	Percent of descents	Percent of ascents
Gulf of	6.9	2.8	1.9	1.4	3.4	1.8	2.3	0.5	0.4	0.2	0.5	0.3	0.3
Mexico	(4.4)	(2.7)	(2.3)	(1.8)	(2.9)	(2.0)	(2.4)	(0.3)	(0.3)	(0.2)	(0.3)	(0.3)	(0.2)
Atlantic	4.0	2.0	1.7	1.0	2.0	2.0	1.0	0.5	0.4	0.2	0.4	0.4	0.2
Ocean	(1.0)	(1.7)	(2.1)	(1.0)	(2.7)	(2.7)	(1.7)	(0.3)	(0.4)	(0.2)	(0.5)	(0.5)	(0.4)

Table 7.3.5 lists the average number of recorded codas per dive cycle phase. Overall, more codas were produced while whales were at the surface than during any particular dive. Most unassigned (unknown) codas were also at the surface, since it is more difficult to assign codas when whales are in very close proximity. A significant portion of codas were recorded during the

descent phase of foraging dives. Therefore, codas are not simply produced when whales are returning to the surface and attempting to come back together after separating for foraging.

Table 7.3.5

Preliminary Average Number of Codas per Dive Phase per Tag for Whales in the Atlantic Ocean and Gulf of Mexico

GOM	**Number of focal codas**				**Number of nonfocal codas**				**Number of unknown codas**			
Tag	**at the surface**	**per dive**	**per descent**	**per ascent**	**at the surface**	**per dive**	**per descent**	**per ascent**	**at the surface**	**per dive**	**per descent**	**per ascent**
Gulf of Mexico	10.2 (15.1)	5.2 (5.2)	2.4 (4.2)	2.7 (4.3)	74.8 (83.5)	6.6 (7.7)	2.7 (4.2)	4.0 (6.6)	38.5 (77.8)	1.6 (2.5)	0.7 (0.9)	1.0 (1.6)
Atlantic Ocean	24.0 (32.5)	4.2 (5.4)	3.2 (4.9)	1.0 (1.1)	41.3 (37.8)	5.0 (6.4)	2.36 (2.22)	2.6 (4.5)	4.7 (4.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)

7.3.3. Problems with RMS Safety Levels for Transients

Seismic signals are measured in a variety of ways. To estimate exposure in a way that is relevant for sperm whales, it is essential to carefully consider the consequences of different measurement decisions. We have identified some specific problems related with rms levels for transients, so present here a summary of the paper "Problems with RMS safety levels for transients" by (Madsen 2005).

Background

Marine mammals use hearing as a major sensory modality, which makes them susceptible to man-made noise. The increasing concerns about the effects of underwater man-made noise calls for a standardized system of how to quantify and mitigate noise exposure with relevant and reproducible measures. Current safety levels for transients impinging on marine mammals are specified as maximum rms (root-mean-square) sound pressures of 180 dB re 1μPa (rms) for cetaceans. This study explores the consequences of using rms measures as safety thresholds for mitigation of impact of various types of underwater noise transients with the same peak-peak pressure.

Methods

Four commonly encountered transient signals (all sampled at 48 kHz) from high-level underwater sources with the same modelled peak-peak received level of 189 dB re. 1μPa (pp) were chosen for analysis: 1) an on-axis version of the p1 pulse of a sperm whale usual click, 2) a 390 msec frequency modulated pulse akin to that of a ping from a mid-frequency sonar, 3) a short transient comparable to the on-axis signature from a powerful, impulse sound source such as an air gun array or an underwater explosion, and 4) the same impulse sound after propagation in a highly reverberant environment. The root of the mean of the squared pressure (rms) of a plane wave in a time window from 0 to T is given by:

$$p_{rms} = \sqrt{\frac{1}{T}\int_0^T p^2(t)dt} \qquad \textit{dB re. 1}\mu\textit{Pa (rms)} = 10\log\left(\frac{1}{T}\int_0^T p^2(t)dt\right)$$

[p(t) = instantaneous pressure]

These formulae for analog signals were implemented in custom-written routines in Matlab 6.0 (*Mathworks*), wherein the squared pressures are summed and divided by the number of samples of the discrete (digital) version of the signal to replace the integration. In addition, scripts to provide duration measures (0:T) were implemented. The analysis window is critical for rms measures of transient signals, since the duration determines the window over which the pressure squared should be averaged. For the same transient waveform, the rms level will decrease with increasing duration of the integration window. Four duration measures were implemented: -3 and –10 dB of the envelope and 90 and 97% of the energy. The envelope was computed by taking the absolute value of the analytical signal and the end points –3 and –10 dB down defined the duration of the transients. The energy approaches used the relative energy in a window that incorporates the entire signal waveform along with short samples of noise on either side by defining the windows by 90 and 97% of the total cumulative energy. Since the rms measure does not take into account the overall energy of the transients, which may have relevance for a damage and sensation point of view, we also computed the energy flux densities on the basis of the four duration measures.

The energy flux density (dB re. $1\mu Pa^2 s$) of transients, propagating as plane waves, the can be approximated by 10log of the time integral of the squared pressure (sum of squared pressures for the discrete version of the signal) over the duration of the pulse, which for the same duration, T, is simply the rms level (in dB) + 10log(T):

$$\textit{Energy density (dB re. } 1\mu Pa^2 s\textit{)} = 10\log\int_0^T p^2(t)dt = 10\log\left(\frac{1}{T}\int_0^T p^2(t)dt\right) + 10\log(T)$$

[T, window length in seconds]

Results and discussion

Table 7.3.6 summarizes the results from the generating rms and energy flux density of the four transients using the different duration measures.

Table 7.3.6

Generating RMS and Energy Flux Density for Four Transients
(RLpp is the received peak-peak sound pressure in dB re. 1μPa (pp). t provides the different duration measures in msec. RMS provides the root-mean-square sound pressure in dB re. 1μPa (rms) for each of the duration measures. E gives the energy flux in dB re. 1μPa^{2}s for each the duration measures.)

Pulse	RL_{pp}	t_{3dB}	t_{10dB}	t_{90}	t_{97}	RMS_{3dB}	RMS_{10dB}	RMS_{90}	RMS_{97}	E_{3dB}	E_{10dB}	E_{90}	E_{97}
Sperm whale p1 pulse	189	0.047	0.105	0.081	0.125	183	180	181	180	140	141	141	141
Sonar ping	189	9	340	353	383	179	177	177	177	158	172	172	172
Impulse free-field	189	10	13	9	10	182	181	182	181	162	162	161	162
Impulse reverberant	189	17	168	627	821	178	172	167	166	160	164	165	165

From Table 7.3.6 it is evident that the different approaches for deriving duration over which the squared pressure is averaged varies considerably. For the well-defined transients the differences are relatively small, but for the reverberant waveform the differences are more than an order of magnitude. Thus, for short averaging times, the rms levels are high and for long integration times the rms measures are low for the same transient. Note that the energy flux density measures do take into account the duration as the energy levels increase as more and more of the transients are incorporated in the integrated pressure squared.

If the peak-peak pressure received levels of the transients were considered as the relevant exposure metric, they would be considered to have an equal impact on the exposed animal. If the rms measures are used, no matter how the averaging duration is determined, the sperm whale click and the free-field impulse will exceed the 180 dB re. 1μPa (rms) limit, while the sonar ping and the reverberant impulse will not, despite the fact that they are carrying more energy than the sperm whale click by two to three orders of magnitude. It is therefore not reasonable to compare the acoustic impact of a mid-frequency sonar or a reverberant impulse with that of a sperm whale click.

By spreading the reverberant impulse, the propagation paths plays an important role in determining whether the rms level received at the animal is considered too high or not, even if the energy is invariant. It seems intuitively reasonable, even conservative, to include as much of the pulse as possible in the averaging window, but when using the rms measure for a reverberant transient for an impulse sound source, it is evident that the method of deriving the window may result in rms sound pressure levels that vary by as much as 12 dB. If the 90% energy measure is used for the displayed pulse, giving a window length of 627 msec, a pulse with a received peak-peak level of 202 dB re. 1μPa (pp) would still not exceed the limit of 180 dB re. 1μPa (rms). Consequently, long, fixed averaging times for calculation of rms sound pressures can yield very short safety radii around a noise source. Unless there is a specified fixed protocol for determining the duration, it is possible to manipulate the rms level by varying the averaging window: the longer the averaging time, the lower the rms level. Safety measures should not leave room for such analytical freedom.

Ears of terrestrial mammalian generally integrate intensity over a time window of some 200 msec, and the same appears to be the case for cetaceans at low frequencies. It might therefore seem reasonable to use 200 msec as the maximum integration time from a detector or sensation point of view. However, in terms of hearing impairment due to a single, high-level impulse, it has been established that the safety threshold for humans scales as 10log(T), where T is the exposure duration, even if T is much longer than 200 msec. Since this issue remains to be clarified for marine mammals, it seems reasonable to apply a conservative approach and provide energy levels integrated both over the actual pulse duration and with a 200 ms integration time if the actual duration is longer than that. Such measures should additionally be accompanied by a figure of the waveform, and information about the recording bandwidth and the duration used for integrating the intensity (as stipulated by the ANSI standard for noise exposure (ANSI 1994)).

Since physical damage and impairment of the auditory system are caused both by high peak pressure and energy density, safety limits for sound exposure should include both a maximum received energy density level along with a maximum received peak-peak pressure level. Such a protocol addresses concerns for physical damage due to short high-pressure pulses as well as the effects of longer transients with lower peak pressures.

It is concluded that rms safety measures are unsuited as a stand alone mitigative measure for transient noise effects on marine mammals irrespective of what the absolute level is (currently 180 dB re. 1μPa (rms) for cetaceans). It has been demonstrated that 1) the rms measure does not take the overall energy exposure into account, 2) different rms measures can be derived for waveforms with identical peak pressure depending on the duration over which the squared pressure is averaged, and 3) the rms measure does not represent the exposure level of transients with high peak pressure and a slowly decaying tail, common in reverberant underwater environments. It is recommended that safety levels include a maximum peak-peak received sound pressure level in concert with a maximum received energy density level. It is suggested that the energy density should be calculated by using the 90% energy approach for derivation of the duration, since the 97% criterion requires high signal to noise ratios, and the –3 and –10 envelope criteria underestimate the durations of slowly decaying transients. It is beyond the scope of this report to discuss the absolute safety levels for received peak-peak pressure and energy density, but there is an urgent need for a careful assessment of such in the light of anatomical, physiological and behavioural data.

7.3.4. Progress on Quantifying Acoustic Exposure of Sperm Whales (*Physeter macrocephalus*) to Airgun Pulses Using Onboard, Acoustic Tags

Background

Sound energy radiated off the axis of an airgun array may be insignificant when compared to the peak pressures generated on the acoustic axis, and have therefore been dismissed on occasion as having any effects on marine mammals. However, the absolute values of these by-products may be of considerable magnitude and their frequency structures may be different than those of the idealized on-axis pulse. So what is considered a relative low-level horizontal by-product from an operational perspective may have absolute levels at frequencies for which the auditory system of the exposed animal is more sensitive and thus have the potential of adverse impacts through threshold shifts, behavioral disruption or masking.

Here we report from a an ongoing and therefore incomplete analysis of acoustic data recorded by onboard D-tags on sperm whale (*Physeter macrocephalus*) during controlled exposure experiments with whales tagged with sound recording tags. This study provides the first data on the actual sound field received by free-ranging toothed whales during exposure to an anthropogenic noise source. We demonstrate that sperm whales receive several pulses with very different temporal and spectral properties for each duty cycle of the airgun array.

Methods

After tagging, the now focal animal was tracked acoustically and visually for 1-2 hours for baseline behavior before controlled exposures were initiated. The source vessel was positioned at an estimated range of more than 2 km from the tagged whale as a conservative approach to avoid that received levels at the whale exceeded a limit of 180 dB//1µPa (rms) as stipulated by the NMFS permit authorizing this research. As the off-axis acoustic output of airgun arrays becomes better understood, this distance may be able to be reduced. At the beginning of the CEE, the individual air guns of the array were turned on gradually in a ramp-up procedure to avoid high-level exposure of nearby, but undetected, whales, and to test response of the focal animal to ramp-up. The CEE lasted between 1 and 2 hours leaving the rest of the tag recording time for post exposure data logging.

In 2003, R/V *Kondor* towed a 31-gun array with 2000 psi firing pressure and a volume of 3090 cubic inches. The far-field, vertical signature of the array had a back-calculated wide-band zero-to-peak source level of 56.9 bar-m, corresponding to 255 dB//1uPa (0-peak). The array was fired every 15 sec with a 30 min ramp up from 1 to 31 guns. In 2002, R/V Rylan T. with the R/V *Speculator* on deck towed a 20-gun array with 2000 psi firing pressure and a volume of 1680 cubic inches. The far-field, vertical signature of the array had a back-calculated, wide band zero-to-peak source level of 41.1 bar-m, corresponding to 252 dB//1uPa (0-peak). The array was fired every 15 sec with a 30 min ramp up from 1 to 20 guns. In both years, a mitigation protocol was adopted to ensure that no animal sighted or acoustically detected in the study area was exposed to levels higher than stipulated by the federal permit under which the experiments were carried out. On that basis, CEEs were halted for periods of time to avoid unauthorized high level exposures of marine animals. A noninvasive, archival D-tag was used to gather data on 3-D movements and sounds impinging on or produced by the tagged whale. Movement of the tagged whales was logged by a depth sensor and 3-axis magnetometers and accelerometers sampled at 50 Hz. In 2002 acoustic data were sampled at 32 kHz with a 12 bit ADC. A 1-pole high pass filter (HP) at 400 Hz (-3 dB) reduced high level flow noise and sigma-delta conversion prevented aliasing. Clipping occurred at received levels of 152 dB//1µPa (peak). In 2003 a second version of the D-tag was used. This version sampled at 96 kHz and 16 bit with an identical 400 Hz 1 pole HP filter, and clipping at 193 dB//1µPa (peak). All tags were calibrated before and after deployment. The pre-whitening filter was compensated for during analysis yielding a flat (within ±1 dB) frequency response from 0.045 kHz to 12 and 45 kHz, respectively. The tags were deployed with suction cups on sperm whales logging at the surface by means of a 12 m cantilevered pole and a RHIB with a four stroke outboard engine. After a pre-programmed recording time, the tags released from the animals and floated to the surface for recovery by means of an attached VHF transmitter. The tag-on times and durations of the 8 CEEs are summarized in Table 7.3.7.

The received level (RL) for mitigation of cetacean exposure is given by a level of 180 dB re 1μPa (rms). This measure however may not be relevant for estimating the level of impact (see previous section), so we have quantified the seismic pulses by peak of the analytical signal (RL_A), peak-peak (RL_{pp}), rms (RL_{rms}) and energy measures (RL_E) to provide the basis for comparison on a number of levels. The peak of the analytical signal was given by the absolute value of the Hilbert transformed waveform. For calculation of rms levels of a transient signal, we have adopted the 90% energy approach (see previous section). The relative energy is computed in a window around the seismic pulse, and the duration (τ) is defined by the sample interval (0:T) containing 90% of the energy content in the window (Figure 7.3.3).

This duration defines the sample interval over which the root-mean-square pressure (RL_{rms}) is computed:

$$10\log\left(\frac{1}{T}\int_0^T p^2(t)dt\right) \qquad \textit{[p(t)=instantaneous pressure]}$$

The energy (RL_E) is given by the rms intensity integrated over the duration τ:

$$10\log\left(\int_0^T p^2(t)dt\right) \qquad \textit{[p(t)=instantaneous pressure]}$$

Table 7.3.7

Tag-on Times and Durations for 8 CEEs

Tag	Date	CEE start	CEE stop	CEE dur
sw02_253a	10/9/02	17:50	19:28	108 min
sw02_254a	11/9/02	12:16	14:19	105 min
sw02_254b	11/9/02	12:16	14:19	105 min
sw02_254c	11/9/02	12:16	14:19	105 min
sw03_164a	13/6/03	18:26	19:26	60 min
sw03_165a	14/6/03	17:01	19:01	120 min
sw03_165b	14/6/03	17:01	19:01	120 min
sw03_173b	22/6/03	17:23	19:23	120 min

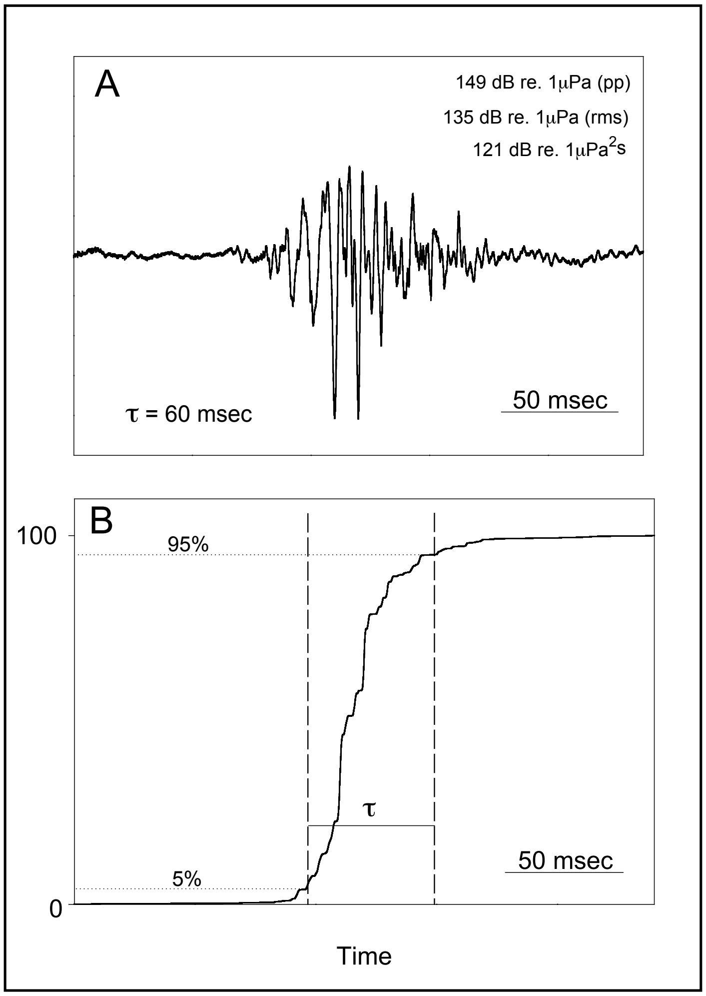

Figure 7.3.3. A) Waveform of a direct arrival airgun pulse on a sperm whale at 450 meters depth. Received levels are given in sound pressure peak-peak, rms and energy flux density. The latter two are computed on the basis of squared pressure values in a 60 µsec window derived with a 90% cumulative energy approach (B).

Both these measures require adequate signal to noise ratios (SNR) to render meaningful data. Accordingly, duration, rms and energy levels of pulses with less than 10 dB SNR were not included. Since the ears of most mammals, dolphins included, integrate low frequency sound over a window of around 200 msec, this duration was used as maximum integration time for RL_{rms} and RL_E. Quantification of the absolute energy distribution as a function of frequency in a way relevant for a mammalian auditory system, is done by using 1/3 octave levels based on the ANSI S1.1-1986 standard. This work is in progress and not included here.

Preliminary results and discussion

Not all CEE's rendered a sufficient SNR to allow for analysis of all pulses. This section provides examples of representative data and discusses the analytical work in progress. The acoustic exposure of the animal consisted of two or more temporally separated pulses with different properties for every duty cycle of the air gun array. These are the result of a direct arrival followed by a series of pulses generated by multipath propagation in water and sediment. Figure 7.3.4 provide an example of such a multipulsed event recorded on a sperm whale at 30 meters depth. The first arrival is a well defined transient with a short duration of around 50 μsec and with most energy between 0.5 and 2.5 kHz (Figure 7.3.4B and 7.3.5). Note how there is energy all the way up to the Nyquist frequency at 16 kHz. The second arrival is a much more reverberant pulse that arrives some 500 msec after the first arrival. The waveform is smeared out in time and is likely the combined effect of a bottom reflection and energy traveling in the sediment. While this pulse also contains energy at higher frequencies, it is dominated by energy below 200 Hz.

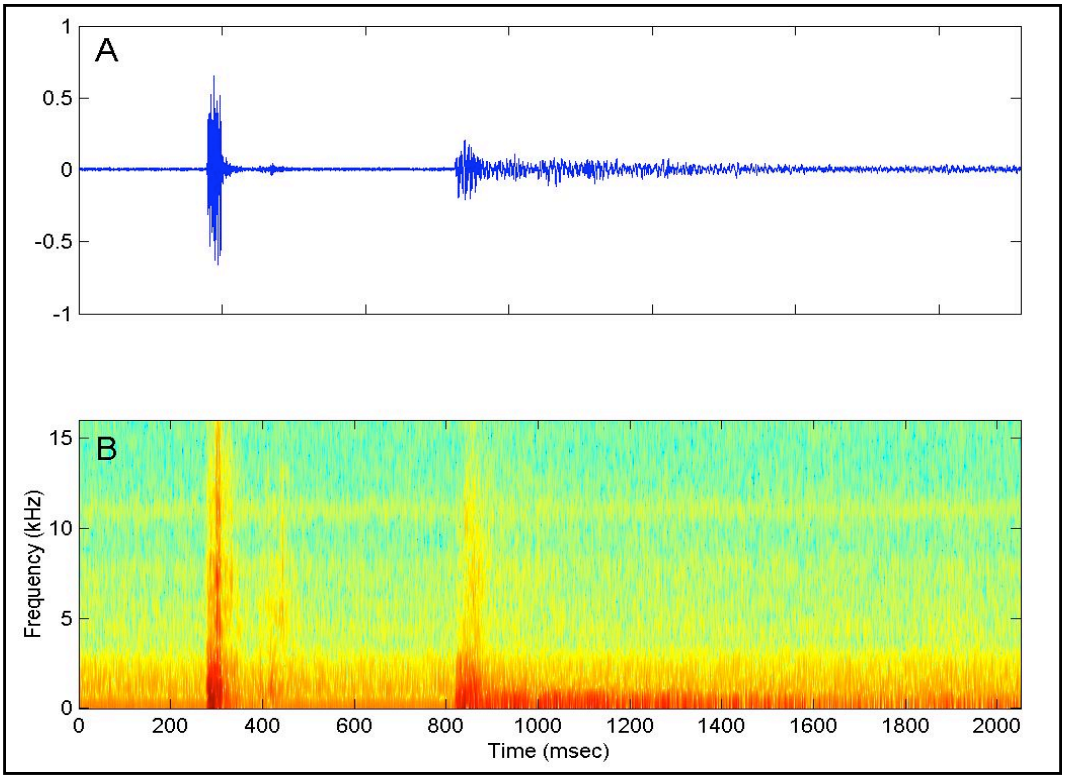

Figure 7.3.4. Example of a multipulsed event recorded on a sperm whale at 30 meters depth. Shown are A) waveform of the first arrival and a bottom bounce/bottom ducted second arrival as received by a sperm whale at 30 meters depth, and B) spectrogram of the waveform of A. FFT size 1024, Hann windowed data, 90% overlap.

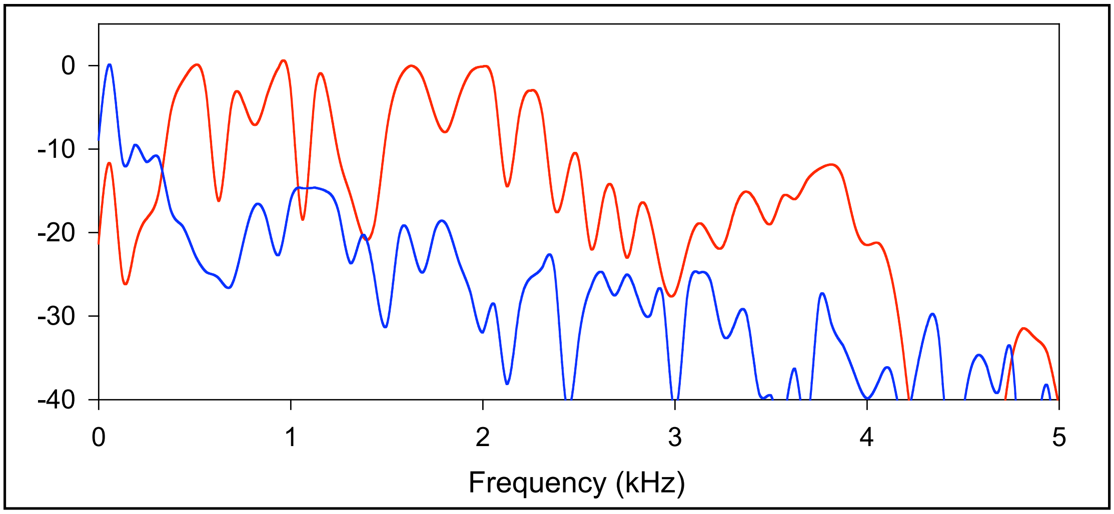

Figure 7.3.5. Power spectra (FFT size 512, bin width 62.5 Hz) of the parts of the waveforms in Figure 7.3.4 containing 90% of the energy. Note the lack of low frequency energy in the first arrival (red) and the dominance of low frequency energy for the second arrival (blue).

Figure 7.3.6 provides an example of the levels of first arrival pulses a sperm whale close to the surface experience during an entire CEE. The tag of the whale recorded 470 pulses during this exposure, but missed some when the whale was at the surface with the tag out of the water. Note how the difference in dB's between the three measures are somewhat interrelated, but that there is considerable variation over time. This is due to the variable duration of the pulses, which in turn affects the crest factors of the waveforms. All these pulses are dominated by energy above 500 Hz, so the whale is receiving absolute levels of up to 160 dB re 1µPa (pp) from pulses carrying little if any energy below 500 Hz.

Preliminary observations

The data analyzed so far in this ongoing study have demonstrated that sperm whales are exposed to a series of pulses with different spectral, energetic and temporal properties for each duty cycle of the air gun array. The analysis shows that some of the direct arrivals have dominant energy at much higher frequencies than currently reported or modeled for air gun arrays. While this energy is radiated off the axis of the array, the absolute levels of these high frequency pulses may reach levels of more than 140 dB re 1µPa (rms). This replicates results of Goold and Fish (1998) demonstrating that airguns produce significant energy at frequencies that may evoke high sensation levels in toothed whales that all have their most sensitive range of hearing outside the 0-1000 Hz band modeled by the industry, and therefore not normally considered sensitive to airgun pulses.

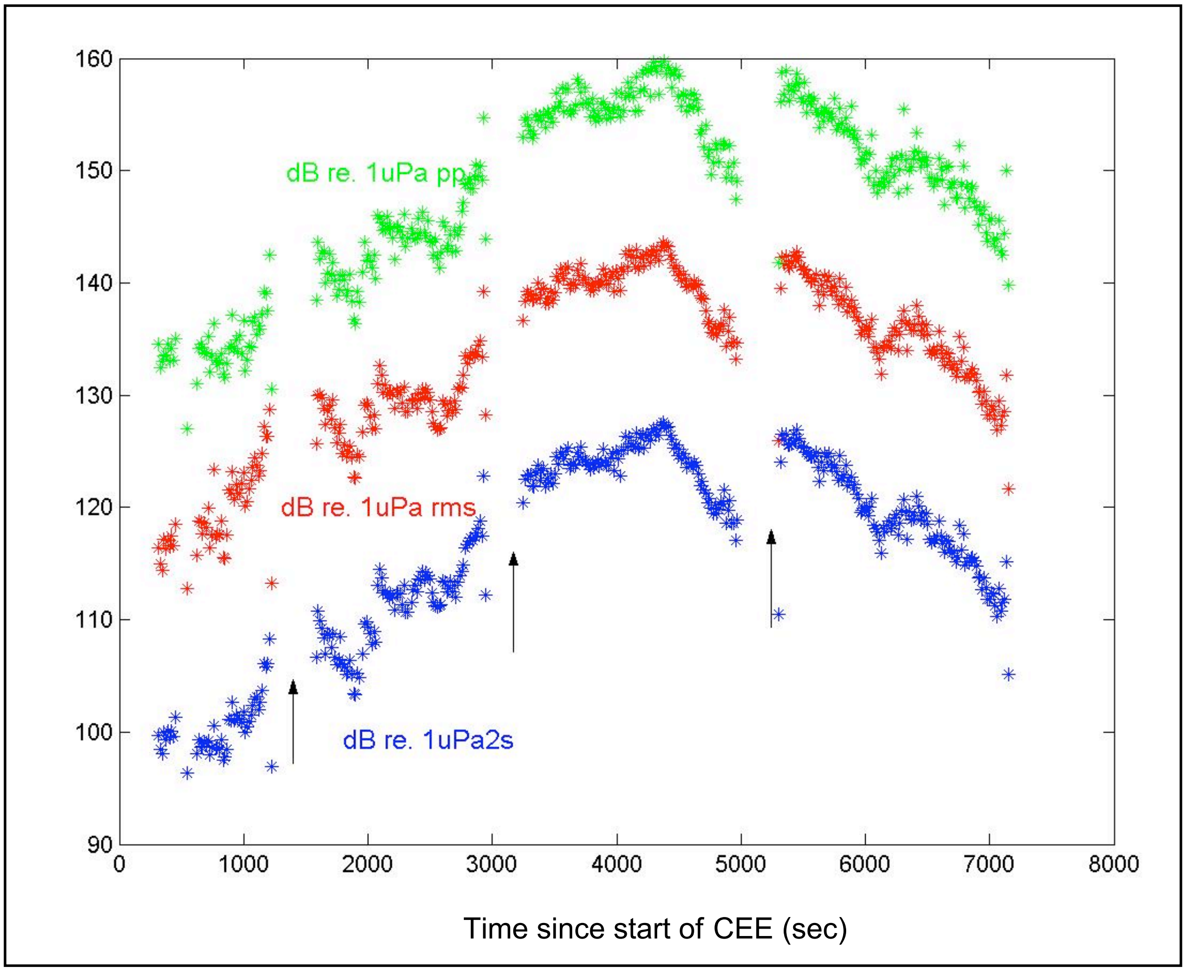

Figure 7.3.6. Received levels from the first arrivals at whale SW03_173b. Levels are provided as peak-peak sound pressure (green), rms sound pressure (red) and energy flux density (blue). Arrows mark surface periods where the tag is out of the water.

Figure 7.3.7 plots all received levels for whales where range to the array could be derived at the time of the first two pulse arrivals. There is no simple relationship between received levels of the first pulse arrivals and the range to the seismic array no matter whether the received peak-peak sound pressure levels (RLpp; Figure 7.3.7a) or sound exposure levels (SEL; Figure 7.3.7b) are considered. Rather it is seen that the received levels reach a minimum between 5 and 9 km and then start increasing again at ranges between 9 and 13 km. It must be emphasized that these received levels as a function of range are generated from 6 different whales during two field seasons with different seismic arrays. Nevertheless, it is clear that the above picture emerge as a combination of both seasons, and we can conclude that sperm whale exposure to the first pulse arrivals can be just as high (160 dB re. 1μPa, pp) at 12 km as at a range of 2 km from the array. When looking at the received levels of the secondary arrivals (Figure 7.3.7c and d), it is seen that primarily bottom propagated pulses have higher received levels at 5 to 13 km than at ranges closer to the seismic sources.

