Joint Interim Report
Bahamas Marine Mammal Stranding
Event of 15-16 March 2000

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Executive Summary

Overview

On March 15 and 16, 2000, a multi species, mass stranding of 17 cetaceans was discovered in the Northeast and Northwest Providence Channels of the Bahamas Islands (a mass stranding is defined as two or more animals). Seven of the animals are known to have died, ten other animals were returned to the water alive. A comprehensive investigation into all possible causes of the stranding was quickly launched. Based upon necropsies of the dead animals it was preliminarily determined that they had experienced some sort of acoustic or impulse trauma that led to their stranding and subsequent death. Detailed microscopic studies were initiated to identify the mechanism by which this acoustic or impulse source caused trauma. Most, but not all, lines of investigation have now been completed.

Based on the way in which the strandings coincided with ongoing naval activity involving tactical mid-range frequency sonar use in terms of both time and geography, the nature of the physiological effects experienced by the dead animals, and the absence of any other acoustic sources, the investigation team concludes that tactical mid-range frequency sonars aboard U.S. Navy ships that were in use during the sonar exercise in question were the most plausible source of this acoustic or impulse trauma. This sound source was active in a complex environment that included the presence of a strong surface duct, unusual underwater bathymetry, intensive active use of multiple sonar units over an extended period of time, a constricted channel with limited egress, and the presence of beaked whales that appear to be sensitive to the frequencies produced by these sonars. The investigation team concludes that the cause of this stranding event was the confluence of the Navy tactical mid-range frequency sonar and the contributory factors noted above acting together. Combinations of factors different from this one may be more or less likely to cause strandings. Research should focus on identifying problematic combinations so they can be avoided. The actual mechanisms by which these sonar sounds could have caused animals to strand, or their tissues to be damaged, have not yet been revealed, but research is under way. This research, along with other research on the impacts of sonar sounds on marine mammals, increased knowledge of marine mammal densities, increased knowledge of causes of beaked whale strandings, increased knowledge of beaked whale anatomy, physiology and medicine, and further research on sonar propagation, will provide valuable information for determining which combinations of factors are most likely to cause another mass stranding event. SURTASS LFA, another Navy sonar, had no involvement in this event.

This report reviews the evidence that led to the above conclusions, describes a program of research aimed at answering the outstanding questions on the impacts of tactical mid-range frequency sonar, and lists interim mitigation measures for future sonar operations. All technical terms used in this report are defined in a Glossary at the end. This is an interim report; Conclusions and Recommendations appearing here could change somewhat as final results become available. The major findings of each part of the investigation are summarized below.

Biological Investigation

A biological report compiled by NOAA describes the stranding event and the results of biological examinations that were conducted on the dead animals. Seventeen cetaceans involving four species (Cuvier's beaked whales, Blainville's beaked whales, Minke whales, and a spotted dolphin) were found stranded within a 36 hour period along a 240 km arc in the Northeast and Northwest Providence Channels of the northern Bahamas Islands. Only odontocetes (toothed whales) are known to mass strand. Beaked whales mass strand much less often than other odontocetes. Cuvier's beaked whale mass strand more frequently (20 known events) than other beaked whale species. Only two other mass stranding events of beaked whales have been reported for the Bahamas since 1864. From their condition, the animals in this investigation most likely all stranded on March 15, although some were not discovered until March 16. Strandings were first noted at the southern end of the channels and reports proceeded northwest throughout March 15.

Seven animals died, including five Cuvier's beaked whales, one Blainville's beaked whale, and one spotted dolphin. Of the six necropsies that were performed, only three animals (one Cuvier's beaked whale, one Blainville's beaked whale, and the spotted dolphin) were sufficiently fresh to clearly examine the lesions. Two of six animals were buried for two days and were later exhumed for complete necropsy. A sixth animal was examined five days later and found to be in advanced decomposition. The necropsy on the spotted dolphin revealed the animal died with systemic debilitating disease. It was considered unrelated to the mass stranding event cluster.

All five beaked whales examined by necropsy were in good body condition, and none showed evidence of debilitating infectious disease, ship strike, blunt contact trauma, or fishery related injuries. Three of the beaked whales had food remains in their stomachs. Some type of auditory structural damage was found in four beaked whales examined, specifically bloody effusions or hemorrhage near and around the ears. The most significant findings, which were found in the two freshest specimens, consisted of bilateral intracochlear and unilateral temporal region subarachnoid hemorrhage with blood clots bilaterally in the lateral ventricles. Pathologists concluded that the hemorrhages occurred before death and would not necessarily have been fatal or have caused permanent hearing loss in terrestrial mammals. However, such hemorrhages are debilitative and may have compromised hearing or navigational abilities, resulting in disorientation and subsequent stranding. Three animals also had small hemorrhages in the acoustic fats (along the jaw and in the melon), but it has not yet been determined whether these hemorrhages occurred before or after death.

The most likely cause of the observed trauma was either acoustic or impulse injuries. Pathological analysis alone cannot differentiate between far-field blast effects and acoustic induced injury from single or multiple events. However, review of acoustic records show that no explosions occurred at the time of the strandings. Therefore, by deduction, it is reasonable to assume that the hemorrhages were acoustically induced. The beaked whales showed evidence of overheating, cardiovascular collapse, and physiological shock, a cascade of physiological events that commonly results in death after stranding. They were the most likely immediate cause of death, although the offshore acoustic event triggered this cascade of events.

Passive Acoustic Recording

A report prepared by NOAA notes that the agency was operating two passive acoustic monitoring arrays that could detect sounds from the Bahamas during the time frame in question. One array, that was located 100 nautical miles south of the stranding site was not recording continuously and may have missed an explosion if one occurred. The other array, located on the mid-Atlantic ridge, was recording continuously, but showed no evidence of an explosion or geological event (earthquake etc.). These recordings ruled out the possibility that a distant explosion could have been the causative acoustic event.

Ship Movements and Acoustic Modeling

Commander in Chief, U.S. Atlantic Fleet prepared a report (presented here in abstract only), which describes in detail the timing and courses of U.S. Navy ships in the Northeast and Northwest Providence Channels on March 15, 2000, the kinds of sonars used, modes of operation, and frequencies and power settings employed. The ships were operating in the Providence Channels because of unfavorable political conditions in their usual range near Vieques, Puerto Rico.

Numerous ships transited from the southeast to the northwest in generally the same pattern in which strandings were discovered. Five ships used their mainframe active sonar in the channels during the time of interest. A detailed acoustic analysis was prepared for four of them (referred to as ships A, B, C, and D). Ships A and B operated the tactical mid-frequency sonar designated AN/SQS-53C [center frequencies 2.6 and 3.3 kHz (kilohertz) usually at source levels of 235 dB]. Ships C and D operated sonar designated AN/SQS-56 (center frequencies 6.8 to 8.2 kHz, usually at source levels of 223 dB). Ships B, C, and D were in the channel from approximately midnight March 14 to approximately noon March 15. Ship A and five others were in the channel from approximately 6 AM to approximately 4 PM on March 15, four to six hours behind ships B, C, and D.

During the 16 hour period in which the ships transited the channel using sonar, each ship pinged its sonar approximately every 24 seconds, with pings from nearby ships staggered in time so as not to coincide. Because the ships did not operate at the same frequencies, and because the ships with the same frequency sonars did not operate in the same temporal and spatial proximity, there is little likelihood of increased sound pressure level from multiple, simultaneous pings.

An acoustic modeling report by the Office of Naval Research (ONR) describes how sound from the above-mentioned tactical mid-range frequency sonars would have propagated in the Providence Channels the day of the stranding. Using environmental data from the day in question, as well as historic data for the site in question, various acoustic propagation models were run. The propagation model and Monte Carlo methods used to simulate natural variability amount to a worst-case example. The models all yielded very similar results, indicating a surface duct that would have concentrated sound in the top 200 m of water. Thus, reverberation from the sides or bottom of the submarine canyons likely did not contribute significantly. Likewise, the calm seas did little to stop the reflection and caused fewer air bubbles, which dissipate sound energy. Actual animal locations at the time of exposure are unknown, so there is no precise measurement of the amount of

ensonification the stranded animals received. Finally, modeling was limited by the lack of evidence supporting a specific Receive Level at which tissue damage will occur for the beaked whales in question.

The models show the sound pressure level that whales could have encountered from these sonars in various parts of the channel. In reviewing the modeling data, it is important to differentiate between the sound pressure level at the source (SL), which is measured at a distance of one meter from the source, and the sound pressure that the animal would receive, or the Receive Level (RL). Additionally, it is important to note that due to spherical spreading of sound, absorption, reflections, scattering, and other phenomena, SL drops markedly as one moves away from the source.

In brief, modeling for the AN/SQS-56 sonar indicated sound pressure levels greater than 180 dB would usually have been encountered no more than 300 m from the source horizontally, and no more than 200 m vertically (the depth of the duct). For the AN/SQS-53C sonar operated at nominal source level of 235 dB, the model indicates sound pressure levels greater than 180 dB would usually have been encountered no more than 1,000 m from the source horizontally, and no more than 200 m vertically. During a brief time period when ship B operated its AN/SQS-53C system at a higher power setting, the model indicates sound pressure levels greater than 180 dB no more than 5,000 m from the source horizontally, and 1,400 m vertically. This period of increased Source Level is not likely to have caused all 17 strandings because it did not move in a south to north pattern nor cover the whole 240 km span of the stranding sites. All these are very narrow swaths in comparison to the width and depth of the Providence Channels, and most likely in comparison to the distribution of the beaked whales in question.

The rise time of the signal, the time required for the signal to grow from zero to maximum amplitude, can have an impulse-like effect if it is short enough. The rise time of these sonars was 0.4 to 0.1 millisecond, depending on signal frequency. This is not considered brief enough to have an effect like an explosion.

Finally, the modeling team concluded that it was not likely that sound pressure level was increased by multiple, simultaneous sonar pings. The greatest additive effects occur when signals have nearly identical phases and amplitudes. These sonars did not ping simultaneously, so the conditions for an additive effect were almost never met.

Follow-up Research Actions

A report by the Office of Naval Research summarizes the follow-up research actions that are needed to understand factors that contributed to the stranding event. The Recommended Research Actions section details research that would help to 1) identify the mechanism(s) that led to the physiological effects observed, and 2) mitigate the effects of these sonars in future operations. This list does not purport to be an exhaustive compilation of all possible actions, but does describe projects already under way, being planned, or feasible but not yet funded, which collectively are intended to reduce or eliminate further strandings of this type.

Conclusions and Recommendations

To the maximum extent practical, the Navy will adopt measures in its future peacetime training, including those involving the use of tactical mid-range sonars, to avoid the taking of marine mammals. Under the circumstances investigated in this report, two actions are recommended for the Navy. These are to understand the mechanisms by which sonar sounds affect marine mammal tissue or behavior, and to concurrently put into place mitigation measures that will protect animals to the maximum extent possible and not jeopardize National Security.

Biological Investigation

MASS STRANDING EVENT IN NORTHERN BAHAMAS, MARCH 15-16, 2000

Abstract: From March 15-16, 2000, there was a mass stranding of 17 cetaceans in the Bahamas. The strandings were clustered within a 36 hour period over three islands (Grand Bahama, Abaco, and North Eleuthera), and coincided with U.S. Navy activities in the area. During this time period, nine Cuvier's beaked whales (*Ziphius cavirostris*), three Blainville's beaked whales (*Mesoplodon densirostris*), two unidentified beaked whales, one spotted dolphin (*Stenella frontalis*), and two Minke whales *(Balaenoptera acutorostrata*) were reported stranded. At least seven of the animals are known to have died (carcasses were recovered), and six of these animals were necropsied. The remaining live whales were pushed off the beach and/or escaped to deeper water. The fate of those animals is unknown. Initial gross necropsy, computerized tomography examination and full head necropsies on those beaked whales not returned to the water showed that the animals were in good body condition (5 animals), that there was no macroscopic indication of debilitating infectious disease (5 animals), and that the animals had temporal region subarachnoid hemorrhage (1 animal) and hemorrhage in the intracochlear duct (2 animals) and acoustic fats (3 animals). These findings are consistent with an acoustic or impulse injury that caused the animals to strand, six of them then to subsequently die as a result of cardiovascular collapse due to extreme physiologic stress associated with the physical stranding (ie, hyperthermia, high endogenous catecholamine release). The spotted dolphin and minke whales stranded in different geographic areas than the rest of the animals (beaked whales). The findings in the spotted dolphin postmortem examination showed evidence of chronic disease and debilitation. The spotted dolphin showed no auditory trauma in common with the beaked whales based on gross and computerized tomographic lesions (no hemorrhage in the inner ears and acoustic fats); therefore, this animal was not considered part of the mass stranding event. The minke whales returned to deeper water and were not reported to re-strand. One of the animals spent over 24 hours on the beach and was physically removed to deep water by a boat, the other minke whale stayed in a shallow enclosed harbor for two days before being escorted out to deeper water by boats. Because these two animals did not die and were not examined while in shallow water or on the beach, no definitive statements can be made about the cause of their stranding, their survival, or their injuries. However, the stranding of minke whales in the Bahamas is unusual. This report summarizes the preliminary biological findings of the ongoing investigation of this mass stranding event. A final report summarizing the findings of the complete investigation will be published in 2002 after peer review.

Introduction

Mass strandings are defined as two or more cetaceans (excluding cow/calf pairs) that are found ashore alive or dead and which are spatially and temporally correlated (Wilkinson, 1991). From 1987 to 1999, eighteen cetacean species were represented in mass strandings along the east coast of the United States. Only odontocetes (toothed whales) are known to mass strand. In the U.S., the most frequent species to mass strand are: Atlantic white sided dolphins (*Lagenorhynchus acutus*), short finned pilot whales (*Globicephala macrorhynchus*), long finned pilot whales (*Globicephala melaena*), common dolphins (*Delphinus delphis*), rough toothed dolphins (*Steno bredanensis*), and pygmy sperm whales (*Kogia*

breviceps) (Walsh, et al, 2001). Species that mass strand are typically more social and pelagic animals which are often less accustomed to shallow or in-shore habitats (Geraci and Lounsbury, 1993). Some geographic areas have a higher incidence of mass strandings, whereas other mass strandings may occur following specific weather or oceanographic events. Causes of mass strandings are varied. Often many animals in a particular mass stranding event appear physically normal, and frequently no cause of the stranding or mortality is evident upon gross examination. More often than not, response to mass strandings overwhelm the stranding network even in areas which have standardized protocols and considerable resources and experience. The sheer volume of work or the decomposition of the carcasses may preclude in-depth studies of the stranded animals, but every effort is made to examine animals as thoroughly as possible to allow more complete investigations of causes of mass strandings.

Mass strandings of beaked whales, in general, are much less common than mass strandings of pilot whales or white-sided dolphins and are more often associated with islands rather than mainland coastlines. Historically from 1838 through 1999, there were 49 reported mass stranding events of beaked whales for a total of 226 animals and a mean average of 5.4 animals per event (excluding those events in which numbers of stranded animals were not documented). (These data were obtained from the Cetacean Distribution Database, compiled by the Marine Mammal Program, National Museum of Natural History, Smithsonian Institution). The largest number of beaked whales that stranded in a single event was a mass stranding of 28 Gray's beaked whales (*Mesoplodon grayi*) which occurred in New Zealand in 1875 (Haast, 1876). The earliest reported beaked whale mass stranding was of Northern bottlenose whales (*Hyperoodon ampullatus*) in which four animals stranded on November 14, 1838 in Norway. Blainville's beaked whales (*Mesoplodon densirostris*) have been uncommonly reported in mass strandings. Historic records show that this species was involved in only one other mass stranding that occurred in 1989 in the Canary Islands (Vonk and Martel, 1989; Simmonds and Lopez-Jurado, 1991).

Cuvier's beaked whales *(Ziphius cavirostris)* have been the most frequently reported mass stranded beaked whale worldwide. There have been 21 known events through 2000 totaling more than 129 animals with a mean average of 6.2 animals per event. Although the first reported single stranded Cuvier's beaked whale was in 1804, the first mass stranding of that species was reported in May, 1963 in Genoa, Italy. Cuvier's beaked whale mass stranding events have been reported more frequently in the last 20 years (Table 1) than previously reported. However, the reporting and detection networks have been much more organized and effective in many countries in the last two decades than in previous ones. Reports of strandings are a combination of effort, actual frequency, and species identification. Since 1974, there have been six multi-species mass strandings involving beaked whales (excluding this current event). In all six events, the Cuvier's beaked whale was again the principal species involved.

From a historical perspective, the Bahamas mass stranding event occurred in an uncommon geographic location and involved an unusually large number of animals of mixed species. Mass strandings in the Bahamas are unusual. There are only two other records of mass strandings in the Bahamas (4 Cuvier's beaked whales which stranded on February 5, 1968 and 3 Blainville's beaked whales which mass stranded on March 5, 1998). In 1991, Simmonds and Lopez-Jurado (1991) reported an apparent association of beaked whale mass strandings with naval/military activities but concluded that the reason for the unusual strandings can only be the subject of speculation since no pathological examinations had

been done on the animals. Most of those correlated events involved the Cuvier's beaked whale as the principal species (Frantzis, 1998). To date the mass stranding which has been most intensely investigated was of Cuvier's beaked whales which stranded during May 12-15, 1996. This mass stranding was externally reviewed by a SACLANTCEN Bioacoustics Panel held in La Spezia, June 15-17, 1998. Because of the lack of comprehensive necropsy and complete tissue analyses, the possibility of a pathological cause for the 1996 strandings could not be determined. This panel concluded that an acoustic link could neither be clearly established nor eliminated as a direct or indirect cause for the May 1996 strandings. The panel recommended that since the effects of sound on marine animals vary according to species, additional research was needed to determine the hearing characteristics and behavior of the entire range of marine species. The recognition of the need for more information on the anatomy and physiology of beaked whale hearing and head structures led to the two fresher head specimens being collected in this current investigation.

This report only contains a brief summary of the biological information completed to date. The complete data set from ongoing analyses and final conclusions will be available in a final report to be completed early in 2002. Although there were no fresh animals on which complete necropsies were performed, the evidence obtained from partial collections of the freshest animals included the best samples to date that are likely to show defined lesions which may lead to a cause of injury. Data collection from future responses that are rapid and utilize standardized collections from mass and single stranded beaked whales will increase our understanding of the morphology and physiology of beaked whales and the types of disease, lesions and mechanisms of injury in these species.

Epizootiology

Stranding Occurrence. The strandings were clustered temporally (within a 36 hour period) and spatially (along a 240 km arc including Grand Bahama, Abaco, and North Eleuthera islands) (Figure 1). The first beaked whale stranding was reported at 07:30 (local time; 12:30 Zulu time) on March 15 (live Cuvier's beaked whale), and the last stranding was reported on March 16, 2000 (dead Cuvier's beaked whale). All of the animals reported on March 15 (n=11) were initially described as live strandings, and only one of these reported strandings was found dead that day. All of the strandings subsequently reported on March 16-17, 2000 were of dead animals (n=6). Strandings occurred first at the southern end of the arc and moved northwest throughout the day (Figures 1 and 2, and Table 2). Since the reporting time does not always reflect the stranding time, and the animals that were reported on March 16 were dead and showed some signs of decomposition, the initial time of stranding for all the animals in this cluster most likely was on March 15, 2000. Figures 2a-e reconstruct the temporal and geographic correspondence between ship movements and individual strandings.

Of the 17 cetaceans reported, 14 were first reported as live strandings. Ten of the animals were pushed off, escorted to deep water, or swam away from shore (2 Minke whales, 2 unidentified beaked whales, 2 Blainville's beaked whales, and 4 Cuvier's beaked whales). It is not known whether these animals survived, since none of the animals have been recognized as re-stranded or re-sighted to date (Balcomb and Claridge, 2001). The sex and age class composition for this mass stranding is incomplete, since age and sex class are not yet confirmed for many of the animals. General age classification is made by animal length but will be confirmed using growth layer groups in teeth. Skin samples were obtained for genetic analyses from two of the live animals that were pushed off (1 Cuvier's beaked whale and

Table 1. List of Cuvier's beaked whale mass strandings globally as recorded in the Cetacean Distribution Database, National Museum of Natural History, Smithsonian Institute. (Zc= *Ziphius cavirostris* or Cuvier's beaked whale; Sc= *Stenella coeruleoalba* striped dolphin; Md= *Mesoplodon densirostris* or Blainville's beaked whale; Me= *Mesoplodon eurapaeus or* Gervais beaked whale; Ha = *Hyperodon ampullatus* or Northern bottlenose whale; UB = unidentified beaked whale).

Species	Numbers	Date (mo/yr)	Location
Zc	>15	5/1963	Genoa, Italy
Zc	5	12/1965	La Parguera, Puerto Rico
Zc	4	2/1968	Normans Cay, Exumas, Bahamas
Zc	4	4/1974	Bonair
Zc/Sc	3/1	12/1974	Corsica
Zc	3	3/1975	Anegada Island, British Virgin Is.
Zc	3	1/1980	South Shore, Bermuda
Zc	4	1981	Ferry Beach, Bermuda
Zc	6	3/1983	Baltra, Galapagos Islands
Zc/Md	12/1	2/1985	Fuertoventura, Canary Islands
Zc/Me	5/1	6/1986	Mala, Canary Islands
Zc/Me	?/2	7/1987	Los Jameos del Agua, Canary Islands
Zc/Ha	3/1	11/1988	Fuertoventura, Canary Islands
Zc/Md/Me	19+/3+/3+	10/1989	Fuertoventura, Canary Islands
Zc	4	2/1991	Buck Island, U.S. Virgin Is.
Zc	12	5/1996	Kyparissiakos Gulf, Greece
Zc	3	8/1997	Greece
Zc	5	7/1998	Aguadilla, Puerto Rico
Zc/Md/Ba/ UB	9/3/2/2	3/2000	Bahamas
Zc	4	5/2000	Madeira Archipelago

1 Blainville's beaked whale), as well as from all of the dead animals, so sex can be determined and species be confirmed. Photographs were obtained of the Minke whales, and six of the live beaked whales. One of these live beaked whales had been previously photodocumented in the area during ongoing photo-identification research (unpublished data, Bahamas Marine Mammal Survey Group). No samples were taken, nor are photos yet available, from two of the unidentified beaked whales; therefore, species confirmation, sex, age class, and animal condition cannot be confirmed.