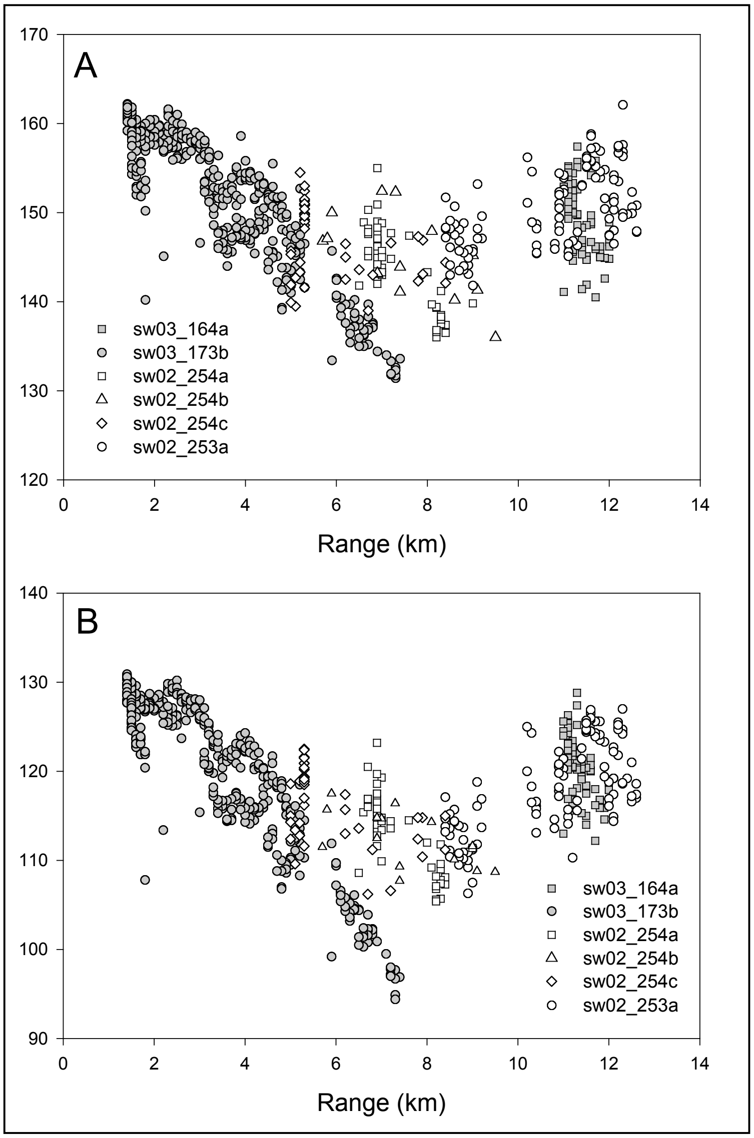

Figure 7.3.7. Received levels for whales. Shown are A) Received peak-peak sound pressure levels of the first arrival for each airgun pulse that could be analyzed as a function of range from all CEEs where range to the whale could be derived. The highest levels closest to the source were clipped. The data are from 6 different whales during two seasons using two different seismic arrays. Note how the received levels reach a minimum between 5 and 9 km, whereafter the received levels actually increase again with range. B) Sound Exposure Levels (SEL, dB re. 1μPa^{2}s) for the same pulses as displayed in figure A). C) Received peak-peak sound pressure levels of the second arrival for each airgun pulse that could be analyzed as a function of range from all CEEs where range to the whale could be derived. Note how the received levels of this pulse component actually increase with range beyond 5 km. D) Sound Exposure Levels (SEL, dB re. 1μPa^{2}s) for the same pulses as displayed in figure C).

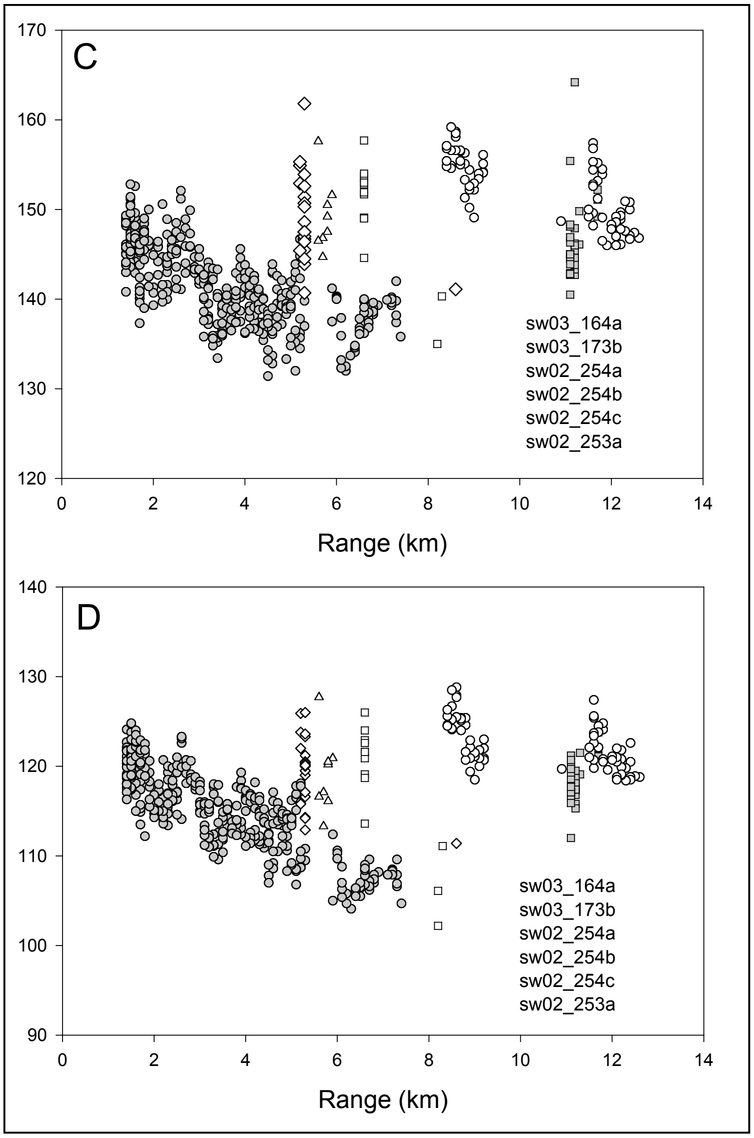

Figure 7.3.7. Received levels for whales (continued).

The complex propagation conditions over ranges of kilometers in a deep water habitat like the Gulf of Mexico do not comply with the different zones of exposure outlined by Richardson et al. (1995) that are based on the assumption that received levels decrease with range. If the received levels measured here in the range from 1.4 to 13 km have no effect on the whales, the complex propagation conditions of different pulse components can be ignored from a mitigation perspective. However, if the range of received levels measured here does have effects on the exposed animals, we face a major challenge of how to mitigate under such conditions, where the whales will dive in and out of high and low exposure levels at considerable ranges.

7.3.5. Analysis of Whale Movement and Behavior in Relation to Controlled Experimental Exposures From a Seismic Array

Background

We conducted a set of controlled exposures of transmissions using two types of seismic arrays in 2002 and 2003 on sperm whales in the Gulf of Mexico as part of the SWSS project. The goal of these controlled experimental exposures of a potentially disturbing sound source was to carefully measure the behavior of the subject whale before, during and after exposure to the source, and to relate any observed responses to biologically-relevant parameters in the life-history of sperm whales. Potential responses that are being measured by the WHOI team in the SWSS study include avoidance of the source by a tagged whale, and behavioral changes related to the cost and benefit of foraging. The D-tag allows us to collect information directly from whales to track two behavioral responses related to the locomotory cost of foraging, and the number of attempts to capture prey. We discuss above the evidence that sperm whales produce echolocation click buzzes during prey capture events (Section 7.2). Thus, assuming that prey size and the proportion of successful captures to attempts is roughly constant over the time period of the experiment, buzz rates can be used as a measure of foraging attempts by a tagged sperm whale.

The second energetics related behavioral response that can be tracked by data collected by D-tag is the relative energy flow utilized by the whale for locomotion (Figure 7.3.7). Information related to this energy outflow is provided from different sources from the D-tag. First, depth and orientation data enables us to model the drag and buoyancy forces that operate on sperm whales, so the energetic work required for a whale to overcome those forces can be calculated (Miller et al. 2004b). The whale transfers this energetic work to the seawater by thrusting movements of its flukes, which are also registered by accelerometers in D-tag (Johnson and Tyack 2003; Miller et al. 2004b).

In this section is reported: 1) how the spatial geometry of each experiment is tracked, which allows us to calculate avoidance metrics, 2) how buzz rates are calculated as a function of exposure condition, 3) how fluking movements are quantified as a function of exposure conditions, and 4) what statistics are used to test for effects of exposure condition. Preliminary results based upon our analyses to date are presented.

Methods

Spatial geometry: In the experiments we conducted, great care was taken to position the airgun array source vessel in a desired location relative to a tagged whale, and relative to other sperm whales in the area for mitigation purposes. The locations of the source and observation vessels were tracked using on-board GPS receivers. Positions of the research vessels were then merged with the track of the tagged whale to complete the spatial geometry of each experiment. The relative positions of the source vessel and tagged whale are also crucial for interpreting and modeling the level at which sounds were recorded on the tag attached to the subject whale. Information on the relative positions of simultaneously-tagged sperm whales can also be obtained using sounds received on the tags.

The location of the tagged whale was tracked using the location where the whale was tagged and a 3-dimensional pseudo-track grounded by visual fixes of the whale when it was observed from the observation vessel. The pseudo-track is a dead-reckoning track based upon the 3-D orientation of the whale, which is recorded by D-tag. The speed of the whale along the dead-reckoning track, and the influence of currents on the position of the whale, is estimated using the best available information on local conditions. Ground-truthing of the pseudo-track was accomplished using visual fixes from the observation vessel. A whale sighted with clear signals received from the VHF beacon on the tag can be identified as "definitely" the subject whale. When VHF signals were not strongly heard in the field, "likely" positions can be obtained by post-processing analysis of the tag and visual data to determine sightings that match both the timing of surfacings by the tagged whale and the position of the whale based upon the corrected pseudotrack. We used "likely" positions for two experiments where the VHF signal was weak.

An example of the spatial geometry for the controlled exposure experiment on sw02_253a is shown in Figure 7.3.8. In this case, the whale was tagged at 28.4815°N and 88.9032°E. The whale proceeded to move south for one dive after which the sound transmission began for two dives, followed one post-exposure dive. From the geometry of the experiment, we can calculate the range and bearing from the whale to the source vessel, as well as the pitch to the source vessel from the whale's position at depth (Figure 7.3.9). This information is used as input data for modeling the propagation of sound received by the tag attached to the whale, and also for an analysis of avoidance by the whale.

Based on this corrected pseudo-track, the direction-of-movement of the whale was calculated over 30-min intervals in all exposure conditions. The average bearing from the tagged whale to the source boat during this 30-min interval provides a reference around which we can track the movement of the whale (Figure 7.3.9, middle). Note that the whale's direction-of-movement did not change significantly at the start of playback. Avoidance of the source by the whale would be reflected in the whale moving away from the source ship during transmissions. As can be seen in this case, the whale did not appear to orient away from the source. Circular statistics were used to combine the movements of each whale relative to the airgun source vessel, and to each whale's previous direction of movement (Zar, 1984).

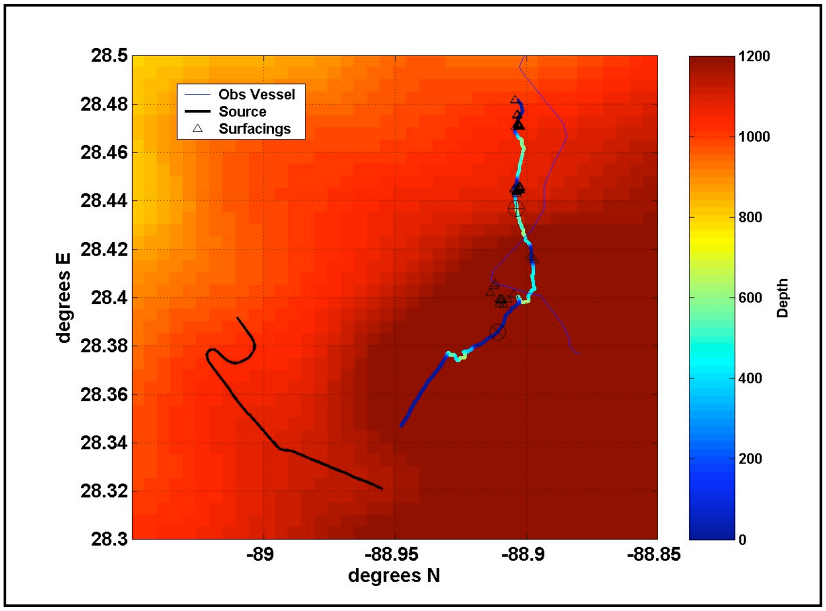

Figure 7.3.8. Geometry of CEE sw02_253a. The 3-D movement of the whale is shown as a color track over the local bathymetry. Note that the surfacing positions tracked from the observation vessel (blue line) fall close to the surfacing location of the pseudotrack. Seismic transmissions from the source vessel (black line, shown during transmissions only) began and ended where the + and x symbols are located on the whale track, respectively. The whale's direction-of-movement was calculated for 30 min. time intervals in pre-exposure, rampup, full-array, and post-exposure conditions.

Buzz rates and locomotion cost as a function of exposure condition: Buzzes are easily identified in the tag record by inspection of the click waveforms, spectrograms, and by listening (Miller et al. 2004a). The timing of all buzzes was recorded using a standardized audit datasheet, and linked to the timing of exposure for each experiment. Both pitching motions and thrust contribute to the accelerometer signal, and the magnitude of these depend on the tag position on the whale, so it is not possible to measure fluking amplitude except in a relative way. To eliminate effects of orientation relative to the gravity vector on pitch changes that arise from fluking movements, pitching movements were quantified in a "whale-frame" fashion by electronically gimbaling the 3-D accelerometer to a low-pass filtered record of the whale's orientation. Pitching movement was then calculated from the gimbaled accelerometer record following published methods (Johnson and Tyack 2003). As has been previously described for orientation changes (Miller et al. 2004a), the amplitude (calculated as rms energy) of oscillations in pitch also increase within 15s of a prey-capture buzz (mean increase by whale 41%; t_{41}=10.49, P<0.001). To distinguish locomotion movements during search from movements related to prey capture, we excluded pitching energy within (+/-) 15s of the end of the buzz (Miller et al. 2004b).

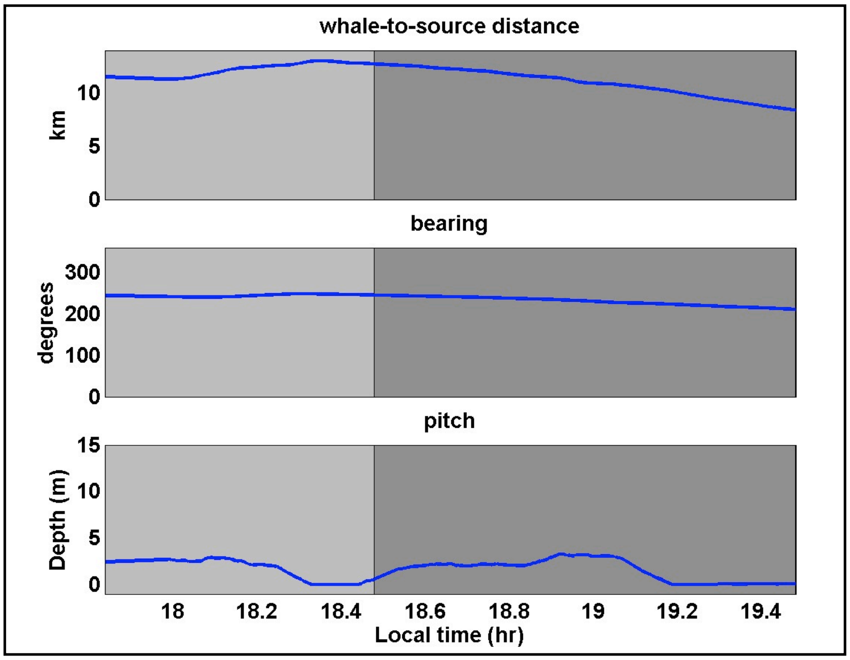

Figure 7.3.9. Distance, bearing and pitch from the tagged whale to the source vessel throughout the exposure period.

When assigning periods of time to a particular condition, care must be taken to assure that time intervals are consistently applied across exposure condition with relation to animal behavior, and that data points are independent. For example, sperm whales produce buzzes primarily in the bottom phase of dives, but only rarely during ascent and descent, and almost never when the whale is near the surface (Miller et al. 2004a). Thus, buzzes rates should only be calculated during the time interval when the whale is in the bottom phase of a dive. Analysis of serial correlation of buzz rates was conducted for non-CEE sperm whales tagged in the Gulf of Mexico. This analysis showed that there was little serial correlation of buzz rates, neither from dive to dive nor across subsequent sub-dive intervals. Buzz rates vary from dive to dive and within dives, likely as a function of prey availability (Miller et al. 2004a), so buzz rates were calculated over roughly 10min time intervals during the bottom phase. For locomotion cost, similar care must be taken to consider the fact that buoyancy forces acting on whales change strongly with depth and whether the whale is moving upward or downward in the water column. Thus, exposure condition must be applied on a whole-dive, or consistent subdive, basis to locomotion costs. When linking locomotion cost directly with foraging attempts, we used the same time intervals during the bottom phase as for calculating buzz rates.

We used four exposure conditions based upon the timing of the source playback within the tag record. <u>Pre-exposure</u> are periods of time before any seismic transmission from the source vessel has taken place, <u>ramp-up</u> is the interval during which only a subset of the airguns in the array are being fired, <u>full array</u> is the interval when all guns in the array are being fired, and <u>post-exposure</u> is the period after the final transmission from the source array. Intervals when the array was stopped due to mitigation purposes were classified as post-exposure condition, as the whale had no information that the sound would subsequently resume.

For each experiment, the response data for each experimental condition were recorded for each animal. Analysis of buzz-rates and whale-specific pitching energy from all D-tag deployments on sperm whales revealed that these behaviors were significantly altered during the first dive after tag attachment relative to subsequent dives. Data were only recorded for 1-2 dives following tagging before playback starting during the CEEs conducted in 2002, so the pre-exposure period for those subjects was not long enough to represent post-tagging baseline. Because of this problem, and to assure that equal sample sizes were represented in all conditions, we had to remove the pre-exposure condition entirely from the analysis. Ramp-up as an exposure condition was also not considered as it consists of a mix of very low-level transmissions at the start increasing to full array over a 25-30 minute period. Therefore, all of our analyses only compared full-array versus post-exposure conditions.

Statistical techniques
We used a repeated-measure ANOVA design, referred to as a "split-plot" design, to assess changes in buzz rate and pitching movement by exposure condition. In this design, each whale is assigned to either a "no-sound control" or "experimental" group, with exposure condition including all periods of exposure to the full airgun array. The interaction between condition ("full-array" or "post-exposure") and group ("no-sound" or "experiment") is assessed with the F-statistic denominator being the mean-square interaction of condition with whale nested within its group (SPSS 1996). This mixed-model ANOVA design treats individual whales as the unit of analysis with denominator degrees of freedom equal to the number of whales (20 total) minus two (Zar 1984).

Bayesian methods were used to calculate posterior probabilities for three different models (no effect, increase or decrease) for buzz rate and pitching movement. Posterior probabilities are a quantitative comparison between different models expressed as an odds-ratio, and answer the question of interest – "with what probability does the behavior alter with exposure?" These probabilities were calculated via reversible jump Markov chain Monte Carlo (Green 1995).

All 20 whales were used and an additive noise effect model considered:

$$X_{ijk} = \mu + \alpha_i + \beta_j + \varepsilon_{ijk}$$

where X_{ijk} is the observed behavioral measure (buzz rate or pitching movement) for whale "*i*" with airgun effect "*j*" (=0/1 for airgun noise absent/present) and replicate "*k*". The term μ is the underlying mean behavior of the whales, α_i the individual effect for whale "*i*", β_i the airgun effect, and ε_{ijk} random effects assumed to be independent and normally distributed. Based on data from the 20 whales, we calculated posterior probabilities of the three models defined by $\beta<0$, $\beta=0$ and $\beta>0$ for buzz rates and pitching movement. Bayesian priors were set using data from the baseline D-tag data set (O'Hagan 1998). The $\beta<0$ and $\beta>0$ models were specified as a half-normal distribution with a hierarchical prior specified on the variance in order to reflect prior uncertainty in the effect size of β. We modeled the variance of the half-normal curve as a Gamma distribution with expected values of 169 and 0.023 and standard deviations of 100 and

0.023 for the buzz rate and pitching models, respectively. A half normal distribution was chosen to represent the viewpoint that small effects should be more common than large effects, and that the effect should tail off. Interpretation of the posterior statistics was insensitive to reasonable prior specifications of all the parameters.

Preliminary Results

In total, we conducted CEEs on 8 tagged sperm whales in the Gulf of Mexico, four in 2002 and four in 2003 (Table 7.3.8). The seismic vessel started ramp-up at distances of 7.3-12.5 km (Table 7.3.8). We were unable to quantify the low sound exposure levels at the start of ramp-up due to masking from flow noise on the tag. During the full-array condition, whales passed as close as 1.5-11.1 km and had maximum distances of 5.7-12.8 km. They received maximum sound pressure levels of airgun sounds of at least 152-162 dB peak-peak re 1μPa (135 – 147 dBrms re1μPa, sound exposure level of 115 to 135 dB re1 μPa^2s; Madsen et al., submitted). Interestingly, as discussed in the previous section, the received levels of the airgun pulses were not correlated with distance beyond 6 km (Madsen et al., submitted), likely due to complex acoustic propagation through a stratified water column and interaction with the seafloor (DeRuiter et al., submitted).

Table 7.3.8

CEE Details

(Includes whale identifications, three measures of the sound intensity of pulses received at the whale, and source-whale distance during the full array condition. SPL refers to sound pressure level in dB re 1 μPa, and SEL to sound exposure level in dB re 1 μPa^2s. Times are local, CDT.)

Parameter	**CEE Number/ Year**							
	1 / 2003	**2 / 2003**	**2 / 2003**	**3 / 2003**	**4 / 2002**	**5 / 2002**	**5 / 2002**	**5 / 2002**
Whale ID	sw164a	sw165a	sw165b	sw173b	sw253a	sw254a	sw254b	sw254c
Tag on time	9:48	13:35	13:38	14:46	16:38	10:13	10:28	10:34
Tag off	23:20	06:19	06:05	20:38	20:58	21:45	22:52	22:56
CEE start	18:26	17:01	17:01	17:23	17:59	12:16	12:16	12:16
CEE end	19:26	19:01	19:01	19:23	19:15	14:20	14:20	14:20
SPL pk-pk	140-157	136-160	135-160	131-162*	142-162	136-155	136-152	139-154
SPL rms	125-146	123-147	120-147	111-147*	123-144	121-140	121-135	125-139
SEL	112-129	106-130	105-130	94-131*	106-127	105-123	108-117	106-123
Start distance (km)	12.1	No info	12.5	7.3	11.5	11.7	12.1	11.5
Full-array dist (km)	11.1-11.7	No info	3.1-10.2	1.5-5.7	8.5-12.8	6.9-9.9	5.4-9.9	5.0-9.2

*Value underestimates the actual received level, as some signals were clipped.

We identified 13 tag records that were appropriate to use as no-sound control whales from other tag deployments on sperm whales in the Gulf of Mexico (n = 5) , Mediterranean Sea (n = 6), and Atlantic Ocean (n = 2) between 2001 and 2003. These tagged whales were those from which we had recorded four or more deep dives, and which did not receive notably intense anthropogenic sounds during the first four dives. For control whales, the third dive was classified as "full-array", and the fourth dive "post-exposure", and all foraging behavior analyses were conducted in the same fashion as for the experimental whales.

Tagging effects

To evaluate whether reactions to tagging might influence sperm whale behavior, we examined buzz rates and pitching movements during the bottom foraging phase (Miller et al. 2004a) of each dive and dive duration for 24 and 13 non-experimental sperm whales for which we obtained two and four or more dives, respectively. Relative to the second dive post tagging, the first dive had a lower bottom-phase buzz rate (-14.4% t_{22} = -2.17, P=0.041), a non-significant decrease in fluking energy (-4.9% t_{23} = -1.49, P=0.15), and shorter duration (-7.3%, paired t_{23} = -2.45, P=0.024). Using repeated measures ANOVA, dives 2-4 did not differ for buzz rates or pitching energy (buzz-rate: $F_{2,11}$ = 0.240, P=0.79; pitching-energy: $F_{2,11}$ = 0.148, P=0.86), though dive 4 was somewhat shorter than dives 2 and 3 ($F_{2,11}$ =3.81, P=0.055). These results indicate that behavior during the first recorded dive appears to be influenced by the tagging operation, but that subsequent dives are relatively unaffected.

We were able to obtain usable pseudo-tracks for 7 of the 8 tagged whales (not for sw165a). For these whales, movement before exposure relative to that during ramp-up was non-randomly distributed (Rayleigh r = 0.92, z = 5.9, P<0.001; mean difference 95% CI -12.º to 36.2º), and was statistically identical to movement in the pre-exposure intervals. Likewise movement during full-array conditions was statistically equivalent to that in combined pre-exposure and ramp-up intervals (Rayleigh r = 0.93, z = 6.1, P<0.001; mean difference 95% CI -18.5º to 34.1º). In contrast, whale movement was distributed randomly relative to the source bearing in both ramp-up (Rayleigh r = 0.57, 0.1<P<0.2) and full-array conditions (r = 0.52, 0.1<P<0.2). These results suggest that these whales did not avoid the airgun source, but continued on their previous direction-of-movement.

Seven of the eight whales made at least one deep dive in all 3 conditions. The remaining whale (sw173b) rested at the surface for an unusually long interval, and commenced deep-diving immediately following the final airgun transmission in that experiment. Resting bouts as made by sw173b have been observed on 10 other occasions, with durations never exceeding 2 hours while the bout made by sw173b was over 4 hours duration. These observations suggest that this whale might have responded to sound exposure by delaying its foraging dives and resting at the surface. One other whale (sw253a) stopped deep-diving near the end of the full-array period but then resumed deep diving 13.1 min after the experiment had stopped (Fig. 7.3.10). Short shallow dives are relatively common between long foraging dives, so this dive pattern cannot conclusively be attributed to the sound exposure.

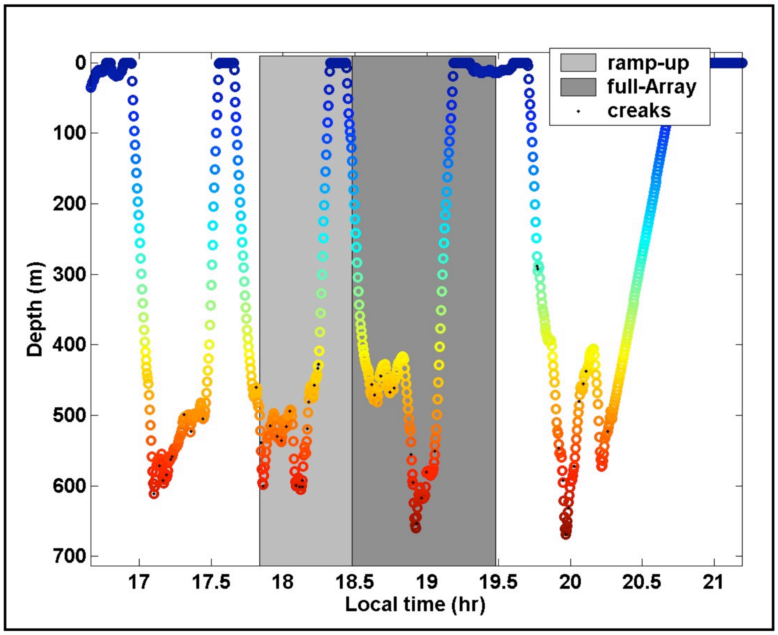

Figure 7.3.10. Dive profile of sw02_253a with timing of exposure conditions and buzzes indicated. Note the shallow dive starting during the full-array condition, and that the whale resumed deep-diving once transmissions ceased.

For the seven whales which made a dive (or dive sub-portion) in full-array and post-exposure conditions, lower pitching movements were observed during full-array exposure, with a mean 6.4% less than that during the post-exposure control. This difference was statistically significantly different from the 13 no-sound control whales ($F_{1,18}$ = 7.41, P = 0.014). Bottom-phase buzz rates of the 7 experimental whales that dove in both conditions were 19.0% lower during the full-array condition, but this effect was not statistically significant relative to 13 no-sound control whales ($F_{1,18}$ = 2.37, P = 0.141). Bayesian analysis determined that the model with a reduced buzz rate had 3.6 times more posterior support than the model with no effect and 28 times more support than the model with an increased buzz rate. The model with the reduced buzz rate had a mean effect size of 20.1%, with a 95% credible interval (40.78%, 2.71%). For pitching movements, the model with reduced movements during exposure had 2.9 times more support than the model with no effect, and 19 times more support than the model with increased pitching movements. The model with reduced pitching movements had a mean effect size of 5.5%, with a 95% credible interval of 0.6%-11.6%.

We visually inspected the percentage change in buzz rate from full-array to post-exposure as a function of received level and source-whale distance during full-array exposure for all 8 whales. The whale most closely approached (sw173b) delayed deep diving until just after exposure stopped, leading to an exposure buzz rate of zero. The difference in buzz-rates of the 7 remaining whales between exposure and post-exposure appeared somewhat dependent on the distance between the whale and the source (Fig. 7.3.11). In contrast, we found no trend between the change in buzz-rates and the intensity of the airgun sounds recorded by the tag on the whale.