Of the seven animals that died, six were necropsied (4 Cuvier's beaked whales, 1 Blainville's beaked whale, and 1 spotted dolphin). Sex and reproductive status were confirmed on those animals that were necropsied: 3 females (2 Cuvier's beaked whales, 1 spotted dolphin) and 4 males (3 Cuvier's beaked whales and 1 Blainville's beaked whale). One Cuvier's beaked whale was identified as a female but was not necropsied, and reproductive status was not determined. Age class has not yet been confirmed on most of the animals. However, teeth were obtained from four

of the six necropsied animals for age estimation using growth layer group analysis and analysis is pending export of teeth from the Bahamas.

Response and Investigation. The Bahamas Marine Mammal Survey (BMMS) group and Dr. Alan Bater, a veterinarian designated by the Bahamas Department of Fisheries, initially responded to these strandings. Upon request from Dr. Bater, the National Marine Fisheries Service (NMFS) sent an investigative team consisting of pathologists and biologists. Since the stranding event, the investigation team has involved NMFS, the Bahamas Marine Mammal Survey group, the Smithsonian Institution -National Museum of Natural History, Woods Hole Oceanographic Institute, Dr. Bater, and consulting experts to examine the epizootiology of the strandings and subsequent mortalities (Table 3).

Gross Findings and Computerized Tomography

Specimen condition. Of the six necropsies performed, only three animals (1 Cuvier's beaked whale, 1 Blainville's beaked whale, and 1 spotted dolphin) were sufficiently fresh to provide relatively clear lesions for evaluation and interpretation (the actual necropsies were conducted hours after death and/or heads were frozen soon after death for later examination). Only one of these was a complete necropsy (spotted dolphin) in which the animal carcass was thoroughly examined by trained personnel and organs were examined and tissues collected. Two of the six animals were buried two days following their death and were later exhumed (within four to sixteen hours) for complete necropsy and collection of the ears. A sixth animal was examined five days later and found to be in a state of advanced decomposition indicating that the animal had stranded and died several days prior to examination (on the same day as the other strandings). The tissues from the two exhumed animals were severely decomposed. The heads of six animals were examined by gross dissection. Three were badly decomposed and were examined on-site post exhumation, and three heads were reasonably fresh (1 Cuvier's beaked whale, 1 Blainville's beaked whale, and 1 spotted dolphin). The three best- preserved specimens, two beaked whale heads and one intact spotted dolphin carcass, were frozen on site for later examinations by computerized tomography (CT) followed by gross dissection and histology.

Findings.

<u>Spotted Dolphin.</u> Gross necropsy of the spotted dolphin showed that the animal was in poor body condition with associated disease. Computerized tomography scans and subsequent dissection revealed that this animal had extensive sinus disease, necrotic deposits from long term inflammation of the middle and peribullar areas bilaterally, and evidence of systemic debilitating disease. The spotted dolphin stranding site was acoustically isolated from the main exercise and from the duct that occurred in the Providence Channels, leeward waters in which the beaked whale strandings occurred. Due to the dissimilar pathology (see below), distant geographic
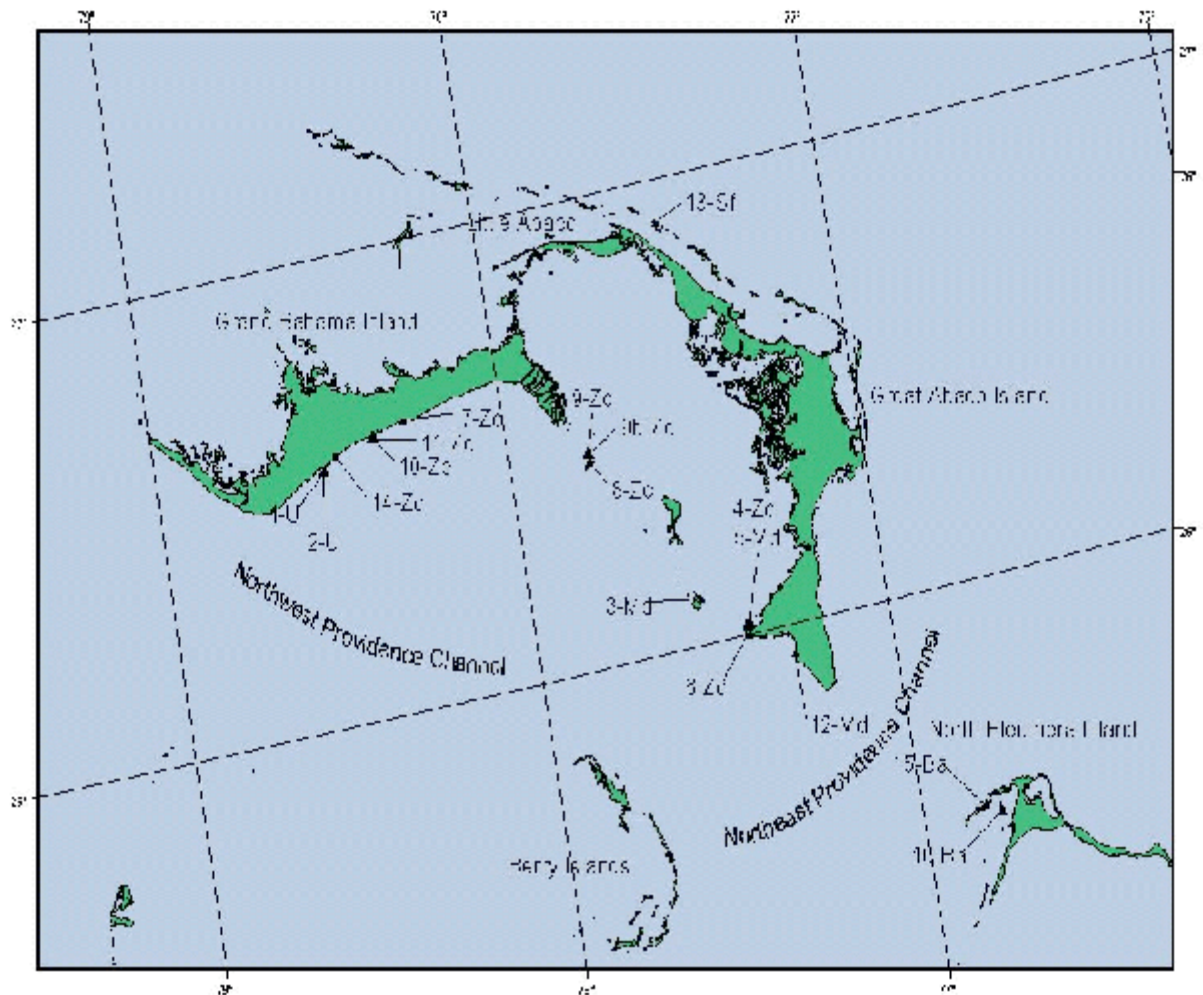
Locations of Strandings in the Bahamas

Figure 1: Location of animals that were reported stranded on March 15-17, 2001 in the Bahamas. (Zc = Cuvier's beaked whale; Md= Blainville's beaked whale; Ba = Minke whale; Sf = spotted dolphin).

location of this stranding relative to the rest of the strandings (Figure 1), presence of a land barrier and currents that separated it from acoustic sources on the other side of the island, and the absence of conspecifics or other delphinids in this stranding event, the stranding of this animal was considered unrelated to the mass stranding event cluster. Therefore this animal will not be considered in further discussions in the investigation of this mass stranding event; however, the CT scans and histopathology of the ears will be used in the ear pathology database for comparisons.

Figure 2: Maps of strandings relative to ship positions (ships A-D) when sonars were turned on and sound field modeling was performed (See pages 32-35). The maps depict ship position at Zulu time indicated at the heading of each map, and strandings that occurred at that time or in the 1.5 to 2 hours between the maps. The strandings indicate the time of the first report of the stranding and the color of the flag indicates whether the animal was first reported alive (yellow) or dead (red). Each flag position may represent more than one animal as indicated by the times associated with each flag. On Figure 2b, three strandings occurred between 0700 and 0900 near the same point and are represented by one flag. The ships A-D are the same as indicated in the modeling report on pages 32-35.
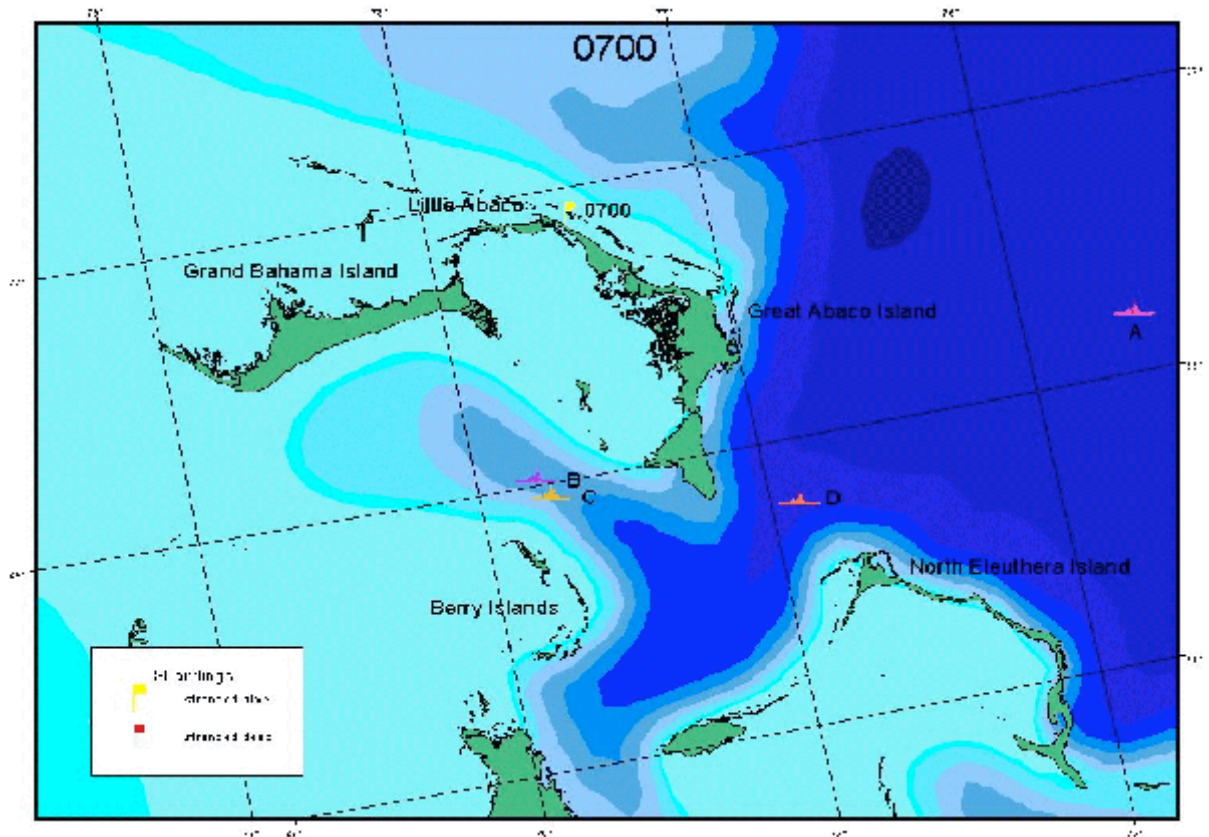

Figure 2a: Map of strandings at 0700 relative to ship positions (ships A-D) when sonars were turned on.
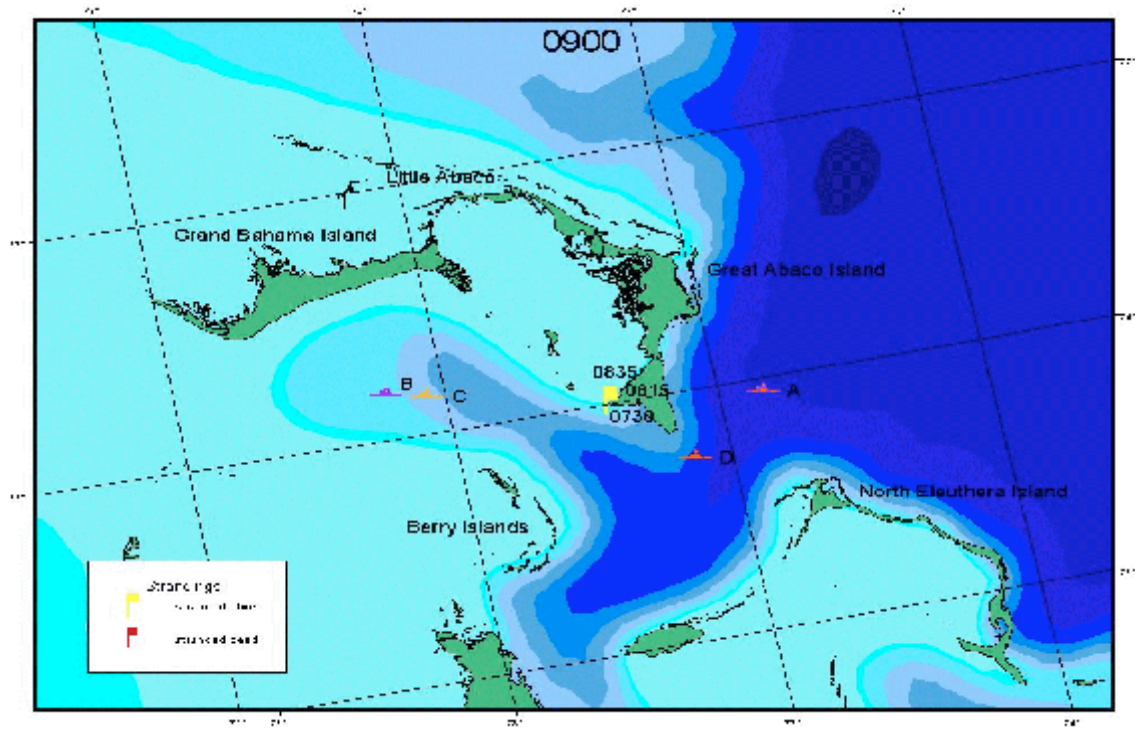
Figure 2b: Map of strandings at 0900 relative to ship positions (ships A-D) when sonars were turned on.
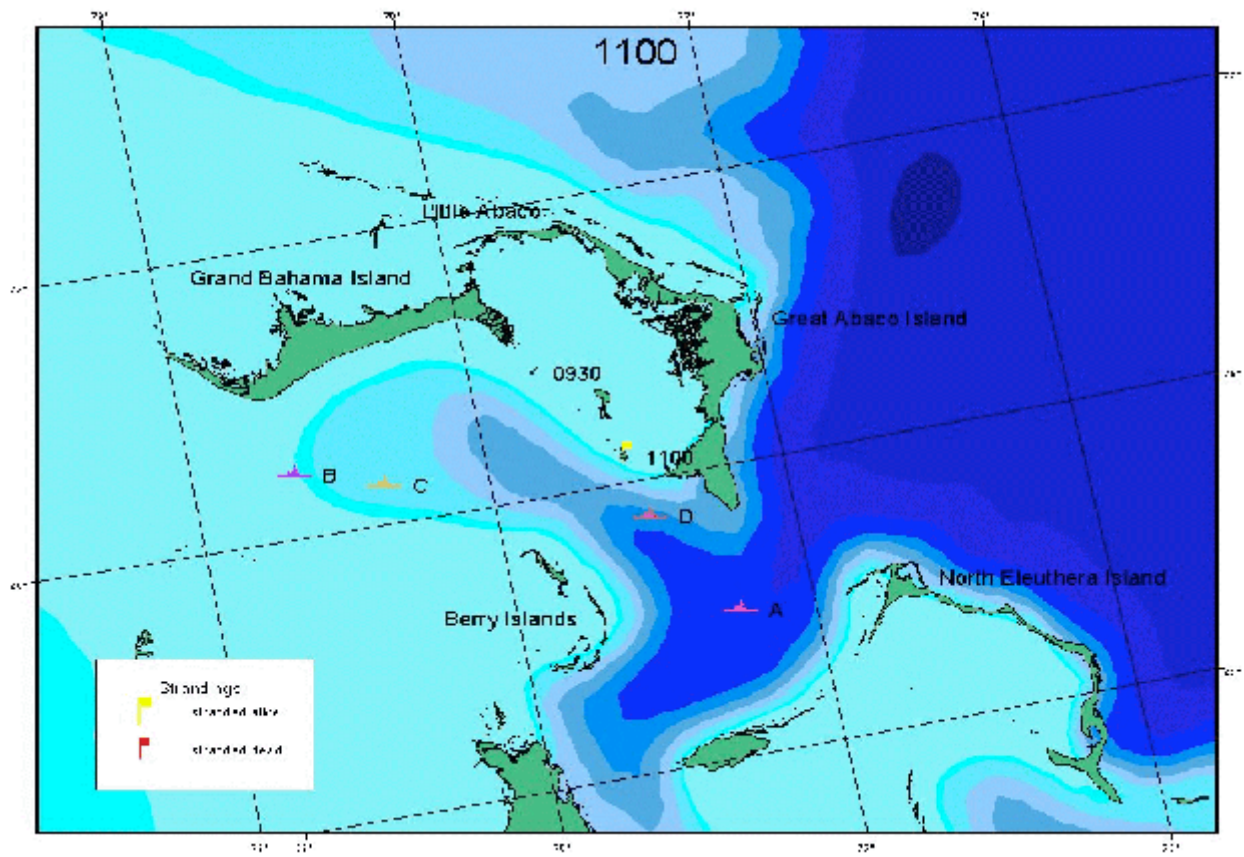
Figure 2c: Map of strandings at 1100 relative to ship positions (ships A-D) when sonars were turned on.

Figure 2d: Map of strandings at 1230 relative to ship positions (ships A-D) when sonars were turned on.

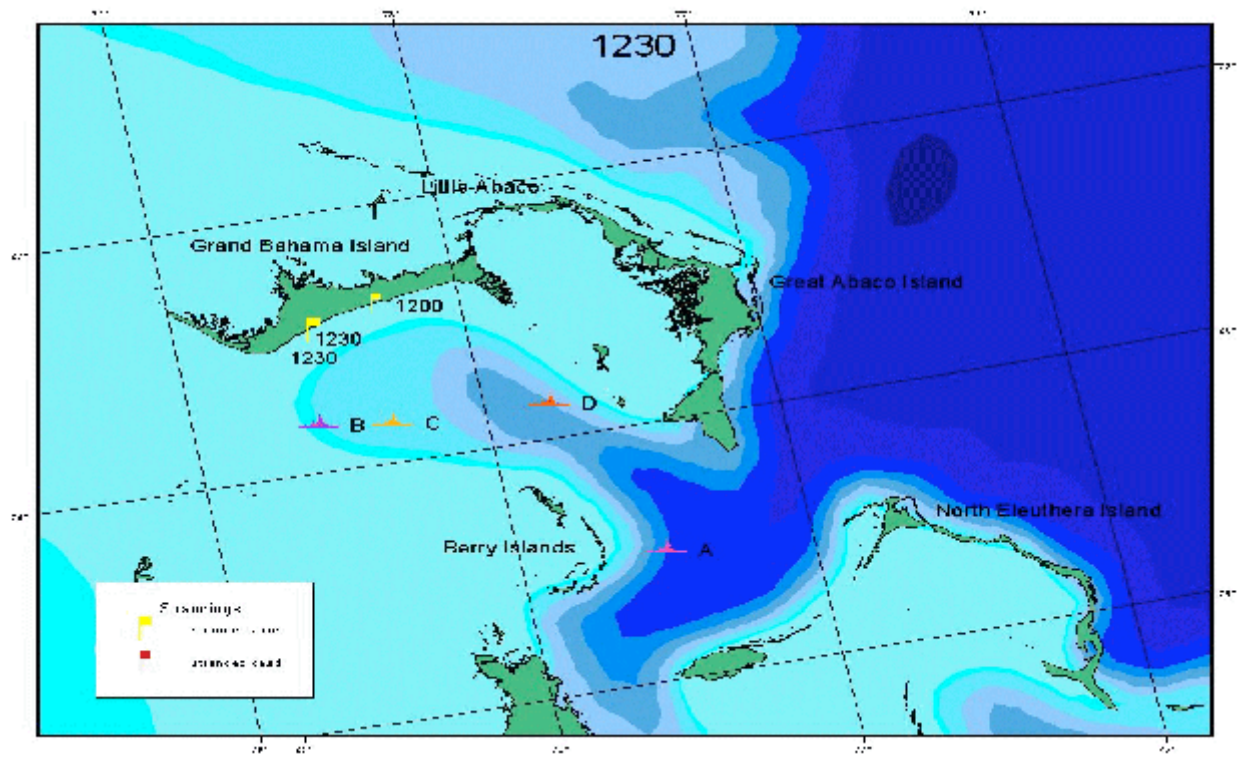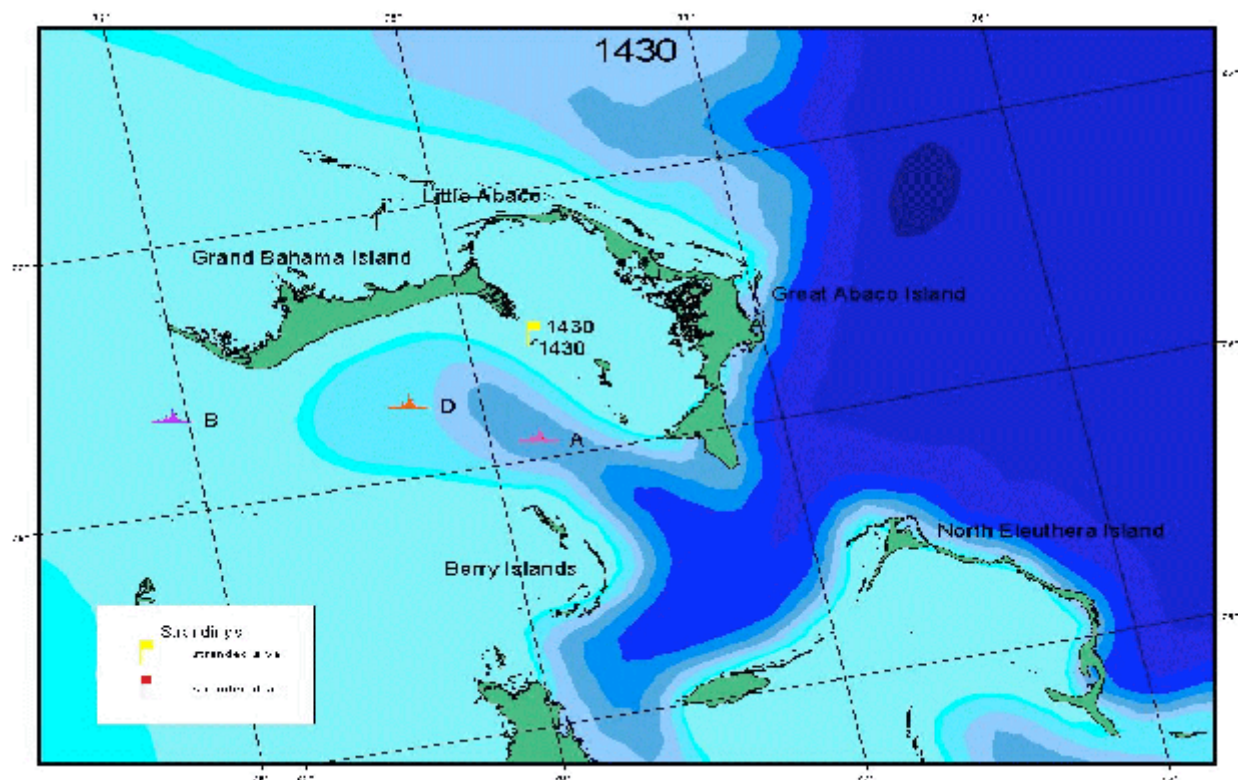**Figure 2e:** Map of strandings at 1430 relative to ship positions (ships A-D) when sonars were turned on.

Beaked Whales. All beaked whale carcasses examined by necropsy had similar gross (n=5) and cranial CT findings (n=2). Even the moderately decomposed animals had lesions in common with the fresher animals, although the most reliable findings are those found in the freshest tissues. Gross necropsy showed that all five beaked whales examined were in good body condition, and none showed evidence of significant debilitating infectious disease, ship strike, blunt or other overt contact trauma, or fishery related injuries. The male Blainville's beaked whale, which was the best preserved beaked whale, had renal capsular hemorrhage, mild lung hemorrhage, and heart muscle lesions which are often seen in strandings (Turnbull and Cowan, 1998), and bruising of the larynx. There was no evidence of external or subcutaneous hemorrhages such as those seen in boat strikes or interspecific aggression in any of the beaked whales examined. There was no evidence of gastric obstruction from ingested marine debris or fishery interactions which have been found in some single stranded beaked whales along the U.S. Atlantic coast. Many of the beaked whales did have, however, superficial abrasions typical of beach stranded live animals or animals that have rolled in the surf while alive.

The results from the beaked whale head dissections and CT scans revealed no evidence of fractures or cutaneous/subcutaneous hemorrhages nor other evidence consistent with blunt trauma or primary blast shockwave from an explosion. There was strong evidence indicative of acoustic

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trauma in the two freshest beaked whale heads. The most significant findings consisted of bilateral intra-cochlear and unilateral temporal region subarachnoid hemorrhage with blood clots bilaterally in the lateral ventricles in the Blainville's beaked whale and intra-cochlear hemorrhages in the Cuvier's beaked whale (Figure 3).
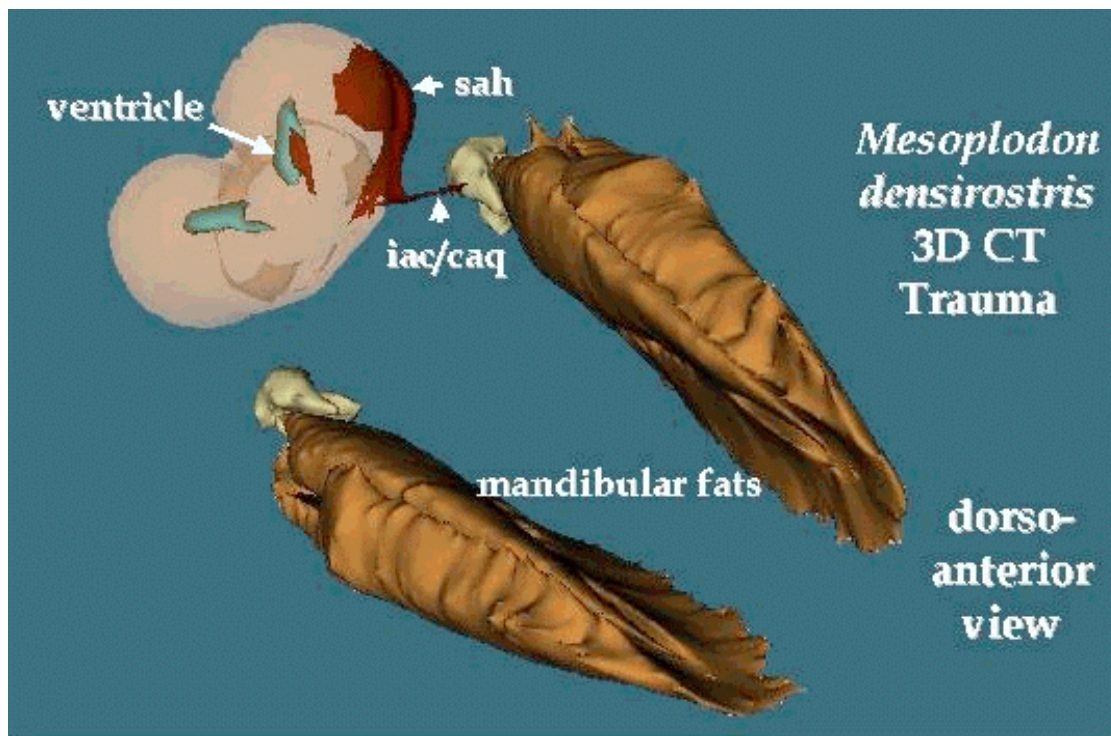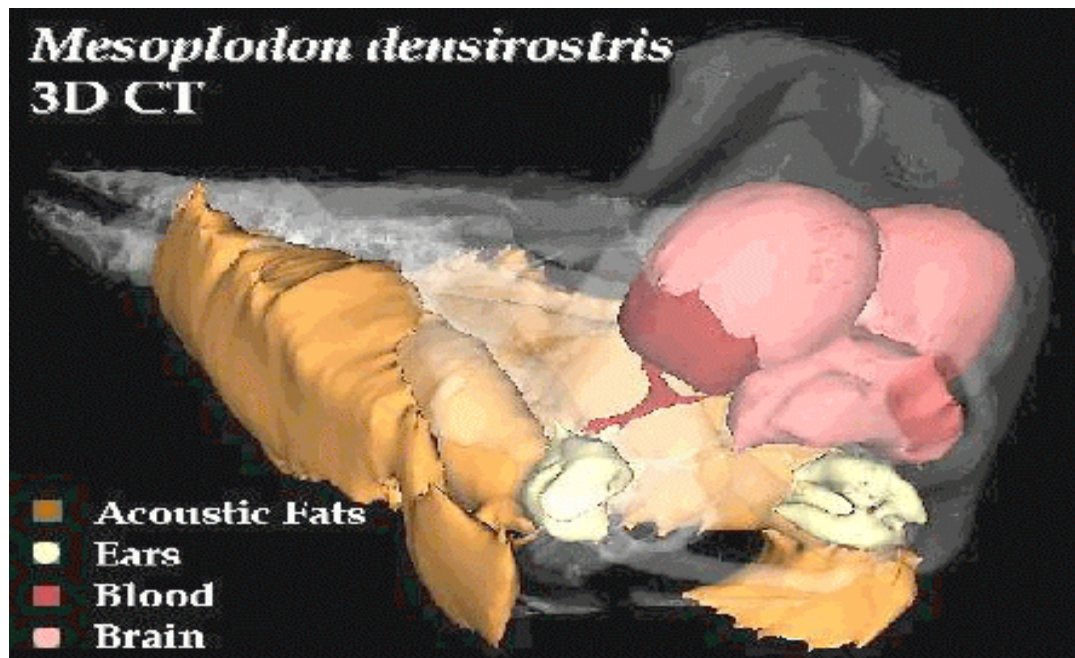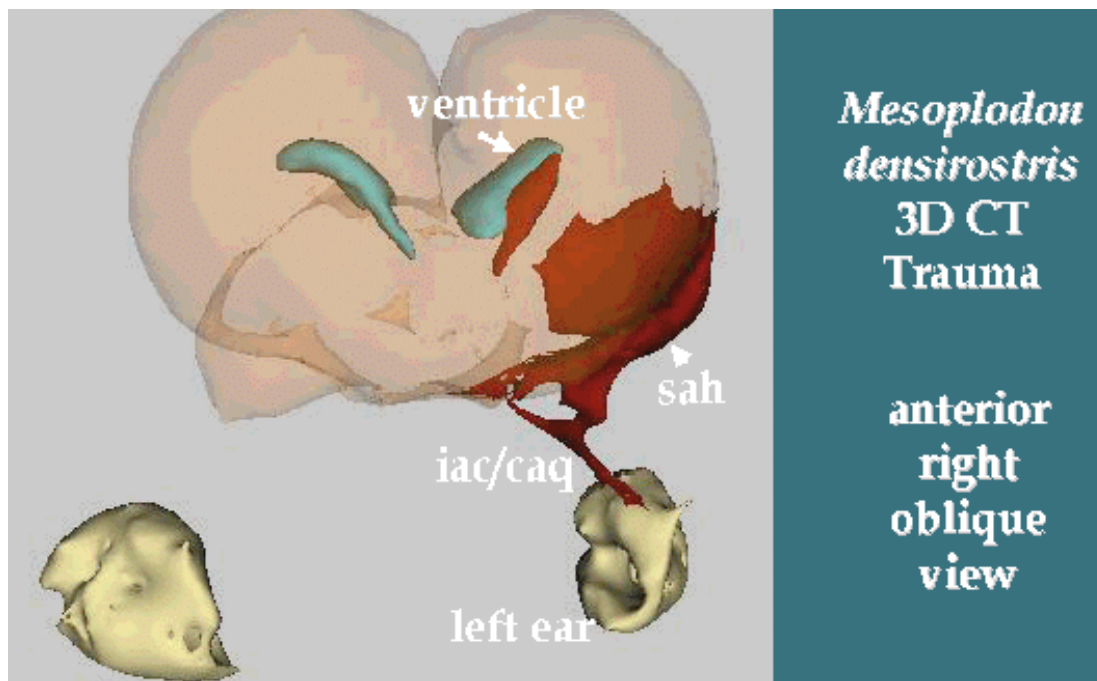
Figure 3: Three dimensional reconstruction of two dimensional computerized tomographic images of the freshest specimen, Blainville's beaked whale. The images point out the positions of the hemorrhage found in this specimen relative to identifiable head structures. (sah = Subarachnoid hemorrhage; iac = internal auditory canal; caq = cochlear aquaduct; ventricle = lateral ventricle of brain).

Similar ear injuries were seen grossly in the two moderately decomposed Cuvier's beaked whales as well as intracranial staining. In simpler terms, there were deposits of blood within some of the inner ear chambers, and in at least one animal the blood trail can be traced to a hemorrhage in a discrete region of a fluid space surrounding the temporal regions and within a ventricle of the brain. Some type of auditory structural damage findings are present in all four beaked whales examined (all showed bloody effusions or hemorrhage near and around the ears). However, for the decomposed animals, these findings by themselves would not be definitive because of the difficulty of distinguishing them from necrotic or non-lesional autolytic changes. However, the presence of these changes in light of matching lesions in the fresher animals increases the likelihood that they were incurred before death. The presence of blood in only restricted intracranial spaces and the intact inner ear membranes in the best preserved ear are not consistent with simple post-mortem pooling. Indiscriminate post-mortem pooling is generally greater in the gravitationally dependent or down side on the beach and occurs throughout the whole ear because normal ear tissues that seal and divide the inner ear are lost through post-mortem degradation. The pattern of injury in the two freshest animals, therefore, suggests the ears were structurally intact and the animals were alive at the time of injury. In summary, this pattern of damage is most consistent with acoustic trauma. Additional analyses, such as light microscopy, are underway on all specimens that will better characterize the damage and determine with greater certainty any contributory causes (see histopathology section).

Life history

Stomach contents were examined from three animals (2 Cuvier's beaked whale and 1 Blainville's beaked whale). No prey remains were found in the stomach of the Blainville's beaked whale; however, the two Cuvier's beaked whale stomachs contained small quantities of cephalopod and crustacean remains that were consistent with other beaked whale prey examinations (Clarke, 1996). Age class determinations are underway using examination of growth layer groups in sectioned teeth. Renal parasite identification and genetic analyses are also pending.

Histopathology

Post cranial histopathology. Two independent pathologists examined tissues from four animals (3 Cuvier's beaked whales and 1 Blainville's beaked whale). In two of the Cuvier's beaked whales (Zc 10 and Zc 11), advanced post-mortem decomposition hampered histological interpretation of the tissues. Neither the exact cause of death nor any contributory disease was evident in these two severely decomposed animals. However the acute pulmonary edema and congestion observed in these two animals are common nonspecific findings seen in stranded cetaceans, particularly in those which strand live and subsequently die on the beach. Examination of tissues from the remaining Cuvier's beaked whales (Zc 7 and 14) revealed moderate to severe autolysis which precluded in-depth analyses. Inflammatory changes were seen in the lymph nodes of the fresher animal (Zc8); however, these inflammatory changes are commonly seen in stranded wild odontocetes, often associated with parasitism. The Blainville's beaked whale (Md12) tissues were the freshest of the four sets examined, and analyses of multiple organs, post-cranially, did not reveal a cause of death or evidence of chronic, debilitating disease. The heart showed evidence of acute myocardial contraction band necrosis, a not uncommon finding in stranded odontocetes, which has been attributed to elevated endogenous catecholamine in other animals and humans (Turnbull and Cowan, 1998). The kidneys showed evidence of acute capsular and subcapsular hemorrhage. Multiple organs showed signs of congestion and mild hemorrhage, a common non-specific terminal finding in stranded odontocetes. In addition, this animal also showed evidence of inflammation in the lungs and associated lymph nodes similar to that commonly associated with parasitism in wild odontocetes. Parasites are common in free ranging whales.

Cranial/ear histopathology. Final tissue analyses, results and interpretations are pending for several animals (Zc10, 11, 8 and Md12). Soft tissues were collected from the head of one Blainville's beaked whale (Md12) and one Cuvier's beaked whale (Zc8) and have been examined by two pathologists. Brain tissue is currently being examined from these two animals for structural lesions and for evidence of infectious disease such as morbillivirus. Ear tissues were collected from three Cuvier's beaked whales involved in the Bahamas investigation, one Blainville's beaked whale from the Bahamas mass stranding, the spotted dolphin from the Bahamas stranding, other delphinids and *Ziphius* from unrelated single and mass strandings. The tissues have been prepared, cut, and examinations are currently underway. Preliminary histological results from two sets of *Ziphius* ears (Zc10 and Zc8) that were decalcified using acid and acid/EDTA combinations show the presence of an eosinophilic precipitate (indicating an antemortem insult), blood in primarily the apex and base of the cochlea (suggesting a neural canal and CSF entry to the ear), loss of auditory neurons and metabolic tissues, and labyrinthine collapse. These findings are consistent with multiple pathologic conditions, including impulse trauma,

aging, and subarachnoid hemorrhage effects. Acoustic fat tissue from the Blainville's beaked whale and one Cuvier's beaked whale are being re-examined, and tissues are being processed for further pathological examinations. Histologic analyses are underway on six additional ears including ears from three of the affected beaked whales as well as from control specimens. Control specimens include ears from beaked whales that were single strandings, not associated with this event.

Discussion

The necropsy findings described above show that there were significant cranial lesions among the beaked whales in this event, but not in the single delphinid. The findings suggest that some acoustic or pressure event occurred that had characteristics especially significant or traumatic for these beaked whale species. Based on the current medical and experimental data, the hemorrhagic patterns observed in these animals can be found in the following etiologies: birth trauma, spontaneous subarachnoid hemorrhage and hyperemia, vestibular atelectasis, diathetic disease (i.e., disseminated intravascular coagulation and septicemia), direct or contact concussive trauma, auditory concussion from non-impulse sources, sonic booms, baro-trauma, and concussive acoustic trauma, particularly from blasts or intense impulse events. Age of the stranded animals eliminates birth trauma as a cause. Spontaneous subarachnoid hemorrhage is also not likely due to the low probability that so many animals would be affected simultaneously. When diathetic diseases are present, there are usually significant concomitant hemorrhages noted in multiple organ systems either as small or large hemorrhages, which were not observed in these animals. Diathetic conditions, typically attributed to terminal Disseminated Intravascular Coagulation, have been seen in stranded marine mammals, but are evidenced by multi-organ hemorrhages. However, whales and dolphins are known to have unusual clotting mechanisms and this may or may not have played a role in the suite of injuries seen in this investigation. Some odontocetes are known to have an absence of Hageman's Factor (clotting factor XII) and Fletcher Factor activity (plasma Prekallikrein) (Walsh et al, 2001; Parry, 1993), and Sei whales were noted to have prolonged partial thromboplastin time with no detectable Factor XII, XI, or Fletcher Factor (Saito et al., 1976 and Bosssart et al., 2001). Studies of hemostasis have not been performed on beaked whales, therefore, their clotting mechanisms are still unknown. It is unknown whether beaked whales have similar anomalies or other clotting differences and whether clotting mechanisms or dysfunctions unique to beaked whales or cetaceans may have had a role in the hemorrhages noted in these animals. Contact concussive injury was ruled out since there was no other external, internal, or subcutaneous evidence indicating blunt force contact trauma. Contrecoup injuries (leading to leptomeningeal hemorrhages) are possible with an animal struggling on the beach. However, this type of injury has not been commonly observed in individual stranded marine mammals nor in a group of stranded animals, and contrecoup is not adequate to explain the bilateral trauma observed in some of these animals. Therefore, the most likely causes of the traumas seen are acoustic or impulse injuries; however, technically the analyses to date cannot differentiate between far-field blast effects and acoustic induced injury from single or multiple sources. Acoustic monitoring revealed no explosions at the time of the strandings. Therefore, by deduction, it is reasonable to assume the injuries were acoustically induced.

The combination of timing, location, species composition, and pathologies in this stranding event has several important implications. First, the good body condition, lack of chronic disease (in contrast to

the spotted dolphin), and lack of external hemorrhage or fractures suggest that these animals did not die of a chronic or debilitating disease process nor of an acute blunt trauma such as a ship strike or near-field blast. Blunt trauma was ruled out by the absence of superficial contusions or correlated fractures. The acoustic record has ruled out a sudden blast event. Second, the presence and distribution of intracochlear blood and subarachnoid hemorrhage in these animals is consistent with a transient, intense pressure or acoustic event (but is not pathognomonic). Third, the observed bilateral intracochlear blood and temporal region subarachnoid hemorrhage do not necessarily indicate permanent hearing loss. Such pathologies are not necessarily fatal in terrestrial animals, however we do not know what effects these would have on survival in deep diving marine mammals. While in humans these lesions are often accompanied by painful headaches, they typically result in no permanent hearing loss (Schukneckt, 1993). Similar, experimentally-induced lesions in research animal models also result in temporary rather than permanent hearing loss in the majority of animals (Reinis et al, 1980) and not death. However, it must be noted that subarachnoid hemorrhage can be a serious event and can lead to increased intracranial pressure and significant parenchymal damage and death (Summer et al, 1995). The severity of the lesions is dependent on their duration, location, and size. In addition, the effects of subarachnoid hemorrhage and intracochlear blood in deep diving mammals or mammals with coagulopathies may be more profound than in terrestrial mammals.

The pathologic lesions indicative of cardiovascular collapse and shock are common findings in stranded animals. Cetaceans are physiologically and morphologically adapted to live in an aquatic environment with uniform distribution of pressure over all of their body (Ridgway, 1972) providing near-weightlessness. The water environment also provides a rapid mechanism to disseminate body heat. On land when stranded, cetaceans can overheat rapidly, particularly when they are sick or feverish prior to stranding and may develop physiological shock and cardiovascular collapse. These types of lesions, which were found in the stranded beaked whales, are likely to be the immediate cause of death in this event, rather than death resulting directly from an impulse or pressure event. However, the animals likely stranded due to an acoustic insult. That is, an acoustic event is presumed to be a contributing factor to the observed trauma and subsequent stranding resulting in death of the animals. Although the actual causal heirarchy or chain of events may never be known in this mass stranding event, the evidence in the two freshest animals examined provides a plausible theory that the damage and possibly stranding were initiated by an impulse or acoustic event.