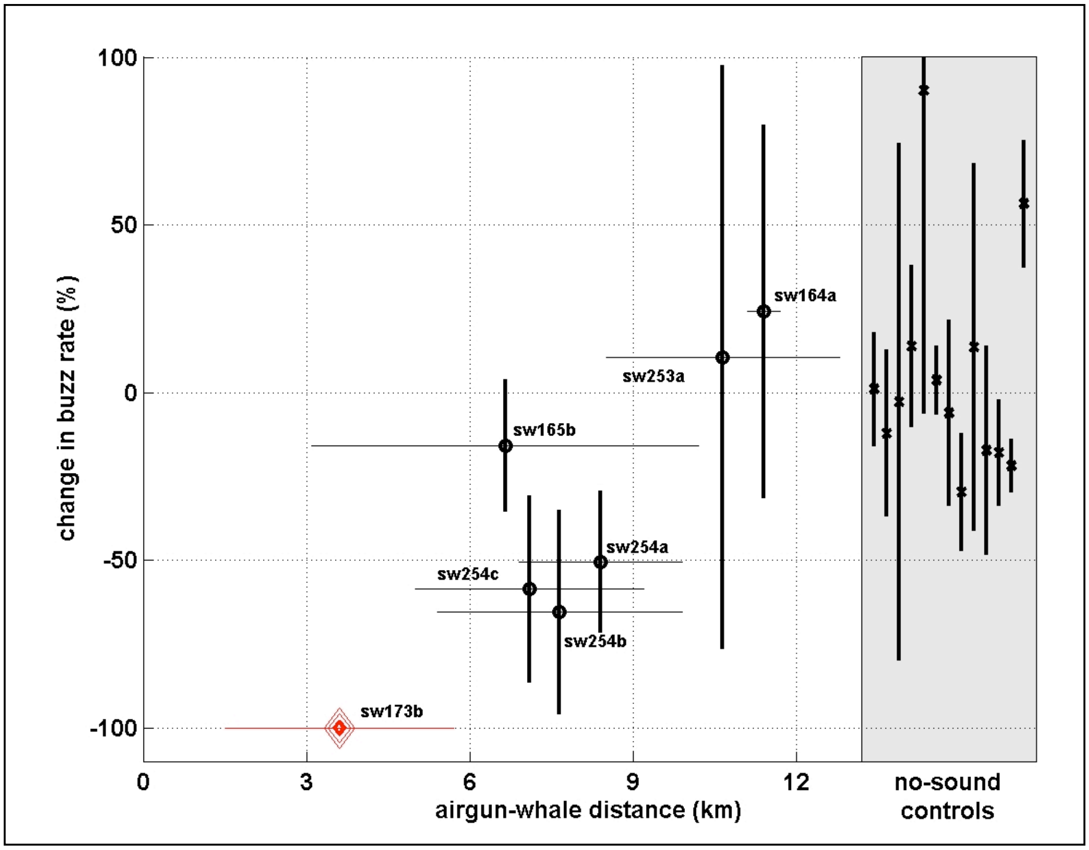

Figure 7.3.11. The percentage change in buzz rate from exposure to post-exposure conditions relative to the post-exposure rate is plotted against the distance from the seismic vessel to the whale. Shown are (left half) 7 of the 8 experimental whales (no tracking information was available for sw165a) and (right half) the 13 no-sound control whales. The horizontal bars are one standard error of the percent difference in buzz rate. For experimental whales, the horizontal line indicates the range of distances between source and whale during full-array exposure, and the symbol is plotted at the mean of the closest and furthest distances. This figure combines the mean change in buzz rate during dive-bottom subintervals marked in black with the 100% difference in buzz rate observed for whale sw173b. This is marked with a red diamond as it reflected a different type of response: sw173b did no foraging dives during exposure, but started foraging after the final seismic pulse.

Discussion

This study demonstrated the ability of the tag to record behavioral responses to exposures that were measured directly on the whale and experimentally controlled. All eight experimental whales continued on their course of travel and did not avoid the seismic vessel throughout the playback. All eight whales also continued their diving behavior pattern throughout the 30 min ramp-up period, though two whales subsequently showed dive changes that might indicate avoidance of deep-diving during full-array exposure. One of the eight whales (sw173b) remained at the surface in a resting bout which was twice as long as any of 10 resting bouts recorded from sperm whales using the D-tag. The unusual duration of this resting bout, which ended immediately after the final airgun pulse suggests that this whale avoided conducting a foraging dive while the airgun was transmitting nearby. This could therefore be considered a vertical avoidance response, although the whale may not have experienced lower received levels at the surface than it might have at some depths.

For the remaining seven whales, all had lower pitching movements during full airgun-array exposure compared to the post-exposure period, and the mean difference of 6.4% was statistically significant relative to the no-sound control whales (P = 0.014, N=7 experimental whales and 13 no-sound control whales). Thus, all eight experimental whales seemed to respond to exposure to airgun sounds in a fashion expected to result in reduced energetic expenditure for locomotion. Buzz-rates were lower on average by 19.0% during exposure, but that difference was not statistically significant relative to the no-sound control whales (P = 0.141). We do not know what percentage of buzzes lead to prey capture, nor the caloric value of prey. However, the interpretation that reduced buzz-rates predict reduced a foraging rate could only be incorrect if whales had a higher success rate, or caught more valuable prey, when airgun sounds were present than under normal conditions, which seems unlikely.

Given the sample size of exposure subjects, we followed the advice of Ellison (1996) and conducted a Bayesian analysis to quantify the odds-ratio for whether our data support models of increase, decrease, or no change in buzz rate and pitching movement. The result indicates that a decrease in buzz rate is 3.6x more likely than no change given our data, a Bayes factor considered to be "substantial", or "positive" evidence for an effect (Jeffereys 1961; Kass and Raftery 1995, summarized in Ellison 1996). The same analysis indicates that a decrease in pitching movement is 2.9 times more likely than no change. The data provide strong evidence against the models of increased buzz rate and fluking movements, with Bayes factors of 29 and 19 in favor of the models with a decrease versus those with an increase.

We visually inspected the difference in buzz rate and pitching movements of all 8 whales, including sw173b, both as a function of the range of received levels and distance from the whale to the seismic vessel during the full-array condition. No pattern was clear except for the difference in buzz rate versus distance (Fig. 7.3.11). The whale most closely approached did not forage at all until after the airgun transmissions ceased. Whales tested at intermediate distances foraged but had a lower buzz rate during exposure, while the buzz rates of the two most distant whales tested appeared largely unchanged. The three whales tested in experiment 5 (sw254a, sw254b, and sw254c) had quite similar differences in buzz rate in full-array exposure relative to post-exposure. While they were all tested at similar distances, some other shared context during that experiment (i.e., prey type) might have shaped their response to airgun exposure. Received levels did not correlate with the distance between the whale and the seismic vessel (Madsen et al., submitted). The distance-related pattern on buzz rates (Fig. 7.3.11) may indicate that the seismic sounds themselves were not aversive at the distances we tested, but that sperm whales responded to the proximity of the airgun array. Clearly more data are required to test this trend which is apparent in our data.

While these results should not be considered conclusive, this study does provide some evidence that airguns affect the foraging behavior of sperm whales, and should help define hypotheses about effect size and describe natural variability in these important behaviors. While pitching movements are completely under the animals' control, buzz-rate reflects an interaction between whale behavior and prey encounters, which should have additional sources of variability. We calculate that the statistical power to reveal a 25% decrease in buzz rates at the $P<0.05$ level from a sample of seven whales is just 15%. To reach 50% and 80% power, we estimate that 21 and 50 additional trials may be required, respectively (under the assumption that pre-exposure data remains unavailable).

Compared to opportunistic studies, the controlled exposure methodology with D-tags allows a statistically powerful dose-response analysis of detailed individual foraging behavior. Disadvantages of this approach include the challenges of tag attachment, which was required for any trial to be carried out. The fact that suction-cup tagging appears to affect normal behavior immediately following attachment also requires a long tag-attachment time to allow collection of unaffected pre-exposure data. These methodological challenges limited the number of experiments that could be performed within the budget constraints of the program, which included a substantial expense for a dedicated seismic source vessel. Our study also had lower statistical power than originally planned because of decisions made by governmental funders and industry partners to reduce the field effort, which reduced the power of the study. In fact, additional trials were planned for 2004, but governmental funders and industry partners cancelled the scheduled research and redirected research funds to other activities.

The cancellation of the planned 2004 fieldwork was particularly costly to this study as we had solved by 2003 the technical problems of reliable tag-attachment duration to allow a sufficient post-tagging period to elapse before using data as a measure of the pre-exposure baseline (see Table 7.3.8). Our use of the post-exposure period as a control for this chapter was necessary because the first dive after tagging may be affected by the tagging operation, and the pre-exposure data collected in 2002 data did not include a sufficient time post-tagging to reduce concern about these identified tagging effects. As we were not able to use the pre-exposure data for the statistical analysis of buzz-rates and pitching movements, we were limited to detection of effects that ceased when the airguns stopped. If any such effects continued into the post-exposure control period, this would weaken the observable difference between exposure and post-exposure conditions. Therefore, our results might be considered as minimum estimate of the possible effect of airguns on sperm whale buzz-rates and pitching movements.

Despite the small sample size, our results provide evidence that airgun operations alter the foraging behavior of sperm whales in the Gulf of Mexico, and likely reduce their foraging-rate at distances beyond current the current 500m mitigation range required in the Gulf of Mexico (Allen 2004). Reduced fluking movements during exposure versus post-exposure were observed for all of the tested whales, with no indication that range or received level was correlated with this change. In contrast, delay of diving and reduced bottom-phase buzz-rates appeared to result in a decreased rate of foraging attempts in a distance-dependent pattern. Putative mechanisms for reduced capture-attempt rates include delay of diving to avoid high-intensity exposure under the airgun array, disruption of the whales' foraging behavior during foraging dives, or possibly behavioral reactions by the prey species. We do not believe that direct acoustic masking or jamming of echolocation signals by the airgun pulses is likely as the duty cycle of airgun pulses is low and the received level of the brief and intermittent pulses did not appear to modulate the behavioral responses.

Playback experiments of seismic pulses to captive squid (*Sepioteuthis australis*) noted behavioral responses including increase in swimming speed, depth changes, and increased startle responses at levels of 156-161 dBrms re 1µPa (McCauley et al. 2000). Seismic survey operations have also been noted to impact fish distribution and catch rates of commercial fisheries (e.g., Engås et al. 1996, but see Wardle et al. 2001). While it is unlikely that these particular squid and fish species are the primary prey base of sperm whales in the Gulf of Mexico, it is possible that some of the behavioral changes observed in the sperm whales may be consequence of behavioral changes in their prey.

The tested whales have repeatedly experienced airgun sounds in the Gulf of Mexico, and this increases the likelihood that habituation or sensitization to these sounds through experience influenced how the tested whales reacted to the sounds. Behavioral reactions at the onset of ramp-up were minimal, though the concern of tagging effects limited our ability to statistically analyze detailed measurements of pre-exposure behavior. However, the behavior of whales tested during closer range full-array exposure differed from the immediately following post-exposure period (e.g., by delay of deep diving or reduced pitching and buzz-rates during dives). The observed changes may result in some degree of reduced cost of locomotion during the full-array condition. The two most distant whales reduced pitching movements during dives even though foraging attempts were unaffected, however, suggesting that there may not be a strong link between the change in pitching motion and buzz rates. Care should be taken when extrapolating these results to sperm whales generally, particularly in areas with less history of seismic exploration.

Unlike baleen whales (Richardson et al. 1995), the sperm whales in our study did not avoid airguns either during ramp-up or full array conditions. Sperm whales in the Gulf of Mexico may not automatically swim away to avoid closer-range danger zones, though delay or avoidance of deep diving may provide some protection from high sound levels directly underneath an airgun array. Reactions of sperm whales that are naive to airgun sounds could reveal to what extent habituation or sensitization might influence the effect of airguns on sperm whale foraging.

Interpretation of the results of the controlled-exposure experiments must consider broader considerations including the exposure history of whales in the study area and considerations of how group social organization might influence responses of individuals.

7.3.6. Measuring the Distance Between Whales Using Acoustic Recording Tags

Although sperm whales, like many deep-diving odontocete cetaceans, are well known to form close aggregations while swimming at the surface, little is known about their separation distances while diving. Specifically it is not known whether these whales forage as a closely-coordinated unit or maintain distance and forage asynchronously. Such information is important to interpret the significance of individual movements, for example in response to anthropogenic sound, and also to detect more subtle, group level disturbance. Many odontocetes make regular click sounds while foraging and recordings of these from towed arrays of hydrophones have been used to estimate the location of whales. However, in most cases, the accuracy is insufficient to reliably predict how animals are separated. As part of the MMS SWSS program, we have developed an alternative and more accurate method for estimating the distance between pairs of diving sperm whales whales as well as their relative orientation using acoustic recording tags. The method enables studies of synchronization and movement during foraging, with relevance to measuring group-level responses to anthropogenic sounds. Understanding how and whether sperm whales coordinate foraging will be important for validating statistical treatment of individual whales during CEEs when more than one whale has been tagged.

Method

The persistent clicking of deep diving odontocetes during foraging dives provides an excellent sound source for passive tracking. Both fixed or floating platforms with suspended hydrophones (Clark 1999; Møhl et al. 2003) and towed arrays of hydrophones (Thode et al. 2002; Zimmer et al. 2003) have been used for passive tracking. Mohl et al. (2003) have used an array of GPS-synchronized drifting sound recorders to track sperm whales. Individual whales were tracked in 3-dimensions using hyperbolic navigation based on the difference in arrival time of clicks to multiple (minimum of 4) hydrophones. Such a system can be accurate if the whale is inside, or not far outside, the transcribing polygon of listening stations but is costly to deploy and maintain. Towed arrays of closely-spaced hydrophones have also been used to determine the bearing to individual sperm whales and, via multipath tracking, their range and depth (Thode et al. 2002; Zimmer et al. 2003). Zimmer et al. (2003) report tracking an individual for 8 hours using a 128 element array while Thode et al. (2002) have shown tracks for descending sperm whales recorded with 2-elements. However, in both cases, careful maneuvers were required of the source vessel to stay close enough to the target whale and, at least with the short array, accuracy is unlikely to be sufficient to measure distance between close whales with any confidence.

Although the above passive methods could potentially be used to measure the distances between multiple whales, this application has not been reported. The accuracy of such a distance measurement would depend upon the distance to the whales versus the aperture of the listening devices, the number of listening devices and their timing accuracy. To achieve high accuracy, a large number of closely-placed listening devices are required, a difficult and costly proposition. A different approach, described here, uses non-invasive acoustic recording tags placed on the whales themselves. When clicks made by a tagged whale are heard on the tag carried by another whale, the time delay between source and receiver can be measured very precisely. As the tags are asynchronous, having no common timing reference, the measured time delay is the sum of the travel time and the clock offset between the two tags. These two components can be separated if the return path time delay is also known, i.e., if the second whale also produces clicks which are heard by the tag on the first whale. An advantage of this method, in comparison to the remote sensing methods discussed above, is that the travel time between the whales is measured directly and so is accurate over a range of separation distances. The tags also measure depth and orientation enabling computation of the horizontal distance between, and the relative orientation of, each pair of tagged whales. Knowing the depth of each whale and the sound speed profile for the study area, the path-integrated sound speed can be estimated and used to improve the distance estimate. Finally, the method is entirely passive, relying on the vocalizations of the whales themselves, and does not require a nearby vessel or listening platform. Clearly, the major disadvantage of the method is the need to deploy multiple archival tags on whales. Although this seems a substantial hurdle, the authors have now achieved multiple simultaneous DTAG carries 11 times on sperm whales with up to 3 tags being placed at a time.

Under the MMS program we have developed algorithms for extracting distance and orientation information from multiple acoustic recording tags. The first step is a technique for predicting clock offset and travel time. There are two key obstacles to be overcome. The first is clock drift between the two tags. In common with other acoustic recording tags, size and battery power constraints prevent the use of a high accuracy reference clock in the DTAG. GPS synchronization is also infeasible due to the infrequent surfacings of sperm whales. As a result, the audio sampling rate, and therefore the time reference, may vary by up to ±50 ppm (parts-per-million) from its nominal value and will also vary with the ambient temperature. This means that two tags that were initially synchronized precisely could drift by up to 0.4 s in the course of a one-hour dive typical of a sperm whale. Clearly a method for predicting and correcting the clock drift is essential for time delay estimation. The second problem is how to recognize the clicks from one tagged whale in the recording made on another whale. This is especially difficult when there are many whales clicking. We have developed a pattern recognition method to overcome this problem and a least-square-error fitting method for estimating clock drift. The result is a sequence of predictions of the slant range between each pair of whales.

The second step in the analysis is to estimate the relative position and orientation of each pair of whales by combining the slant range with the depth and orientation (i.e., pitch, roll and heading) of each tagged whale. Despite having a globally-referenced orientation sensor (i.e., compass heading, pitch and roll) in each tag, the relative orientation of two tagged whales cannot be deduced directly from the tag sensor data and must be inferred from the sequence of measured slant ranges. This is because the relative location of the two whales is not known except during the occasional surface observations which generally cannot be extrapolated far into long dives. As an example, if whale A is traveling north and is due west of whale B who is traveling west, the relative orientation or aspect of whale B from the viewpoint of whale A will initially be 0º, increasing to 90º as whale A swims north and whale B passes behind. If, instead, whale B was due west of whale A but both kept their headings, then its aspect would be initially 180º subsequently decreasing but never reaching 90º. Clearly, even if both whales hold constant, known, headings, their relative orientation is a complex time-varying function of their unknown relative movement. Given that the distance between two whales can be established accurately using the method given above, the missing information is the bearing of one whale with respect to the other, i.e. the angle of the line between the horizontal locations of the two whales, when one of the whales (the reference whale) is placed at the origin. We have developed a non-linear least-squares fitting method to estimate this angle in tandem with the clock drift and have evaluated the method by simulation. We have also checked the method for consistency against data-sets where 3 whales were tagged and the relative location of the whales could be deduced directly from the slant ranges without needing orientation data.

Results

Four multiple-tag data sets were collected during the SWSS cruises, two of which included an airgun controlled exposure. Although data from these latter two deployments will be reviewed elsewhere in the report, we present here preliminary estimates of the distance between whales for one of the deployments using the above method to exemplify both the practicality of the method and the scope of new biological insight possible. Figure 7.3.12 summarizes the depth (lower panel) and distance-between (upper panel) for a 13-hour tag deployment on three sperm whales in a loosely-coordinated group. The reliable diving behavior of these sperm whales made it possible to track the inter-whale ranges over a large percentage of the deployment. The whales were initially close together with slant ranges of less than 500 m and horizontal ranges considerably smaller where dives coincided. After some three hours, one of the whales separated from the other two reaching a distance of some 1500 m while the other two drew close together. Finally, all three whales separated to distances of 1500 - 3000 m, which was maintained before and after an extended surface interval. Intriguingly, the times of greatest separation coincided with the greatest synchrony in dive cycle suggesting that the click sounds may serve a dual purpose of coordinating movement between whales in addition to their function in echolocation. If this is the case, and there is a foraging advantage in wide separation, then anthropogenic sound from a variety of sources could impact such group behavior by masking clicks from distant whales. Given the distances between whales noted here, masking could occur at exposure levels considerably lower than those likely to cause harm to, or provoke a strong response from, an individual. Group separation distance, and possibly diving coordination, may then provide a sensitive measure of disturbance. These data will also be important for evaluating whether correlation of behavior in these three individuals creates a problem for treating each individual as a separate unit of analysis statistically.

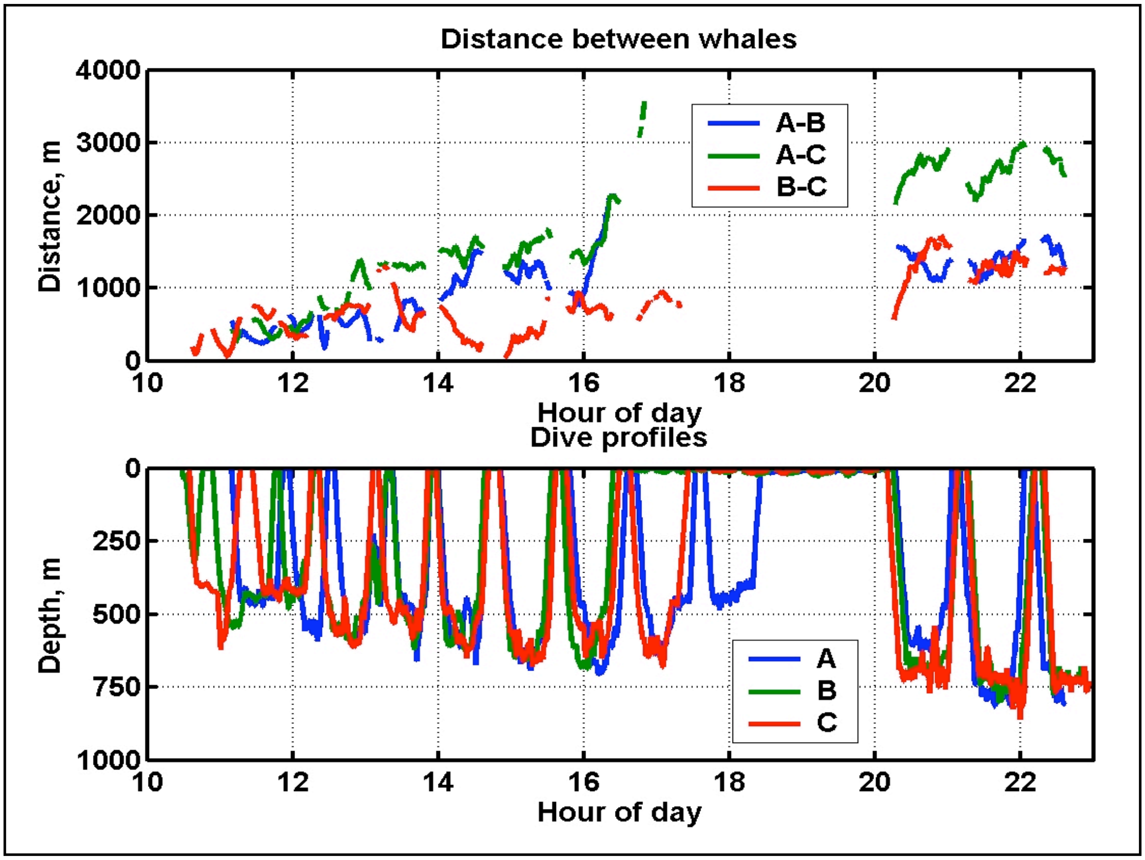

Figure 7.3.12. Calculated distance between 3 tagged whales and their dive profiles over a 13 hour period. A notable feature is the tight diving synchrony at nighttime, and between 14:00-17:00, despite separations of over 1.5km between whales.

7.4 Field Cruises for D-tag/CEE

SWSS D-tag Cruise: Gulf of Mexico, 19 August 2002 – 15 September 2002

Platforms

R/V *Gyre*, Captain Dana O. Dyer III (TAMU)
Tagging vessel R2 (MMS), an aluminum-hulled RHIB with gasoline outboard engines.
Seismic vessel M/V *Rylan T* using the airgun source array from M/V *Speculator*

Cruise Objectives

The primary objective of this cruise was to measure the response of sperm whales in the NE Gulf of Mexico to controlled exposures of seismic airgun sounds and various control sounds. We observed and recorded whale behavior using a combined acoustic and movement recording tag "D-tag", in tandem with supporting visual and acoustic observations from the R/V and the tagging vessel, R2. Tagged animals were exposed to playback of a no-sound control. No-sound controls are critical for establishing relatively undisturbed behavior, and are being used to identify risk factors for disturbance, such as feeding specializations, or acoustically mediated social interactions. In the second part of the cruise, tagged animals were primarily exposed to controlled exposures from a seismic vessel made available in collaboration with IAGC/IRFC. A secondary objective of the cruise was to make oceanographic measurements using flow-through and ADCP sensors, and CTD or XBT casts when and if this was consistent with tagging operations and controlled exposures. Lastly, during transit from Galveston to waters off the Mississippi delta visual and acoustic survey were undertaken along the 1000-m isobath to document the presence or absence of sperm whales in these waters. This cruise also collected skin and biopsy samples for genetic study and took photographs of flukes for identification of individuals.

Location of Activities
Figure 7.4.1 shows the general course and major tagging areas for the cruise.

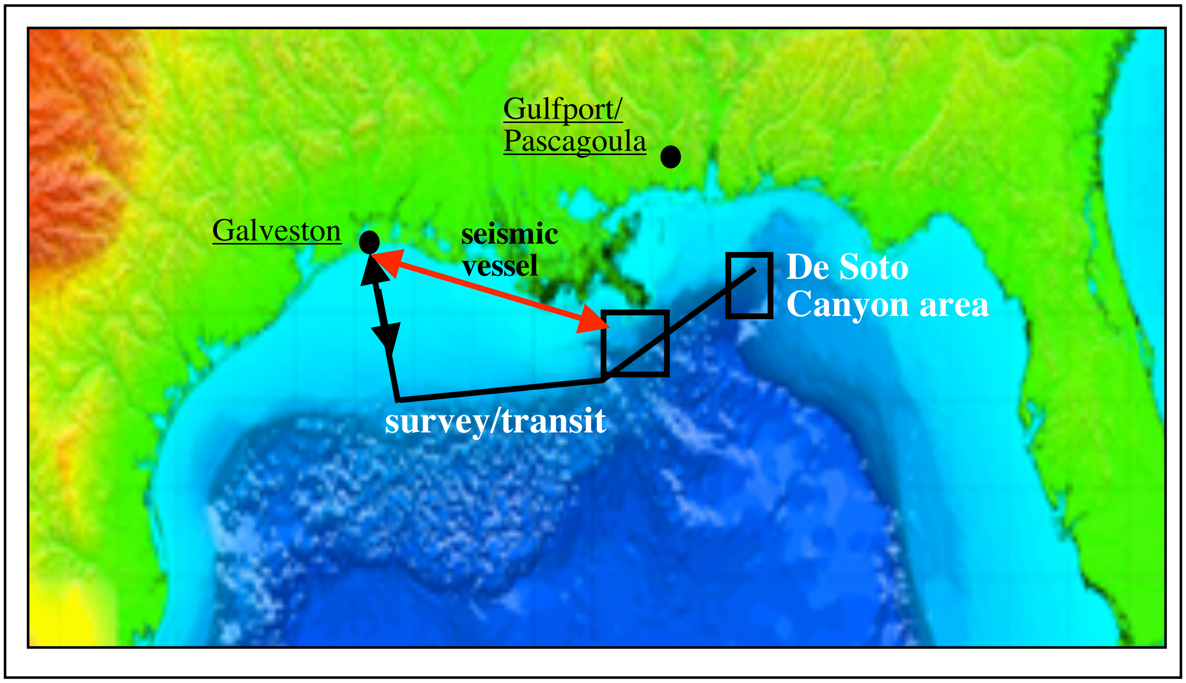

Figure 7.4.1. General course and major tagging areas for cruise.

The study was conducted between the 700-m and 1500-m isobaths, mainly in on or near the 1000-m isobath, between 93°W and 88°W in the northern Gulf of Mexico. This region includes the continental slope south of the Mississippi River delta between the Mississippi and DeSoto Canyons. Based on historical sightings and recent reports from satellite-tagged (S-Tag) whales, we knew there was a high-probability of encountering pods of sperm whales in this area.

Overview of Cruise Activities

Despite lost days due to delays and weather, the experiments were an unqualified success. Nineteen sperm whales were tagged. All tags were recovered yielding over 77 hours and 14 Gbytes of digital data. Several notable events occurred including the longest D-tag deployment to date (15 hrs), a synchronized dive by a pair of tagged whales, and three whales tagged at the same time. Foreign whale codas were played to tagged animals but, although two attempts were made, uncertainty in the position of the tagged whales precluded the opportunity to playback familiar codas. Most importantly, two controlled-exposure experiments of whales to an operating seismic vessel were achieved, including one with three simultaneously tagged whales. Seventeen fluke photographs were taken of 13 animals for photo-identification and three frame-sets (measured length of animals) were made. Fourteen sperm whale skin samples were collected, thirteen from D-tag suction cups and one from biopsy sampling equipment. The visual team enjoyed 13 days of good visual working conditions and the acoustics team recorded data on 20 of 25 days from two hydrophone arrays aboard the *Gyre*, as well as numerous days from the array aboard the *Rylan T./Speculator*. Thirty-eight XBT probes were dropped, eight CTD casts were taken, and chlorophyll concentrations were measured from 75 water samples. Continuous vertical profiles of horizontal currents were collected whenever whales were not present, and continuous near-surface measurements of temperature, salinity, and fluorescence were recorded whenever the vessel was underway.

All D-tag activities were made under NMFS permit 981-1578-01 and permit 981-1578-02 granted to Peter Tyack.

SWSS D-tag Cruise: Gulf of Mexico, 3 June 2003 – 24 June 2003

Platforms

R/V *Maurice Ewing* (LDEO)
Tagging vessel Balaena (WHOI; 24' RHIB with outboard engines) and tagging vessel R2 (MMS; an aluminum-hulled RHIB with gasoline outboard engines)
Seismic vessel M/V *Kondor Explorer* with airgun source array

Cruise Objectives

The goal of the cruise was to deploy digital sound recording tags (DTAGs) on sperm whales in the northern Gulf of Mexico and then expose the tagged whales to controlled levels of airgun sound from an attending seismic survey vessel. The data set from the cruise includes a range of visual, navigation and shipboard acoustic observations in addition to the tag data. The objective in analyzing this combined data set is first to develop a baseline model for the behavior of unexposed sperm whales and then to examine the data taken from exposed animals for significant departures from baseline behavior.

Overview of Cruise Activities

The cruise took place between 3 and 24 of June and made use of two vessels. The R/V *Maurice Ewing*, operated by Lamont-Doherty Earth Observatory (LDEO), acted as the observation platform while a seismic source vessel, the M/V *Kondor Explorer* made available by the International Association of Geophysical Contractors (IAGC/IRFC) and a coalition of industry sponsors, provided the controlled sound source. Two small tagging vessels, the R2 and the

Balaena, were operated off the *Ewing*. The procedure in the 2003 cruise largely followed that of the successful 2002 cruise on the R/V *Gyre*. However two new technologies were used in 2003 to overcome limitations found in 2002.

A new tag design, called the DTAG-2, was deployed in 2003. This tag had an extended dynamic range as compared to DTAG-1 overcoming a clipping limitation with the latter that reduced the accuracy of received level estimates for loud sounds. The physical size and mounting arrangement of DTAG-2 are also enhanced to achieve longer attachment times. In practice, both DTAG designs were used in SWSS 2003. Three DTAG-1 tags were deployed with an average attachment duration of 3.8 hours, comparable to the average of 4 hours in 2002. In contrast, the 8 DTAG-2 deployments had an average attachment duration of 8.7 hours, a dramatic improvement. The 3-phase controlled exposure experiment (CEE) design we have developed requires at least 4 hours with 6 hours being preferred. The CEE design has had to accommodate to the expected tagging duration, and last year's data suggests the benefit of prolonged pre-exposure and post-exposure intervals. Clearly the increased longevity of DTAG-2 enabled more successful CEE trials because of the longer attachment duration. A concern has been raised that the new tag design is more prone to slide on the body of sperm whales than the older version making VHF tracking difficult. In fact this is not the case: 4 of 11 tags in 2003 slid down the body of the whale during deployment resulting in poor placements. Of these 1 of 3 were DTAG-1s and 3 of 8 were DTAG-2s. Poor placements typically resulted from attempting to tag in high swell and the presence of relatively thin whales, rather than due to a deficiency in the tag design.

A new data logging and real-time GIS display system was used during the 2003 cruise to handle observation and navigation data collected on the *Ewing* as well as navigation data sent from the *Kondor* via a radio modem. The system was created in a collaboration between WHOI and the NATO Undersea Research Centre to address a key need identified in previous cruises: the ability to display real-time navigation and observation data before and during a CEE in order to direct the source vessel accurately towards the tagged whale. The system functioned extremely well and was crucial for planning CEEs in the widespread groups of whales encountered in the 2003 cruise.

Fieldwork in 2003 was conducted under National Marine Fisheries Service (NMFS) permit 981-1707 issued to Dr. Peter Tyack. The permit included the requirement that no marine mammals or sea turtles be exposed to sound levels above 180 dB re 1μPa RMS. To comply with the permit, Dr. Tyack and co-investigators developed a mitigation protocol defining the procedure should species other than sperm whales be observed during CEEs. Beaked whales were sighted on two occasions during seismic operations and the mitigation procedure was invoked. Although this interrupted a calibration experiment that was added to the cruise late in the planning process, it did not curtail any CEEs: on the one occasion in which a CEE was abandoned following the mitigation procedure, the tag also released from the whale prematurely and would not have collected data through a full CEE. A key practical consequence of the 180 dB mitigation radius was that the desired high level (up to 160 dB) CEEs were difficult when the tagged whale was within a widespread group as was often the case in 2003. As no whale in the group could be exposed beyond 180 dB and the available propagation models for the airgun array were conservative, relatively low level CEEs resulted. The full-bandwidth three-dimensional propagation of signals from airgun arrays needs to be better understood and modeled for CEEs to more closely approach the permitted ceiling of exposures.