In summary, the gross examinations of the beaked whales to date reveal hemorrhages in the acoustic fats of the head, the inner ears and some spaces around the brain with no evidence of external blunt force trauma or chronic debilitating disease. These results lead to a preliminary finding of *in vivo* (in the live animal) acoustic or pressure related trauma. Examinations of the more decomposed animals revealed similar lesions, but decomposition prohibited definitive interpretation. The numbers and coincidence of the strandings combined with these consistent interindividual necropsy findings suggest a broad geographically distributed pressure related trauma. However, we are continuing to examine tissues to further understand and define the injuries. The pathologies in the two freshest animals are consistent with an auditory or impulse trauma event. In other animals (terrestrial) and humans this type of impulse trauma event compromises hearing or the vestibular system, but is not immediately or directly fatal. A final report summarizing all the findings and conclusions is expected to be published in early 2002.

Table 2: Chronology of individual animal stranding in the March 15-16, 2001 mass stranding in the Bahamas (Sf = Spotted dolphin; Md = Blainville's beaked whale; U = unidentified beaked whale; Zc = Cuvier's beaked whale).

Date	Local Time	NMFS #	BMMS #	Location	Latitude	Longitude	Condition @ Report	Est age class	Sex	Length	Disposition (examined condition code)	Necropsy/ Samples
3-15-00	7:00	Sf-13	1	Powell Cay, Abaco	26.54.307	-77.28.974	Stranded live	immature	F	5 ft	died during rescue (code 2)	Yes/Yes
3-15-00	7:30	Zc-6	2	Rocky Point, Abaco	25.59.802	-77.24.344	Stranded live	juvenile	N/A	est 12ft	pushed off	No/Yes
3-15-00	8:15	Zc-4	3	Sandy Point, Abaco	26.01.079	-77.24.150	Stranded live	sub-adult	N/A	est 17 ft	pushed off	No
3-15-00	8:35	Md-5	4	Sandy Point, Abaco	26.01.271	-77.24.049	Stranded live	young adult	N/A	est 14 ft	pushed off	No
3-15-00	11:00	Md-3	5	Gorda Cay, Abaco	26.05.908	-77.31.163	Stranded live	young adult	N/A	est 14 ft	pushed off	No/Yes
3-15-00	12:00	Zc-7	6	High Rock, G.B.	26.37	78.17	Stranded live	juvenile	F	15 ft	found dead	No/Yes
3-15-00	12:30	U-1	8	Peterson Cay, G.B.	26.33	-78.31	Stranded live	adult	N/A	est 18 ft	pushed off	No
3-15-00	12:30	U-2	9	Peterson Cay, G.B.	26.33	-78.31	Stranded live	calf	N/A	N/A	pushed off	No
3-15-00	14:30	Zc-9	10	Red Shank Cay, G.B.	26.28	-77.46	Stranded live	Adult	M	est 18 ft	Swam away	No
3-15-00	14:30	Zc 9b	11	Red Shank Cay, G.B.	26.28	-77.46	Stranded live	N/A	N/A	est 18 ft	Swam away	No
3-15-00	17:30	Ba-15	12	Royal Island, N. Eleuthera	25.31	-76.49	Stranded live	Sub adult	N/A	est 21 ft	pushed off	No
3-16-00	9:30	Zc-8	15	Water Cay, G.B.	26.26.13	-77.45.943	Dead-code 3	Sub-adult	M	16 ft	found dead (code 2)	Yes/Yes

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Date	Local Time	NMFS #	BMMS #	Location	Latitude	Longitude	Condition	Est age class	Sex	Length	Disposition (examined condition code)	Necropsy/ Samples
3-16-00	12:00	Ba-16	7	Meek's Patch, N Eleuthera	25.30	-76.47	Stranded live	adult	N/A	est 27 ft	pushed off	No/No
3-16-00	after noon	Zc-10	13	Gold Rock Creek, G.B.	26.36	-78.22	Reported as live stranding	adult	F	18 ft	found dead (code 3)	Yes/Yes
3-16-00	after noon	Zc-11	14	Gold Rock Creek, G.B.	26.36	-78.22	Reported as live stranding	sub-adult	M	17 ft	found dead (code 3+)	Yes/Yes
3-16-00	1:00	Md-12	16	Cross Harbor Creek, G.B.	25.56.447	-77.16.533	Reported dead	juvenile	M	11 ft	found dead (code 2)	Yes/Yes
		Zc-14	17	Old Freetown, G.B.	26.35	-78.29	Reported dead	N/A	M	18 ft	found dead (code 4)	Yes/Yes

Condition codes: code 1 = alive; code 2 = fresh dead; code 3 = moderate decomposition; code 4 = advanced decomposition; code 5 = mummified/skeletal; code 6 = dead condition unknown.

Table 3: Investigators for Specimen Analysis

Investigator	Sample	Analysis	Purpose	Status
Ruth Ewing, D.V.M National Marine Fisheries Services	Formalin fixed samples from four whales	Histopathology	Tissue examination to identify disease processes and cause of death.	Finalized initial, re-cut in progress
Thomas Lipscomb, D.V.M., Dipl. A.C.V.P. Armed Forces Institute of Pathology	Formalin fixed samples from four whales	Histopathology	Tissue examination to identify disease processes and cause of death.	Finalized initial, resubmission acoustic fats
Darlene Ketten, Ph.D Harvard Medical School Woods Hole Oceanographic Institute	Fresh frozen head from *Mesoplodon* (1) and *Ziphius* (1); one spotted dolphin carcass, formalin fixed ear samples from two decomposed *Ziphius*; control ears	Computerized Tomography; histopathology; 3-D reconstruction	To determine morphology and pathology of acoustic tissues	CT scans complete on 2 heads, 2 ears; histology complete on 2 ears, pending on 4 ears
Patricia Rosel, Ph.D. National Oceanic Service, NOAA	Frozen and DMSO preserved skin (5 Zc and 1 Md)	Genetic analysis	To verify species and determine familial stock.	Pending
Charles Potter Smithsonian Institute	Frozen skull (4)	Skull morphometrics	To verify species, evaluate general morphology	Pending flensing and completion of Ketten work
Bill Walker, Ph.D.	Stomach contents (3)	Prey examination and speciation	To evaluate diet for comparison with known beaked whales prey	Report finalized
Aleta Hohn, Ph.D. National Marine Fisheries Service Southeast Fisheries Science Center	Teeth (4)	Growth layer groups	Estimate of age	Teeth not extracted (2), teeth need to be imported (2) Pending
Peggy Krahn, Ph.D. Environmental Conservation Division Northwest Fisheries Science Center	Blubber (4)	lipid type analyses; organochlorine analyses	body or nutritional condition organochlorine tissue residue studies	Final report received.

Investigator	Sample	Analysis	Purpose	Status
Murray Daily, Ph.D. The Marine Mammal Center	Parasites	Parasite species identification.	To identify parasite infection type relative to other beaked whales	Pending
Glenn Sandberg, M.D. Armed Forces Institute of Pathology	Brain tissue and meninges	Histolopathology	Pathology of brain tissues for more detail on hemorrhage and potential predisposing causes	Received tissues, special stains pending
Sherman McCall, M.D. Armed Forces Institute of Pathology	Brain tissue/lung tissue	RT-PCR	infectious diseases	Re d tissues Sept 2001, report pending 4 wks

Passive Acoustic Recording

On March 15, 2000, two NOAA acoustic recording stations were operating in areas that would have detected intense acoustic or pressure events originating in the Bahamas region. NOAA analyzed the records from these two sites for signs of explosions, earthquakes, volcanic activity, or underwater landslides coincident with the stranding.

The first record analyzed was from the Tongue of the Ocean, approximately 100 miles south of the stranding site. The array consisted of 12 hydrophones mounted on the bottom at about one mile depth covering the frequency band from a few hundred Hz to about 45 kHz. Each hydrophone was sampled once every 11 seconds and the spectral amplitudes were recorded. That is, the record was a time series of spectral amplitudes, not a time series of sound pressure. This procedure prevented the system from adequately recording brief events, such as explosions, although it could have recorded longer lasting earthquakes, underwater landslides, or volcanic eruptions.

Dr. John Proni, Atlantic Oceanographic and Meteorological Laboratory, Miami, analyzed the data from March 15, and provided an analysis to the joint investigation team on June 5, 2000. This record showed no evidence of geological activity or explosions. Absence of evidence of an explosion was not surprising, given the sampling procedure described above.

Dr. Christopher Fox, Pacific Marine Environmental Laboratory, Newport, Oregon, made the second set of recording using six autonomous hydrophones in the mid-Atlantic ocean between 15° N and 35° N latitude. The hydrophones recorded continuously in the frequency range 1-50 Hz, and were moored in the oceanic sound channel, allowing long-range detection of low-frequency events. The recorders stored data internally for a year and had to be retrieved to examine the record. Detailed information about the recording array is available at www.pmel.noaa.gov/vents/acoustics.html.

Records from March 2000 were retrieved from the array in March 2001. All hydrophones recorded flawlessly for the entire year. Dr. Fox examined the data for all natural or human activities that produced intense, low frequency sounds from the Bahamas region during March 13-16, 2000 inclusive. The data were examined at 1-second resolution using standard time-frequency spectrograms. The spectrogram display was synchronized such that sound events from the Bahamas region (26.5° N and 77° W was used as the general location) appeared in line across the workstation display and would be easily recognized.

Although numerous earthquakes were detected from around the Atlantic, and seismic airgun sounds were detected from the Nova Scotia region, there was no indication of any unusual sources of low-frequency acoustic energy emanating from the Bahamas region during the March 13-16 time period. This result eliminates the possibility that tissue damage observed in beaked whales resulted from a distant explosion or geological event.

Ship Movements and Acoustic Modeling*

Introduction

In cooperation with NOAA fisheries, as the agency investigating the stranding event, the U.S. Navy undertook an investigation of possible sources of acoustic energy active at the time of the stranding event. The Navy also modeled the acoustic propagation characteristics of the environment to provide information about the likely acoustic exposure for animals in the Northeast and Northwest Providence Channels during the time period of interest. See Glossary for a discussion of factors to be considered in propagation.

Several possible sources of acoustic energy were investigated, including noise from harbor and shoreline construction, lightning, gunnery exercise, explosive noise such as (illegal) fishing activities, vessel traffic, oceanographic research, and naval exercises involving the use of standard, hull-mounted mid-frequency range tactical sonars. The search identified tactical mid-range sonars as the most plausible source of acoustic energy that met the necessary criteria of location, timing, and sound amplitude that could have reasonably accounted for the widely separated multiple strandings. The sound sources involved, their usage pattern during the time of interest, and the propagation pattern of the sound in the environment are detailed in the subsequent sections of this report. The results reported here are the outcome of analyses by Navy underwater acoustics experts, with the results checked and augmented by an external review panel of independent experts from several different research and academic institutions (see authors listed at end).

Background

Throughout this paper the term deciBel (one tenth of a Bel) or dB will be frequently encountered. Please see the Glossary for a discussion of this important unit.

Ship movements and sonars used. Active sonar (see Glossary for a tutorial) is the best acoustic method of detecting submerged submarines. However, proficiency at submarine detection is difficult to acquire and maintain, so the Navy regularly exercises its forces in this task. Simulators are available for training, but they do not fully replicate the difficulty of detecting and tracking submarines at sea. Actual training at sea is necessary to ensure effective deployment of active sonar in the detection of potentially hostile submarines. For several decades the Navy has conducted antisubmarine exercises in the islands near Puerto Rico. But in March 2000 political conditions at the Navy training range at Vieques, Puerto Rico were not favorable, so the Navy was conducting some of its training exercises elsewhere. The Bahamas were selected as an alternate site.

During the period of interest, five U.S. Navy ships that were using active sonar passed through the Providence Channels in a generally southeast to northwest direction. The exact tracks of four of the five ships that were using active sonar are plotted in Figures 4a-d. These ships, designated A, B, C, and D, moved through the Providence Channels in two loosely affiliated groups approximately four to six hours apart. Ships B, C, and D traveled with the first group through the channel, and were present there from about midnight (local time) on March 14 to about noon on March 15. Ship A was present in the channel, in company with several other U.S. Navy ships, from approximately 6 AM on March 15, until about 4PM

on March 15.

Ships A and B operated the tactical mid-range frequency AN/SQS-53C, and Ships C and D operated the tactical mid-range frequency AN/SQS-56 sonar. These two types of sonar are designed to emit sounds that will be reflected by nearby submarines and thus detected by the searching ship's listening sonar sensors. Similar sonar systems are standard operating equipment on board many vessels throughout the world's navies, and are generally referred to as tactical mid-range sonar systems to distinguish them from navigational sonar systems, fish finding sonar systems, etc.

Characteristics of individual signals and signal sets. The AN/SQS-53C sonar operated at center frequencies of 2.6 and 3.3 kHz. For the most part, ships A and B operated their respective 53C sonar systems at a nominal source level of 235 dB, except for a period of approximately four hours on the morning of March 15 when ship B operated its sonar system at a source level greater than 235 dB (the exact level is classified and cannot be stated here, although it was used to produce the model run in Figure 5c). The AN/SQS-56 sonar operated at center frequencies of 6.8, 7.5, and 8.2 kHz at a nominal source level of 223 dB. Since the bandwidths of all signals did not exceed 100 Hz, these can be considered very narrow bandwidth signals, and their propagation through the water column was modeled at the center frequency (Figures 5a-d).

Tactical mid-frequency range sonar systems are capable of producing a variety of waveforms, each designed for specific tasks. For example, narrow band, constant frequency signals (CW) are good for detecting movement (Doppler effects) but are relatively ineffective where environmental reverberation (sound reflection) is prevalent. On the other hand, signals that sweep quickly up or down in frequency (Frequency Modulated or FM signals) work well in reverberant environments, but don't detect movement as well. As a consequence, tactical mid-range sonars often emit several different signals in rapid sequence before waiting some time to listen to the returning echoes of the different signals. In this particular exercise, the first 53C sonar (Ship B) emitted a series of three half-second signals (or pings) during a two second ping cycle, followed by a 24 second silent period. The silent period is a function of how far the sonar is "looking." In this scenario the sonars were generally looking about 20,000 yards away (18.3 km) and the interval between looks was therefore 24 seconds. The second 53C sonar (Ship A) emitted one second, one and a half second, and two-second ping series as it passed through successive thirds of its passage. These details are captured in the cumulative ping-seconds figures presented in Figure 5c-d. (See Glossary for a discussion of ping-second).

Shape of the emitted sonar beams. These sonars are actually an array of several individual sound sources arranged in a curved geometry. By operating the individual sources in precise timing relative to each other it is possible to produce a beam of sound that does not project equally in all directions. In the SQS-56 sonar the sound beam was emitted in a vertically flat direction, or parallel to the surface, at a depth of 20 feet (6.1 meters) with a vertical beam width of about 30 degrees (15 degrees up and down from a plane at 20 feet depth). The actual process of beam forming is more complicated than this, but for the purposes of this discussion, the characterization is sufficiently accurate to enable us to visualize the resulting projected acoustic energy. The SQS-53C sonars form a vertical beam in the same manner as the 56 sonars. But in the 53C the beam was steered about 3 degrees vertically down, with the depth of the source at 26 feet (7.9 meters). Since the breadth of the beam is a function of signal frequency the relatively lower frequency of the 53C results in a broader beam of about 40 degrees (versus the 30 degrees of the 56 sonar). In very rough seas the pitching of the ship can affect the vertical orientation

of the sonar beam relative to the surface, but during this time period the seas were calm, with wave heights of 2-3 feet (0.6-0.9 meters), and the sonar beam was assumed to be unaffected by ship motion.

The SQS-56 sonar is omni-directional in the horizontal plane, meaning that sound was radiated equally in all horizontal directions (360 degrees). Think of a disk of sound 30 degrees tall vertically, but extending equally in all horizontal directions around the ship. The disk is quickly "warped" by the sound propagating characteristics of the environment, but the idea of a disk of sound is helpful in thinking about the initial radiation of sound from the sonar source. The 53C sonar can also radiate sound in all directions in the horizontal plane like the 56 sonar, but may also emit sound in a 120-degree arc in front of the ship. That arc can be steered from side to side, but is typically centered in the direction of travel of the ship. In the example of Ship B, which emitted three pings (CW-FM-CW) in rapid succession over two seconds, the first two pings were 120 degree beams and the last ping was omni-directional. Again, these details are captured in the cumulative ping-seconds shown in Figure 5c-d.

For the sound field modeling exercise, the sound field was not calculated for the entire 120 or 360-degree field, but sample fields were calculated for selected directions and the sound field was interpolated for the areas in between. For the 120-degree beams the sound propagation was calculated in three directions; straight ahead in the center of the beam, and 60 degrees on either side of center. The sound propagation for the SQS-56 sonars and the 53C in omni mode was omni-directional, so propagation was calculated in four cardinal directions of 0, 90, 180 and 270 degrees, independent of the direction of travel (see Figures 4a-d).

Signal Amplitude. The nominal source level (in terms of sound pressure level or SPL) produced by the AN/SQS-56 sonars was 223 dB referenced to 1 micro Pascal at one meter distance from the nominal source point. The shorthand expression of this measurement is sometimes written as 223 dB//micro Pascal (SPL). All numerical expressions of dB used in this paper will be //micro Pascal (SPL), unless otherwise stated.

The nominal source level of the AN/SQS-53C sonars was 235 dB, with two exceptions. The first is a decrease to 225 dB for that portion of Ship A's track starting at 1630Z (1130 local time) until the ship exited the Providence Channels about 3-4 hours later. The second exception is an increase to a level greater than 235 dB by Ship B for a four-hour period from approximately 1100-1500Z (0600-1000 local time). (The exact level is classified and may not be reported here. However, modelers used the correct value in their model runs, and the results are shown in Figure 5c). The cumulative ping seconds illustrate these changes graphically as reduced or increased sound fields with changes in source level (see Figures 5a-d.)

In reality sonars may fail to achieve the nominal maximum due to hull fouling, equipment aging or other mechanical factors. But since no calibration measurements were made of actual source levels during the exercise, the modelers had to assume that the sonars were operating at the highest stated levels they were capable of attaining at the specified setting. Actual source levels could have been lower than the nominal level used in the model, but would not have been higher.

The nominal source level is a calculated level that translates the complex array output into a simplified expression of a single point source. Although no single source within the array ever attains the nominal

amplitude, and there is no actual physical point where the nominal sound level is reached, for the sake of simplicity the output can be characterized as if a single point source at the center of the array and operating at the nominal source level had produced it. In other words, an array operated at a nominal level of 235 dB does not in fact attain 235 dB in any place, but the sound propagates as if it were generated by a single point source at 235 dB.

Rise time. Sounds that rise very rapidly to high amplitude (have a fast rise time) can duplicate the effects of irregular impulsive sounds like explosions, thunder, air gun pulses, or seismic activity. The potential for impulse noise effects from sonars with rapid rise times needs to be considered in an analysis of potential physiological effects from exposure to sonars. (See Glossary for a further discussion of rise time).

Effects of Multiple Sound Sources. No two sonars were operated at the same frequency, in the same area, at the same time. To do so would only create confusion for the sonar operators in each ship listening for their own return echoes. In the exercise carried out in the Bahamas the sonars did not operate at the same frequencies, and similar sonars were operated at significant temporal and spatial separations; therefore, the potential for even a very small temporally and spatially confined increase in sound pressure from multiple sonar operations is not a consideration.

It is instructive, however, to consider the possible consequences of two sonars operating at the same frequency in the same time and space, in order to better understand how cumulative sound energy would affect the received pressure level at a receiver (such as a whale or receiving sonar). If the two ships were operating at the same frequency, and if the levels received from each sonar were within 10 dB of each other (e.g. 152 and 160 dB), a localized increase could be produced for a brief time. The rule of thumb, which can be validated by carrying out the calculations, is that if the received levels are within 0 to 1 dB, the resultant perceived level would increase by 3 dB. If the received levels differ by 2 to 3 dB, the resultant perceived level would increase by 2 dB. If the received levels differ by 4 to 9 dB, the resultant perceived level would increase by 1 dB. If the difference in the received levels is 10 dB or greater the resulting perceived difference in the received level is less than 1 dB. The small difference attainable under these very limited circumstances may surprise readers not familiar with acoustics, but can be better appreciated if one keeps in mind that sound is actually a cyclic wave of pressure increase and therefore the pressure from both sources must be in phase (both over average pressure or both under average pressure) at the exact same time and place. Also, the decibel scale is a ratio, not an absolute measure, and it is expressed on a logarithmic scale (meaning that 3 dB is equal to a doubling of the ratio between absolute and reference pressure, while 10 dB is a tenfold difference and 20 dB is a 100-fold difference). A sound that is 10 dB lower than another would only add ten percent to the total signal, resulting in a maximum 0.1 dB change in the total amplitude whereas two sounds of equal amplitude could result in a doubling of total amplitude if perfectly in phase (a 3 dB increase).

Sound Propagation Modeling Parameters

Sources of data, summary of results. Characterizations of physical parameters during the exercise were derived from one expendable bathythermograph (XBT), a device that measures temperature versus depth as it descends in the water column. The modeled sound field propagation is based on this single profile of the water column taken during the transit of the U.S. Navy ships on 15 March, plus archived data sets for the Providence Channels obtained from the U.S. Navy Oceanographic Office (NAVOCEANO) and

other sources. Since historical data for the same time period closely resembled the profile obtained on March 15, 2000, it increases our confidence that the inputs to the models have captured the actual conditions during the exercise.

The impact of individual and combined variables on overall propagation was modeled for a variety of plausible scenarios so that the potential impact of uncertainly in a given factor, such as surface roughness, could be quantified (sensitivity analysis). Generally speaking, sound propagation was most strongly affected by the sound velocity profile of the water column, which was well documented by on-site and historical databases for the area. Other variables affected sound propagation very little, and usually in a manner that reduced sound propagation. The basis for these generalizations is explained in greater detail in the following sections.