Out of 14 days in which the *Kondor* was available to perform CEEs, we conducted 3 complete experiments with a total of 4 whales, a similar success rate as in 2002 (the 2002 result was 2 CEEs to 4 whales in 11 days). Of the remaining 11 days, 8 were spent with bad weather or no whales and on one good-weather day we were unable to tag any of the whales approached. CEEs were aborted on two occasions, one due to mitigation as described above and the other due to poor VHF tracking of the tagged whale, which was already in the presence of an uncontrolled seismic survey. One day when whales were not sighted was used to perform a calibration experiment on the *Kondor* seismic array. A key limiting factor in 2003 was the formation of a large wide-spread group of sperm whales in the northern gulf. This area coincided with an on-going seismic survey from vessel Neptune. Based upon our experimental design, to obtain independent samples of CEE response, we need to move at least 10 miles after each CEE. However, animals were scarce outside of the main accumulation and considerable time was spent trying to find whales distant from the Neptune. The added requirement to deploy an EARS buoy, calibrate its location, and use the *Kondor* to obtain calibrated measurements of airgun sounds also cost days that could otherwise have been devoted to CEEs. Nonetheless, the cruise was a complete success producing high quality CEE and baseline samples at the same rate as in the 2002 cruise. Due to funding constraints, the total amount of field time was reduced in 2002 and 2003 from the original goals of the SWSS proposal, but the rate of successful CEEs is consistent with the original proposal.

SWSS D-tag Cruise: North Atlantic, 7 July 2003 – 31 July 2003

Platforms
R/V *Delaware*
Tagging vessel Balaena (WHOI), a 24' RHIB with outboard motors.

Cruise Objectives

The MMS funded 'Sperm Whales in the North Atlantic' study was a cooperative effort between the Northeast Fisheries Science Center (NEFSC) of the National Marine Fisheries Service and the Woods Hole Oceanographic Institution (WHOI). The study built upon on-going survey work in the North Atlantic by NEFSC and a multi-year tag-based controlled exposure project in the Gulf of Mexico (the SWSS project) by WHOI. The goals in combining these two methodologies were to (i) obtain baseline data on the behavior of sperm whales in the North Atlantic to compare against data from the Gulf of Mexico and the Mediterranean, (ii) assess the potential of the North Atlantic study area for controlled exposure experiments similar to those carried out in the Gulf of Mexico under the SWSS program and (iii) estimate the surface presence of sperm whales to improve survey-based population estimates.

Overview of Cruise Activities

The field effort took place between the 7th and 31st of July, 2003, on board the R/V *Delaware*. Both WHOI and NEFSC personnel participated in the cruise. The WHOI group of 7 included a tagging engineer, acoustic observers, and visual observers. WHOI also supplied a 24' RHIB for tagging, a towed hydrophone array, and the visual and acoustic data collection hardware and software. The tag boat was a fiberglass-hulled Novurania, called the 'Balaena', owned by the tagging group at WHOI. The Balaena, has two counter-rotating 4-stroke Yamaha 110 hp outboard motors chosen for their low acoustic noise. The Balaena was stowed on the aft deck of the R/V *Delaware* and lowered over the starboard side using the main crane. The tight fit of the Balaena on the deck made deployment difficult especially given the persistent roll of the R/V *Delaware*. However, there were no incidents during deployment or operation of the small boat. The Balaena was captained by Wayne Hoggard from Southeast Fisheries Science Center, an expert boat operator with experience of approaching sperm whales gained during the MMS-funded SWAMP trials. DTAGs were delivered using the cantilever-pole method and Mark Johnson operated this system. The other tag-boat crew, Natacha Aguilar de Soto and Peter Madsen, performed the duties of acoustic tracking, permit data fulfillment and video camera operation. All D-tag and biopsy/genetic typing activities were made under a NMFS permit #981-1707 granted to Peter Tyack, which lists Mark Johnson as a co-worker. In addition to tagging, the Balaena crew took video for photo-identification and sizing of whales. Fecal samples were collected from diving whales and skin samples were preserved from recovered tags. As radio tracking of tags from the *Delaware* was impacted by strong interference, the Balaena assisted with radio tracking of tagged whales and in recovering tags. Night-time recoveries of tags were achieved fairly efficiently from the *Delaware* although this required that the acoustic array be winched in.

Two hydrophone arrays were carried onboard the *Delaware* for acoustic tracking. The WHOI-supplied three-element hydrophone array was built for the SWSS program and deployed from the *Delaware* as a streaming array (i.e., without a depressor) using a mechanical capstan. The array was used throughout the experiment and performed well. Two software systems were used in parallel for acoustic tracking. The first, Rainbow Click from the International Fund for Animal Welfare (IFAW), provided reliable bearing estimates for distant sperm whales. The other program, developed by Walter Zimmer of the NATO Undersea Research Center in La Spezia, Italy, was most effective for close whales and was used during focal follows. Sound from the array was recorded continuously on an Alesis hard-drive recorder at a sampling-rate of 48 kHz while tracking and 96 kHz during focal follows. Acoustic observations were logged using custom software also developed by Zimmer. Sound samples were acquired digitally using Logger software from IFAW. A staff of 4 observers operated the hydrophone array providing 24 hour coverage throughout the cruise except in high sea states and during high speed transits. A summary of the tracklines covered by acoustic watches is shown in Figure 7.4.2 indicating also where sperm whales were heard.

Visual observations were made from the flying bridge of the *Delaware* and conformed to one of two protocols. While sperm whales were not present, the visual effort was led by NEFSC in a survey study. When sperm whales were located, the visual effort operated in a focal follow mode, using a protocol and data logging system developed under the SWSS program. The data logger combined navigation and observation information into a database and provided a real-time display for both the visual and acoustic personnel. The software for this system was developed cooperatively by WHOI and SACLANTCEN and was managed by Marilena Quero of WHOI. The visual data collection effort operated well throughout the campaign with the results summarized in Figure 7.4.3.

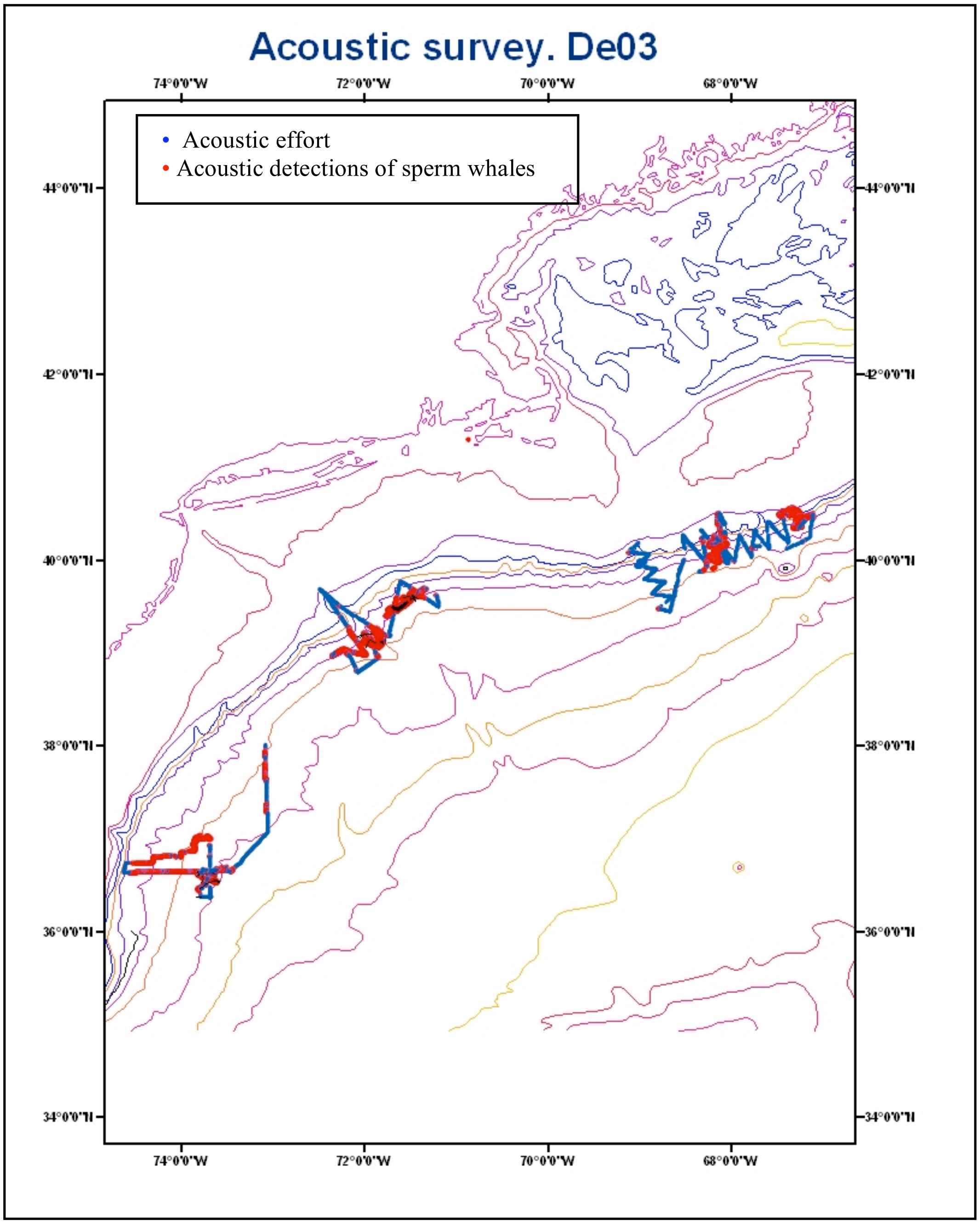

Figure 7.4.2. Acoustic survey tracklines for the *Delaware* cruise.

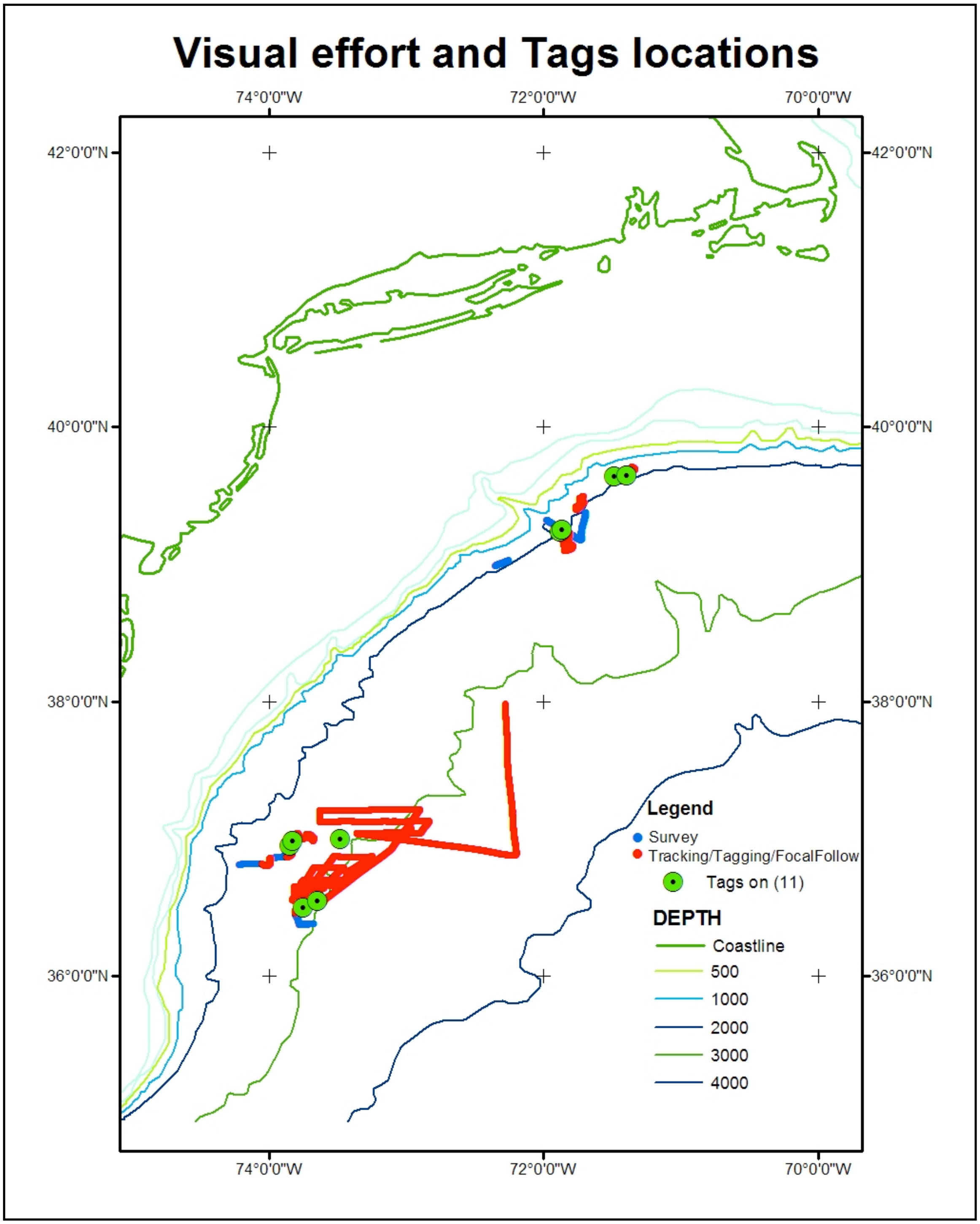

Figure 7.4.3. Visual survey and focal follow tracklines for the *Delaware* cruise.

A total of 12 tags were delivered in 7 operational days with sperm whales with the results given in Table 7.4.1. Weather was the main limiting factor: only about 45% of available at-sea days had sufficiently good weather for tagging. Considering that sperm whales were located and tracked by the *Delaware* on many of the bad weather days, the encounter rate of whales was excellent. Overall, we found the whales straightforward to approach - comparable to the most successful year in the Gulf of Mexico. 24 approaches were required to deliver 12 tags and only on one day of tagging attempts were we unable to deliver a tag. On a majority of good weather days we delivered 2 or more tags. A summary of time expenditure on the cruise is given below.

Table 7.4.1

DTAG Data Sets for the *Delaware* Cruise, North Atlantic, July 2003

Date	**Time**	**ID**	**Tag id**	**Record time / carry time (hours)**	**# of full deep dives**	**Sampling Rate, kHz**	**Skin/Fecal sample**	**Comments**
7/16/03	10:44:17	sw197a	202	2.1 / 2.1	2	96	S	
7/16/03	12:01:41	sw197b	209	2.4 / 2.4	2	96	S	Breached off
7/20/03	11:42:10	sw201a	202	3.7 / 3.7	0	96	S	Breached off
7/20/03	15:15:13	sw201b	207	3.2 / 3.2	2	96	-	
7/21/03	12:10:59	sw202a	202	1.0 / 1.0	1	96	S	Breached off
7/21/03	12:55:43	sw202b	209	2.0 / 2.0	0	96	S	
7/25/03	11:59:02	sw206a	202	3.8 / 3.8	4	96	S	
7/25/03	-	sw206b	205	0 / 6.3	-	96	F	Battery failure
7/25/03	13:12:45	sw206c	209	2.6 / 2.6	3	96	S	
7/26/03	11:28:00	sw207a	202	6.4 / 6.4	4	96	S	
7/26/03	-	sw207b	209	0 / ?	-	96	S,F	Lost at sea
7/31/03	-	sw212a	13	0 / 0	0	32	-	Breached off

Total cruise days		26
Comprising:	Lost to bad weather	11
	Successful tagging	6
	In-transit or dock-side	6
	Good weather but no sperm whales	2
	Unsuccessful tagging	1

With two exceptions, the attachment durations were fairly short (1.0-6.4 hours, see Table 7.4.1). This was due, in part, to a large number of breaches: 5 out of 12 tagged whales breached, in most cases ending the attachment. It is not yet clear whether this was in response to the tag and, if so, what leads to this sort of heightened sensitivity. A high percentage (75%) of tags yielded skin samples. Two tags failed to yield a data-set: one was not recovered due to poor weather and a possible failed VHF transmitter. A second tag had a battery failure during deployment and did not record. The cause of this problem has now been identified and rectified in the design. A third tag remained attached for less than a minute due to a breach.

Despite the short attachments, we sampled each of the usual behavioral modes of sperm whales: foraging dives, socializing, resting, and traveling. The set of 18 deep dives provides a strong initial baseline for estimates of foraging attempts and energy expenditure using metrics developed in the SWAMP and SWSS programs. In addition to sperm whale vocalizations, the tags recorded sounds from other nearby odontocetes including pilot whales, bottlenose dolphins and spotted dolphins. The sounds of passing vessels and explosions from a distant naval exercise were also collected.

Overall we found the study area to be an exceptionally good site for sperm whale tagging. However the potential for poor weather and few long attachments make the area less attractive for controlled exposure experiments. Any such experiments would also need to examine the extent to which frequent naval exercises may have pre-exposed the population to impulsive sounds.

8 SPERM WHALE LOCATIONS AND OPPORTUNISTIC SEISMIC SURVEY LINES

The International Association of Geophysical Contractors (IAGC) made available to SWSS proprietary locations and dates of seismic survey lines from 2002 and 2003 in the Gulf of Mexico. These data were compared to locations of sperm whales detected as part of SWSS. This section reports on these comparisons of opportunistic seismic survey lines and sperm whale locations. Section 8.1 presents the analysis for sperm whales that had been tagged with the OSU S-tags. Section 8.2 presents the analysis for sperm whales that had been visually observed during SWSS cruises. Both analyses are preliminary.

8.1 Seismic Survey Activity and the Proximity of S-Tagged Whales

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[1]Marine Mammal Program, Oregon State University

Introduction

Researchers from Oregon State University's Marine Mammal Program tagged sperm whales in the Gulf of Mexico with satellite-monitored radio tags (S-tags) during June/July 2002 and July 2003. The Argos Data Location and Collection System was used to obtain position data from the S-tags (Mate et al. 1997). These whale locations from the S-tags were compared to positions of active seismic vessels in the Gulf of Mexico in an attempt to determine whether satellite-tracked sperm whales occurred less frequently than expected in the vicinity of active seismic vessels (a possible indication of vessel avoidance). A total of 1,167 high-quality locations (i.e., locations estimated to be within 1000 from actual location) from S-tags on 33 sperm whales was correlated with a total of 6,821 seismic lines from the period 6 June 2002 through 16 August 2004. Seismic vessel information was provided by IAGC members and included the start and end times and locations of central shot points for each seismic line.

Methods

Argos classifies high quality locations as LC1, LC2, and LC3 with resolutions such that 68% of calculated locations are predicted to be within 350–1000 m, 150–350 m, and <150 m, respectively, of the true position (Harris et al. 1990). All high quality locations from the 33 S-tagged whales were edited to eliminate erroneous data. Positions resulting in speeds between locations more than 15 k/h were eliminated as being above the maximum capability of the animal therefore suspect in validity. When a whale location occurred between the start and end time of a seismic line, the position of the central shot point at the time of the whale location was interpolated from the start and end locations; then the distance between the whale and central shot point was calculated. Only locations within 25 km of an active vessel were considered in this analysis under the assumption that behavioral changes would be more apparent closer to the vessels.

We hypothesize that if there is no behavioral response to an active vessel, the distances between whales and seismic vessels should be randomly distributed. Conversely, if the distribution is non-random, it may be an indication of a response of the whales to the presence of an active seismic vessel. The distribution of distances was tested for randomness in two ways. The first method compared observed distances with expected distances, normalized to area, using a chi-square test for a significant deviation from randomness. The second method employed a Monte Carlo simulation of equivalent random data sets to compare with the observed data. Assumptions inherent in this analysis are that whale location accuracies are within Argos criteria, and that temporal variation and vessel differences do not affect responses in significant ways. Also vessel speeds and headings were assumed to be constant so that interpolated positions between start and end locations were accurate.

Results

A total of 30 high quality locations from 12 animals were determined to be within 25 km of an active vessel (consisting of 53% LC1, 30% LC2 and 17% LC3 locations). The time differences between start of the seismic line and whale location varied from 0.65 h to 4.8 h (mean = 2.2 h; sd = 1.24 h). Distances were tabulated into 5 km classes (Table 8.1.1). No distances were less than 5 km and five of the 30 locations were 5 - 10 km from a vessel. When more than one observation was obtained from an individual, its contribution to the distance class was inversely weighted by the total number of observations for that animal. This addressed possible effects of pseudoreplication (Machlis et al. 1985) maintaining a total sample size of 12 animals yet utilizing all the observations.

Applying the first method, the expected number of observations out of 12, in each 5 km class, was calculated by normalizing to the proportion of area the class represented in a 25 km radius circle (Figure 8.1.1). A chi-square test was performed comparing the observed frequencies with the normalized expected frequencies. There was no evidence (*p*-value = 0.71) that the data were non-randomly distributed.

For the Monte Carlo simulation, 1,000 sets of 12 randomly created locations within a 25 km radius of a central point were tabulated into 5 km classes. Using 1,000 simulations is considered a realistic number of randomizations for determining significance at the 5% level (Manly 1997). A sample size of 12 was used instead of modeling the weighting of the observed data set so that comparisons could be made with discrete values. The number of sets, containing the same number of values as observed (rounded to the nearest integer value), was calculated. The average for each class was also compared (t-test) with the observed value (Table 8.1.1). There was no evidence that the observed set came from a non-random distribution of distances since all simulated set proportions were greater than 5% and all t-test were non-significant (*p*-values > 0.05).

Because of the relatively small sample size (12) used in the analysis, it is important to consider the potential power of the statistical tests. To determine if 12 values are sufficient to detect a non-random distribution, additional Monte Carlo simulations of varying sample sizes were performed. By increasing sample size, the percent of simulated data sets with the same value as the observed set decreases. Results indicate a sample size of at least 75 is required to produce less than 5% of the sets with no distances less than 5 km; therefore, if an observed set of data consisting of 75 distances had no values less than 5 km, the data set would be considered non-randomly distributed at the 5% significance level. For the other distance categories, a sample size of at least 25 was required to produce less than 5% with values the same as the observed results.

Table 8.1.1

Tabulation of the Number of Occurrences in Each Distance Class for the Observed Data Set and the Expected Number for an Area-normalized Randomly Distributed Data Set of n=12
(The mean and standard deviation of each distance class from a Monte Carlo simulation of randomly distributed locations (1,000 sets of 12 distances) and the number of sets with the same number of class values as the observed.)

Distance class	**0-5 km**	**5-10 km**	**10-15 km**	**15-20 km**	**20-25 km**
Observed data set count (n=12)	0	1.33	0.83	4.25	5.58
Area-normalized randomly distributed count (n=12)	0.48	1.44	2.4	3.36	4.32
Mean (std dev) of Monte Carlo sets (n=1000)	0.5 (0.71)	1.4 (1.16)	2.4 (1.41)	3.3 (1.5)	4.4(1.66)
Monte Carlo sets[1] with value x	597 x=0	330 x=1	196 x=1	206 x=4	128 x=6

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[1] Number of simulated data sets out of 1,000 with same number of class values as the observed data set rounded to an integer

Discussion and Conclusions

Although distances between whales and active vessels appear to be randomly distributed, these results cannot refute a possible behavioral response because of a lack of sufficient sample size. The number of individuals would need to be doubled to have the power to detect a non-random distribution from 5 km and further. A much larger sample size (n=75) is needed for analysis closer than 5 km. Two additional sources of uncertainty are (a) the lack of controlled positional errors from the Argos-derived locations and (b) the possibility that avoidance occurs at spatial or temporal scales undetectable by the satellite transmission schedule. Moreover, the use of a central point to estimate the distance between the whale's location and a potential sound source may obscure responses to earlier or later closer approaches. Future studies would greatly benefit from the use of GPS derived locations and expanded sampling efforts.

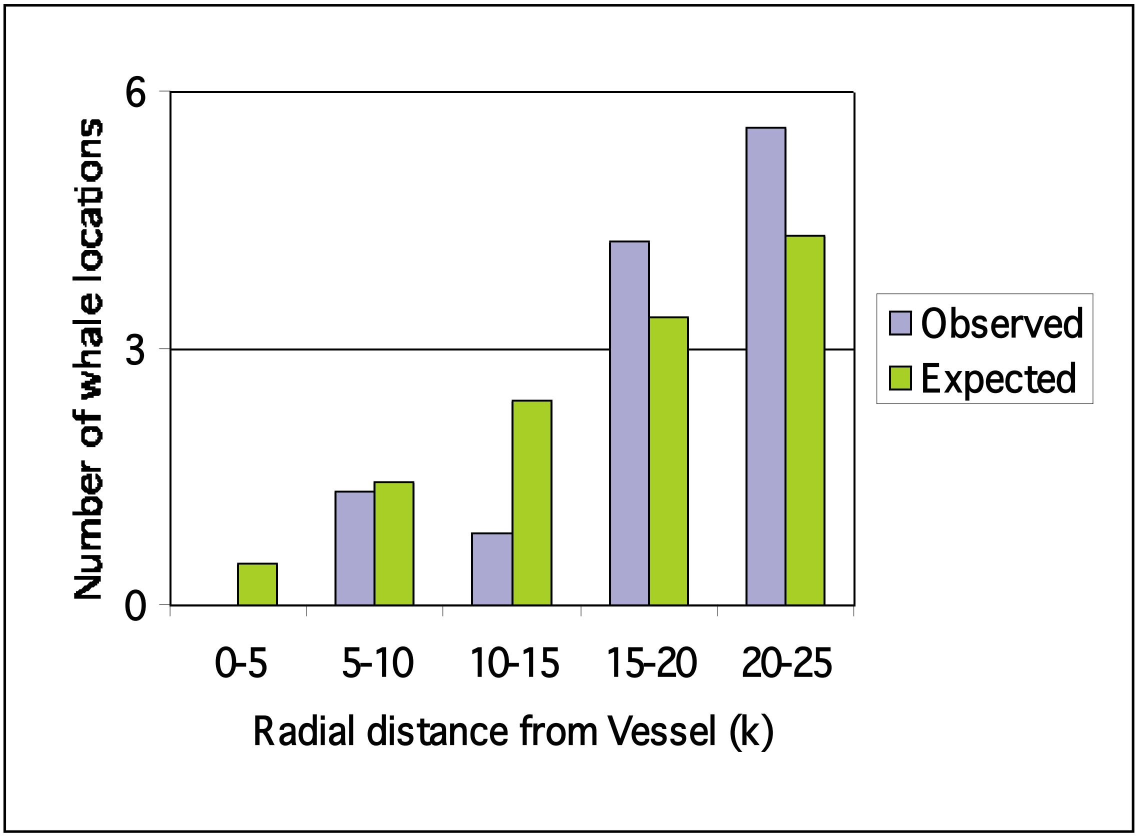

Figure 8.1.1. Comparison of the frequencies in 5 km classes of the observed distribution of distances (<25 km) between whales and active seismic vessels with expected values assuming a random distribution (n=12).

8.2 Comparison of Sperm Whale Headings Before, During and After Seismic Lines

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[3]Ecologic LTD.

Introduction

Responses of sperm whales to seismic airguns is a particular focus of investigation for the SWSS program. Two major projects within SWSS have looked for responses at widely different scales. The D-tag team have been able to measure very fine scale responses to exposures during controlled experimental exposures, lasting for of the order of a couple of hours, to airguns within 10s of kilometers. By contrast, data from the S-tags have been analyzed to investigate larger scale responses of tagged animals opportunistically exposed to real seismic surveys in the Gulf of Mexico. To be detected on satellite tracks, movements will usually have to be of the order of several miles. Here we examine responses at an intermediate scale to opportunistic exposures to seismic arrays at ranges of tens of miles. Sperm whale research cruises in the Gulf of Mexico took place at a time when seismic vessels were also operating in various parts of the Gulf. In this section we combine information on seismic survey vessel location and activity, compiled and kindly made available by IAGC, with visual observations of sperm whales at the surface made at the same time by visual observers on the RV *Gyre*.

Methods

During the SWSS cruises teams of visual observers maintained a watch for cetaceans from the flying bridge of the *Gyre* during all daylight hours, weather permitting. Most searching was done using two pairs of stand-mounted Big-Eye (25x150) binoculars supplemented by scans with naked eye or with 7x50 binoculars. Once groups of sperm whales had been detected, either by the visual team or by an independent acoustic team monitoring towed hydrophone arrays, the vessel's course and speed were adjusted to maintain contact with the whale groups so that they could be tracked and followed, typically for several hours. Small boats were usually launched to allow individual whales to be tagged, or for biopsies or identification photographs to be taken. The principal task of the visual team was then to locate sperm whales as they surfaced, to track them and to guide the small boats to them using radio communication.

During these group follows data were collected from the visual teams in a standardized manner using the Logger (by Douglas Gillespie, International Fund for Animal Welfare) data collection program. Logger saved datasets as a coordinated database and also produced a real time map of ship's tracks and whale locations. One member of the bridge team entered data into Logger as soon as it was available so that the times of sightings were probably recorded with an accuracy of better than 10 seconds. The visual observers provided, for every cluster of whales seen at the surface, the range and bearing, measured relative to the ship's head from a the big eye's bearing ring, cluster size and composition and the whale's heading (also estimated relative to ship's head). As Logger was configured to collect ship's heading (provided by a gyro compass) and ship's position (from GPS) from the ship's NMEA data line, the true heading and actual latitude and longitude of each whale could be calculated. Ranges were calculated from big-eye reticule measurements using a visual basic program (gratran) which used the equations relating angle subtended between a floating object and the horizon presented in Gordon (1990) and Lerczak and Hobbs (1998).

Observers always provided data for their initial sightings of an animal and, if it was sighted, for the final observation of the animal fluking up to dive. Sightings were assigned numbers automatically by Logger so that first sightings and fluke ups for a particular cluster could be identified as being linked during data entry. These tracking data were processed so that each record represented an observation of a particular cluster at the surface. When a fluke up as well as a linked first sighting was observed a surface time was calculated for the encounter. Note: this may be less than the true surface time because whales would rarely be seen as they surfaced, but it should be a fair index of surface time to allow comparison.

In this area, whale groups were typically encountered as assemblages which might be dispersed over several miles with whales being seen at the surface in clusters of one or two individuals. Whales in clusters almost always had the same heading and swim speed, while clusters within an assemblage also exhibited fairly consistent movements and headings.

Proprietary data summarizing particular seismic surveys for 2002 and 2003 were made available by IAGC as data files in a variety of formats. Data were extracted from these to build a database of seismic line “events”: the time and location of the start and end of each line. Where available, data on the size of the airgun array used for the survey were also stored.

The tracking and seismic data were combined using a program written in Visual Basic. A particular line start or line end event was considered linked to all tracking data which was recorded within 100 miles and within two hours of the time at which the sound of the event would reach the tracking platform. The travel time of sound from the seismic vessel location to the tracked whales’ locations were added to each line start and end time. Note that if a line lasted for less than two hours or there was less then two hours of down time before a line start or after a line end, then only the tracking data within that shorter time period were considered linked to the event. For each linked tracking event the range and bearing to the seismic start or end location was calculated and the whale’s heading relative to the bearing to the seismic line event was determined. For each line start or end event summary statistics were calculated separately for linked tracking data recorded both before and after the event time. Thus, for a line start, the tracking data for the two hours before the start and the first two hours of the line were summarized separately.