Sound Speed Profile. The XBT data, and archived NAVOCEANO data consistently show an evenly mixed upper layer of near constant temperature. In terms of sound speed profiles this means that sound speed increases smoothly with depth (pressure). This is a common winter-spring condition in many parts of the world, and it results in a near-surface ducting of sound due to the increasing speed of sound with depth. As sound goes deeper, the increasing speed of the sound causes it to deflect back up toward the surface, where it is reflected back into the duct, with some loss to the air-water interface. Relatively little acoustic energy leaves the duct and enters deeper water, so the propagation characteristics of deeper water and the absorptivity or reflectivity of the bottom substrate are of relatively minor importance in determining the main route of sound propagation within the channel. All oceanographic models used during the analysis (Fromm and McEachern, 2000) produced a duct about 150 to 200 meters thick for the frequencies of interest, and the duct was very even throughout the channel, from near shore to the center of the channel. The main effect of differences in duct thickness would be a slight shift in the range or depth of loudness peaks or troughs, but little effect on the maximum and mean sound pressure level on the scale of kilometers or miles. In other words, actual sound field measurements, if they had been measured, would have shown little deviation from the models, even if duct thickness varied within the roughly 50-100 meter thickness predicted, or if duct thickness were more regionally variable within the Providence Channels.

Absorption. Some acoustic energy is lost to absorption as the sound travels. Most of this absorption is due to the acoustic energy being converted to mechanical energy in the flexion of certain molecules dissolved in seawater, such as magnesium sulfate and boric acid (Urick, 1983). The amount of absorption typically increases with increasing source frequency. The amount of absorption is also a function of the temperature, salinity and acidity (pH) of the water. Good data existed for salinity and temperature in the area, and pH was assumed to be 8. The pH of seawater does not vary much, and sensitivity analysis of the effects of altering the pH value indicated that error in the selection of pH value would have induced an error of less than 5% in the model outcome, which is well within the uncertainty of the model itself.

Sea Surface Roughness. It is probably somewhat intuitive to understand why a flat smooth water surface will better reflect sound back into the duct than a rough surface, much as a smooth surface acts as a better reflector of light than a rough surface. This subject has been well studied and there are well-accepted formulae for calculating the effect of surface roughness on sound propagation. The Providence Channel is fairly well protected from open ocean swells, and weather conditions during the period of interest were mild, with wave heights of 2-3 feet. Such conditions yield propagation results little different from a

perfectly flat surface for these sonar frequencies. Any effect of increasing surface roughness and wave height would have reduced the predicted propagation distances.

Bubbles. Air bubbles entrapped in the water column most commonly occur near the surface as a consequence of wave action. Bubbles reduce sound transmission by scattering and absorbing sound, with the effect on different sound frequencies being a function of bubble size. Bubbles also reduce effective sound speed at lower frequencies. All of these effects would result in a reduction of sound propagation. Since all records indicate calm seas and excellent propagation conditions, it was assumed that there was no significant reduction of sound propagation from bubbles in the water.

Biological scatterers. The swim bladders of fishes, similar gas-filled spaces in some marine invertebrates, and the carapaces of zooplankton can all contribute to scattering of sound, and reduced propagation. Since their effect is to reduce sound propagation, the worst case-modeling scenario assumed no biological scatterers, and therefore no reduction in sound propagation. Most scatterers tend to vertically migrate over the course of the day, from near surface at night to the lower limits of the photic zone during the day (several hundred meters deep in this region). Therefore, the surface duct area probably contained very few biological scatterers during the daylight portion of the exercise, which would also bolster an argument for not assuming that there was any attenuation of the sound by biological scattering.

Bottom type. Since most of the radiated energy from the sonars went into the surface duct, only a small part of the radiated energy projected downward at sufficiently steep angles would escape the duct and have interacted with deep water and the bottom. The thick, silty sediment at the bottom of the Providence Channels is highly absorptive and little energy would have been re-radiated into the duct from sound reflected off the bottom. Altering the model by replacing the actual sediment type with a more reflective bottom material such as sand still did not produce an appreciable re-introduction of sound into the duct from bottom-reflection.

Internal Waves. Internal waves can be induced by tidal water movements, current flow between different masses of water, and other effects. Generally their effect is observed in scattering in the sound field, but with most of the sound energy contained in the surface duct, the main effect of internal waves in this context would be to alter the thickness of the surface duct. Because the water column was so evenly mixed, internal waves were probably not present. Nevertheless, several modeling scenarios were tried without any appreciable impact on the sound pressure levels observed in the surface duct.

Combined effects. The propagation models were also run with combinations of all of the above environmental features. Since these features tend to increase scattering and absorption, their combined effect was even greater transmission loss than any other scenario. For that reason, results discussed below and presented in Figure 5a-d, did not include the potential for increased scattering and absorption from bubbles, biological scatterers, and internal waves.

Propagation Modeling

Several methods were used to model the propagation of acoustic energy through the water. The simplest models assume spherical spreading around the source in all directions until sufficient disruption of linear

propagation is encountered, such as bottom reflection or a surface duct. From the point where spherical spreading is no longer an appropriate model, a simple cylindrical spreading model is used, and sound is assumed to be equally loud from the top to the bottom of the cylinder (Urick, 1983; Richardson et al, 1995). Using the modeled parameters of duct strength and thickness, the simple spherical-cylindrical spreading model produced results very similar to more sophisticated models, as might be expected in this well-mixed environment. Since no one acoustic model routinely and directly accounts for all the environmental processes that can potentially affect propagation, several different types of models were run. These included RAM, a parabolic equation model (Collins, 1993, 1995); CASS/GRAB, a ray-based propagation model (Weinberg and Keenan, 1996); KRAKEN, a normal mode model (Porter, 1995); and OASES, a wave number integration model (Schmidt, 1997). All models delivered very similar results, further reinforcing our confidence in the results.

Model Results

56 Sonars (Ships C and D). The horizontally omni directional signal of the 56 sonars, operated at a nominal source level of 223 dB and dropped below 180 dB within a range of 300 meters of the source. Due to the vertical beam pattern and the sound propagation conditions, there was virtually no radiation of sound exceeding 180 dB below the surface duct. Again, it is important to iterate that the selection here of 180 dB is an arbitrary received level used only to illustrate the scale of the sound field; it is not meant to imply any special significance of the 180 dB level. One could refer to the range at which the received level drops to 200, 160, 118.3 or 100 dB. The selection of 180 dB provides a level that is sufficiently far from the ship to convey a meaningful distance, but not so far that the sound field more often than not falls below baseline ambient levels or hits shore within the confined spaces of the Channel before reaching the specified level (as would be the case if levels like 120 or 110 dB were used).

53C Sonars (Ships A and B). For the 53C sonars operated at 235 dB nominal source level, the maximum range at which 180 dB might have been received was 1,000 meters (1 km) in the surface duct. As was the case for the 56 sonars, the 53C sonars operated at 235 dB did not radiate sound pressure levels above 180 dB below the surface duct. The radiated sound pressure levels fell below 160 dB at an average range of 34 kilometers within the duct, and 10 kilometers below the duct.

For the one 53C sonar that was operated at a nominal source level of greater than 235 dB for four hours, the range at which the sound pressure level fell below 180 dB was 5 km in the duct and 1.4 km below the duct. The ranges at which SPL fell to 160 dB were 50 km in the surface duct and 29.1 km below the duct. Model results were carried to levels below 160 dB, but for simplicity results have been discussed at two simple benchmark levels of 180 and 160 dB. The selection of these two values for discussion is not intended to imply any biological significance; the reader is again reminded to keep an open mind about what level of received sound pressure might be biologically relevant in this stranding event. It may be tempting to focus on the unique four hour period when source levels were higher than at other times, and attempt to correlate all strandings with this one period. However, the spatial and temporal relationship between this period of higher source levels and the individual strandings is not good. Also, the uncertainty about the time span between when an animal may have been ensonified and when it was finally observed as stranded does not enable us to speculate too precisely about when and to what extent animals may have been ensonified.

Cumulative Sound Exposure. These results are an expansion of the data presented in Fromm and

McEachern (2000).   The discussions of sonar operating parameters and environmental conditions, itemized in the preceding pages, combine to generate a complex, temporally changing scenario of variance in ping frequencies, amplitudes, ship movements, and sound propagation fields.   Perhaps the best way to capture this complex scenario in a single snapshot is to map cumulative ping-seconds (Figures 5a-d).   Results are presented only for the two ships operating 53C sonars, since their louder source levels relative to the 56 sonars give them a larger footprint than the 56 sonars would have shown.

The reader should also remain aware that the mapped data are the worst case levels taken at the depth where sound pressure level was greatest (usually around 15 meters depth within the duct). For animals moving both vertically and horizontally within this field, the cumulative exposure would be a function of time spent in quieter regimes vertically or horizontally outside these maximum levels, since it is not realistic to assume that an animal would remain in one place long enough to receive the full duration of exposure at one point on the map. At the risk of sacrificing accuracy for ease of comprehension, the simplest characterization of the ping-seconds display is that it represents the maximum exposure that could have occurred for a receiver remaining within the duct (without surfacing or diving intervals) at a given locality. Further interpretation of the biological significance of these ping-second maps would require a good understanding of the 3-D geometry of the sound fields, as well as the 3-D movements of animals within the sound field. Currently available integrative modeling tools, like the Acoustic Integration Model (AIM) (Ellison, unpublished) would enable the sound fields discussed above to be populated with modeled animals based on published data concerning local abundance, habitat use, diving and behavioral patterns. Plausible sound exposure regimes could thus be generated as an aid to discussions about the range of plausible exposure scenarios, maximum exposures, and cumulative exposures for animals that stranded and/or experienced physiological damage

* This report was abstracted from a longer report (Fromm and McEachern, 2000) for which the contributing authors were:

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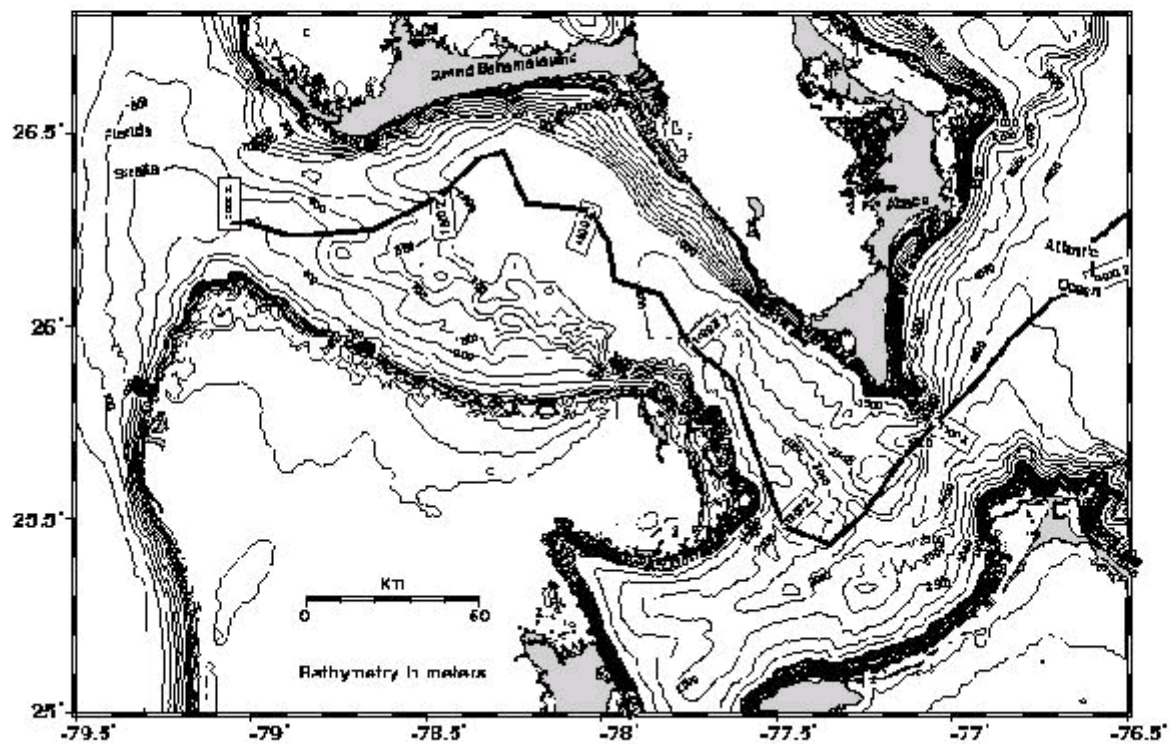Dr. Henrik Schmidt. Massachusetts Institute of Technology

Figure 4a. Track of Ship A (53C sonar), showing times (Zulu) and vectors where sound field modeling was performed.
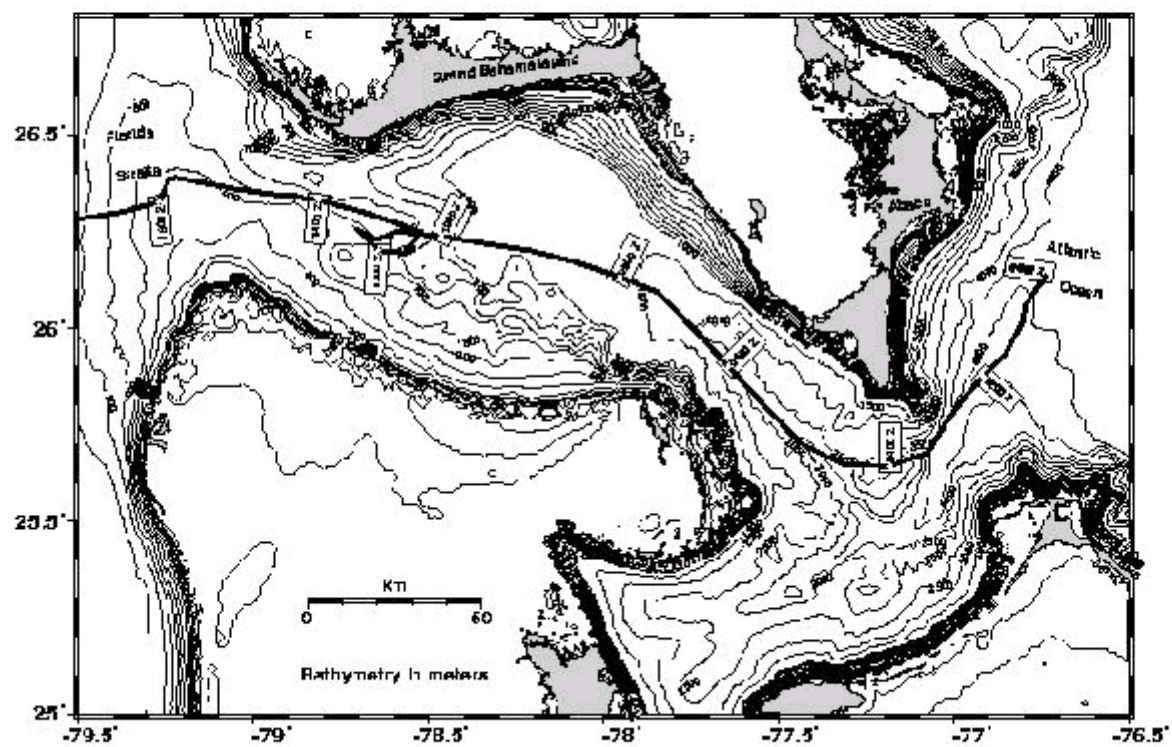
Figure 4b. Track of ship B (53C sonar), showing times (Zulu) and vectors where sound field modeling was pe rformed.
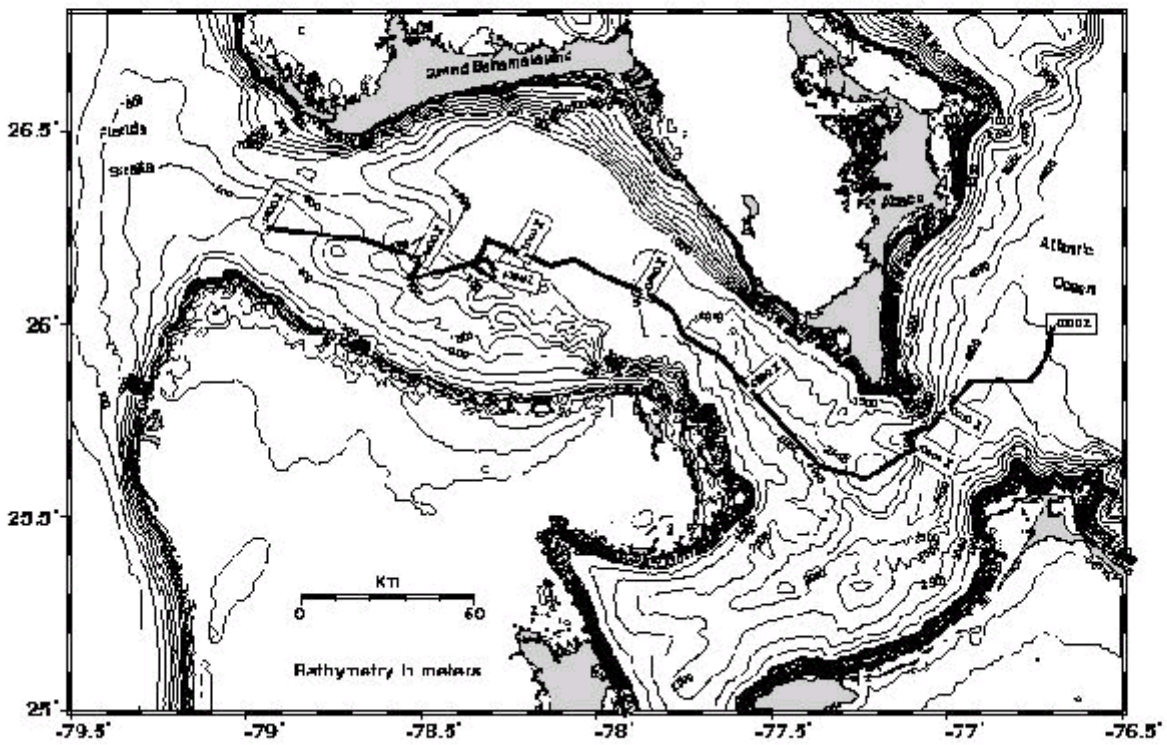
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Figure 4c. Track of ship C (56 sonar), showing times (Zulu) and vectors where sound field modeling was performed.
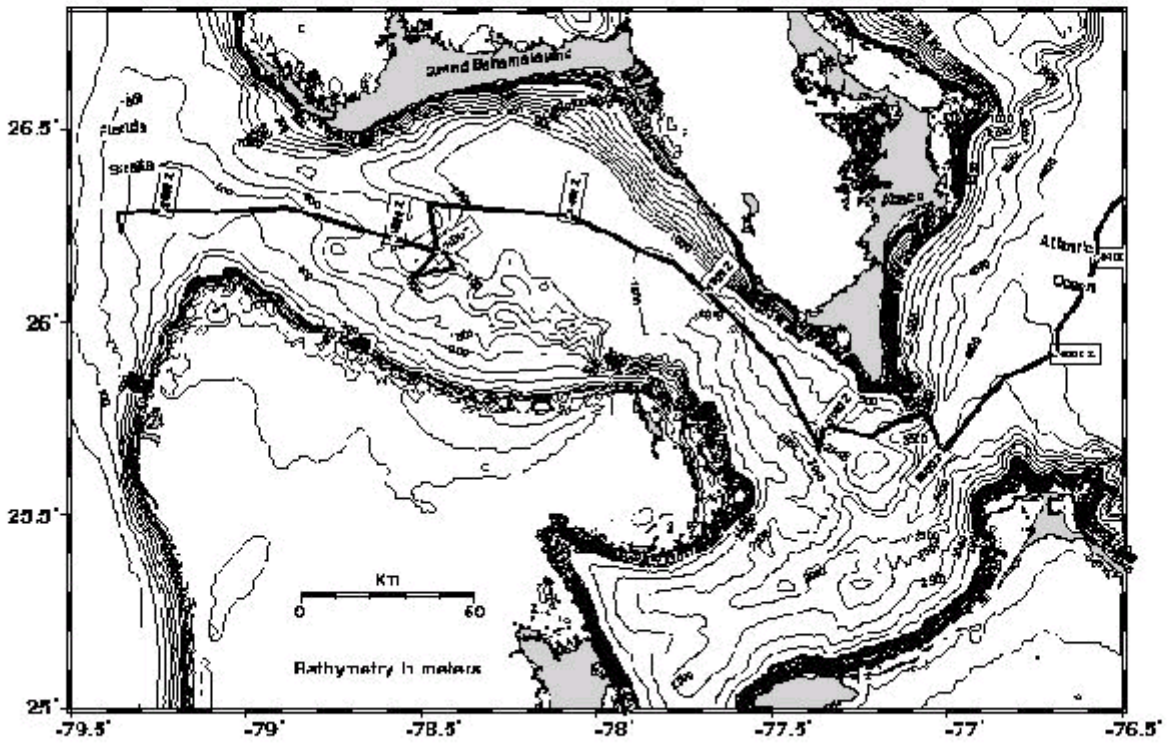
Figure 4d. Track of ship D (56 sonar), showing times (Zulu) and vectors where sound field modeling was performed.