The following summary statistics were calculated for each seismic event: mean and standard deviation of whale heading relative to the location of the seismic vessel (calculated using vectors), mean range and bearing from the tracked animals to the line start, mean surface time (only for animals seen to fluke) and rate of sighting clusters at the surface. These data were analyzed as a series of matched pairs of before and after data for specific line starts and line ends. Matched pairs statistical tests, control for much variation not due to the treatment, and are more sensitive in detecting changes between the matched samples. In this case, we investigated changes in parameters before and after line starts and before and after line ends.

In addition, vessel tracks and whale locations and headings for the two hours before and after the time at which seismic events would have been heard at the *Gyre*, were plotted as maps and as animations using Logger and examined for obvious changes in behavior.

Results

During the SWSS 2002 S-tag and 2003 mesoscale cruises tracking data were collected from 2080 surfacing events. IAGC datasets provided start and end times and locations for 5684 seismic lines throughout both years. Combining these datasets yielded 29 line starts and 31 line ends within 100 miles for which there were both before and after tracking data.

The closest range for a seismic start was 6.7 miles. Only two starts were observed at less than 10 miles and only three less than 20. The distribution of ranges from tracked whale clusters to matched seismic line starts and end is shown in Figure 8.2.1. The somewhat clumped distributions probably represent the effects of particular surveys occurring at different ranges from major whale aggregations.

Figure 8.2.2 shows the distribution of all recorded whale cluster headings relative to the bearing to linked seismic lines for all lines within 50 nm. The distribution of relative headings is quite uniform and there is no indication that whales are preferentially heading either towards or away from the seismic vessel. Because whales in aggregations tend to show consistent headings over periods of several hours these data points are not independent. They are presented here for illustrative purposes but are not tested statistically.

To test whether whale behavior was modified when seismic lines started or ended, summarized data (average relative heading, average surface time, and sighting rates), were compared before and after line starts and before and after line ends using Wilcoxon signed rank non parametric tests for related samples. No significant differences were detected. Tests were repeated using data for ranges out to 100 miles, for ranges less the 50 miles and for ranges less than 25 miles. The results of these tests are summarized in Table 8.2.1.

Figure 8.2.3 presents Logger plots showing the boat's movement as well as whale locations and heading for two hours before and two hours after examples of line starts at shorter ranges. These plots were also viewed as animations. No obvious changes in movement or heading are evident in these.

Discussion

This analysis provides no indications of responses from sperm to seismic line starts or line ends at ranges of 10s to a hundred miles. This observation is generally in line with those reported in Madsen et al. (2002c) that large male sperm whales in Norway showed no obvious response to seismic pulses at a range of 20 km.

A number of caveats need to be kept in mind when considering this negative result.

1. Generally, observations were made at substantial ranges from the seismic vessel. There were rather few observations at ranges less than 20 miles. This data set can only inform us about lack of responses at ranges of this magnitude.

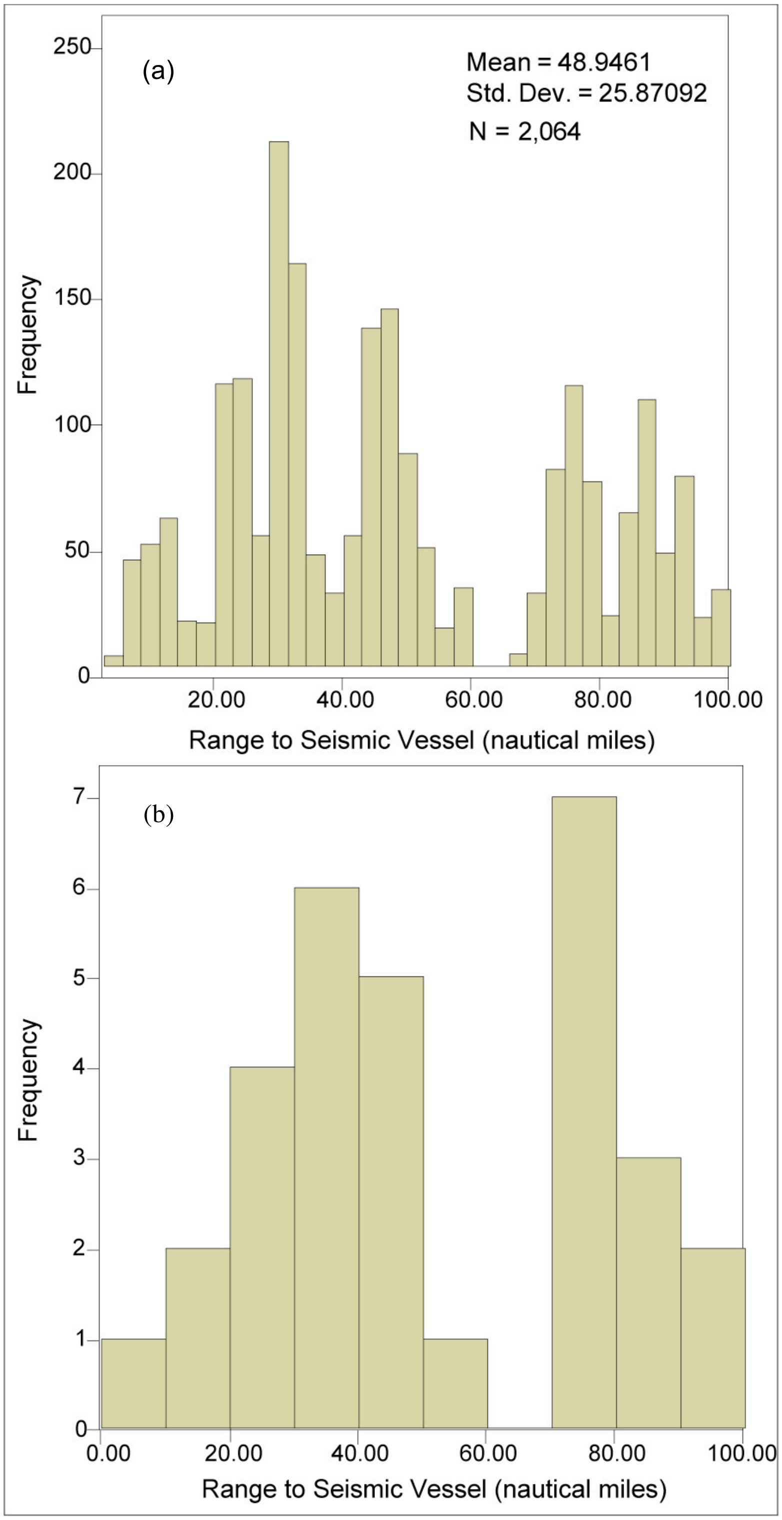


Figure 8.2.1. Ranges from all seismic line starts and ends to (a) matched tracking data and (b) mean ranges for seismic end events.

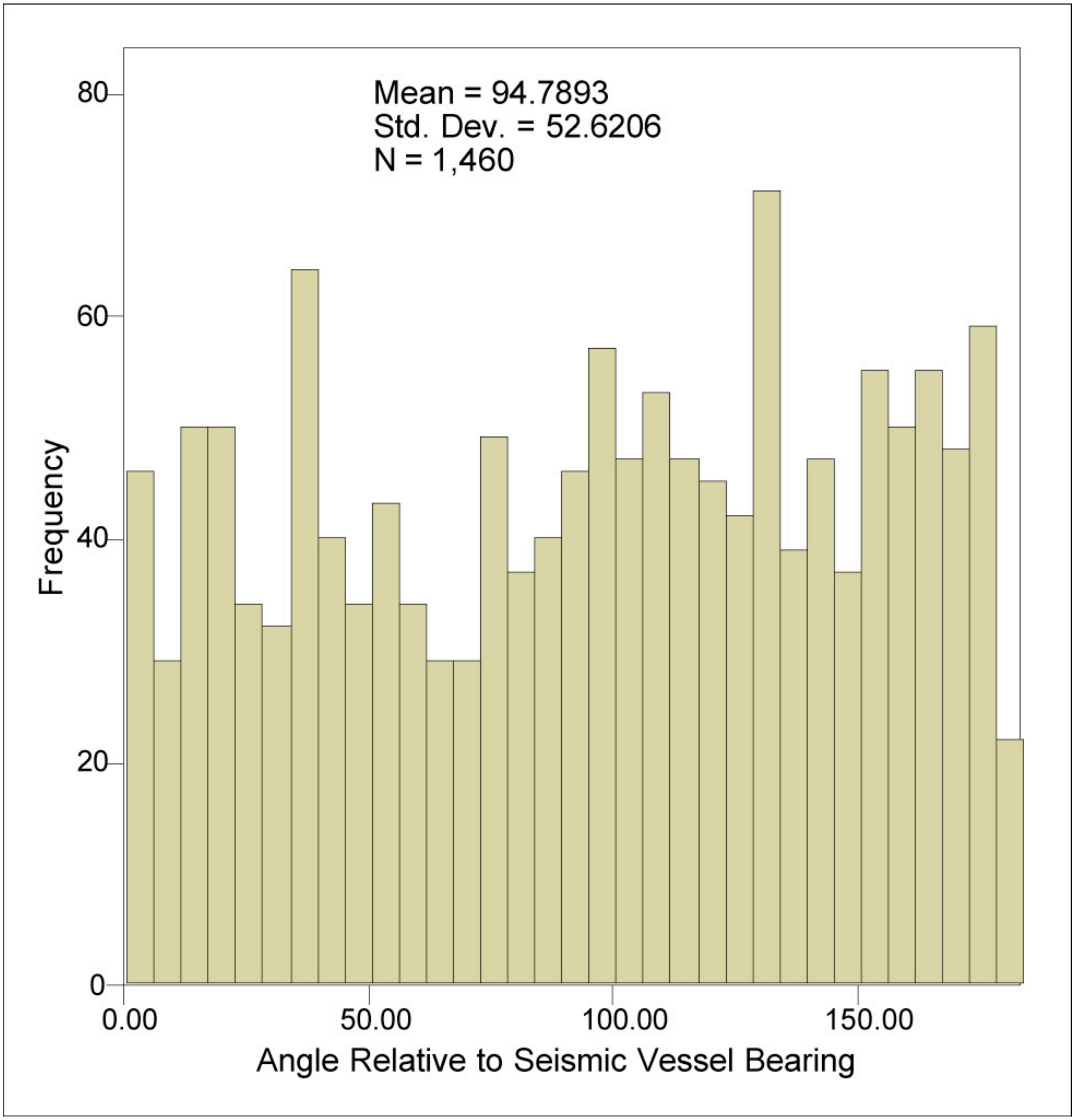


Figure 8.2.2. Distribution of all recorded whale cluster headings relative to the bearing to linked seismic lines for all lines within 50 nm of the cluster.

Table 8.2.1

Comparisons of Relative Heading, Surface Time and Sighting Rates Before and After Seismic Line Starts and Seismic Line Ends at Different Ranges

	Before Mean (n)	**After Mean (n)**	**Significance (2 tailed)**	**Range to Seismic Vessel Nautical Miles**
Seismic Line Starts				
Relative Heading	108 (28)	102 (28)	.524	<100
Surface Time (secs)	905 (23)	460 (23)	.125	<100
Sighting Rate (Sighting hr^{-1})	11.1 (27)	11.29 (27)	.962	<100
Relative Heading	106 (16)	108 (16)	.717	<50
Surface Time (secs)	457 (14)	403 (14)	.470	<50
Sighting Rate (Sighting hr^{-1})[1]	11.1 (16)	12.1 (16)	.756	<50
Relative Angle	121 (6)	124 (6)	.463	<25
Surface Time (secs)	450 (5)	386 (5)	.138	<25
Sighting Rate (Sighting hr^{-1})	10.1 (6)	11.7 (6)	.917	<25
Seismic Line Ends				
Relative Heading	105 (30)	111 (30)	.309	<100
Surface Time (secs)	571 (23)	720 (23)	.753	<100
Sighting Rate (Sighting hr^{-1})	11.8 (29)	15.7 (29)	.214	<100
Relative Angle	101 (17)	110 (17)	.332	<50
Surface Time (secs)	420 (15)	403 (15)	.910	<50
Sighting Rate (Sighting hr^{-1})[1]	12.8 (16)	17.8 (16)	.469	<50
Relative Angle	82 (5)	77 (5)	.893	<25
Surface Time (secs)	418 (4)	298 (4)	.273	<25
Sighting Rate (Sighting hr^{-1})	13.6 (5)	22.6 (5)	.225	<25

2. The observation method can not be considered very precise. Some of the recorded parameters, such as whale heading, are difficult to estimate at ranges of over a mile using binoculars. Whales were also likely to be responding to many other factors, including the small research boats which were closing with them for tagging and photo-id.

3. Photo-id analysis and satellite telemetry has shown that many of the whales in the Northern Gulf of Mexico are long term residents.. Such residents will have been exposed to seismic survey noise in the Gulf of Mexico for several years, if not decades. The specific whales we observed would also have been exposed to the specific particular seismic surveys being considered for some time before our observations started.

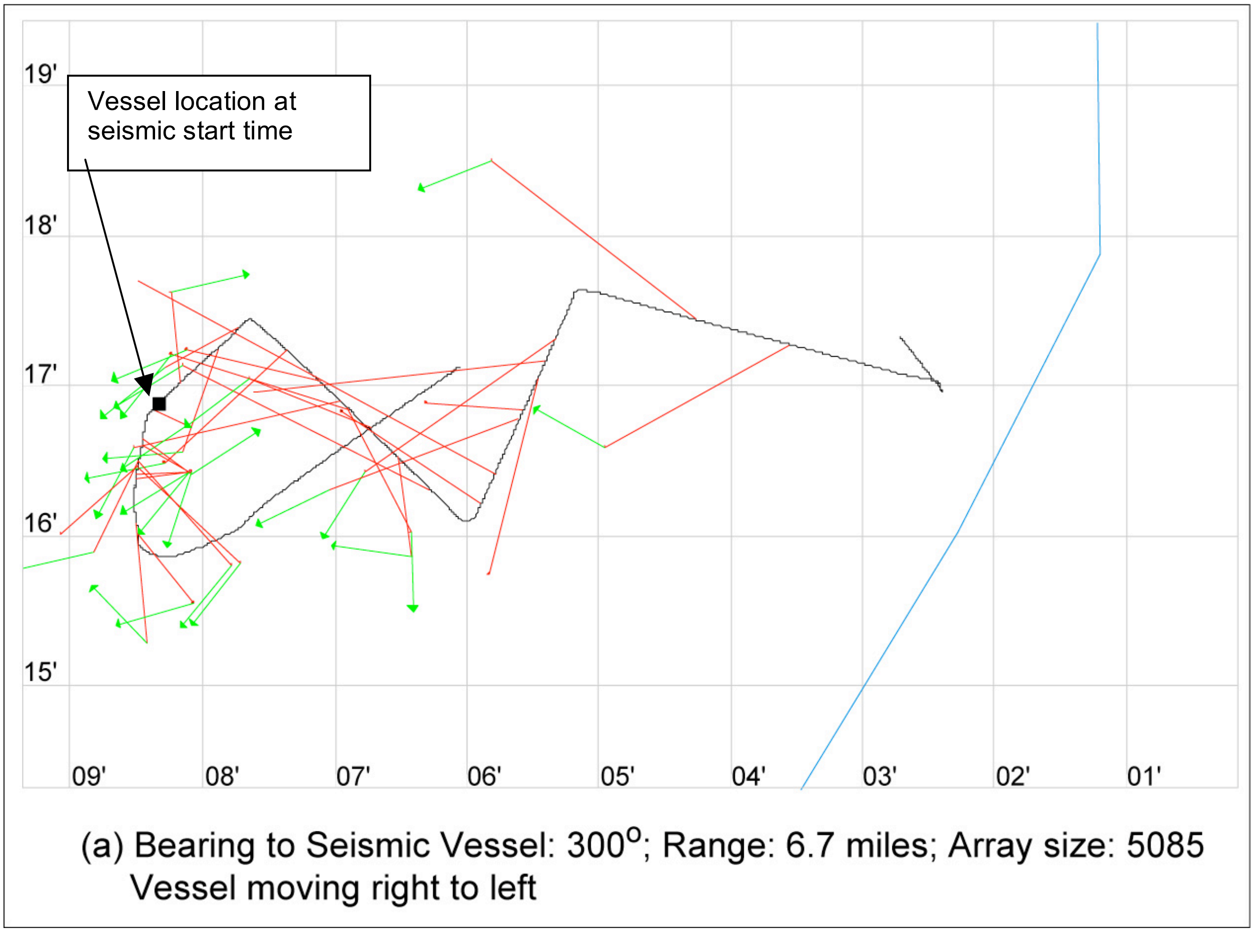
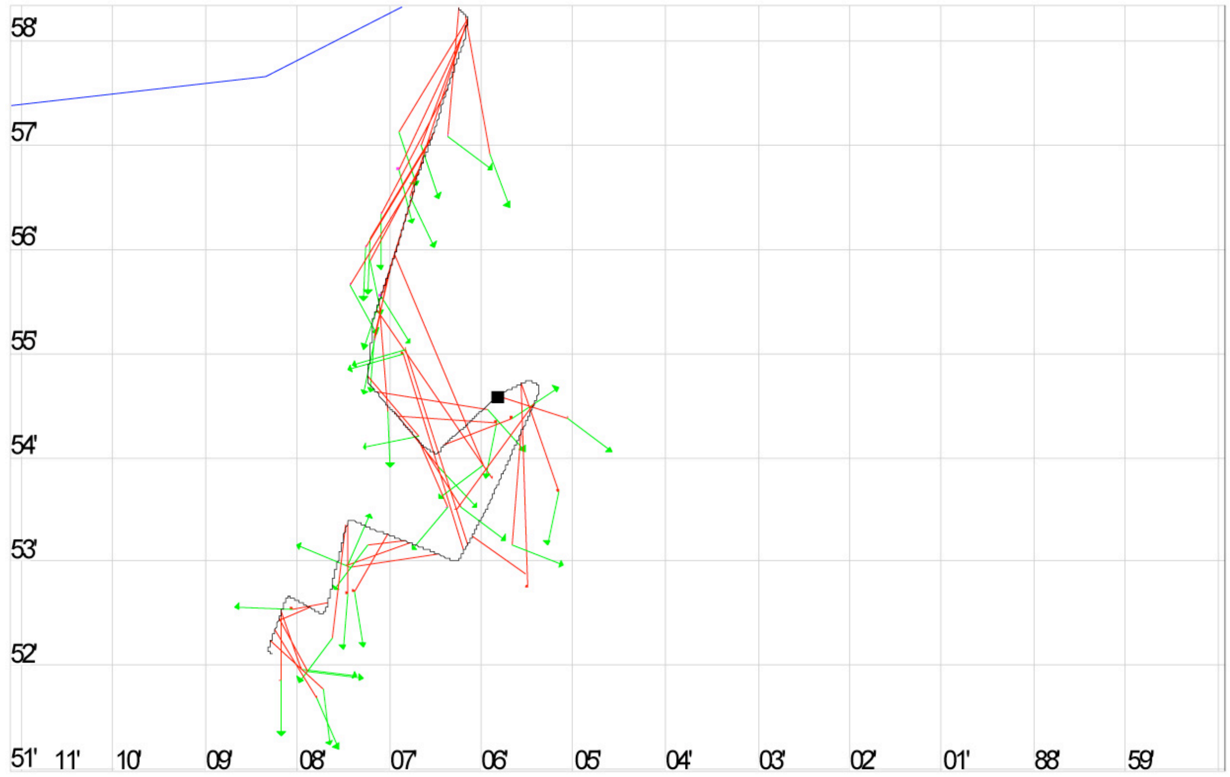


Figure 8.2.3. Maps showing *Gyre* tracks and sperm whale locations and headings for the 2 hours before and after selected seismic survey line starts. *Gyre* track is shown as the black line. Red lines extend from the *Gyre* track to the location of whales sighted at that time. Green arrows show the direction of movement of the tracked whale clusters. Blue line shows the track of the seismic vessel. The black square on the *Gyre* trackline shows the vessel's location at the time of the seismic start.

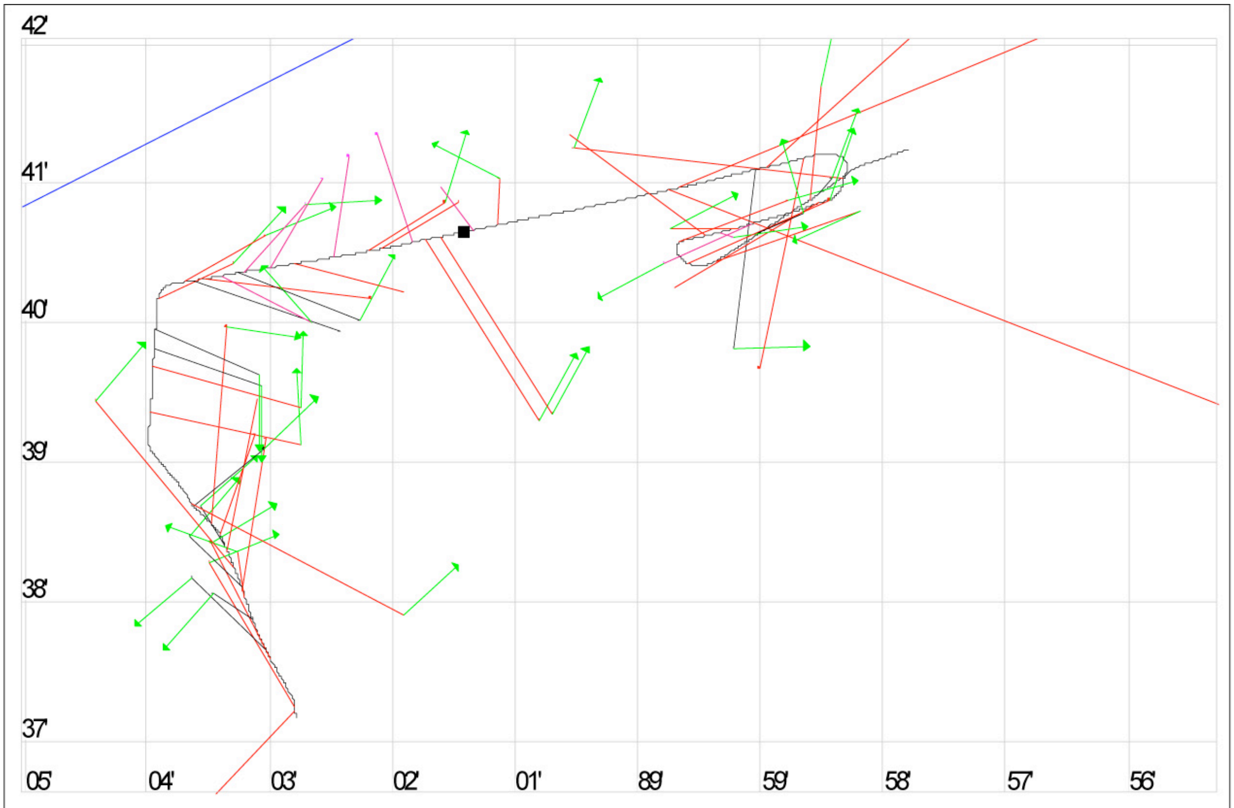
The low number of observations at reasonable ranges that result from purely opportunistic studies like this one point to the necessity of either undertaking controlled exposure experiments or conducting field work closer to areas in which seismic surveys will be carried out. The former course of action can be very expensive if full scale sources are to be used, the latter strategy requires considerable cooperation from seismic operators.

This analysis would not have been possible if IAGC had not taken the initiative to collate data on seismic surveys in the Gulf of Mexico. This points to the importance of maintaining databases of human noise making activities in this way. Any future use of data like this would be facilitated if data are collected in a standard format. The very small number of observations that were made at short or moderate ranges points to the necessity of either conducting experimental exposures or collaborating with seismic operators to make opportunistic observations close to seismic surveys to obtain data on behavioral responses at short ranges.



(b) Bearing to Seismic Vessel: 157°; Range: 9.5 miles; Array size: 5085
Vessel moving top to bottom

Figure 8.2.3. Maps showing *Gyre* tracks and sperm whale locations and headings for the 2 hours before and after selected seismic survey line starts. (continued)



(c) Bearing to Seismic Vessel: 187°; Range: 21.6 miles; Array size: 5085
Vessel moving right to left

Figure 8.2.3. Maps showing *Gyre* tracks and sperm whale locations and headings for the 2 hours before and after selected seismic survey line starts. (continued)

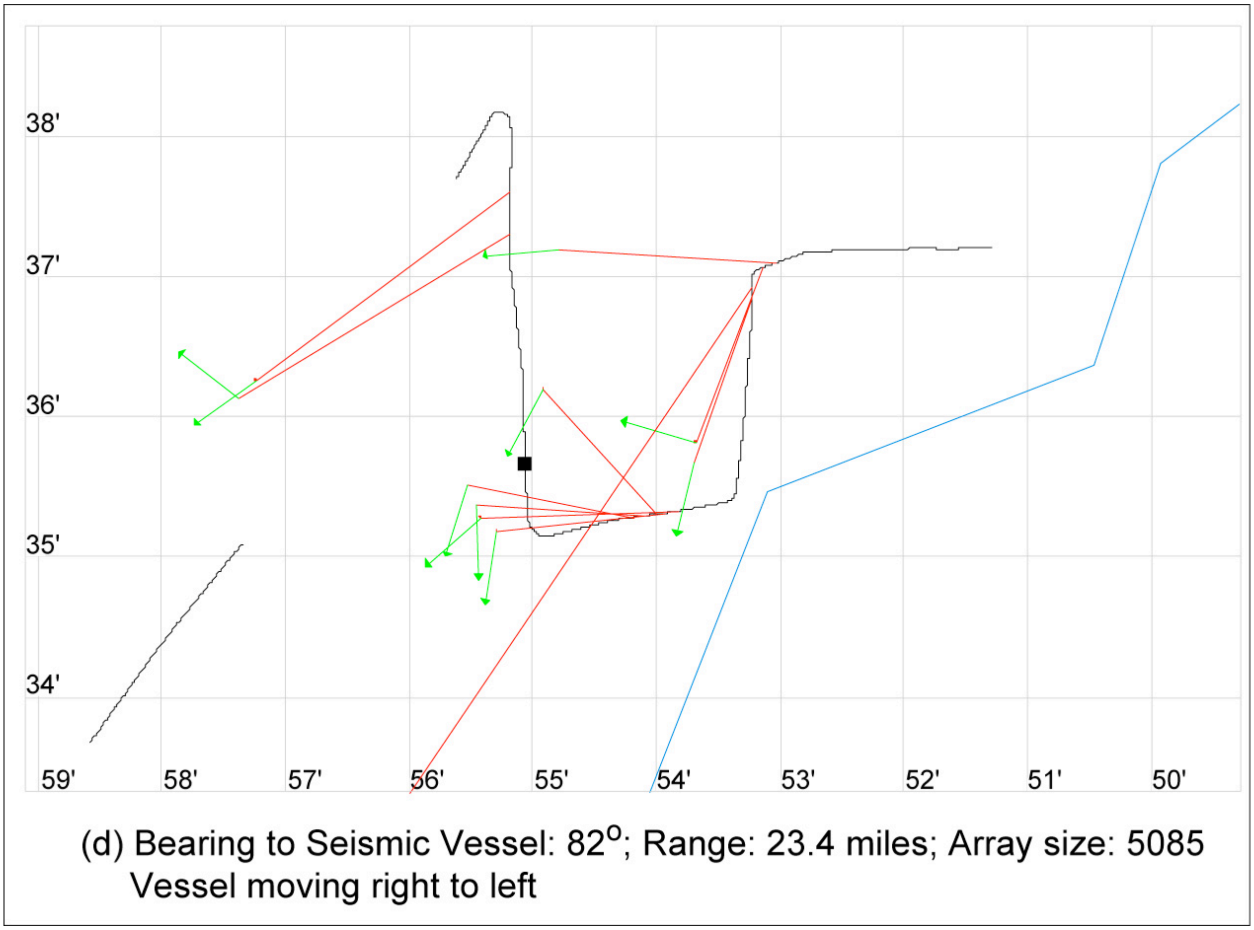
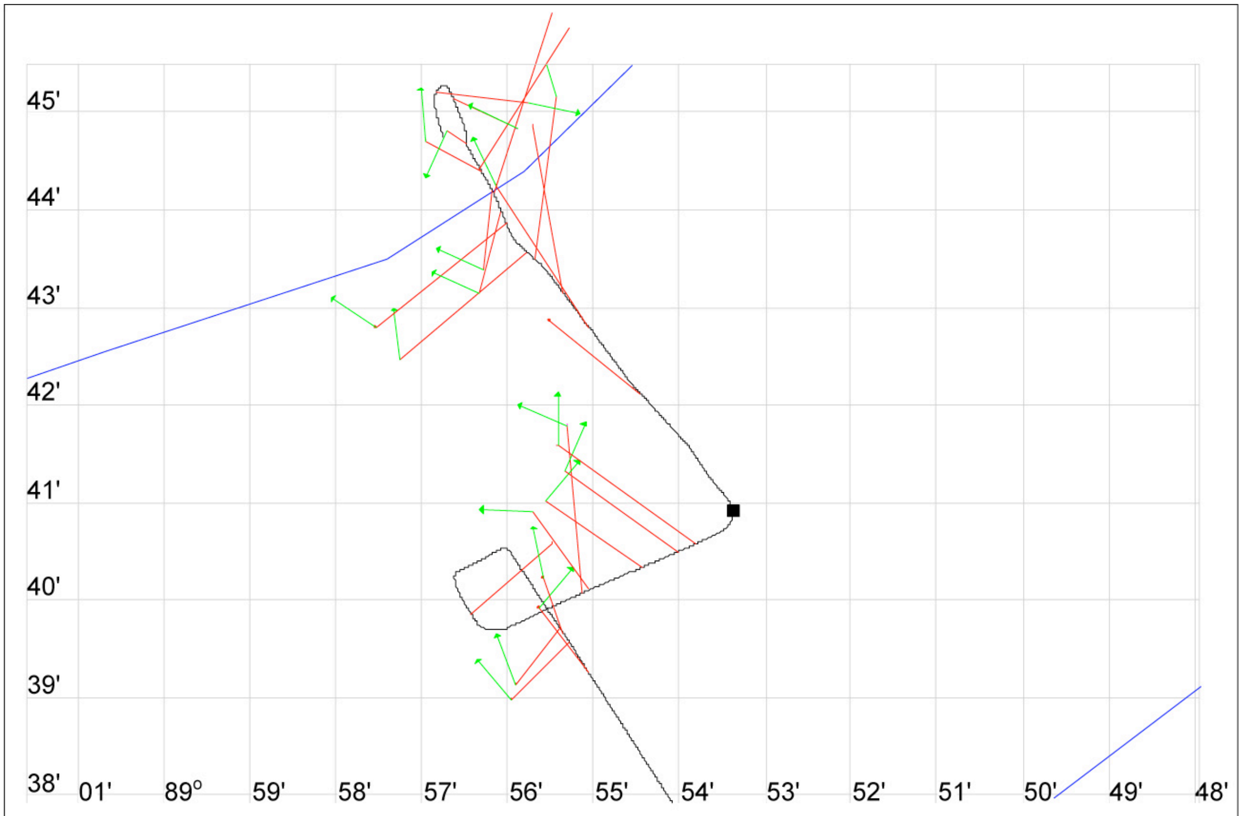
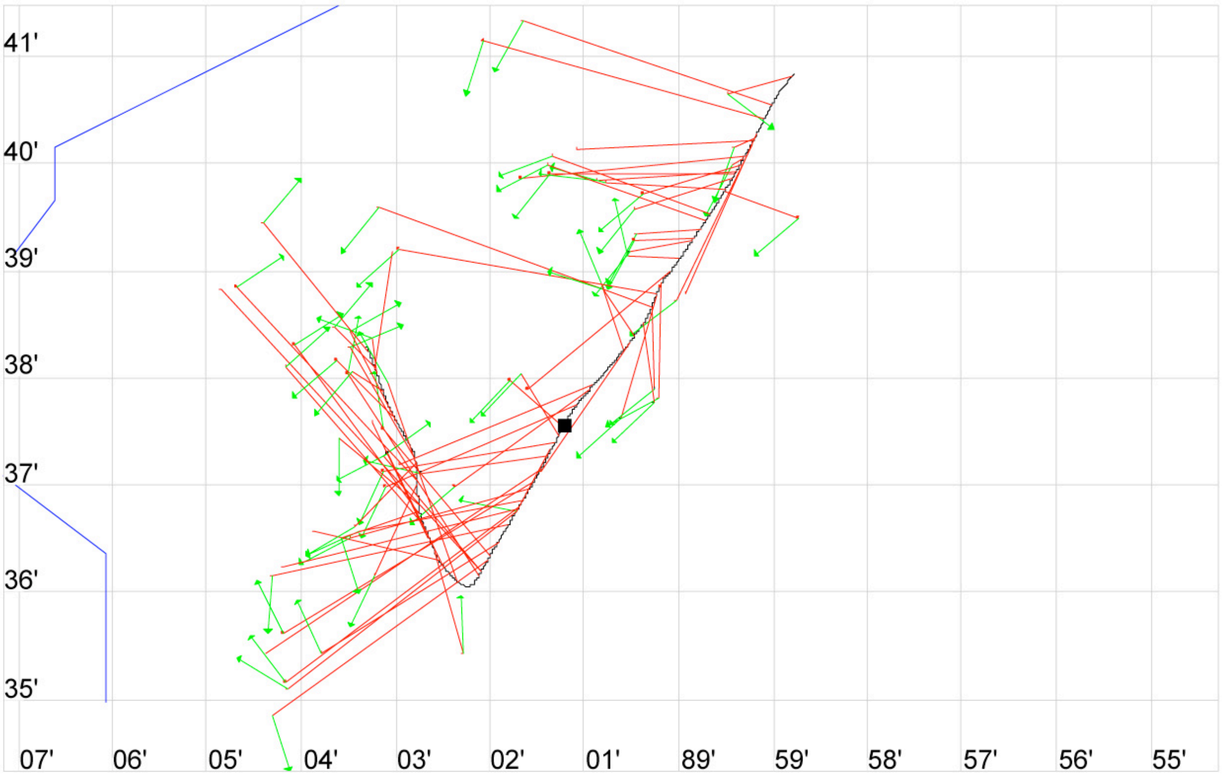


Figure 8.2.3. Maps showing *Gyre* tracks and sperm whale locations and headings for the 2 hours before and after selected seismic survey line starts. (continued)



(e) Bearing to Seismic Vessel: 300°; Range: 6.7 miles; Array size: 5085
Vessel moving right to left

Figure 8.2.3. Maps showing *Gyre* tracks and sperm whale locations and headings for the 2 hours before and after selected seismic survey line starts. (continued)



(f) Bearing to Seismic Vessel: 101^{o}; Range: 46.2 miles; Array size: 5085
Vessel moving top right to bottom left

Figure 8.2.3. Maps showing *Gyre* tracks and sperm whale locations and headings for the 2 hours before and after selected seismic survey line starts. (continued)

9 SPERM WHALE 3-D PASSIVE ACOUSTIC TRACKING DURING SWSS 2002-2004

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Sperm whales are a very vocally active species, and detecting their signals, or "clicks," using towed passive acoustic arrays has become a standard procedure for locating and monitoring for the presence of these animals. Most passive array systems also have the ability to estimate the direction from which a particular sound is arriving from, by measuring the signal's arrival time difference at two hydrophones spaced a few meters apart. The range to a whale can be estimated by measuring how the measured bearings from a particular animal shift over time while the observation platform is moving. If the velocity of the platform is much larger than that of the animal, then the bearings will converge to a particular range over a 3-10 minute interval. Unfortunately, the speed of seismic vessels is not much faster than sperm whale swimming speeds, so at present there is no reliable way for ranging sperm whales using standard mitigation procedures. In addition, knowledge of the animal's depth becomes important for mitigation purposes whenever the animal of concern is deep-diving and the acoustic source is highly directional at certain frequencies, as is the case with seismic airgun arrays.

In 2003 and 2004 the SWSS project supported efforts to develop a three-dimensional tracking method for sperm whales using various combinations of towed acoustic gear. All methods rely on the fact that sperm whale sounds have such a short time duration that the surface-reflected acoustic path can often be distinguished in time from the direct path arrival. The basic concept was first demonstrated during the 2002 SWSS D-tag cruise, using data from two towed arrays. The idea was demonstrated again in 2003 by simulating a large-aperture towed array, by attaching an autonomous acoustic recorder to a rope attached to a standard passive acoustic array. Based on these results, the IRFC provided funds to build a dedicated towed array to demonstrate routine 3-D tracking of sperm whales during the 2004 SWSS S-tag cruise. The 400 m long "tandem" towed-array system was successfully deployed from the R/V *Gyre* during the entire cruise, and over two weeks of acoustic data were recorded, mostly at night, and a near real-time ranging algorithm was assembled in the field. Some initial 3-D tracks have been analyzed, and their veracity checked using a variety of methods. The effects of ray-refraction from a depth-dependent sound speed profile have also been evaluated, and to date seem to be negligible for ranges of 1 km or less. Aspects of this algorithm have been published in the peer-reviewed literature. The two analytical formulas and one numeric algorithm discussed here have been independently checked using the timing of bottom-reflected returns, and collectively they seem to be a promising alternative to standard methods of 3D acoustic tracking that would require a large-aperture volumetric array.

The tracking results derived from the methods presented here are at present being integrated with backscattering measurements collected by Kelly Benoit-Bird, Oregon State University, as part of the SWSS 2005 S-tag cruise. In addition, data collected on the 2005 S-tag cruise from an acoustic "b-probe" tag are being merged with data from a towed array to perform a very large-aperture array, demonstrating that acoustic data combined from a recording tag and a towed array can be combined to permit 3-D tracking of other untagged animals over extended ranges.

9.1 Background

The use of towed arrays for passive acoustic monitoring (PAM) and bearing estimation of marine mammal sounds is a mature technology. Several commercial vendors provide towed array hardware, and there are at least three public or proprietary software packages for automatically extracting bearings from two hydrophones of a towed array.

Unfortunately, none of these packages currently provide an accurate, automated means for immediate ranging of acoustic detections. At present ranges are generally estimated by measuring how a set of bearings measured from a moving platform evolve with time, but this procedure assumes that the vessel is moving much faster than the animals in question. At typical tow speeds of 4 knots for seismic vessels, this assumption is invalid. Furthermore, obtaining a range estimate via this approach usually requires several minutes of continuous vocalizing, and assumes that individuals vocalizing simultaneously can clearly be distinguished, conditions which are not met by several cetacean species.

Some algorithms assume that measuring the received level of a signal, and comparing this level to a reference database of typical source levels, can provide a range estimate, but data on source levels are scarce, several marine mammal sounds are now understood to be highly directional (Møhl et al. 2000; Thode et al. 2002), and the logarithmic relationship between received level and range makes this approach very insensitive to range.

Finally, for certain species of deep-diving mammals, including sperm whales and presumably beaked whales, the depth of an animal really needs to be known to distinguish the "slant range," or the distance between the array and the animal, from the "horizontal range," or horizontal distance between the array and the animal. For highly directional sources this distinction may be important—the received sound level obtained by an animal 1 km directly below a towed airgun array would be substantially different from that received by an animal at 1 km horizontal range, even though the slant ranges for both animals would be the same.

The MMS 3D tracking effort uses signals collected across a large-aperture PAM system to estimate animal ranges and depths, while making no assumptions about an animal's signal characteristics. The concept was first demonstrated off the R/V *Gyre* and R/V *Ewing* in 2002 and 2003. In 2004 a dedicated prototype towed array system was assembled with IRFC support. The total "tandem" array is comprised of six hydrophones on a single cable, arranged as two sub-arrays of three phones each, with the sub-arrays separated by 200m. Each sub-array also has a pressure transducer that permits the depth of each sub-array to be logged independently.

In the following sections the theory behind the tracking system is reviewed and illustrated using data collected for a proof-of-concept tests conducted in 2002. Field work in the 2003 and 2004 field seasons is then discussed. The 2004 season in particular is covered in great detail, including a description of the field season, an analysis of results to date, and an appendix (Section 9.6) containing technical specifications of the new "tandem" towed array.

9.2 Concepts

The 3-D tracking method requires at least two widely-separated hydrophones to obtain the horizontal range and depth of acoustically active sperm whales, and would thus be suited for eventual use on a standard seismic vessel, where the passive acoustic arrays (streamers) can be over a kilometer long. Instead of relying on four hydrophones deployed as a three-dimensional array (which would be difficult to deploy and process), the method used here exploits surface multipath (or “ghosts”) to reduce the number of required hydrophones to three, and permits the phones to be deployed along a single towed cable. The horizontal separation between the widely-spaced hydrophones needs to be at least 200 m in order to obtain adequate range and depth resolution at 1 km horizontal range. The method does not require the use of multipath from the ocean bottom, but when such bottom returns are detected they can provide an independent confirmation of these tracking procedures (Thode et al. 2002).

There are actually two separate algorithms for tracking the range and depth of a sperm whale. Technique “A” requires only two hydrophones, and was tested in 2002 and 2003 (Thode 2004). The second technique, “B,” requires a third hydrophone, but seems considerably more robust to ship noise and uncertainties in hydrophone depths, and was the focus of work in 2004.

Description of “A” Technique Using 2002 Data

On 5 September 2002, a feasibility test of method “A” was conducted during the DTAG cruise on the R/V *Gyre*, during weather conditions that were too rough to permit tagging activities. Two arrays (one from Woods Hole Oceanographic Institution (WHOI), the other from Ecologic LTD.) were deployed simultaneously in a semi-tandem configuration. The Ecologic array was deployed approximately 300 m behind the stern, whereas the WHOI array was deployed 20 m behind the vessel, using a dive wing to obtain a depth of 100 m. Figure 9.1 illustrates the concept.

Figure 9.2 shows a spectrogram display that demonstrates the measurements required to calculate the animal location. he top spectrogram display shows data from one hydrophone from the forward array, and the bottom display shows a simultaneous recording from a hydrophone on the rear array. The display shows how three pieces of information can be obtained from each sound, or ‘click’ an animal makes: the difference between the arrival times of the direct and surface-reflected paths($P_{ds,x}$) on the forward (*F*) and rear (*R*) hydrophones, and the arrival time difference between the direct paths on both hydrophones (P_{dd}).

From geometric considerations the following expression can be derived relating slant range from the forward array(P_d) to these three parameters, assuming straight-line ray propagation (Thode 2004):

$$\frac{z_{a,F}}{z_{a,R}} = \frac{P_{ds,F}\left(2P_d + P_{ds,F}\right)}{P_{ds,R}\left(2P_d + 2P_{dd} + P_{ds,R}\right)} \qquad \text{(1a)}$$

Rearranging for the slant range P_d:

$$P_d = \frac{P_{ds,F} - \left(P_{ds,R} + 2P_{dd}\right)\left(P_{ds,R} z_{a,F} / P_{ds,F} z_{a,R}\right)}{2\left(P_{ds,R} z_{a,F} / P_{ds,F} z_{a,R}\right) - 2} \qquad \text{(1b)}$$

The ratio on the left-hand side of (1a) is the ratio between the two hydrophone depths. Thus if the array depths are known, the slant range can be determined, from which the whale depth (z_w) can be computed using the formula

$$z_w = \frac{P_{ds,R}\left(2P_{d,F} + P_{ds,R}\right)}{4z_{a,R}} \tag{2}$$

The horizontal range can then be computed from Eq. (2) and the slant range. Note that the separation between the two hydrophones does not have to be known, if only whale depth and range are desired. Indeed, Eqs. (1) and (2) are equally valid for a vertical array deployment. However, if the animal's azimuth is also needed, then either the hydrophone separation needs to be measured, or one of the two locations must be occupied by a two-element hydrophone array, instead of the single hydrophone previously assumed. In addition, if one of the hydrophones is recorded on an autonomous recorder, the horizontal separation would need to be known to compensate for recorder clock drift.

The algorithm performance would be best whenever the animals are directly ahead or behind the towing vessel, and performance would degrade whenever the animals are broadside of the arrays (when P_{dd} is effectively zero).

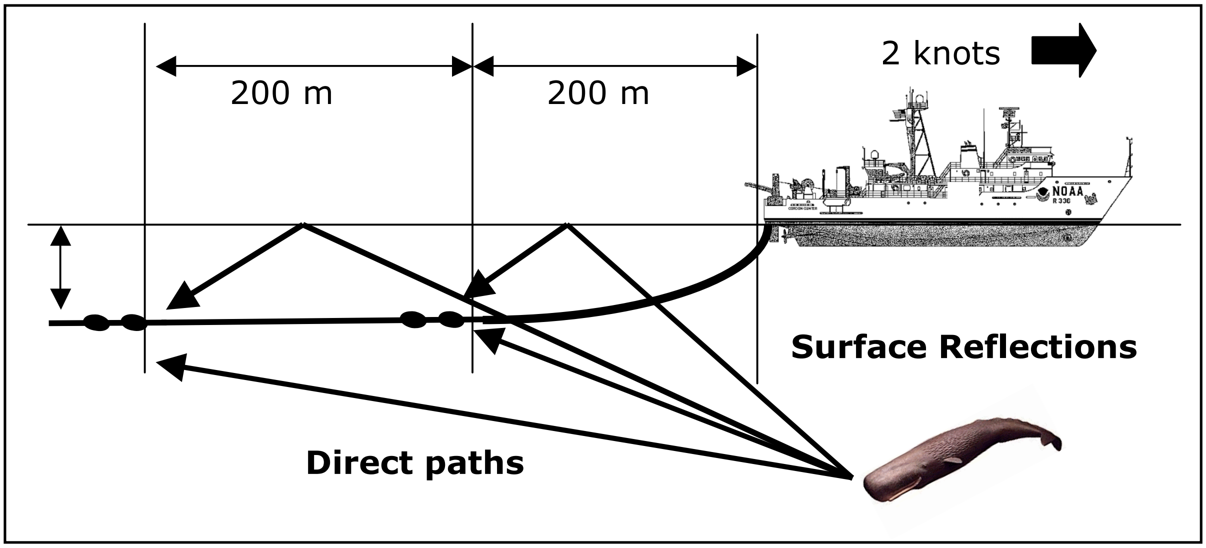


Figure 9.1. Illustration of 3-D tracking concept. Surface-reflected paths provide enough information to derive range and depth of a sperm whale, provided that at least two hydrophones are widely separated.

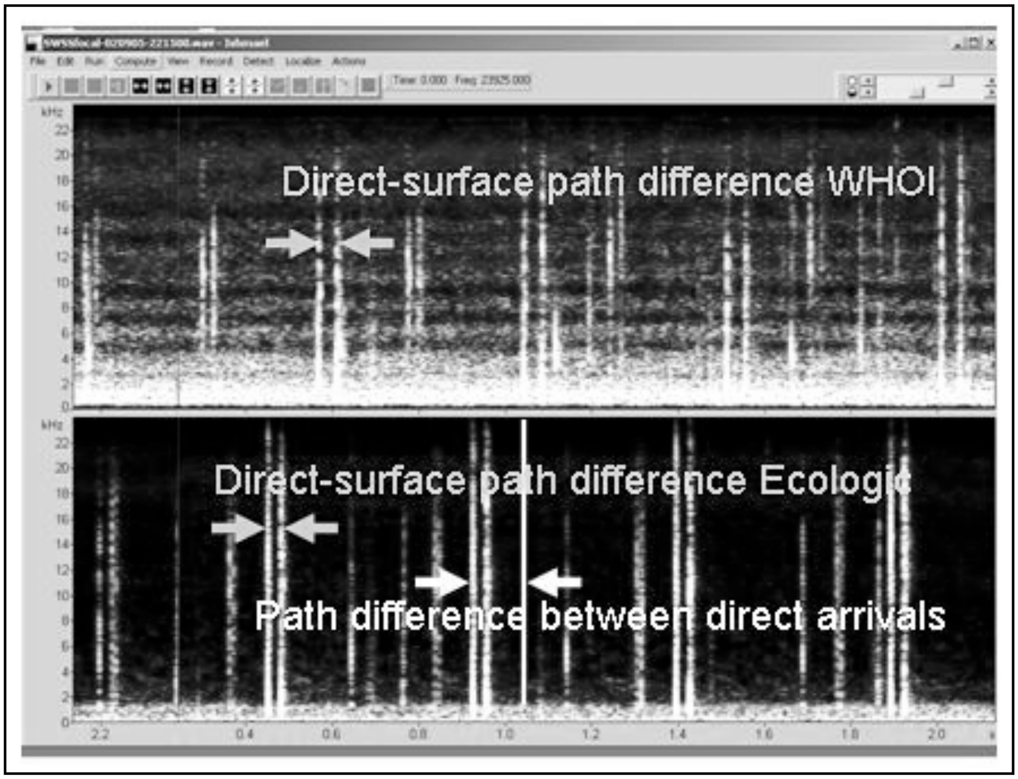


Figure 9.2. Spectrograms of data collected during 2002 3D tracking experiment, as viewed with Ishmael (Mellinger 2002) software. The top display is from a hydrophone of the forward array, and the bottom display is from a hydrophone in the rear array. The three arrival-time differences indicated in the diagram can be used to obtain animal range and depth, if both array depths are known.

An example of applying this method to the 2002 data is shown in Figure 9.3. Two clean dive profiles are clearly visible, and were obtained from whales forward of the bow, while the blue track was derived from a whale broadside to the arrays, which yielded an unstable inversion. Unfortunately, the depth of the WHOI array was not known at the time, so the depth had to be estimated.

Summary of “A” Method

In summary, the “A” tracking method requirements and restrictions are as follows:

(1) Two hydrophones must be spaced at least 200 m apart to track whales at to 1 to 2 km range. Ideally, one of the locations should contain a short-aperture towed array, so that the animals’ azimuths can also be obtained.

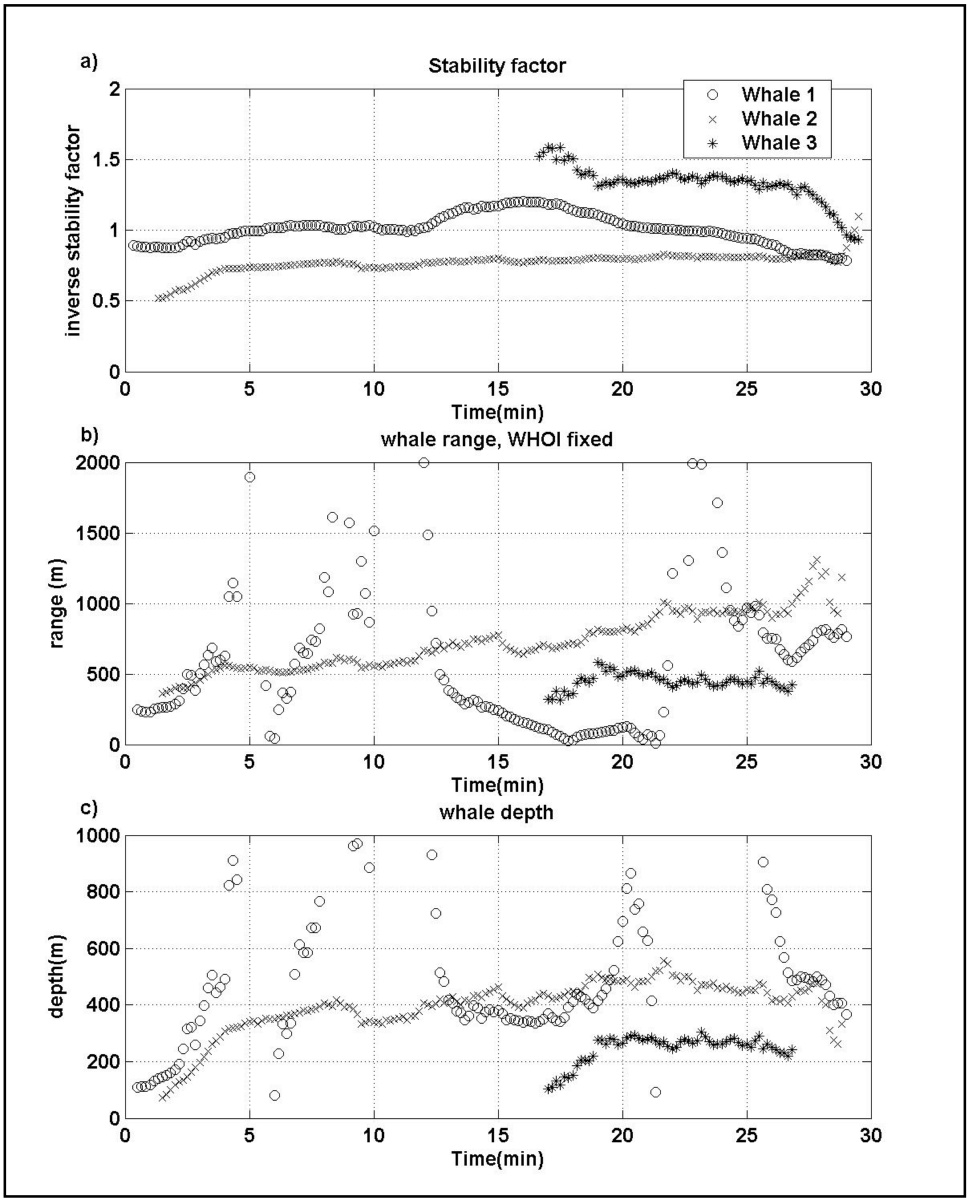


Figure 9.3. Derived ranges and depths of three whales in 2002 using 3D passive acoustic localization algorithm "A". Whales 2 and 3 are forward or behind the ship, and can be tracked consistently, while Whale 1 is broadside to the two arrays, a situation that makes Eq. (2) unstable.

(2) The best resolution is achieved if the animals are either directly ahead or behind the vessel towing the hydrophones, in other words, *endfire*. This orientation is completely different than what is desired for measuring bearings from a towed array. In that case, the best bearing resolution is obtained when the animal is *broadside* of the array.

(3) Each hydrophone should be at least 30 m deep, in order to obtain large values of $P_{ds.}$. Consequently, if arrays are used, the array tow speeds generally must be low, less than 3 knots, unless the hydrophone cable is attached to a dive wing.

(4) The hydrophone depths must be recorded accurately and continuously. The deeper the array, the less precise the measurement needs to be, but 1 m accuracy seems to be a good rule of thumb.

(5) The change in water sound speed with depth should be sufficiently low such that the straight-line travel time approximation assumed in Eq. (1) is valid. Generally, studies evaluating the effect of ray curvature on travel time have concluded that the extra time delay is small for target ranges less than 1 km (Thode et al. 2002; Wahlberg et al. 2001), but the results of Eqs. (1) and (2) should be compared with a full-scale acoustic propagation model, such as SCOOTER or BELLHOP (Porter 1991), in order to validate the straight-line assumption. Later in this chapter such an analysis is conducted.

<u>Description of "B" Technique</u>

While method "A" was demonstrated to work in 2002 and 2003, a sensitivity analysis found that the results were highly dependent on accurate measurements of the hydrophone depths. Thus an alternate approach for tracking sperm whales, "B", was developed between 2003 and 2004. The differences between the arrival times of the direct and surface-reflected paths ($P_{ds,R}$) on the rear (R) hydrophone are still used, as is the arrival time difference between the direct paths on both hydrophones (P_{dd}). However, an estimate of the direct path bearing on the rear hydrophone (η_d) is now required, instead of $P_{ds,F}$. Thus an additional hydrophone is needed at the rear position to create a short aperture "sub-array" that can estimate acoustic arrival angles. The separation L between the forward and rear hydrophone sites also has to be known. Given this information one finds the slant range from the forward hydrophone site to be

$$P_{d,F} = \left(\frac{1}{2}\right)\frac{2LP_{dd}\cos\eta_d - L^2 - P_{dd}{}^2}{P_{dd} - L\cos\eta_d} \qquad (3)$$

from which the whale depth can be determined from Eq. (2). The method assumes that the vertical tilt of the rear subarray is equivalent to the effective tilt of the entire cable between the forward and rear hydrophone (i.e. the towed array cable is effectively straight between the forward and rear hydrophone). If this is not the case, expanded forms of (3) can be derived. The expression in the denominator of Eq. (3) indicates that the method will work as long as the animal is close enough such that the "wavefront" defined by the pulse is curved. Put another way, Eq. (3) should work as long as an acoustic bearing measured from the front hydrophone site differs from a bearing measured at the rear site. The requirements and restrictions for the "B" method are the same as those listed for "A", except that the "B" method has better broadside performance.

9.3 Details of SWSS 2003 Work

<u>Deployment and Data Pre-processing</u>

During May and June of 2003 the deployment illustrated in Figure 9.4 was conducted from the R/V *Ewing*, operated by the Lamont-Doherty Earth Observatory for the National Science

Foundation (NSF). Instead of deploying two separate array cables, a single array, manufactured by SEAMAP Inc., was deployed roughly 300 m behind the stern. The array had four hydrophones unevenly spaced over a span of 50 m, each of which sampled at 48 kHz. Depth data were measured by a pressure transducer embedded in the array, which were converted into a data string that could be sampled over a serial port by a laptop. During the times to be discussed here, the SEAMAP depth varied between 37 and 50 meters.

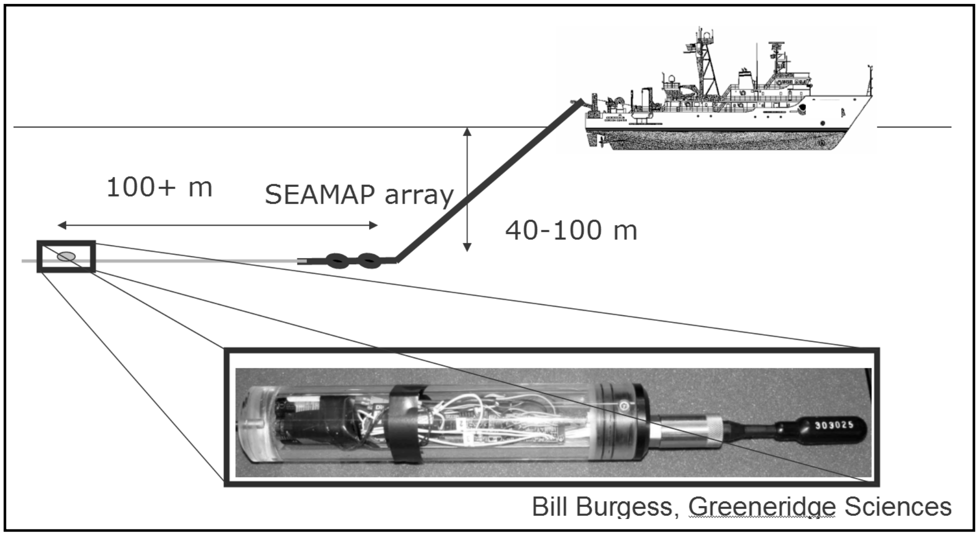


Figure 9.4. Deployment of 3-D tracking system in 2003. System was formed by attaching an autonomous acoustic recorder (developed by Greeneridge Sciences) to a 260 m long rope tied to the rear of a commercial towed array (SEAMAP).

An autonomous flash-memory acoustic recorder (Burgess 2000), built by Bill Burgess of Greeneridge Sciences Inc., was taped to a 261 m 5/8 in. polypro rope. A 15 lb shackle that served as an end anchor was tied to one rope end, while the other was attached to the end of the SEAMAP array. The recorder had a pressure transducer to log a time-stamped depth, which varied between 42 and 62 m over the results presented here. It also had 1 Gb of flash memory, sufficient to record at 8.192 kHz for nearly 17 hours. In order to retrieve the data the entire assembly had to be retrieved from the water.

The acoustic data on the recorder were time-aligned with the SEAMAP data by cross-correlating the ship engine noise recorded on both hydrophones. First, both time series were interpolated and decimated to produce two time series sampled at 8 kHz. Next, a digital high-pass filter was applied to both time series to emphasize frequencies above 500 Hz. Although ship noise was present at lower frequencies, flow noise on the autonomous recorder dominated the lower frequency bands, decorrelating data in that frequency range. As the hydrophone depths and the length of the rope between the recorder and SEAMAP array were already known, the time lag expected from the cross-correlation between the hydrophones could be estimated, and the acoustic data were subsequently time-aligned. The autonomous recorder clock drift relative to the SEAMAP array was not linear, but experienced rapid shifts about once an hour, which seemed to correspond to large changes in ship course and speed.

Neither the rope deployment, nor the attachment of the autonomous recorder to the rope, was very sophisticated. As a result the acoustic data from the autonomous recorder was extensively clipped at rates varying between 50 to 600 times per second. Fortunately, since sperm whale sounds are impulsive, the subsequent signal processing could still extract useful information.

Demonstration of Automation of "A" Method

An advantage of using surface-reflected paths for tracking animals, besides reducing the number required hydrophones, is that it simplifies the signal processing. In this section the methods for extracting estimates for $t_{ds,f}$, $t_{ds,r}$, and t_{dd} are presented, assuming that any needed pre-processing, such as time-synchronization, has already been performed on the forward and rear time-series.

The first step in tracking a group of animals is to run the acoustic data through a pulse detection program, such as Ishmael (Mellinger 2002), that outputs a set of times at which the spectral power over a certain bandwidth exceeds a threshold value. This set of possible click detections is designated t_{pulse}, where t^{i}_{pulse} is the i-th detection of that set.

The next step involves distinguishing a set of direct paths from one individual from surface reflections and direct paths from other animals. There are two ways to do this. If the forward hydrophone location actually contains two hydrophones separated by a few meters, as was the case in 2003, then the direct paths from different animals can be isolated by plotting the estimated bearing of detected pulses vs. time. Bearings from surface reflections can be distinguished from those of direct paths due to their higher angular variance.

If data are only available from a single hydrophone at the forward location, as was the case in 2002, then the direct paths can still be identified by plotting the time difference between sequential detections, $t^{i+1}_{pulse} - t^{i}_{pulse}$, as a function of time (Figure 9.5). The most likely pulse to arrive after a true direct path is the associated surface reflection, unless a direct path from a different individual arrives first. As the time separation $t_{ds,f}$ is generally less than 50 msec, the likelihood of a direct path falling within this interval is relatively small, as long as four animals or less are present. Plotting the time differences is thus a crude way of estimating $t_{ds,f}$ from a single hydrophone. Since no two whales generally share the same $t_{ds,f}$ value at a given moment, multiple animals can often be separated within a single time series.