Sound Level doseGT160 dB over depth range 015m

Figure 5a. Ship A (53C sonar in the second group). This figure illustrates the cumulative ping-seconds at levels above 160dB produced by this ship during its transit of the Providence Channel.
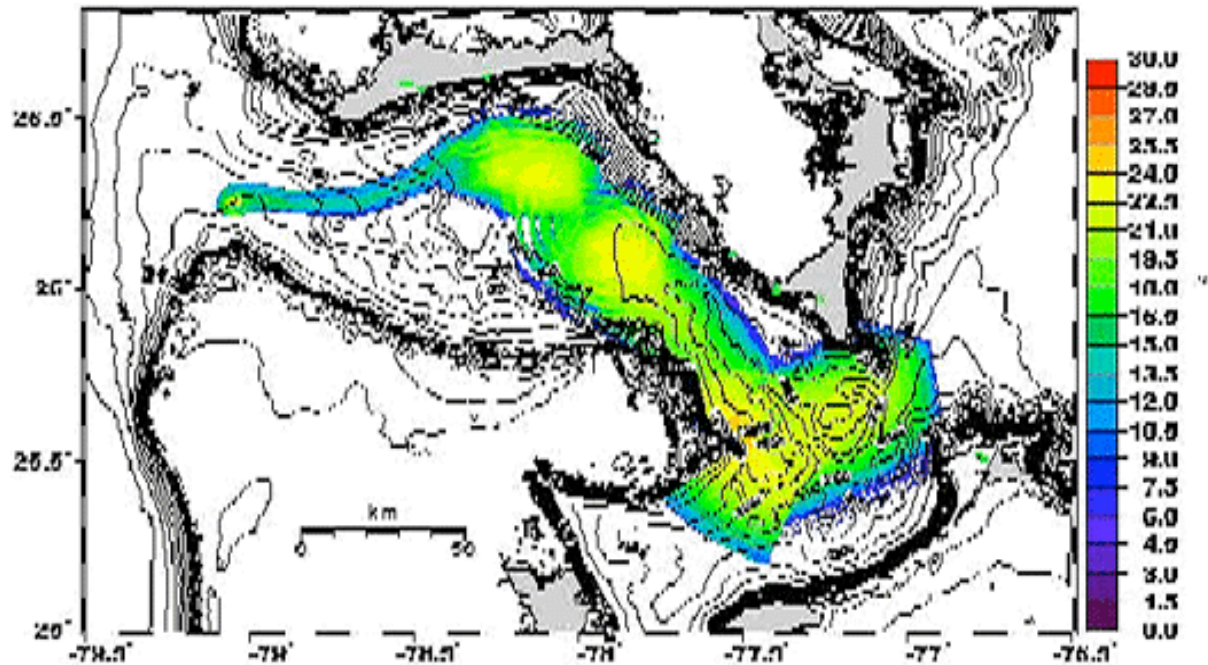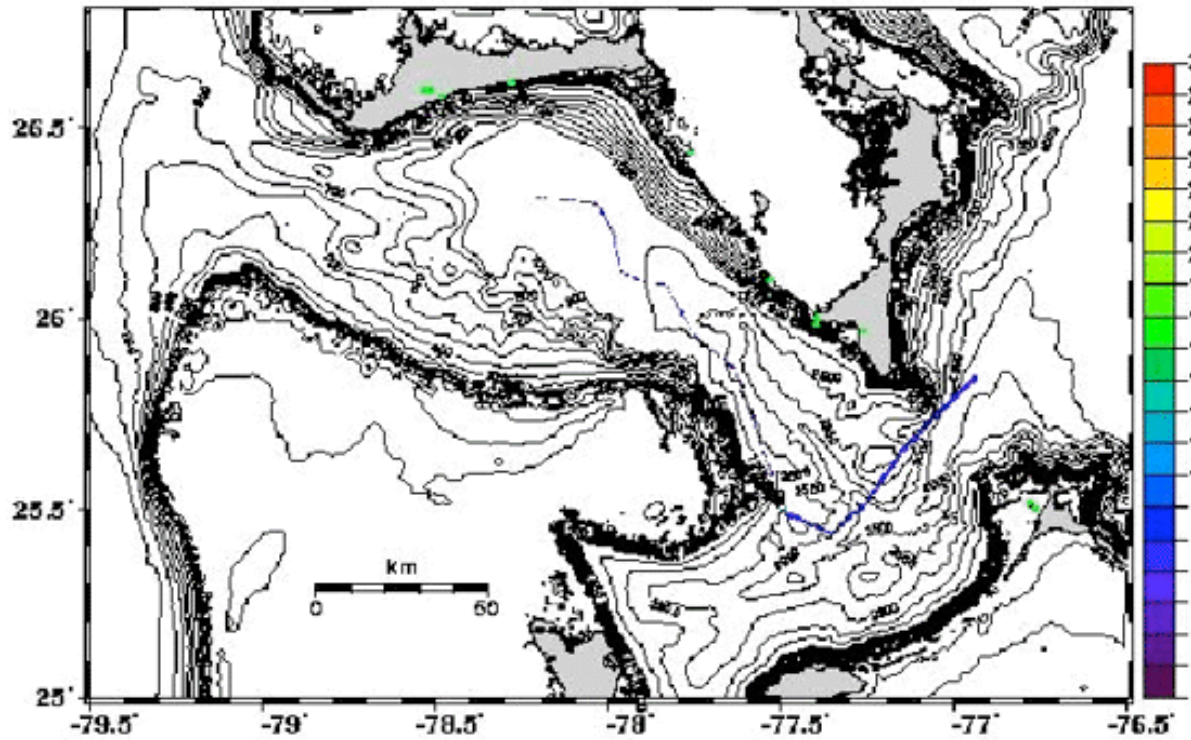
Figure 5b. Ship A (53C sonar in the second group). This figure illustrates the cumulative ping-seconds at levels above 180dB produced by this ship during its transit of the Providence Channel.

Figure 5c. Ship B (53C sonar in the first group).   This figure illustrates the cumulative ping-seconds at levels above 160dB produced by this ship during its transit of the Providence Channel.

Figure 5d Ship B (53C sonar in the first group). This figure illustrates the cumulative ping-seconds at levels above 180dB produced by this ship during its transit of the Providence Channel.
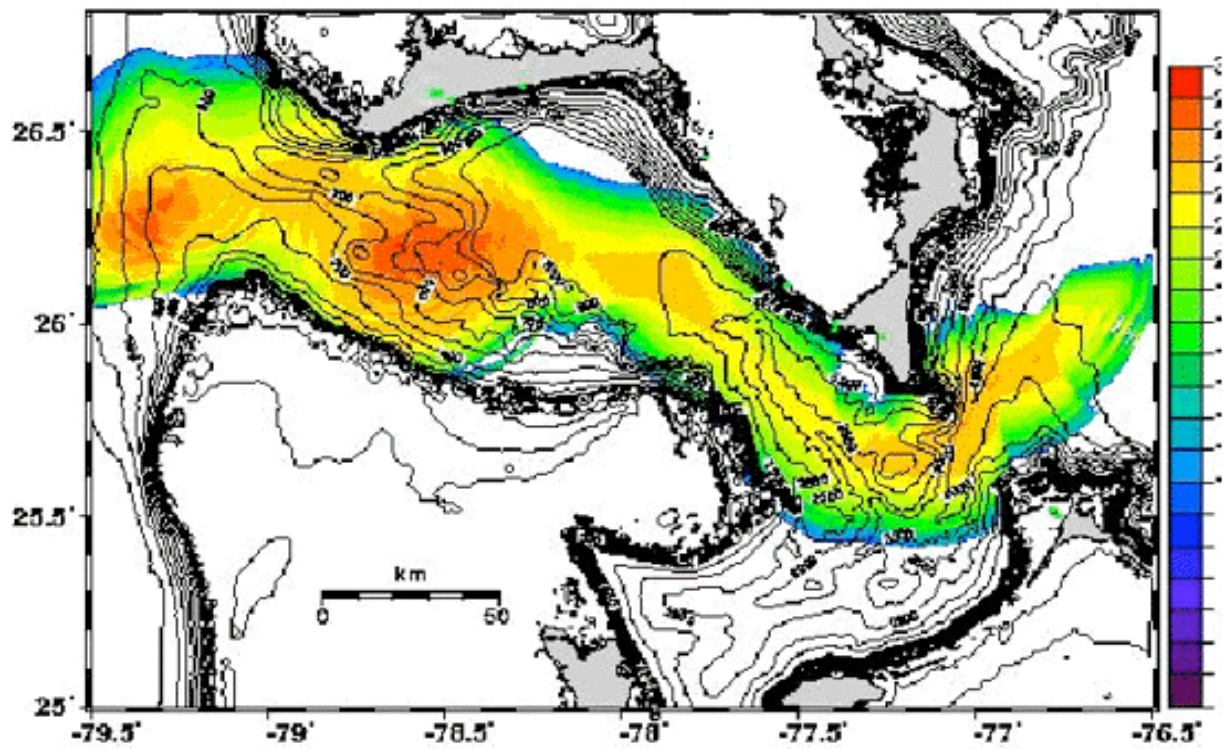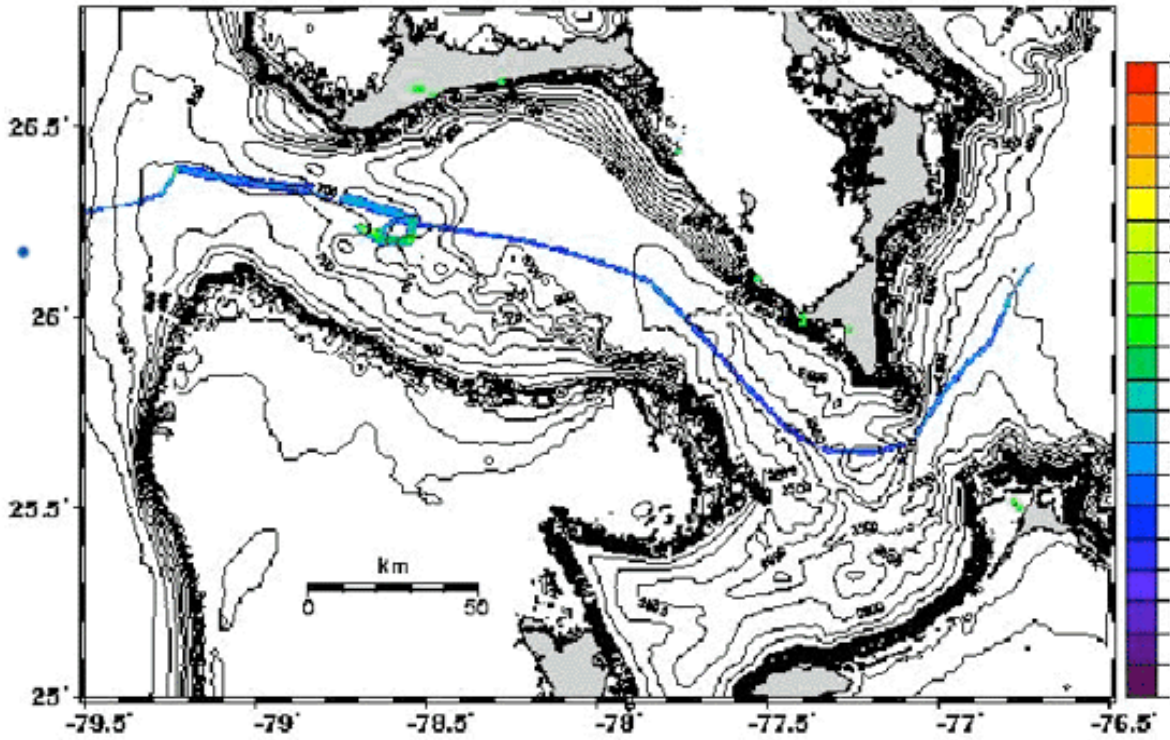
Follow-up Research Actions

Background

Despite the relatively detailed information we have on human activities in the vicinity of the strandings, and despite the detail and quality of data obtained from the stranded animals, there are still many unanswered questions about the stranding and its causes. From the coincidence of strandings and sonar use in both time and geography, and from the nature of the observed physiological effects, the investigation team concludes that tactical mid-range frequency sonars aboard U.S. Navy ships were the most plausible sound source involved in this strandings. However, this sound source acted within a set of environmental factors that included the sound propagation characteristics present at the time, the underwater bathymetry, a constricted channel with limited egress avenues, and the presence of beaked whales that appear to be sensitive to the frequencies projected by tactical mid-range frequency sonar. Focusing on the interplay between the sound source and these environmental factors is much more likely to reduce future strandings than focusing on the sound source as the sole cause.

The following list of proposed research actions was prepared by Dr. Robert Gisiner, Marine Mammal Science and Technology (S&T) Program Manager for the Office of Naval Research, at the request of the Navy team collaborating with NOAA Fisheries in the stranding investigation. The list is based on similar research solutions to related problems; solutions developed over the past five to seven years under funding by the Office of Naval Research. Additional useful guidance was received from the National Research Council panel on the Effects of Low Frequency Sound on Marine Mammals (National Research Council, 2000), and an external review of the ONR Marine Mammal S&T program held on July 2000 (unpublished).

Wherever possible, these suggested actions have already been started by redirecting funding and research effort that had been devoted to closely related tasks. Other actions are still in the planning stages, awaiting concurrence from the stranding review team and the scientific professional community, or in some cases awaiting completion of formal proposal preparation, approval of requisite permits and authorizations, and funding.

The proposed research actions are presented in terms of how they will help clear up existing uncertainties about the causal relationships between sonar sound and the observed circumstances of the March 15, 2000 stranding event. We do not claim that this is an exhaustive list of the possible actions that might be taken to clear up remaining questions about causal mechanisms of the strandings, and welcome suggestions for possible actions that might have been overlooked.

Problem Statement

Because at least some of the beaked whales stranded had physiological problems that were likely associated with sound exposure, we need to investigate the entire range of potential effects of sound, from physically injurious effects to conditions of mild behavioral response. Since we cannot be sure that the physical symptoms were necessary to cause the behavioral act of stranding, it is important during the follow-up investigations to not assume that because one phenomenon has been investigated and explained, that the other problem is necessarily also solved. The proposed research actions are therefore arranged in approximate order of severity of effects investigated. The list concludes with those

research actions aimed at applying to predictive models that information gained in the studies of physiological and behavioral effects. The ultimate goal of the suite of research actions is to avoid the concurrence of circumstances that led to the 15 March stranding event.

Emphasis on beaked whales does not imply that the team ignores the presence of Minke whales in this event. No data exist on Minke whale hearing ability, or on the pathway by which sound reaches their ears and brain. Research into the responses of Minke whales to sonar will have to begin with these basic questions. No more sophisticated questions are possible, given the present state of knowledge.

Proposed Research Efforts

Physical Injury. While it may not be possible to safely and humanely test the conditions that lead to physical injury of live animals, an experimental protocol has been developed to test for blast damage effects on dead specimens, and it can be adapted to look for injurious effects of sonar sound (Ketten, unpubl.). The procedure makes use of dead animal specimens obtained by the National Marine Fisheries Service Stranding Networks. The National Marine Fisheries Service maintains the National Marine Mammal Tissue Databank in which tissue samples and analyses are catalogued from dead beach cast marine mammals, or marine mammals that were accidentally killed incidental to permitted fishing or other activities, and are made available for research to aid in the conservation and recovery of these protected species. If the specimens are freshly dead, and are properly preserved, many mechanical properties of tissues remain functional for periods after death and can offer valuable insights into the same processes in live animals, but without placing live animals at risk of injury. This is the approach that has been adopted by Dr. Darlene Ketten of the Woods Hole Oceanographic Institution, under funding by ONR, and other partners, including the Chief of Naval Operations (CNO N45). This approach to investigating the injurious effects of underwater explosions has been endorsed by over six leading environmental and humane organizations.

Modifications to the explosives testing procedure that would allow us to test specifically for sonar effects on beaked whales are detailed in this paragraph. As they become available, specimens of beaked whales from the National Marine Mammal Tissue Databank would be given an intact test for anatomical integrity (CT scan) and then be instrumented to record the received energy from a 53C sonar placed in varying degrees of proximity to the specimen and operated with the same parameters used in the Bahamas exercise. Following sound exposure, the intact specimen would be removed from the water, CT scanned again and subjected to a fine scale dissection, with follow-up analyses of tissue damage as developed for the blast damage study, including examination of the inner ear for fine scale damage not readily observed in standard examinations.

The test would be done in an enclosed body of water (a lake), using the same 53C sonar found on U.S. Navy ships, and the initial test waveforms will be the same waveforms used during the Bahamas exercise. Subsequent testing with different waveforms will allow us to determine how specific the injuries observed in the Bahamas are relative to a particular frequency or waveform. The anticipated outcome would be a set of loudness, frequency structure, duration and other acoustic parameters that could be used to establish sound usage guidelines for safe sonar operation in the vicinity of beaked whales.

Additionally, studies with human subjects and laboratory animals may offer insights relevant to this issue. Since 1994, the Office of Naval Research, the Naval Submarine Medical Research Laboratory,

and other partners in the Navy and in the academic research community have conducted research on possible effects of sonar sounds on human divers. These studies have included examinations of lung resonance effects (Rogers et al, 1996), rectified diffusion of hyperbaric gases into the bloodstream (Crum and Mao, 1996), and vibrotactile effects (Verillo et al, 1996). Ongoing studies include investigations of effects of sounds between 500 and 2500 Hz frequency on the psychological state and vestibular system of divers with differing levels of diving experience, and studies of tissue resonance (lung and skull) in pigs and humans (cadaver studies). Results from such studies can be integrated with research conducted directly on marine mammal specimens to develop predictive models for effects that scale with size or tissue properties (density, shape, elasticity, etc.), or effects that may be unique to a single taxonomic group's anatomy and physiology.

Hearing Safety Testing. Under funding by the Office of Naval Research, a number of investigators have developed protocols for safe hearing testing of trained marine mammals. Research efforts have ranged from assessments of the threshold of audibility up to safely recoverable temporary partial reductions in auditory sensitivity (Temporary Threshold Shift or TTS). At the highest safe exposure levels, sounds can induce a temporary decrease in the ear's ability to detect sound, but the temporary decrease lasts only for a few minutes or hours and full recovery is made to normal hearing levels. This is the same phenomenon, sometimes called The Rock Concert Effect, experienced by people, often many times in their lives. The affected individual experiences a sense of reduced hearing ability for a short time, followed by full recovery. Criteria for research protocols with marine mammal participation in such studies requires establishment of normal baseline hearing ability before entering testing, and a full return to those levels before each subsequent test.

At sound amplitudes between the threshold of audibility and TTS, the experimental protocols also produce other indicators of relative loudness, such as changes in response time (louder sounds usually elicit a more rapid response) or signs that the sound is becoming behaviorally aversive, such as interrupting the testing sequence or vocalizing. These data are assembled to generate a scale of increasing loudness that can be applied to other more general contexts, but without placing any animals at risk of permanent partial or total hearing loss. The results of such experiments form an important complement to the experiments described above and below, since the Hearing Safety Tests should produce values below those found to cause injury, and behavioral reaction from wild animals in the field should occur above the threshold of audibility, but below levels high enough to induce TTS or behavioral reactions from trained animals familiar with the sounds and testing protocol.

The experimental protocol designed to assess hearing safety thresholds for tactical mid-range sonars was developed by Dr. Ridgway of the Navy Marine Mammal Program in San Diego (e.g. see Schlundt et al, 2000). The proposed research is an adaptation of an experimental protocol that has been safely used for over five years to test hearing safety threshold for a variety of other pure tone and impulse sound signals. A ship-mounted 53C sonar has replaced the fixed tone generator used in previous experiments. The required range between sonar and test enclosure in order to produce specified sound levels has been measured, and testing of waveforms identical to those used in the Bahamas began in July 2001. The work is being carried out by Dr. Sam Ridgway and his colleagues at the Navy Marine Mammal Research Program facilities in San Diego, California, under funding from the Office of Naval Research and Chief of Naval Operations (CNO N45). All appropriate animal care and use protocols have been reviewed and approved, and the facility is AAALAC certified and inspected regularly by both the USDA Agricultural Plant and Health Inspection Service (APHIS) and National Marine Fisheries

Service.

Although the Hearing Safety Testing studies are necessarily carried out with animals commonly held for research (bottlenose dolphins, beluga whales and California sea lions), and not with beaked whales, the results are still valuable for determining beaked whale safety standards. At present we do not know if the combination of mid-range tactical sonar and unique environmental factors is risky for beaked whales or for other species as well. If dolphins and beluga whales show no difference in their response to the sonar sounds relative to other sounds they've already experienced, and if the other research results made directly with beaked whales (see preceding and following sections) show lower thresholds than predicted by the Hearing Safety Testing with other species, then we can safely assume that the problem is specific to beaked whales. However, if the dolphins and beluga whales show greater sensitivity to the sonar signals than to other sounds, then we would know that there is something specific to the sonar signal itself that is problematic.

Behavioral Effects Studies. The Office of Naval Research and other reviewers have expressed preference for Controlled Exposure Experiments (CEE), in which the researcher controls the level and duration of exposure, versus research protocols that attempt to observe two differing acoustic regimes (e.g. a noisy port area and a quiet bay). The latter approach, often referred to as a Comparative Observational Study (COS), lacks control over the noise experienced by the animals, and other variables beyond the control of the observer, but which could mask effects due to noise alone, such as differences in water quality, food resources, and social conditions.

There are several distinct advantages to the CEE procedure beside the most important feature; being able to control exposure and thus prevent potentially strongly aversive or injurious exposures. CEE also allows the researcher to establish better quality baseline behavioral data using the same animal in the same habitat as both control and experimental subject, thus controlling for variables other than noise that might strongly affect observed differences in behavior. A highly desirable consequence of this aspect of CEE is that it increases the statistical power of small samples sizes, thus reducing the total amount of testing required to produce statistically significant results. Finally CEE is better able to employ control procedures that prevent observer knowledge of the test regime from biasing results. Control of sound on-off, and collection of observational data can be conducted by two independent parties with the result that observers are not necessarily cued by co-variables of an uncontrolled source, such as detection of the presence of a ship, or acoustic and visual evidence of sound production by an uncontrolled source. In CEE, all the outward trappings of sound production can be simulated, without introducing sound, or the test director can initiate a false positive trial by telling observers the sound is on when it is not, thus controlling for observer biases that are an unavoidable consequence of uncontrolled observational data collection.