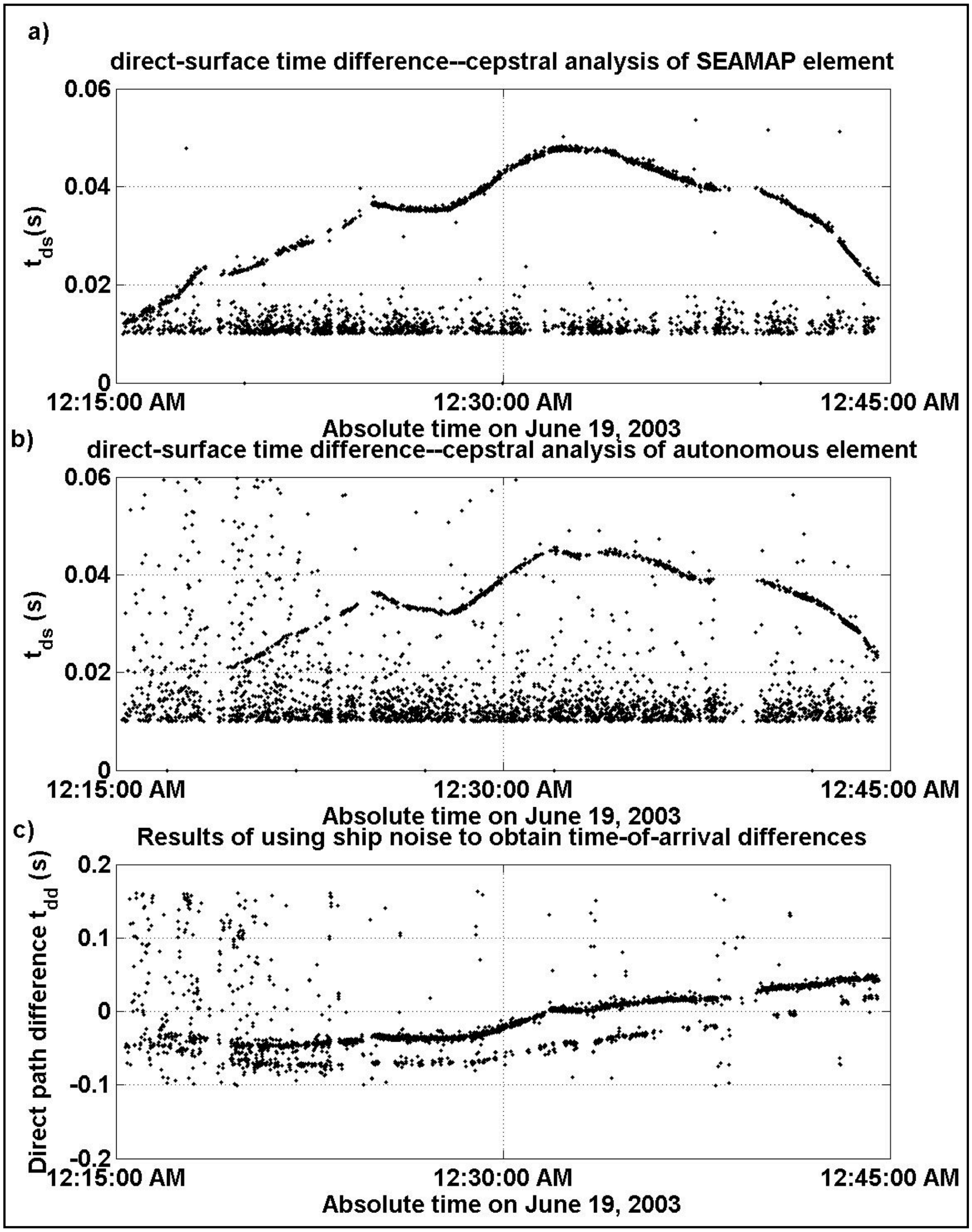


Figure 9.5. Intermediate results of semi-automated 2003 analysis. (a) Time difference between direct and surface arrival on SEAMAP hydrophone, using cepstral analysis. (b) Same as previous, but for autonomous recorder. Even with presence of clipping the relevant information can be recovered. (c) Time difference between arrival of direct path between SEAMAP and autonomous recorder, obtained by using ship noise to time-align the data records.

Once the direct paths are identified, a more precise estimate of $t_{ds,f}$ often can be obtained using cepstral analysis (Zimmer et al. 2003; Wu 2001; Oppenheim and Schafer 1989), a coherent deconvolution technique that works well if the surface-reflected signal can be modeled as a broadband-filtered version of the direct path signal. During the mild summer conditions in the Gulf of Mexico, the ocean surface was smooth enough that these conditions were usually met for the forward and rear hydrophone data, as illustrated in Figures 9.5a and 9.5b, respectively, using 2003 data.

The time delay between front and rear hydrophones, t_{dd} , is then obtained by exploiting the fact that the interval between subsequent clicks by the same animal, or the "inter-click interval" (ICI), must be the same at both hydrophone locations (e.g., Figure 9.2). A routine can be written where the N ICIs following a given direct path arrival at the forward location are compared with a set of candidate pulses at the rear location. All candidate pulses lie within a time L/c of the original direct path arrival at the forward location. For each candidate pulse, the routine checks whether N additional pulses are present at the rear location during future times required by the ICIs, to within a 1 msec tolerance. The candidate pulse that shares the most ICIs is selected as the corresponding direct path for the rear hydrophone location. This "rhythm analysis" technique, illustrated in Figure 9.5c, has been extensively used in automated marine mammal monitoring at various Naval Test ranges (Hu and Vincent 2001; Ward 2001), where it is informally called a "scanning sieve".

An interesting side effect of the rhythm analysis is that the surface reflection associated with the rear hydrophone often emerges as a secondary choice in the output (Figure 9.5c). In other words, the analysis often identifies the arrival time difference between the surface reflection on the rear hydrophone location and the direct path on the forward hydrophone. From the definition of t_{dd} it is apparent that the surface-reflected "ghost" t_{dd} is always more positive than the actual t_{dd}. The time difference between the two curves thus provides an alternate means of computing $t_{ds,r}$. This technique was useful in the 2003 experiment, when clipping and flow noise on the autonomous recorder often precluded cepstral analysis and other coherent techniques (the time period shown in Figure 9.5b being an exception).

Once a display like Figure 9.5 is obtained, a final step involves tracing the curves for the three time quantities, interpolating the samples into evenly-spaced time samples, then inserting the values into Eqs. (1)-(2). Although this tracing process can be automated (Zimmer et al. 2003), the results presented here were obtained by manually selecting the tracks using a graphical user interface.

2003 Results

From the evening of June 18 through the early morning of June 19, 2003, the autonomous recorder configuration illustrated in Figure 9.4 was used to collect additional data to test the "A" tracking procedure. One particularly clean set of time measurements was available between 00:20 and 00:45 CDT, and is displayed in Figure 9.5. The dive profile derived from Figure 9.5 is shown in Figure 9.6. The animal's depth of 400 to 700 m is deeper than those obtained in 2002. The inverse stability factor plot in Figure 9.6a indicates that the animal remained forward of the rear hydrophone location, although the close proximity of the animal precludes a simple interpretation of the stability factor. The plot of horizontal range from the forward hydrophone, Figure 9.6c, indicates that the SEAMAP array passed directly over the animal approximately 12 to 15 minutes into the sequence.

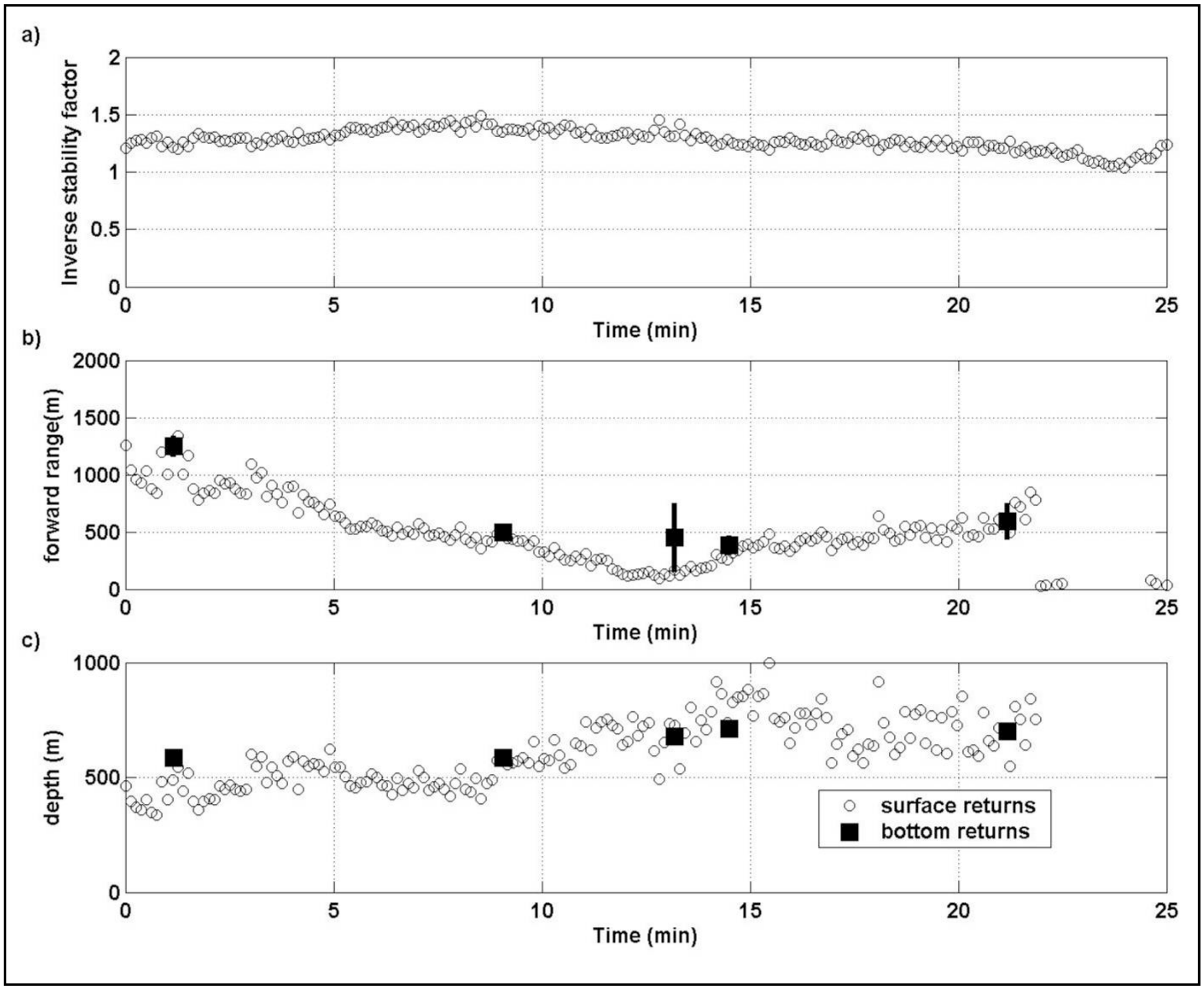


Figure 9.6. Range (top) and depth (bottom) of sperm whale derived from intermediate data from Figure 9.5. Here the R/V *Ewing* inadvertently passed directly over an animal foraging between 400 and 500 m depth.

Sets of bottom-reflected returns were recorded on the SEAMAP array several times during this sequence, and by manual observation of spectrogram displays they could be matched to the corresponding direct-path arrivals, since only two animals were acoustically active during this time. Occasional estimates of the whale position could then be made only using a single-hydrophone (Thode et al. 2002), by measuring sets of bottom returns over a 20 s interval. The array depth estimated from this procedure matched the measured depth of the SEAMAP array to within a few meters. The mean and standard deviations of the positions obtained from each set of bottom-returns are marked as black squares and vertical lines in Figures 9.6b and 9.6c. They overlap the positions estimated by the two hydrophone method to within the standard deviation.

Thus the limited data from 2003 were sufficient to confirm that the tracking technique works, and could be verified by independent methods.

9.4 Details of 2004 Work

In 2004 the scale of the 3D tracking work was greatly expanded over 2003, based on the results demonstrated in 2002 and 2003. Thus the remainder of this section discusses the equipment, procedures, fieldwork, and analysis in 2004 in considerably more detail.

Equipment and data formats

A dedicated towed "tandem" array for the 3D project was built between December 2003 and May 2004. This tandem array consisted of two calibrated "sub-arrays" of three elements each, separated by 200 m of cable (Figure 9.7), with an additional 200 m of lead-in to the deck winch. Thus the rear sub-array was deployed 400 m behind the ship stern. The 200 m aperture would be sufficient for tracking animals within 1-2 km of the vessel, based on a consideration of Eq. (3). An underwater connector (red square in Figure 9.7) at the base of the first array permitted the arrays to be interchangeable, or even converted into two single arrays, providing emergency redundancy for the S-tag cruise requirements. Both sub-arrays incorporated pressure sensors, and a breakout box provided separate acoustic and pressure outputs. Each sensor on the tandem array has between -165 to -170 dB re 1V sensitivity, with a flat frequency response between 100 Hz to over 24 kHz, although usable signal could be obtained past 30 kHz. The presence of a third sensor in each sub-array provided redundancy in case of a sensor failure. Complete details on the towed array system are provided in Section 9.6.

A second array, provided by Ecologic LTD., was deployed off the port side of the *Gyre* (Figure 9.7, bottom). When combined with data from the rear sub-array of the tandem array, acoustic observers were able to distinguish port/starboard ambiguities in the bearings without having to alter vessel course.

The front of the leading array is terminated in a 37 pin shell type in-line connector that mates to a similar connector on a topside breakout box. The topside breakout box contains a 15 volt power supply for the hydrophones, two Omega DP 41 Process indicators for the pressure sensors, power switches for the two indicators, a power switch for the hydrophone power supply, and 6 output BNC connectors for the six acoustic sensors. The breakout box uses standard 120 VAC 60 Hz input power. At first we were concerned that using AC line power instead of a DC battery might contaminate the signal, but these fears proved to be unfounded.

Data from two hydrophones in the forward array and two hydrophones in the rear array were filtered using a Khron-hite model 3944 filter/amplifier before being recorded onto an Alesis ADAT HD24XR hard disk digital recorder, along with two channels from the Ecologic array. Thus a total of six hydrophones were sampled at 96 kHz and stored in 24 bit WAV format. The start time of each recording was entered into both an Excel spreadsheet and the Acoustic Team Microsoft Access database. At first the signal was not filtered or amplified, but beginning on June 1 the signal was high-pass filtered above 100 Hz to eliminate potential DC and high-amplitude line noise. Beginning on June 13 (Song 18 HD 5) an additional 20 dB of gain was added before recording the data.

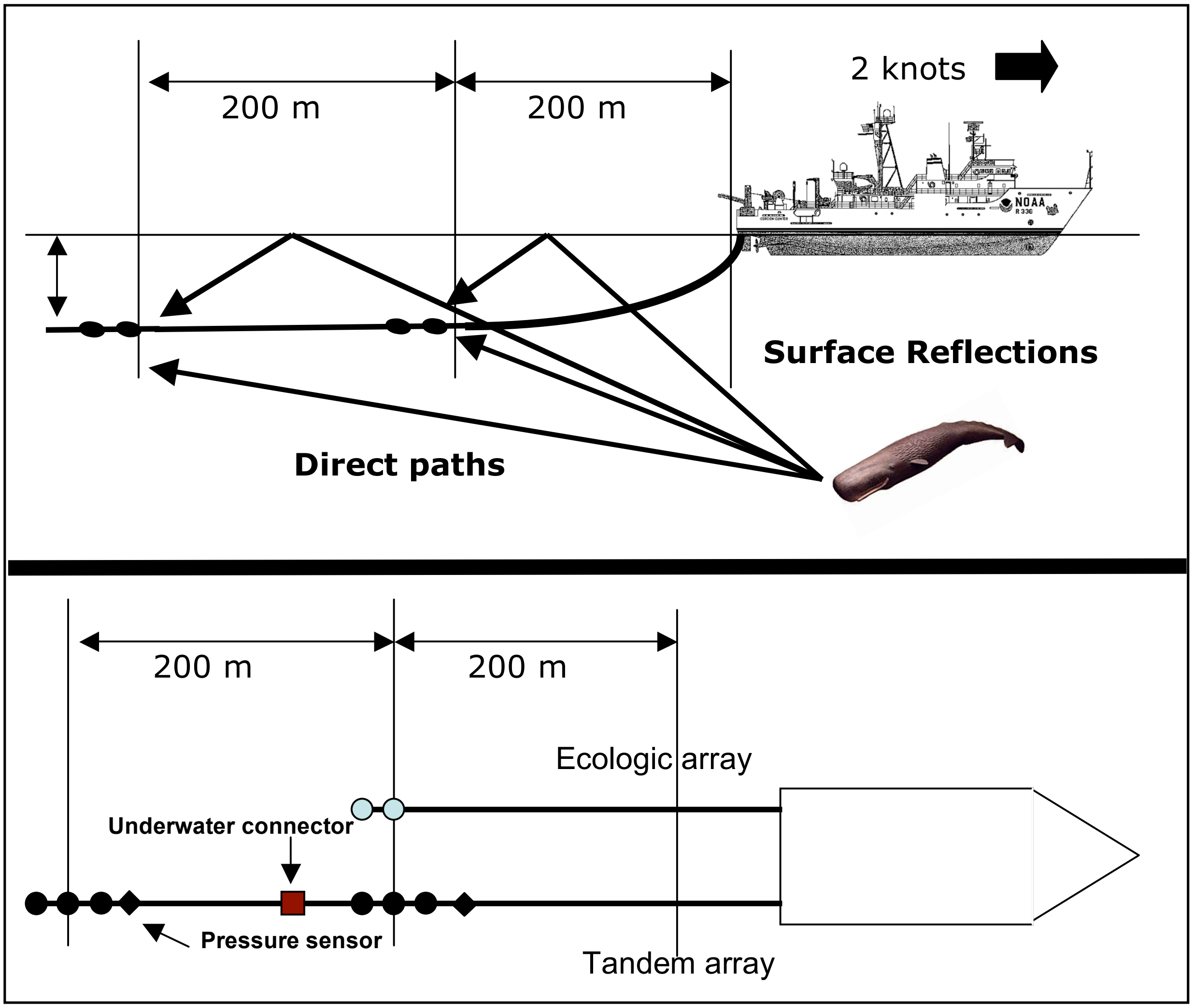


Figure 9.7. Illustration of 2004 3-D deployment off R/V *Gyre*, using a tandem array specifically built for the project. Top: side view of tandem array during S-tag deployment. Bottom: View of S-tag array deployment from above, showing how tandem and Ecologic array were deployed in parallel, which permits bearings of sounds to be determined without a port/starboard ambiguity. The total configuration permitted 3-D tracking data to be collected without interfering with S-tag requirements. Round circle: calibrated hydrophone; blue diamonds: pressure (depth) sensors; red square: underwater connector that would permit array aperture to be extended in 2005.

The two pressure sensors were sampled by two process indicators in the breakout box, and both a digital LED display and a serial port signal were produced. The serial port signals, sent at 9600 baud, odd parity, and 1 stop bit, were sampled by a dedicated laptop. The serial ports were first sampled using Hyperterminal between May 28 and June 4. In the meantime, Eddie Webb of TAMU wrote a Labview program to timestamp the sampled array depths. Beginning June 4 this program was used for the rest of the cruise.

The array was initially deployed without any additional weight on the cable, but it was found that the forward array was being towed too shallow to detect surface reflections needed for range-depth fixing. Thus more weight was added to the cable in two stages: on May 30 a 15 lb. anchor chain was taped about 30 ft forward of the forward pressure transducer, and on June 4 three shaped lead weights (borrowed from the Pascagoula MS NMFS lab) were attached forward of the anchor chain, for an estimated total of 30 lb. of weight added to the cable. The resulting tow depth for the forward array was 30 m at 3 knots, and the rear array at about 55 m depth, which was judged to be acceptable for testing both the "A" and "B" algorithms.

2004 Timeline

The tandem array was delivered three days before cruise departure, where it was discovered that a deck cable connector had not been built into the array. With the assistance of Eddie Webb, a section of the forward array cable was cut to form a deck cable, and a cable connector mailed by Don Norris was incorporated. From May 25 through the 28th the depth acquisition was made operational.

On May 27 the array hit a longline, causing superficial surface damage to the rear pressure transducer and one of the rear hydrophones. A hook was found embedded in the rope drogue, which was subsequently removed. The rear pressure transducer was streamlined, and no further incidents were experienced through June 17.

On May 30 ship noise from the *Gyre* was used to align the Ecologic and Norris array cable lengths so that left/right ambiguities could be resolved without turning the vessel. The acoustic team found that the arrays would often collide whenever ship speed changed suddenly, or during sharp turns, and particularly during both. No sustained damage from the collisions was visible on either array.

By May 30 data of sufficient quality for eventual 3D tracking was being collected, and by June 4 the array setup attained its final form. Over the next two weeks a dive computer was attached to the forward and rear arrays to confirm the accuracy of the pressure transducers. Beginning June 13 digital inclinometers were also attached to the array cable to collect data for testing the assumptions of the "B" tracking algorithm.

One June 11 a simple technique for obtaining whale slant range was tested. By measuring the bearings to an animal simultaneously from the forward and rear arrays, the distance to the whale could be triangulated (Figure 9.8). On this day a single whale was tracked and the tagging boats were directed to within 500 m of the surfacing animal. The ranging algorithm was made into a spreadsheet that became a standard part of the acoustic watch.

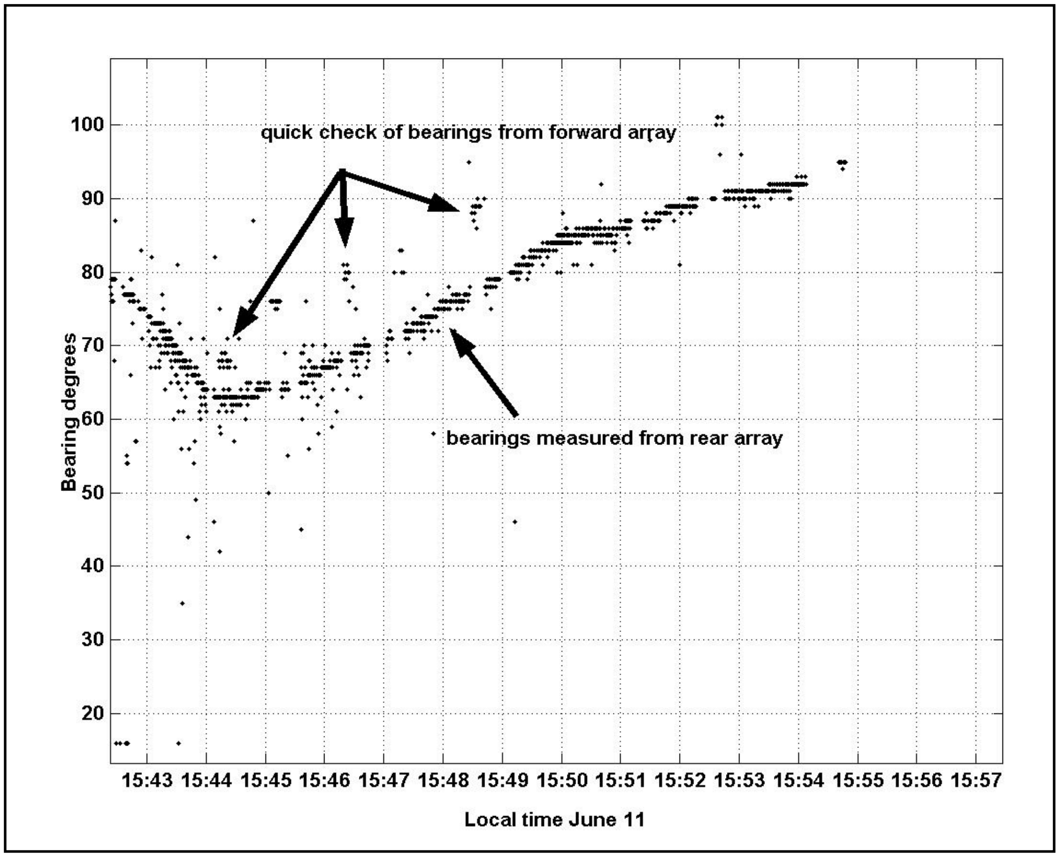


Figure 9.8. Demonstration of how the 2004 tandem array was used to estimate real-time ranges of an animal at fast tow speeds. Every minute or so, the acoustic detection software was switched to monitor signals arriving on the forward sub-array for several seconds, before being switched back to the default monitoring of the rear sub-array. If the bearings between the arrays differ, the range to the animal can be triangulated. The detection of surface-reflected paths is the final portion of the algorithm.

The acoustic team also gained experience on how to tow the arrays as deep as possible while maintaining ship steerage. The *Gyre* seems most acoustically quiet at 600 engine rpm. It was found that having the ship face into the swell worked well, as was moving with the current (as measured with the ADCP). On June 13 the arrays were towed at their deepest depth yet—120 m on the rear array.

Data were recorded whenever dolphins or sperm whale clicks were audible. During the cruise over 720 GB of acoustic data were collected during evenings and other times when other scheduled activities had to be delayed due to weather concerns.

Data Analysis

The analysis of the acoustic data began with a sequence recorded near midnight, June 17, when a single whale at close range was detected, and numerous bottom-reflected returns were audible. A MATLAB graphical-user interface (GUI) was written to permit a convenient review of spectrograms from the forward and rear array simultaneously (Figure 9.9). Note the various time-of-arrival (TOA) measurements, similar to those that appear in Figure 9.2.

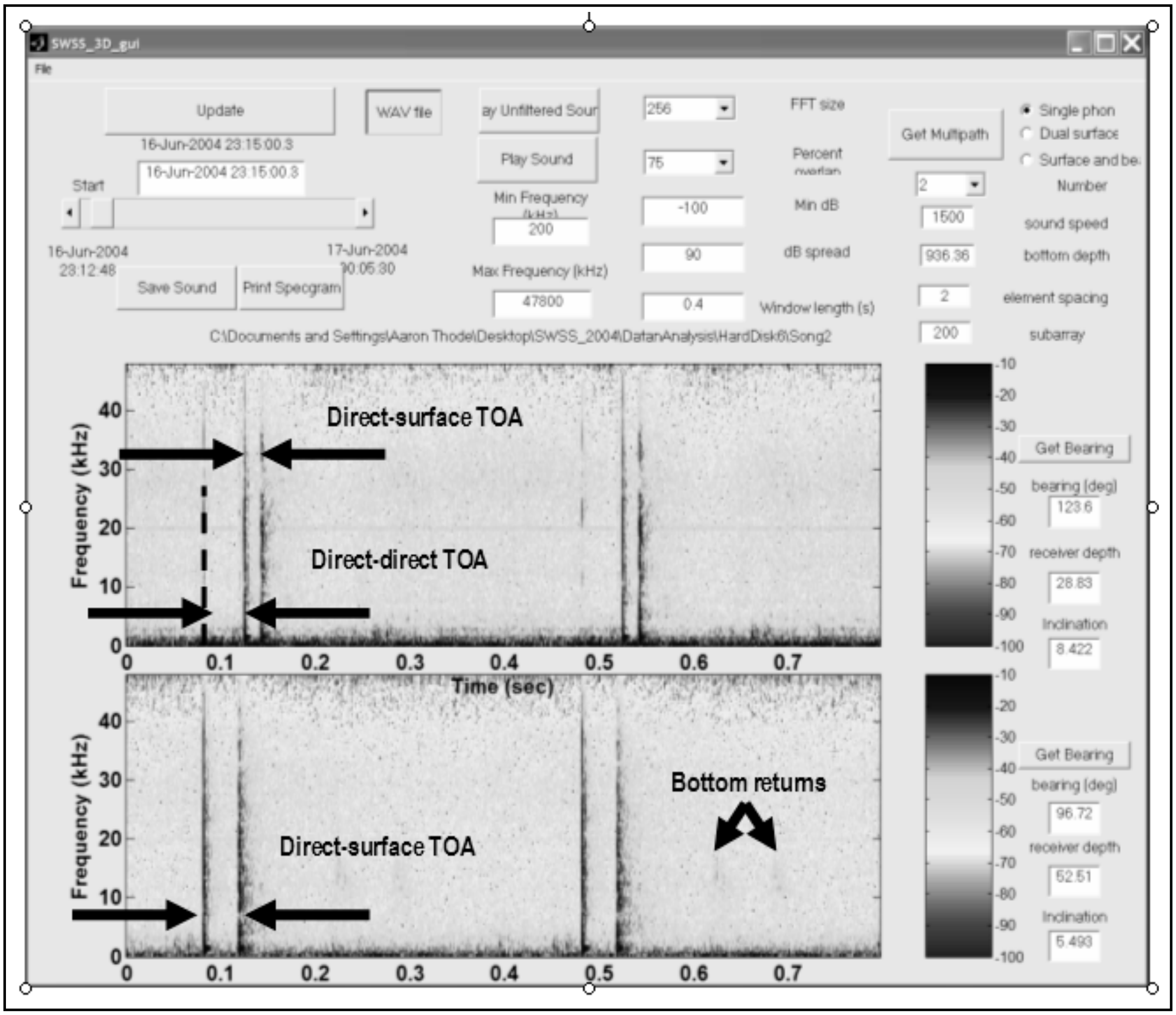
The automated data extraction procedures described in the 2003 data analysis section were applied to a segment of the June 16/17 data, with the results shown in Figure 9.10. Due to extensive ship noise on the forward hydrophone tracking procedure "B" was used, and the results applying Eqs. (2) and (3) to the Figure 9.10 data are shown as a range/depth track in Figure 9.11. One very clear track appears, showing an animal diving quickly to a depth of 500 m, then gradually working back toward the surface, acoustically active during the entire time. Numerous bottom-reflected returns were present, which permitted an independent acoustic track to be made, visible as red circles in Figure 9.11.

This behavior deviates significantly from typical dive profiles measured by tagging activities (Miller et al. 2004b), so much effort in the latter part of 2004 has been spent checking the assumptions used in the tracking procedure. For example, tracking procedure "B" assumes that the array cable shape is basically straight. Independent measurements of hydrophone depth and local array inclinations at both the forward and rear subarrays (Figure 9.12) have shown that the local cable inclinations at forward and rear locations lie within a few degrees of each other; thus the array cable is basically straight and Eq. (3) is valid. Figure 9.13 shows the depth acquisition system.

Ray-refraction effects

Another assumption used in 3-D tracking is that ray-refraction effects caused by depth-dependent sound speed profiles can be neglected for 3-D tracks within 1 km. This assumption may not be valid for the Gulf of Mexico. For example, a June 13 sound speed profile derived from an XBT measurement is shown in Figure 9.14, where it is seen that the sound speed profile decreases rapidly from 1540 m/s at the surface to 1490 m/s at depth. Using the ray-tracing program BELLHOP (Porter 1991) the effect of this sound speed profile on the various time-of-arrival and angular arrival measurements can be modeled (Figure 9.15). These corrections can be pre-computed and then applied to the tracking routine, and Figure 9.16 shows the sound-speed corrected results for the range/depth track. As can be seen, the effects of ray refraction at these close ranges are very small in this example.

Bulk processing of 3-D tracks is currently a work in progress. It is expected that dive depths of the animals will be compared with depths of the scattering layers obtained by TAMU in the near future.