The standard CEE protocol starts with sound exposures so low they are at or near the threshold of audibility (thus providing independent confirmation of results of Hearing Safety Testing, described above). Subsequent exposures are increased by small increments until the first signs of behavioral aversion are detected, at which time testing can be immediately stopped. In a case like the Bahamas strandings, where the behavioral stages of response to the sonar signals are unknown, one has to be concerned about the possibility that the beaching response might be a rather sudden escalation of behavioral response that could pass quickly from relatively mild response to strongly aversive flight, thus placing the subject at risk of stranding if near shore. The safest protocol for CEE would therefore

be to test far from shore so that flight response does not pose a risk of beaching.

The CEE technique is well known in the research community, and there are many research professionals capable of doing this work properly and safely (e.g. see Croll et al, 2001; Miller et al., 2000). At present, no proposal to do this work has been generated or funded. As with any research project involving protected marine life, appropriate permits would need to be obtained before the work could be funded and begun. Since this is a highly sensitive issue, it would be reasonable to expect a greater than usual interest from the nonscientific community, and their input to the action would be essential for acceptance and application of the results.

Given the context issues described above, establishing realistic, meaningful behavioral safety thresholds for beaked whales is perhaps more important than almost anything else that can be done to understand the cause of the March 2000 strandings and prevent a recurrence of similar events in the Bahamas or elsewhere. At present we do not know if the behavior leading to stranding is a consequence only of very loud, injurious sounds, or if it is completely independent of the injurious effects and could occur even at relatively low levels of sound that would produce no physical effects at all. We also do not know if the behavioral response by beaked whales to unfamiliar sound tends to elicit a behavioral response that is maladaptive for this particular context. Examples of behaviors that might have increased risk of unsafe exposure include approaching the sound, or remaining in the surface duct instead of surfacing or diving deeper. We also do not know whether the aversive reaction is unique to the sonar signals used by the U.S. navy ships in the area at the time of the strandings, or whether the aversion extends to a variety of sounds. As mentioned previously in the section on Hearing Safety Testing, knowing whether the aversion is specific or general is critical to designing mitigation responses that will be effective in preventing recurrences of such strandings. For these reasons, CEE has been recommended as a safe means of obtaining behavioral response data from wild animals that could not be obtained in any other way, but consensus on the safest possible approach to this sensitive issue is a necessary first step before developing a specific research plan and soliciting funding to do the work.

Computer Modeling. Some effects, such as acoustic resonance of air spaces and tissues, and responses of muscularly controlled structures to sound, cannot be adequately tested using dead specimens. Computer-aided mathematical modeling may be able to simulate and predict these effects, and can be used in a crosschecking and validation protocol for those effects observed in the Bahamas strandings, or in the tests with dead specimens, described above. A variety of modeling procedures have been applied to marine mammal anatomical studies, ranging from relatively simple rule-based models to very detailed and complex Finite Difference and Finite Element models in which structures and their mechanical properties are measured on very fine scales and simulated on supercomputers. Two projects funded by the Office of Naval Research, one by Dr. Ted Cranford of Quantitative Morphology Consulting, Inc., and another by Dr. Darlene Ketten (previously mentioned) have developed 3-D digitized computer databases of beaked whale anatomy, including the species of concern in the Bahamas strandings. These same researchers, in association with several colleagues, have begun modeling aspects of the anatomy of these or other species, specifically the ears, nasal airways, and acoustic fats of the jaw and melon. ONR, the Strategic Environmental Research and Development Program (SERDP), and the Navy Marine Mammal Program in San Diego have variously sponsored this work. At present the Office of Naval Research has initiated some structural resonance modeling of beaked whale bony structures at Boston University (Dr. David Mountain). This work is part of a larger program to create a general model for noise risk prediction, called ESME (Effects of Sound on the

Marine Environment). ESME also includes modeling of sound transduction by marine mammal ears, and other lines of research generally relevant to this investigation.

The level of effort required to develop an effective model of beaked whale anatomy will be much greater than the effort undertaken in ESME and other ONR programs. Because effective modeling of the relevant anatomical structures will require the interdisciplinary collaboration of anatomists, audiologists, engineers, and mathematicians, an initial first step would likely be a workshop to develop interdisciplinary teams of researchers with specific goals, such as the study of resonance of airways. At present no specific plans have been formulated for the workshop or specific research efforts within this topic.

Stress Assessment. Although the Bahamas stranding appears to be the outcome of an immediate acute response to sound, several reviewers have noted that chronic short or long term sound effects might not manifest themselves in any overt behavioral or physiological effect, but instead only be apparent in symptoms of stress such as depressed immune system function. As a consequence the Office of Naval Research began funding research in marine mammal immune system characterization and assessment of stress (e.g. see Romano et al, in press; Romano et al, 1999). The purpose of the program is to develop the diagnostic tools to detect and accurately characterize stress, and to monitor populations of animals regularly subjected to known acoustic exposures, such as the animals in Navy Marine Mammal Program. This program of research is relatively new (approximately three years) and relies on advances in immunochemistry and immunogenetics only recently developed by human health researchers. Applicability to investigations of events like the Bahamas stranding, with the purpose of determining nonspecific stress effects, is likely to be at least two or three years off.

Where are the Beaked Whales? Application of the knowledge gained from the research described above requires us to know something about the distribution and habitat preferences of beaked whales. Historically, there has been little research on beaked whales, due largely to their tendency to inhabit deep waters, which often places them far from shore. Beaked whales tend not to form large groups, and their behavior when at the surface is generally quiet, making them difficult to detect. There is also some anecdotal evidence to indicate that many populations appear to avoid vessels and human activity.

Nevertheless, considerable published and unpublished data have emerged in recent years, making it possible to attempt some level of mapping of beaked whale populations. If that limited set of observational data were coupled with habitat data, it might also be possible to predict sites within the world's oceans that have not been surveyed, but which might reasonably be expected to contain beaked whales. ONR has received proposals for this kind of research effort, and anticipates funding the work in fiscal year 2002 (October 2001), pending finalization of the Congressional budget later this year.
The proposed research would compile all published and available unpublished survey data on beaked whales, and merge that data with state-of-the-art data on the marine environment, derived from oceanographic surveys and satellite remote sensing of ocean environmental features such as sea surface temperature, chlorophyll production, water movement, and other features. Partners in the research program would include the Naval Oceanographic Office, Naval Undersea Warfare Center, and various academic and research institutions. The project is anticipated to take about one to two years, and would result in a global map of beaked whale populations, and habitats that might reasonably be expected to contain beaked whales.

The accelerated pace of this work is enabled by the fact that ONR and CNO N45 have for the past five years supported a project to collect and map distribution and abundance data for all endangered and threatened marine mammals and turtles in the waters surrounding the United States (The Living Marine Resources Information System, or LMRIS). Aided by researchers from the NOAA Fisheries Science Centers and numerous public and private research institutions, the Navy is currently incorporating LMRIS into its vast holdings of oceanographic data at the Stennis Space Center in Mississippi, in collaboration with the Office of the Oceanographer of the Navy and its various oceanographic centers. The existing hardware and software infrastructure of LMRIS will allow us to accelerate the process of bringing beaked whale information into a data synthesis and mapping toolkit useable by Navy and others. The intended purpose of the research would be to aid in the planning of necessary military training, and other human activities at sea, so that potentially adverse impacts on beaked whales could be avoided.

Beaked Whale Population and Behavioral Data Collection. Studies of the population biology and social behavior of beaked whales are not recommended to be part of the program of research focused on determining the causal mechanisms of the March 15 stranding event. While these data are of general importance for the conservation and informed management of beaked whales, they do not directly inform an investigation of this stranding and its causes. Such research is more properly the domain of agencies charged with the long term monitoring and conservation of protected species, e.g. NOAA Fisheries and other national marine resource agencies. At present there are several multi-year ongoing studies of beaked whale populations, including several in the Bahamas. These programs of study include routine counting surveys to determine population status, photographic identification of individuals, data recording of interactions between individuals, and genetics studies from tissue biopsies.

Beaked Whale Movements and Uses of Sound. Beaked whales are known to generally be deep divers that spend considerable periods of time at depths of 600 meters or more. Anatomically they share many features with odontocete cetaceans, such as dolphins and porpoises, known to employ high frequency active sonar in hunting prey and navigating murky or deep waters. However, it is not currently known whether beaked whales do in fact use active sonar, and if they do, what kinds of sonar signals they emit. We also do not know what kinds of social and communicative sounds they use, and in fact there are very few recorded examples of sounds that can confidently be attributed to beaked whales. Obviously, the types of sounds beaked whales make, and the uses they make of such sounds, are of great importance in determining how manmade sounds might affect feeding and social behavior.

Under ONR sponsorship an attachable tag to record both diving and acoustic data has been developed and tested on several species of marine mammals. The prototype tag was originally developed for attachment to the pelage of elephant seals by a team of researchers from the University of California at Santa Cruz (Le Boeuf, Costa, Crocker, Burgess, et al) and Woods Hole Oceanographic Institution (Tyack). Since that time the tag has been greatly improved and used with suction cup attachment on right whales, sperm whales and pilot whales (Tyack and Johnson, Woods Hole Oceanographic Institution). A similarly improved model is in the final stages of development by Burgess (now with Greeneridge Sciences, Inc.) and is scheduled for deployment on sea turtles and blue whales in the coming year. The tags record several hours of acoustic data (including breathing and heart beats) along with diving data, environmental data (temperature, salinity), and behavioral data (extrapolated from movement data).

We recommend deploying acoustic datalogging tags on beaked whales to provide both acoustic and diving data. These tags have been used in CEE research to verify sound exposures of focal study animals, and to monitor underwater behavior during sound exposures. However, the tags may also be deployed without a controlled sound source, simply to record baseline acoustics and diving behavior. These data will enable us to model cumulative sound exposure for diving animals that may enter and leave several different sound regimes, e.g. ducts, and will enable us to determine the circumstances under which manmade sound may interfere with, or mask, sounds made by the animals themselves, with subsequent adverse effects on navigation, food finding and social communications.

Conclusions and Recommendations

Conclusions

Most, but not all lines of investigation have now been completed. Conclusions and recommendations appearing in this interim report could change somewhat as final results become available.

This was a comprehensive investigation in that all possible causes of the stranding event were considered whether they seemed likely at the outset or not. The goal was to assume nothing and to overlook nothing. Sixteen possible causes of the beaked whale strandings have been unequivocally ruled out by this or previous reports. These are biotoxins (red tide), malnutrition, chronic disease, inflammatory disease, meteorological events, earthquakes, volcanism, landslides, neoplasms (cancer), fisheries injury, blunt trauma from ship strike, nearby explosion, distant explosion, birth trauma, LWAD (a U. S. Navy exercise using sonobuoys), and Low Frequency Active sonar (SURTASS LFA).

Three other primary causes of the strandings or unique injuries seen in this event have been identified but are not considered a principal component for the following reasons. Acute chemical contaminant exposure (pollutants) is a potential cause of a mass stranding or mass mortalities but is highly unlikely in this event given that no mortalities of other species was observed, and there was no evidence of a chemical spill or release. Spontaneous subarachnoid hemorrhage does occur in mammals but would only affect individuals and would be highly unlikely to affect 16 animals (dolphin not included) at one time. Finally, diathetic disease (bleeding disorders), due to such things as leukemia or disseminated intravascular coagulation, would likely be expressed in other organ systems, and is unlikely to have affected all the animals at once.   The role that specializations of the clotting mechanism in whales, dolphins and porpoises played in the lesions seen in this event or in an increased susceptibility to acoustic trauma is unknown and will be further explored.

The fourth possible contributory cause to the strandings and cause of the lesions seen in these animals, and the only one that cannot be ruled out is, intense acoustic signals. Based on the environmental acoustic records and activities reported by the U.S. Navy, the only source of intense acoustic signals in the Bahamas on March 15, 2000 was tactical mid-range frequency sonars. The temporal and spatial pattern in which the sonars were operated is in agreement with the temporal and spatial pattern in which individual whales stranded.

The standard approach used in risk management is to consider the full range of biological and environmental variables that modify the expression of a given trigger agent. Focusing on the interplay among factors gives more options for risk-reduction than focusing on the trigger agent in isolation from the environment. The comprehensive approach referred to is the best way to identify the variables to be considered in managing future risk from tactical mid-range sonar. The variables identified are sound propagation characteristics (in this case a surface duct), unusual underwater bathymetry, intensive use of multiple sonar units, a constricted channel with limited egress avenues, and the presence of beaked whales that appear to be sensitive to the frequencies produced by these sonars. Some of these variables may be more important than others.

Considerable research must be conducted to determine the causal mechanisms whereby tactical mid-range frequency sonars could produce such tissue damage and stranding of the beaked whales in

question. Table 2 shows the studies related to this goal that are still under way. Specifically, research into possible mechanisms is focused on three topics. Vestibular atelectasis (collapse of tissues of the vestibular system, which includes the semicircular canals) has not yet been ruled out because detailed microscopic analysis has not been completed. Injury to the basilar membrane and hair cells of the cochlea (inner ear) still has not been ruled out for the same reason. Tissue damage via acoustic resonance is being studied in the laboratory using tissues from the Bahamas beaked whales, humans, and pigs. Analysis of acoustical fats is also critical. None of these studies is complete yet. All these issues will be revisited in the team's final report.

On March 15 and 16, 2000, a multi species stranding of seventeen marine mammals was discovered in the Northeast and Northwest Providence Channels on Bahamian Islands. The strandings took place within 24 hours of U.S. Navy ships using active mid-range sonar as they passed through the Northeast and Northwest Providence Channels. A combination of specific physical oceanographic features, bathymetry, presence of beaked whales, and specific sound sources were present. Six of the whales and one dolphin (unassociated) died after stranding on beaches. Ten whales returned to the sea alive. The four dead whales from which specimen samples could be collected showed signs of inner ear damage and one showed signs of brain tissue damage.   While the precise causal mechanisms of tissue damage are unknown, all evidence points to acoustic or impulse trauma. Review of passive acoustic data ruled out volcanic eruptions, landslides, other seismic events, and explosive blasts, leaving mid-range tactical Navy sonars operating in the area as the most plausible source of the acoustic or impulse trauma. This sound source was active in a complex environment that, as noted above, included the presence of a surface duct, unusual underwater bathymetry, constricted channel with limited egress, intensive use of multiple, active sonar units over an extended period of time, and the presence of beaked whales that appear to be sensitive to the frequencies produced by these sonars. The investigation team concludes that the cause of this stranding event was the confluence of the Navy tactical mid-range frequency sonar and the contributory factors noted above acting together.

Recommendations

To the maximum extent practical, the Navy will adopt measures in its future peacetime training, including those involving the use of tactical mid-range sonars, to avoid the taking of marine mammals. Under the circumstances investigated in this report, two actions are recommended for the Navy. These are to understand to the greatest extent possible the mechanisms by which sonar sounds affect marine mammal tissue or behavior, and to put into place mitigation measures that will protect animals to the maximum extent practical and not jeopardize National Security. These mitigation measures may change over time as new research is completed. Some of the research that is required to understand the mechanisms of action was presented in the Follow-Up Research Actions section of this report written by ONR. The investigation team recommends that all the research that is listed as under way be continued, and that all the projects that are listed as planned should be implemented. This is a brief summary of research the ONR report listed:

1. Tissue damage caused by 53C sonar (proposed). Beaked whale tissues would be exposed to a 53C sonar signal in a lake. Samples would be examined for damage after exposure to the same operating characteristics used in the Bahamas, and to different characteristics to determine how general or specific such effects may be.

2. Hearing safety tests (initiated). Animals currently in possession of the Navy Marine Mammal Program, trained to participate in studies of temporary threshold shift, would be exposed to 53C sonar signals at a distance to determine its effects on hearing function (dolphins, beluga, sea lions).

3. Resonance in skulls and lungs (under way and proposed). Human divers, pigs, and beaked whale tissues from the Bahamas are being studied for the frequencies and levels that cause tissue damage (in the laboratory).

4. Behavioral effects studies (proposed). Animals in the wild that would be temporarily equipped with instruments that record sound are briefly exposed to sounds of carefully controlled level while the instrument and other monitoring sensors (visual, acoustic, other) record behavioral responses as a function of level.

5. Computer-aided mathematical models (under way). A 3-D digitized database of beaked whale anatomy has been constructed. Finite Element Modeling is used to predict how various tissues would respond during acoustic resonance and other conditions. (Being done in conjunction with 3 above.)

6. Stress assessment (under way). Assays have been developed for use in marine mammals to detect stress hormone level. These assays have been used to detect stress hormone levels in marine mammals exposed to loud sounds in controlled experiments.

7. Beaked whale habitat use (initiated). The kinds of habitats that attract beaked whales need to be identified and flagged for those who plan sonar operations. This contributes to avoiding beaked whale populations, which is the best form of mitigation.

8. Beaked whale sounds (planned). The ways beaked whales make and use sound is an important consideration in studying how human sounds may affect them. Studies with instruments that record sounds (see number 4 above) are needed on beaked whales.

9. Future strandings (planned). Develop protocols and equipment for rapid response to future single or mass beaked whale strandings, both to determine how frequent this type of stranding may be and to develop general information about morphology, physiology and typical pathology histories for this little-known taxonomic group.

10. Studies of blood clotting mechanisms (suggested). Data from other odontocetes suggest possible differences from terrestrial mammal clotting physiology. Follow-up studies are possible to detect unusual clotting physiology in beaked whales, and whether it may have contributed to the observed hemorrhagic symptoms in this stranding.

Other research projects are possible and should be suggested to the investigation team.

Through the auspices of the Marine Mammal Health and Stranding Response Program established under 16 U.S.C. 1421 et seq, NOAA has numerous studies underway or planned to evaluate the causes of strandings and the impacts of human activities on marine mammal health in wild populations (cetaceans and pinnipeds, excluding walrus). A few of the studies and programs relevant to the present investigation are listed below:

1. Stress assessment (ongoing). Studies are underway to develop and validate markers and assays to assess the level of stress in marine mammals. Such studies include hormonal assays to evaluate actual stress hormone levels in blood and feces, assays to evaluate immunological function (which is affected by stress level), and assays to detect stress activated proteins in skin biopsies. Exposure to noise, both acute and chronic, is one of many stressors and may contribute significantly to elevated stress in marine mammals. NOAA is working with field biologists, researchers and the National Marine Mammal Stranding Network to study these parameters in wild marine mammal populations.

2. Stranding Response (ongoing). In partnership with the National Marine Mammal Stranding Network, NOAA is working to establish protocols, provide funding for response and analyses, and investigate the causes of strandings, injury and death in marine mammal populations, including beaked whales. NOAA and partners are working to determine the anomalies, diseases and lesions in wild marine mammals, including deep diving marine mammals which are stranded or by-caught. In addition, NOAA is providing training for stranding response and necropsy to stranding networks in other countries to increase the capabilities to understand causes of strandings and health indices in marine mammals. Such workshops have been conducted in Mexico (2) and Belize with future workshops planned. Finally NOAA partners and scientists provide assistance when requested and able to investigate mortality or stranding events in other countries.

3. Unusual mortality response (ongoing). NOAA coordinates the Working Group on Marine Mammal Unusual Mortality Events (16 U.S.C. 1421c) which advises NOAA on response to and investigations of unusual mortality events. This group along with the NOAA on-site coordinator

will investigate mortality events and unusual mass strandings.

4. NOAA working with partners will develop protocols for beaked whale (and other deep diving whale) research using stranded or by-caught animals. These protocols will ensure that a full multi-disciplinary research approach is used and that valuable data on beaked whale health or life history are not lost to other research interests, and that the stranding network is adequately compensated for additional collection efforts.

5. Clotting parameters (underway). Utilizing live stranded animals, studies will be conducted to evaluate clotting mechanisms in deep diving cetaceans such as beaked whales, sperm whales, and pygmy sperm whales.

Recommended mitigation measures:

1. Forego multi-ship, peacetime active sonar transmissions from mid-range tactical sonar in the Northeast and Northwest Providence Channels unless required for National Security reasons.

2. The Navy will carefully assess and closely scrutinize future training and training areas with an eye toward avoiding those situations where the combination of factors presented in this report (oceanography, bathymetry, sonar usage, etc.) would be likely to occur.

3. If the factors cited in this report are present in another location, and relocation is not feasible, and the Navy must proceed but has not received a Letter of Authorization (LOA) or an Incidental Harassment Authorization (IHA), then:

   - Immediately before the operation use whatever facilities or assets are on hand to visually and acoustically survey for marine mammals

   - Establish a zone of influence appropriate to the existing oceanographic conditions and source level settings

   - Employ properly trained lookouts

   - Implement shutdown procedures if marine mammals are detected within the zones of influence established for those species

   - Immediately after the operation ends (where feasible, usually in near shore waters) survey for injured, disabled or dead marine mammals using whatever survey facilities and assets are on hand, and notify NMFS if any such animals are found so that an appropriate stranding response can be implemented

4. NMFS will continue to conduct broad area surveys of marine mammal locations, migratory pathways and habitats that can be used by Navy planners in selecting exercise sites.

Glossary

Ante-mortem: Before death.

Autolytic: Causing autolysis, the enzymatic digestion of cells (especially dead cells) by enzymes present within them. Destruction or rupture of cells. Causes significant destruction of the tissues or decomposition of the cells with time after death, which hampers or inhibits post-mortem interpretation of tissues and lesions.