SWSS_3D_gui

16-Jun-2004 23:15:00.3
Start 16-Jun-2004 23:15:00.3
16-Jun-2004 23:12:48
17-Jun-2004 00:05:30
FFT size 256
Percent overlap 75
Min Frequency (kHz) 200
Max Frequency (kHz) 47800
Min dB -100
dB spread 90
Window length (s) 0.4
● Single phon
○ Dual surface
○ Surface and be
Number 2
sound speed 1500
bottom depth 936.36
element spacing 2
subarray 200
C:\Documents and Settings\Aaron Thode\Desktop\SWSS_2004\DatanAnalysis\HardDisk6\Song2
bearing (deg) 123.6
receiver depth 28.83
Inclination 8.422
bearing (deg) 96.72
receiver depth 52.51
Inclination 5.493

Figure 9.9. Spectrograms of data collected during 2004 3D tracking experiment, as viewed with a MATLAB graphical user interface. The top spectrogram displays a hydrophone of the forward sub-array, and the bottom spectrogram displays a hydrophone in the rear sub-array. The arrival-time differences indicated in the diagram can be used to obtain animal range and depth, if both array depths are known. Occasionally, bottom returns appear, which permit an independent check of the tracking algorithm. If the bearings of at least one the direct-path signals can be measured, then the direct-surface time-of-arrival (TOA) difference on the forward hydrophone is not required (i.e. tracking method "B" can be used instead of "A").

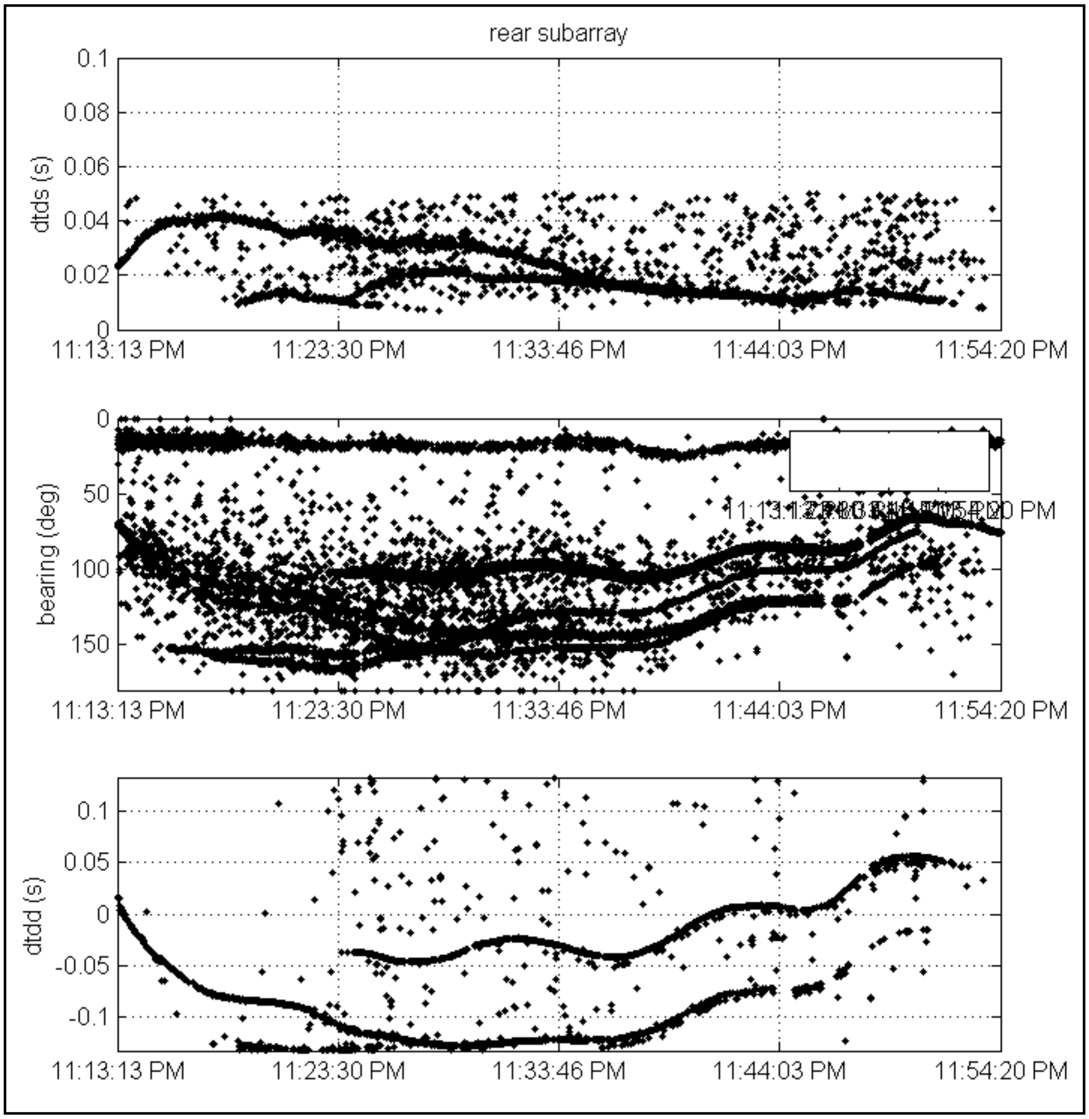


Figure 9.10. Intermediate results of automated 2004 analysis on data collected on June 16, 2004. Top: Time difference between direct and surface-reflected arrivals on rear hydrophone vs. time, using an Ishmael/MATLAB prototype; Middle: Acoustic bearings vs. time on rear sub-array; Bottom: Direct path time delays between sub-arrays. The ship is making a turn after 11:33 PM. These parameters are used for tracking procedure "B".

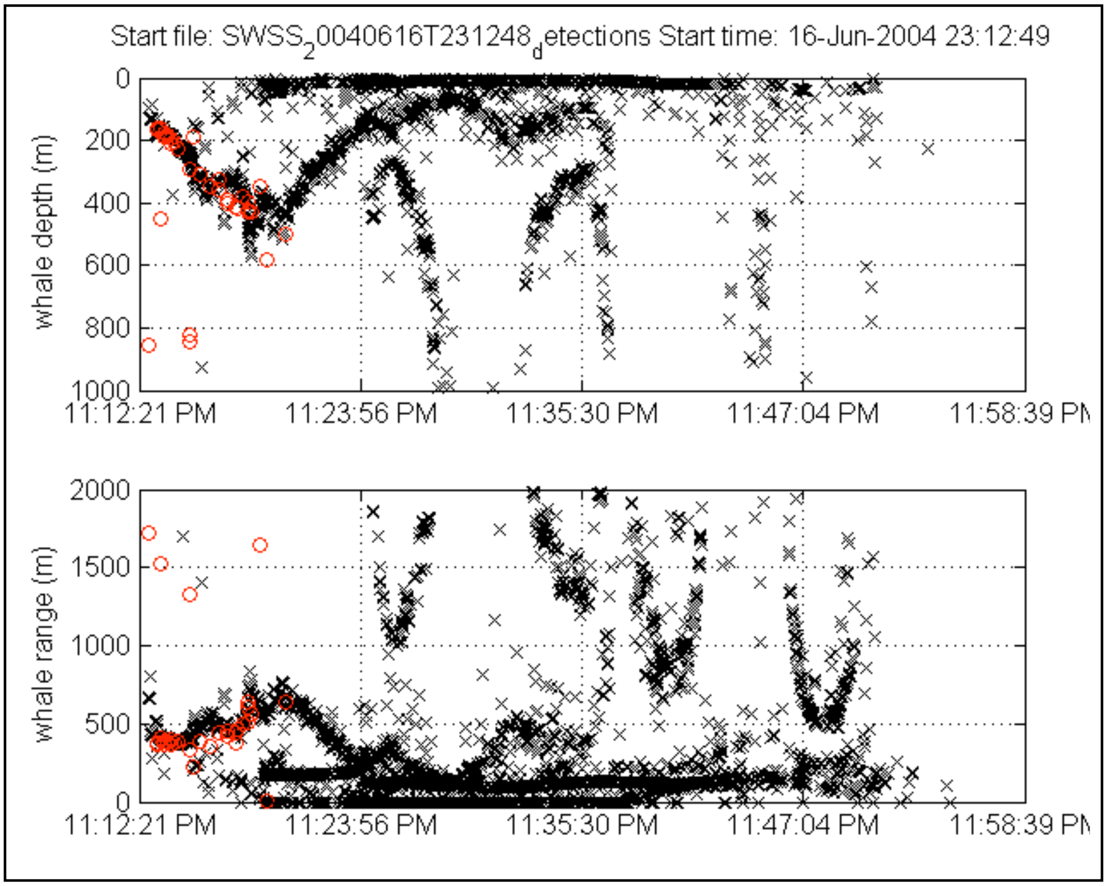


Figure 9.11. Depth (top) and range (bottom) of sperm whales derived from parameters in Figure 9.10. Red circles are independent measurements of whale position using bottom-reflected returns. Note instability of fixes on animals greater than 1 km horizontal range at 11:25:44.

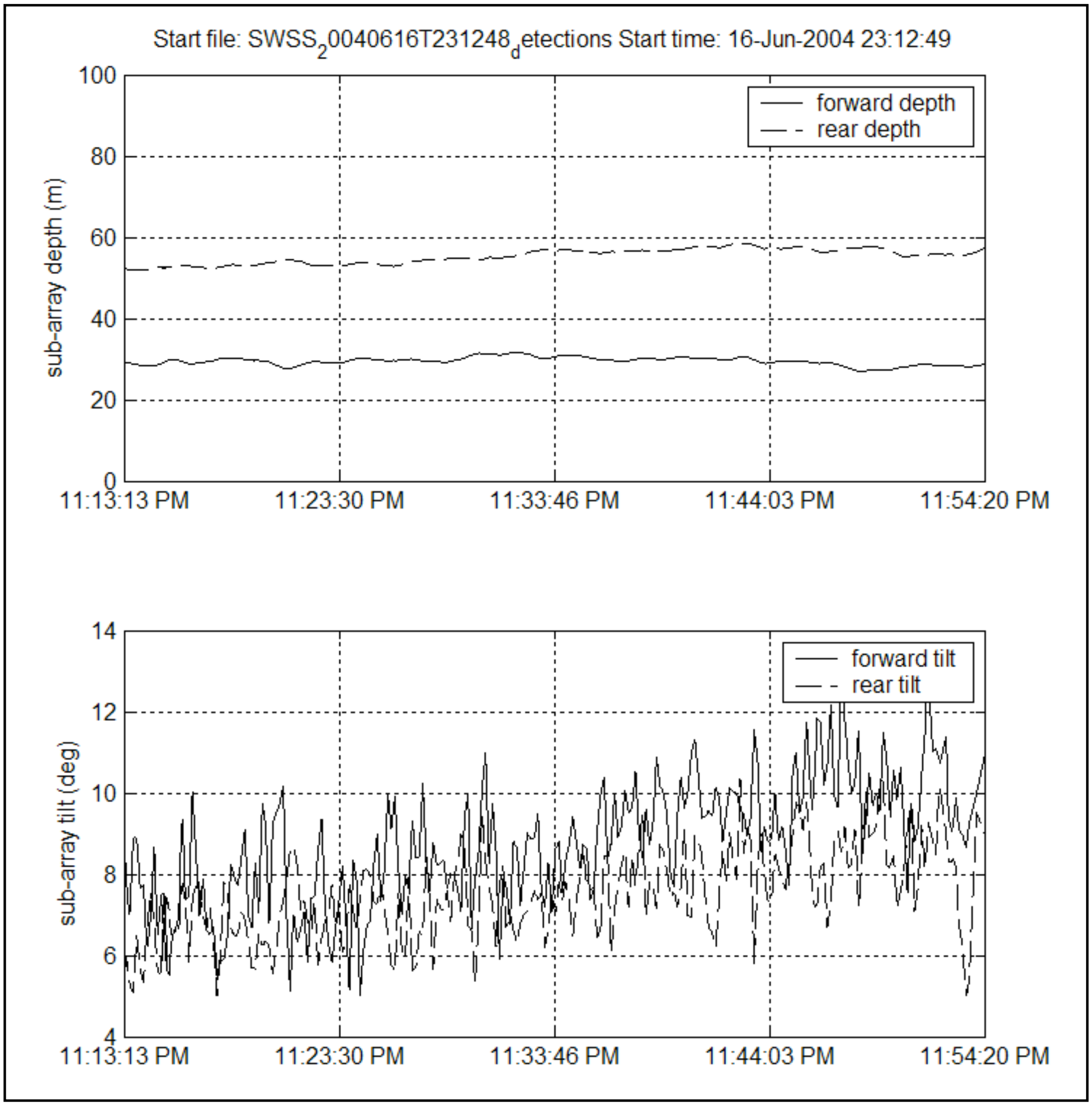


Figure 9.12. Measurements of hydrophone depth (top) and vertical inclinations (bottom) of the forward and rear sub-arrays versus time on June 16, 2004. Note similarity of inclinations of forward and rear sub-arrays.

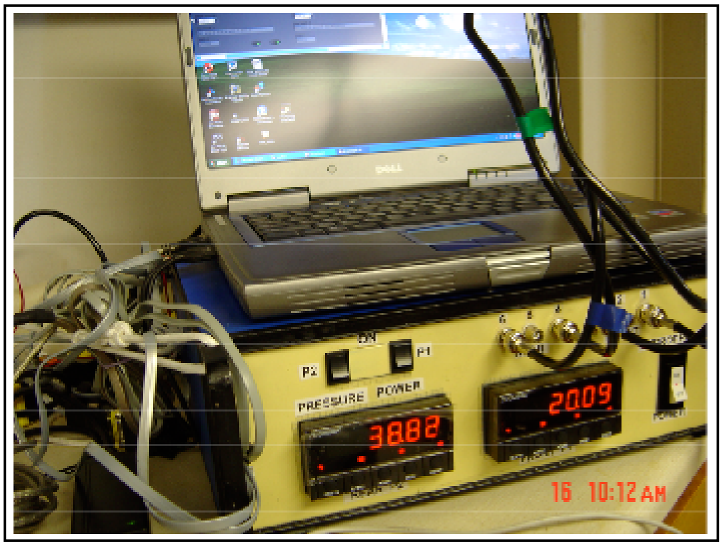


Figure 9.13. Depth acquisition system.

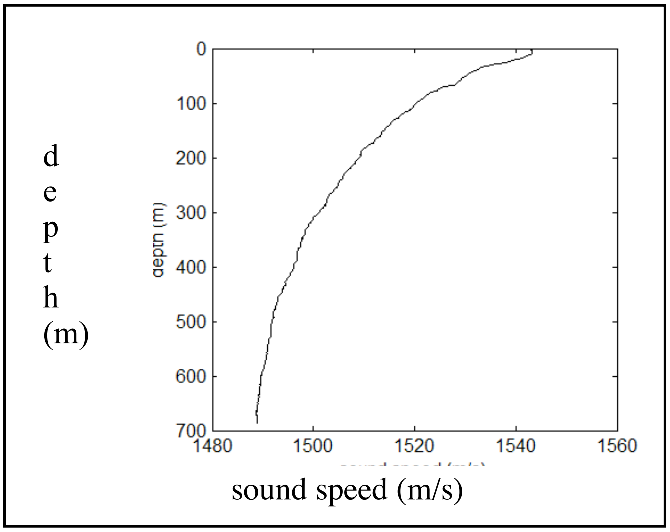


Figure 9.14. Sound speed profile measured on June 13, 2004. Note downward refraction.

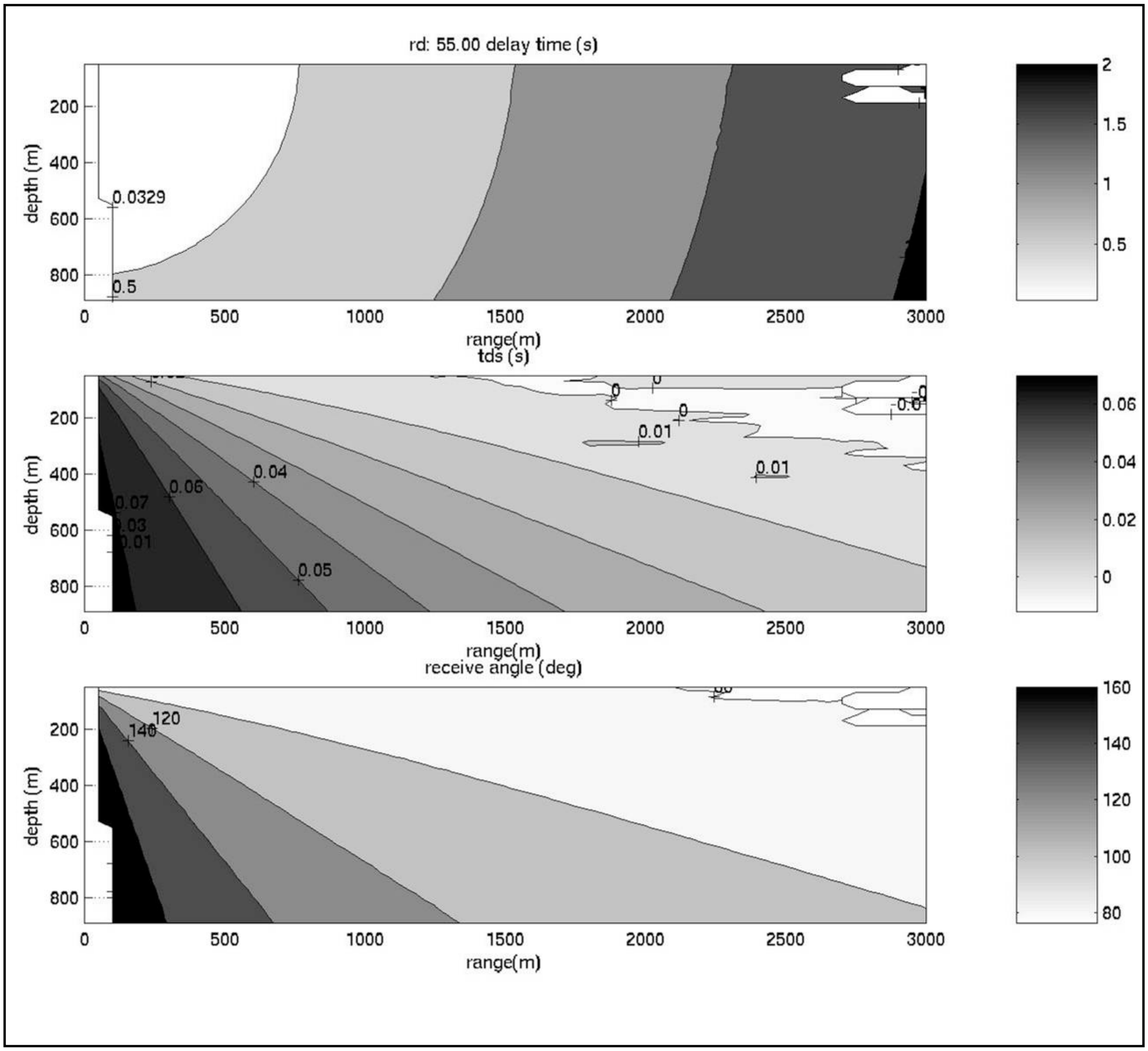


Figure 9.15. Effect of sound speed profile and ray refraction on localization parameters. (top) Path length vs. source range and depth. (middle) Direct-surface time delay vs. source range and depth. (bottom) Measured elevation angle vs. source range and depth. Receiving hydrophone depth is 55 m.

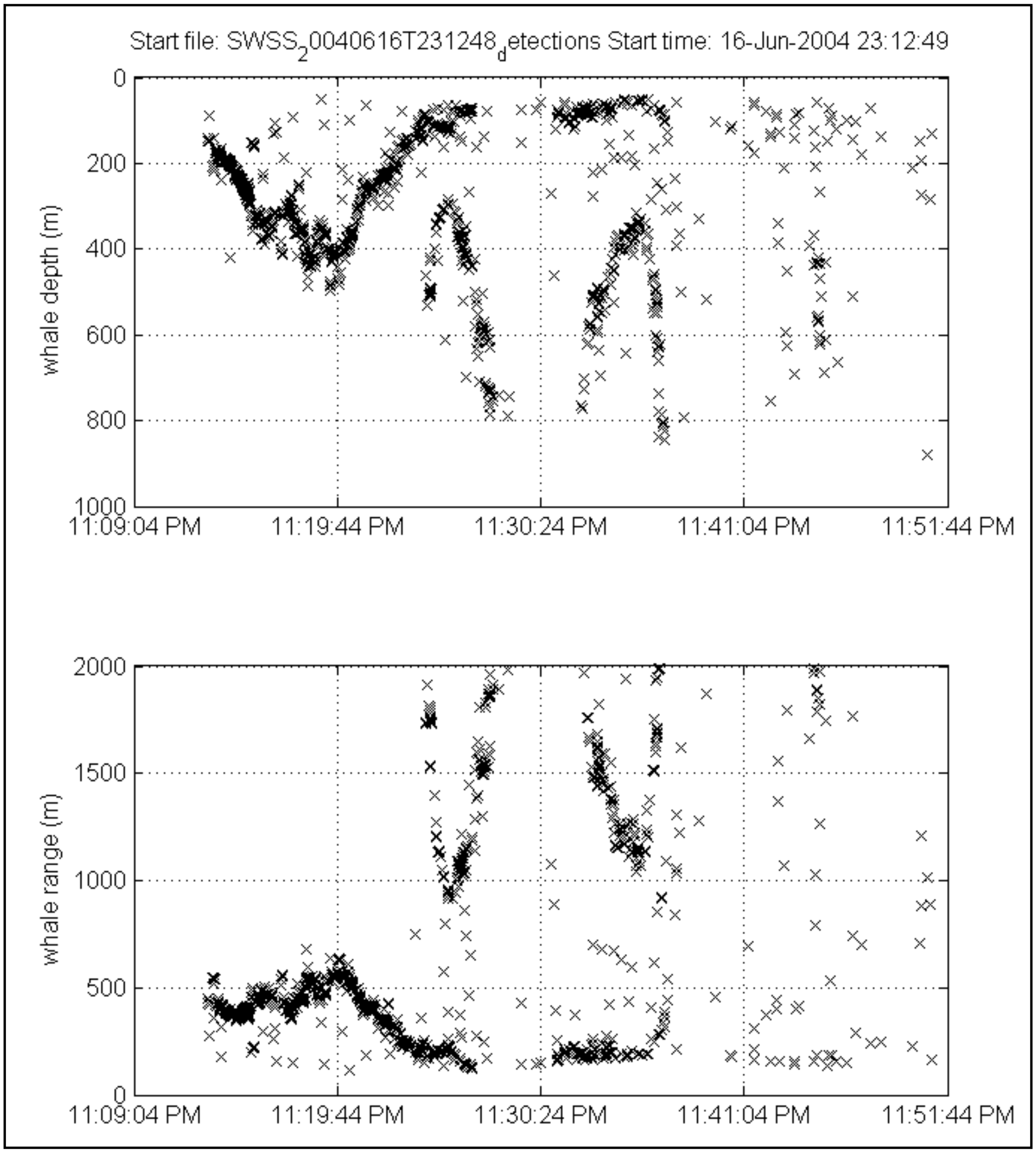


Figure 9.16. Depth (top) and range (bottom) of sperm whales as in Figure 9.11, except the effects of the depth-dependent sound-speed profile shown in Figure 9.14 have been accounted for.

9.5 Conclusion

Over the past two years the passive acoustic 3-D tracking concept has evolved from an untested concept to a system using dedicated hardware in SWSS. Much of the procedure has been automated, and the effects of ray-refraction have been incorporated in a computationally effective manner. In 2005 a prototype real-time 3-D tracking software is expected to be tested, and the array system extended to permit sperm whale tracking to greater horizontal ranges. The advantage of this concept is that the tracking system requires only a single towed array, instead of a volumetric array typically required for 3-D tracking.

The tracking results derived from the methods presented here are at present being integrated with backscattering measurements performed by Kelly Benoit-Bird and TAMU on the 2005 S-tag cruise. In addition, data collected on the 2005 S-tag cruise from an acoustic "b-probe" tag are currently being merged with data from a towed array to perform a very large-aperture array, demonstrating that acoustic data combined from a recording tag and a towed array can be combined to permit 3-D tracking of other untagged animals over extended ranges. The remaining technological project to be tackled is the incorporation of a so-called "vector sensor" to distinguish port detections from starboard, to remove the need to physically alter ship course to determine which side of the vessel a particular acoustic contact is on.

The two analytic formulas expressed here—the "A" and "B" techniques—are probably adequate for tracking ranges of 1 km or less. For greater ranges in the Gulf of Mexico, the numerical "lookup" algorithm presented here would have to be used. The relevance of this research to the greater SWSS goal is the growing awareness that these data can be very useful in helping correlate whale diving activity with other environmental variables, and a real-time tracking system would be useful during future CEE experiments, to ensure that the spatial distribution of all vocally active whales are appropriately arranged with respect to the source vessel. This latter goal can be expanded by combined acoustic data from an acoustic tag with the array data.

Thus what began as an intellectual curiosity has become an applied technique that has already begun to be integrated into the larger-scale biological studies of SWSS and will probably be integrated into potential CEE and tagging experiments in the future.

9.6 3-D PAT Appendix: “Tandem” Towed Array Description

Don Norris, Biomon Inc.

The Dual Aperture Towed Array is a 8 sensor, 440 meter towed underwater hydrophone system. It is composed of two arrays, a forward and an aft array, interconnected by an in-line pair of underwater connectors. Each array has three acoustic sensors separated by one meter from each other and one pressure sensor located about 5 feet in front of the leading acoustic sensor in each array subsection. The two arrays are separated by about 200 meter length (from the #3 or tail hydrophone in the front array measured to the pressure sensor in the aft array). The tail of the array (the aft section) has a disconnectable 70 foot drogue (restricting line type). The front of the leading array is terminated in a 37 pin shell type in-line connector that mates to a similar connector on a topside breakout box. The topside breakout box contains a 15 volt power supply for the hydrophones, two Omega DP 41 Process indicators for the pressure sensors, power switches for the two indicators and a power switch for the hydrophone power supply, and 6 output BNC connectors for the six acoustic sensors. The breakout box uses standard 120 VAC 60 Hz input power.

Acoustic Sensors

The six acoustic sensors are Navy Type I PZT piezoelectric striped cylinders configured as shielded end omnidirectional hydrophones. The sensors in each section have 1 meter from the next sensor. Each sensor includes a two stage preamplifier/line driver signal conditioning electronic section. These provide about 30 dB of gain to the raw hydrophone output and provide various noise reduction components and input/power protection features. Both the hydrophones and the electronics are enclosed in expanded metal screen EMI shields. The sensor electronics are front end overload protected that clamp the input before the output clips, have power supply filtering in excess of 60 dB PSRR, and are reverse voltage protected. These units are unipolar powered by +15 VDC from a small DC power supply in the topside breakout box. Each sensor and electronics assembly is encapsulated in a tough waterproof polyurethane in a finned, flow body shape around the tow cable. The fins may be removed if necessary by cutting off.

Pressure Sensors

Each of the two pressure sensors (one at the front of each acoustic aperture) are Omega PX 305 K1000 (1000 psi) current output sensors. These are supplied by 25 volt excitation from the two topside breakout process indicators and provide a 4 to 20 ma current input to each of the processors. Each pressure sensor is fully encapsulated in a polyurethane body similar to the material used for the acoustic sensors. The flow bodies are blunt faced to allow a fairly smooth and unturbulent boundary area in front of the body where the pressure sensor's port is located. A rubber bladder is connected to the sensing port of each sensor and oil filled with castor oil to allow pressure sensing and preclude sea water (conductive) from getting to the pressure transducer and possibly increasing electronic noise. A small polyurethane sphere fairs the port input and desurges pressure spikes. The pressure sensors are five feet in front of the closest acoustic center in each array subsection. Pressure sensor description is provided in the M1306/0303 data sheet.

Cable, Connectors, and Drogue

The cable is a 12 twisted shielded pair polyurethane jacketed cable with an internal Kevlar strength member. Each cable section (front and back arrays) is about 220 meters long with approximately 200 meters of separation from the front aperture to the rear aperture. There is 70 feet of cable between the last hydrophone sensor in the aft array and the drogue which helps to control the end of the array. The drogue end of the array is terminated in an epoxy attached titanium ring to which the drogue cable attaches using a twist ring. The two 220 meter sections of cable are interconnected by two large underwater stainless 18 pin connectors. The front of the array is terminated in an aluminum shell 37 pin connector that mates to the back connector on the breakout box.

Breakout Box

The breakout box is a small metal housing that contains the 15 volt DC power supply for the hydrophones including an in-line power switch and a 1/4 amp fuse. The 1/4 amp fuse is only for the 15 VDC power supply and not the two pressure indicators. The power supply is described in the Model HA 15-0.5 data sheet. The power supply is powered by 120 VAC 60 Hz through a normal power cord. The box additionally houses two Omega pressure process indicators, one for each pressure sensor. These units are fully described in the DP 41-E Operator's Guide and in the Serial Communications Users Guide. Each unit supplies 10 or 25 volt excitation voltage to an associated pressure sensor and receives the 4 to 20 ma signal back. This signal is converted to an indicational signal and into a serial data stream for PC is in an RS 485 format. The processors may be used stand-alone or interconnected on a Duplex chain to a control PC. The processor boxes are supplied by 120 VAC from the same supply line as the 15 VDC hydrophone power supply and each processor has a separate 120 VAC power switch. Individual telephone type cable assemblies and a Duplex dual to single cable feed through the front of the box. As received, the two individual cables are connected to the backs of the two meters. The top of the box may be removed by 6 small screws to allow access and changing the interconnects. On the 15 volt power supply side of the box are two holes that allow adjustment of the 15 VDC power and access to the high and low output pins of the power supply to measure voltage levels.

Acoustic Characteristics

The nominal sensitivity of each hydrophone is approximately –155 dB re 1 volt/μPa from about 50 Hz to above 30 kHz. Above 30 kHz the sensitivity rolls off at about 12 dB per octave. The spatial response in planes at right angles to the cable axis is completely omnidirectional to well over 50 kHz. In planes parallel to the cable axis, the response to about 20 kHz is omnidirectional, then gradually becomes directive above 20 kHz such that at 50 kHz, the beam width is about 70 to 80 degrees.

Physical

The components within the array are all designed for pressure exposure of 1500 feet minimum corresponding to the full length of array deployed with zero way on the tow ship (array hanging vertically). The array components are designed for tow speeds of 6 knots minimum but should survive 10 knots (although the acoustic performance would be significantly degraded). The array is shipped on spools with significantly smaller bend radius than normal usage but normal stowage and operational bend radius should be considered as about 2 feet minimum. This is primarily to preclude excessive and long term bending on the polyurethane encapsulated hydrophones.

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MARCH 3, 1849

The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

The Minerals Management Service Mission

As a bureau of the Department of the Interior, the Minerals Management Service's (MMS) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS), collect revenue from the Federal OCS and onshore Federal and Indian lands, and distribute those revenues.

Moreover, in working to meet its responsibilities, the **Offshore Minerals Management Program** administers the OCS competitive leasing program and oversees the safe and environmentally sound exploration and production of our Nation's offshore natural gas, oil and other mineral resources. The MMS **Minerals Revenue Management** meets its responsibilities by ensuring the efficient, timely and accurate collection and disbursement of revenue from mineral leasing and production due to Indian tribes and allottees, States and the U.S. Treasury.

The MMS strives to fulfill its responsibilities through the general guiding principles of: (1) being responsive to the public's concerns and interests by maintaining a dialogue with all potentially affected parties and (2) carrying out its programs with an emphasis on working to enhance the quality of life for all Americans by lending MMS assistance and expertise to economic development and environmental protection.