Barotrauma: Refers to trauma induced by sudden changes in ambient or barometric pressures such as those that occur in deep sea diving or airplane descent. This may result in trauma to the ear; the extent of which is dependent upon the pressure differential. Large pressure differentials can result in hemorrhage in the middle ear or rupture of the tympanic membrane.

Cephalopod: Any of the most highly developed class of mollusks, having long, arm-like tentacles around the mouth, a large head, a pair of large eyes, and a sharp, bird-like beak. Many can expel a dark, ink-like fluid. These include: squid and octopus.

Contrecoup injury: Denoting the manner of injury as in the skull or brain at a point opposite that at which the blow was received. E.g. If an animal is struck on the left side of the head, the damage or injury to the brain will show up on the right side of the brain, directly opposite to the blow. This is due to the brain moving inside a fluid filled sac inside the skull.

CSF: Cerebrospinal fluid: The clear fluid normally present within the cavities and between the membranes of the central nervous system which serve to protect the brain and spinal cord.

Cetacean: Literally it refers to three suborders of marine mammals including ancient whales, baleen whales (which include Minke whales), and toothed whales (which include beaked whales, dolphins, porpoises).

Clotting factors (coagulation): Components of blood that are needed for blood to clot or coagulate including specific coagulation proteins and blood platelets. Effective hemostasis (clotting of blood) is dependent on an effective number of functioning platelets, adequate concentrations and activities of fibinolytic and plasma coagulation proteins, and a normally responsive blood vasculature. Bleeding diatheses may be caused by congenital and/or acquired defects in any of these factors. Deficiencies in coagulation proteins are usually manifested clinically as delayed deep tissue hemorrhage and hematoma formation whereas deficiencies in platelets usually are manifested as superficial petechial or ecchymotic hemorrhages, epistaxis, melena, or prolonged bleeding at incision sites. Factor XI, Fletcher Factor, and Hageman Factor (see entries below) are three types of coagulation proteins noted to be absent in all tested cetaceans. These factors are part of the intrinsic clotting cascade (Meyer and Harvey, 1998).

Coagulopathies: diseases that affect the coagulability of the blood.

Cochlear duct: Membranous cochlea which lies within the spiral canal.

Computed tomography (CT): The creation of images showing anatomic information, each image generated by a computer synthesis of x-ray transmission data obtained in many different directions in a given plane.

Congestion: Presence of an abnormal amount of fluid in the vessels or passage of a part or organ; especially, of blood due either to increased influx or to an obstruction to outflow.

Crania (um): The bones of the head.

Cranial: Relating to the cranium or head.

Crustacean: A very large class of aquatic animals (phylum Arthropoda) with a chitinous (hard) exoskeleton and jointed appendages. E.g. Crab, lobster, crayfish, and shrimp.

Debilitation (debilitating): Condition denoting weakness. Morbid process that causes weakness.

DeciBel (dB): Decibel is a dimensionless ratio term that can be applied to any two values; temperature, rainfall, the number of jellybeans in a jar, or sound. Decibels are expressed as 10 times the logarithm of the ratio of a value (V) to its reference value (Vref), or:

$$N \text{ decibels (dB)} = 10*\log (V/Vref)$$

The decibel originated in electrical engineering measurements of transmission line losses, but it is also physiologically significant in that the response of biological ears to sound is logarithmic. (Bartberger, 1965). Decibels should always be accompanied by a reference value that defines the ratio being expressed, unless the reference is clearly stated at the start of the paper. In this paper all references to dB that are not accompanied by a specific reference value are dB of sound pressure level (SPL), referenced to 1 micro Pascal of pressure. Other commonly used acoustic measures, such as Sound Energy Level (SEL), also commonly expressed in dB ratio terms, will be specifically stated as being something other than sound pressure, and a different reference term, such as 1 second-second squared, will indicate that a value other than SPL is being discussed. A further distinction that needs to be kept in mind is whether the dB value is a Received Level (RL) or Source Level (SL). For acoustic sources, the convention is to express the power of the source in Sound Pressure Level at a distance of 1 meter from the acoustic center of the source. In many cases, especially for large sources, this is a theoretical number that never actually exists in the physical world, but is calculated from received levels measured at distances greater than one meter from the source. The source level of a sonar may be 235 or more, but the sound pressure at any one point away from the source is affected by the spreading of sound in all directions, and by absorption, reflections, scattering and other phenomena (discussed in more detail in the section on Acoustic Modeling). The physics of the propagating medium will determine whether the received level at a given point is 170, 180 dB, or some other value for a stated source level. While the source levels of the Navy sonars described here were generally 235 dB (sound pressure level), the received sound pressure level at any point more than a meter from the source would have been lower. How much lower is detailed in the section on Acoustic Modeling.

Delphinids: Family or classification of animals within the Order Cetacea and includes dolphins.

Diathetic: A condition of the body where an individual is more susceptible to a disease or physiological anomaly such as hemorrhage than usual.

Eosinophilic precipitation: Red stained residue observed when tissues are examined by staining with eosin and hematoxylin, two tissue dyes allowing you to see the cellular and tissue structures.

Epidemiology: The study of the distribution and determinants of health-related states (e.g., diseases) or events (e.g., mortalities) in specified populations, and the application of this study to control or mitigate health problems.

Exhume: To remove a body or carcass from a burial site.

Factor XI (thromboplastin antecedent): Circulating blood protein which participates in the intrinsic coagulation cascade. When activated by factor XIIa, it activates factor IX in a reaction requiring no cofactor except calcium ions. Deficiencies have been reported in Kerry Blue Terriers, a female English Springer Spaniel, a Great Pyrenees dog, Weimeraners, and Holstein cattle. In severe deficiencies, mild prolonged bleeding may occur after trauma or surgery. Bleeding tendencies are not immediate but usually delayed by 3-4 days.

Fletcher Factor (prekallikrein): Blood protein that is part of the intrinsic coagulation cascade. Participates in a reciprical reaction of contact activation in which it is activated to kallikrein by Factor XII; the kallikrein then catalyzes further activation of factor XII to factor XIIa enhancing the activation of factor XI. Deficiencies have been reported in a poodle, a family of miniature horses, and a family of Belgian horses. Clinical bleeding problems are not usually apparent however excessive post operative bleeding has occurred.

Gross findings: Observations of organs and tissues in carcasses that are large enough to be made with the naked eye.

Growth layer groups: Layers of cementum or dentin of teeth that are deposited in the tooth on a regular basis with age. These layers are counted to estimate age of the species.

Hageman Factor (Factor XII or contact factor): The first step in the intrinsic coagulation cascade. Trauma to blood or exposure of blood to vascular wall collagen causes Factor XII to be activated which in turn reacts enzymatically with Factor XI triggering the second step in the intrinsic cascade. Deficiencies have been reported in a German shorthaired pointer, Standard poodle and a family of miniature poodles. Affected animals do not usually have bleeding problems, however, humans with Factor XII deficiencies are predisposed to thrombosis or infections. Clinically seen as a test tube abnormality without clinical findings.

Histology: The science concerned with the minute structure of cells, tissues, and organs in relation to their function.

Hyperemia: The presence of an increase in blood flow to an organ or part which may be seen as a reddening of the tissue or organ on gross examination.

Impulse noise: There are no clear boundaries between impulse sounds and tonal ("continuous") sounds, but generally speaking impulse sounds are 1) of short duration (less than 0.1 - 0.2 seconds, and usually much shorter), and 2) have an irregular waveform, rather than the smooth sinusoidal waveform generated by most sonars or speech, for example. However, when a tonal sound source like a sonar powers up rapidly to full power in less than 0.1 second, the onset of the sound can have impulse-like effects (see Rise Time). The effects of impulse differ from tonal sounds in that the rapid overpressure, underpressure or combination of both in rapid succession, may exceed the mechanical resilience of structures and cause damage not seen with equal amplitude but slower pressure changes in tonal sounds. And since impulse is characteristically broadband (made up of many frequencies) effects like TTS may be found in unanticipated parts of the inner ear (a low frequency impulse may exhibit high frequency effects) or effects may be distributed across many frequencies. The ear has protective mechanisms against sudden loud noises that often reduce the effect of impulse sounds relative to tonal sounds. But individual differences in impulse sounds and in physiological protective responses mean that predicting the effects of impulse sound on a given individual is more difficult than for tonal sound. Within a population, impulse sounds tend to result in more varied effects between individuals, relative to exposure to tonal sounds.

Inflammation: Localized heat, redness, swelling, and pain resulting from injury, infection, or irritation.

Interspecific: Occurring or arising between species.

Intracochlear: Within the inner ear or cochlea.

Intra-cranial: Within the skull or more loosely within the head.

Labyrinthine: Relating to the structure of the inner ear comprised of several connected ducts, bony and membranous components. The labyrinth is the canal system within the tympanic bone which houses the inner ear. The labyrinth has a bony component and a membranous component.

Lateral ventricle: A cavity shaped somewhat like a horseshoe which lies within each hemisphere of the brain. The cavity contains cerebrospinal fluid which flows outward to other parts of the brain, spinal cord, and some portions of the cranial and spinal nerves.

Leptomeninges: The pia mater and arachnoid membranes surrounding the brain and spinal cord between which lies the cerebrospinal fluid.

Lesion: wound, injury, or pathological change in the tissues.

Morphology: The science concerned with the structure of animals.

Myocardial contraction band necrosis: Focal hypercontraction and lysis of contractile filaments in small groups of myocardial cells.

Necropsy(ied):   (SYN: autopsy)- An examination of the organs of a dead body (whale) to determine the cause of death or to study the pathologic changes present. Is the same as an autopsy performed on humans.

Necrotic: Death of one or more cells or a portion of a tissue, organ, or carcass resulting from irreversible damage.

Parenchyma(l): The essential and distinctive tissue of an organ as distinguished from its supportive framework.

Pathognomonic: Characteristic or indicative of a disease; typical symptoms, findings or patterns of abnormalities that are specific for a given disease and not found in any other condition.

Pathology: The medical science and specialty practice, concerned with all aspects of disease, but with special reference to the essential nature, causes, and development of the abnormal conditions, as well as the structural and functional changes that result from the disease processes.

Peribullar: Around the bullae, [in this case referring to the tissues and space surrounding the bony housing of the ear].

Peri-mortem: Occurring around the time of death.

Physiology: The science concerned with the normal vital functions and activities of life or of living matter, especially as to how things normally function.

Ping-Second: The term 'ping-seconds' refers to the number of seconds of sonar sound that would have occurred at a specified site and specified level. For example, in Figure 5.d. one can see that most of the track of Ship B produced exposures of 2-8 seconds at 180 dB or higher along its track, but that some areas received more overlapping pings due to changes in ship speed or maneuvering.   Given the variability in ship speeds and maneuvers and changes in sonar output over time, a graphical picture of cumulative exposure is a useful way of visualizing both the extent and duration of exposure to sonar sound experienced at various points within the New Providence Channel during this exercise.   Only two conditions, sound levels above 180 dB and sound levels above 160 dB are shown, though the data could be presented in many different views, e.g. exposures to sound levels between 180 dB and 185 dB only, or between 170 and 175 dB, or exposure to sound levels above 100, 120, or 140 dB. No special significance should be attached to the limited selection of displays provided here for illustrative purposes only.

Post-mortem: Pertaining to or occurring during the period after death.

Propagation (sound propagation):   Several factors must be considered when reviewing the acoustic propagation reported here.   First, there is a difference between Source Level (SL), measured at one meter from the acoustic center the source, and Receive Level (RL), the amount of sound an animal would receive at some distance from the source.   Due to spherical spreading of sound, absorption, reflection, scattering, and other phenomena, Receive Levels drop markedly as one moves away from the source. For example, a Source Level of 235 dB one meter from the source dissipates to a Receive Level of 180 dB at a distance of 200 m to 1000 m from the source, depending on conditions.   Second, the rise time of the signal, the time required for the signal to grow from zero to maximum amplitude, can have an impulse like effect if short enough in duration.   Although frequency spreading and environmental scattering tend to smear the rise time in question and reduce the potential for impulse

like events, they cannot be discounted.

Pulmonary edema: An accumulation of an excessive amount of watery fluid in cells or intercellular tissues of the lungs. Pulmonary edema can inhibit transfer of gases between vessels and the airways and impair respiratory function.   The lungs typically are heavier and less spongy than normal on post-mortem examination.

Renal capsular hemorrhage: Hemorrhage in the fibrous connective tissue covering the kidney (reniculi in cetaceans).

Reproductive status: Sexually mature/immature.

Rise time: The total time from sonar-off to maximum amplitude. For the 53C and 56 sonars, rise time is one or two cycles, which would translate to about 0.4-0.3 milliseconds for the 53C sonars and 0.2 - 0.1 milliseconds for the 56 sonars. These rise times are within the range of signal durations associated with impulse noise. Frequency spreading and environmental scattering would tend to "smear" the rise time as the sound propagated away from the source, thereby reducing the potential for impulse-like effects.

Sinus: A cavity or hollow space in bone or other tissue usually lined by mucous membrane.

SAH: **(Subarachnoid hemorrhage),** presence of blood in the subarachnoid space surrounding the brain (the space between two layers of meninges, the subarachnoid membrane and the pia mater, and normally contains cerebrospinal fluid),   usually spreading throughout the normal cerebrospinal fluid pathways which connect along cranial nerve pathways including those for Cranial nerve VIII to the ear.

Sonar.   Sonar (Sound Navigating And Ranging) may be active or passive. Active sonar projects a sound and then listens for echoes of that sound returning from underwater objects. Passive sonar does not project a sound, but instead only listens for sounds produced by underwater objects.   The Navy uses both active and passive sonar. Active sonar is the most significant sensor for detecting and locating diesel submarines in the complex oceanography of littoral waters. It enables ships to search a larger area more quickly than any other sensor, and it provides the only accurate targeting data for the ship's antisubmarine warfare (ASW) weapons.   However, interpreting sonar data is much more difficult than interpreting radar data because of the complexity of how sound travels under water, especially in littoral waters. Proficiency in these interpretations is gained slowly and lost quickly. Simulators are available for training, but they do not fully replicate the difficulty of detecting and tracking submarines at sea. Ping contact time against actual targets at sea is essential for gaining and retaining ASW proficiency. It is for this goal that ASW exercises such as the one in the Bahamas are staged.

Subcutaneous: Beneath the skin which includes the epidermis and dermis (blubber).

Vestibular atelectasis: Collapse of the membranous walls of the ampullae and utricle of the inner ear triggering in humans chronic unsteadiness and vertigo.

Literature Cited

Balcomb, K.C. III, and D.E. Claridge. 2001. A mass stranding of cetaceans caused by naval sonar in the Bahamas. *Bahamas J. Sci.* 2:2-12.

Bartberger, C. L. Lecture Notes on Underwater Acoustics. U.S. Naval Air Development Center Report No. NADC-WR-6509 17 May 1965

Bossart, G.D., T.H. Reidarson, L.A. Dierauf, and D.A. Duffield. 2001. Clinical Pathology, in CRC Handbook of Marine Mammal Medicine, L.A. Dierauf and F.M.D. Gulland, (Eds.), p.421.

Clarke, M.R., 1996. Cephalopods as prey. III. Cetaceans. *Phil. Trans. R. Soc. Lond. B.* 351:1053-1065.

Collins, M.D. 1993. A split-step Pade solution for parabolic equation method. *J. Acoust. Soc. Am.* 93: 1736-1742.

Collins, M.D. 1995. Users Guide for RAM Versions 1.0 and 1.0p. Naval Research Lab, Washington, D.C.

Croll, D.A., C.W. Clark, J. Calambokidis, W.T. Ellison, and B.R. Tershy. 2001. Effect of anthropogenic low frequency noise on the foraging ecology of *Balaenoptera* whales. *Animal Conservation* 4:13-27.

Crum, L.A, and Y. Mao. 1996. Acoustically enhanced bubble growth at low frequencies and its implications for human diver and marine mammal safety. *J. Acoust. Soc. Amer.* 99(5): 2989-2907.

Ellison, W.T. 2000 (unpubl.) Environmental Quality Program Technical Review: Acoustic Integration Model [EQ22]. Unpublished technical report delivered to the Office of Naval Research EQ program, June 7-8, 2000. Annapolis, MD..

Frantzis, A., 1998. Does acoustic testing strand whales? *Nature* 392:29.

Fromm, D.M., and J. F. McEachern. 2000 (unpubl.). Acoustic Modeling of the New Providence Channel. 29 August 2000, 56 pp. (available from the U.S. Office of Naval Research).

Geraci, J.R. and V.J. Lounsbury, 1993. Marine Mammals Ashore. Texas A&M Sea Grant Publication, Galveston, TX., Pp 133-143.

Haast, J. von., 1876. On a new Ziphioid whale. *Proc. Zool. Soc. London*, 7-13.

Ketten, D. (unpubl.) Experimental Measures of Blast and Acoustic Trauma in Marine Mammals. Annual Report to the Office of Naval Research Program, FY99-00.

Meyer, D.J. and J.W. Harvey. 1998. Evaluation of hemostasis: Coagulation and platelet disorders. In: <u>Veterinary Laboratory Medicine: Interpretation and Diagnosis</u>., 2nd Edition, Saunders Company, Philadelphia, PA, pp 111-137.

Miller, P.J.O., N. Biassoni, A. Samuels, and P.L. Tyack. 2000. Whale songs lengthen in response to sonar. *Nature* 405:903.

National Research Council. 2000. Marine Mammals and Low Frequency Sound: Progress Since 1994. National Academy Press, Washington DC

Parry, B. W., 1993. Hemorrhagic Diathesis. *In* Pathology of Domestic Animals, K.V.F. Jubb, P.C. Kennedy, and N. Palmer (Eds.), Academic Press, N.Y., pp257-265.

Porter, M.B. 1995. The Kraken normal mode program. User's manual, SACLANT Undersea Research Centre, La Spezia, Italy.

Reinis, S., J.W. Featherstone, and D.S. Weiss. 1980. The effects of sonic booms on hearing and inner ear structure. International Symposium on effects of Impulse Noise on Hearing. Pp163-169.

Richardson, W.J., C.R. Greene, C.I. Malme, and D.H. Thomson. 1995. Marine Mammals and Noise. Academic Press, San Diego, CA.

Ridgway, S.H. 1972. Homeostasis in the aquatic environment, In: Mammals of the Sea: Biology and Medicine, S.H. Ridgway, ed., C.C. Thomas, Springfield, Ill., pp 590-747.

Rogers P.H., G.W. Caille, and T.N. Lewis. 1996. Response of the lungs to low frequency underwater sound. Final Report, Navy Contract N00014-93-1-1263.

Romano, T.A., S.H. Ridgway, D.L. Felton, and V. Quaranta. 1999. Molecular cloning and characterization of CD4 in an aquatic mammal, the white whale, *Delphinapterus leucas*. *Immunogenetics*, 49: 376-383.

Romano, T.A., J.A. Olschowka, S.Y. Felton, V. Quaranta, S.H. Ridgway, and D.L. Felten. (in press) Immune response, stress, and environment: Implications for cetaceans. In: <u>Cell and Molecular Biology of Marine Mammals</u>; C.J. Pfeiffer, ed. Krieger Publishing Co., Inc.

Saito, H., M. Poon, G.H. Goldsmith, O.D. Ratnoff, and U. Arnason. 1976. Studies in the blood clotting and fibrinolytic system in the plasma from a sei whale. *Proc. Soc. Exp. Biol. Med.*, 152: 503.

Schlundt, C.E., J.J. Finneran, D.A. Carder, and S.H. Ridgway. 2000. Temporary shift in masked hearing thresholds (MTTS) of bottlenose dolphins, *Tursiops truncatus*, and white whales, *Delphinapterus leucas*, after exposure to intense tones. *J. Acoust. Soc. Am.*, 107: 3496-3508.

Schmidt, H. 1997. "OASES: Version 2.1, user guide and reference manual,"Technical Report,

Massachusetts Institute for Technology.

Schuknecht, H. 1993. Pathology of the Ear, Second edition, Lea Febiger: Philadelphia.

Simmonds, M.P. and L.F. Lopez-Jurado, 1991. Whales and the Military.   *Nature* 51:448

Summer, B.A., J.F. Cummings, and A. de Lahunta,. 1995.   Injuries to the central nervous system.
        In Veterinary Neuropathology. Mosby-Year Book, Inc., St. Louis. Pp 189-207.

Turnbull, B.S. and D.F. Cowan,. 1998. Myocardial contraction band necrosis in stranded
cetaceans. *J. Comp. Pathol.* 118:317-327.

Urick, R. J. 1983. Principles of Underwater Sound, third edition. McGraw-Hill Inc.,
        New York, NY

Verillo, RT, S.J. Bolanowski, F. Baran, and P.F. Smith. 1996.   Effects of underwater environmental
        conditions on vibrotactile thresholds. *J. Acoust. Soc. Amer.*, 100: 651-658.

Vonk, R. and V.M. Martel. 1989. Goose-beaked whales *(Ziphius cavirostris)* mass strandings in the
        Canary Islands. *Proc. Third Ann. Conf. European Cetacean
        Soc.*

Walsh, M.T., R.Y. Ewing, D.K. O Dell, and G.D. Bossart, 2001. Mass Strandings of
        Cetaceans. *In* CRC Handbook of Marine Mammal Medicine, L.A. Dierauf and
        F.M.D. Gulland, (Eds.), pp 83-96.

Weinberg, H. and R.E. Keenan. 1996. Gaussian ray bundle for modeling high-frequency
        propagation loss under shallow water conditions. *J. Acoust. Soc. Am.,* 100: 1421-1431.

Wilkinson, D.M., 1991. Program Review of the Marine Mammal Stranding Networks.
        Report to the Assistant Administrator for Fisheries, NOAA, National Marine Fisheries
        Service, Silver Spring, MD. (available from NMFS Office of Protected Resources, Silver
        Spring, Md).