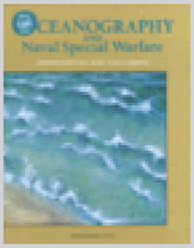

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Preface

Sea, Air, and Land (SEAL) teams and other naval units involved in Naval Special Warfare have been associated with excellence since their creation in 1970. Almost immediately upon inception, Navy SEALs commanded the respect of members of the military community. As their training methods and military exploits have become more familiar, they have also captured the imagination of the American public. SEAL is a term associated with skill, endurance, and commitment. Yet beyond the heroism and public interest, lies an organization that strives to command and utilize the variety of environments within which it operates.

Perhaps because of the unique relationship this group of warfighters has with the sea, SEAL teams, more than any other special warfare unit, depend on environmental information to obtain a tactical advantage in the field. Consequently, oceanographic and meteorological information can be as important to a SEAL team as any single piece of equipment in its arsenal. The ability to provide accurate environmental information and useful predictions will require that our understanding of the SEALs' operating environments continues to grow as their mission evolves. Scientific research will play an important role in the Navy's efforts to support these unique warfighters.

Kenneth H. Brink
Ocean Studies Board, *Chair*

Acknowledgments

The *Symposium on Oceanography and Naval Special Warfare* was a collaborative effort of many individuals within the Navy and academia. Consequently, this report reflects input from a number of individuals. In particular, the steering committee would like to acknowledge the role of those individuals who led working group discussions: Steve Elgar, Waves and Surf; Dave Aubrey, Currents and Tides; Edie Widder, Bioluminescence and Marine Toxins; Chris Fairall, Electromagnetic and Infrared “Above Surface” Signal Propagation and Winds; and Doug Todoroff, Electrooptical and Acoustic “Below Surface” Signal Propagation. The steering committee is indebted to other attendees and experts who also prepared background materials on issues discussed at the symposium, including M. Elizabeth Clarke, Juergen Richter, David Lapota, and Michael Latz.

In addition to the support and contribution of the many attendees, experts, and participants listed above, the steering committee would also like to take this opportunity to acknowledge the efforts of the officers, enlisted personnel, and civilian staff of the Naval Special Warfare Command, the Naval Pacific Meteorology and Oceanography Facility, the Expeditionary Warfare Training Group Pacific, the Office of Naval Research, the Office of the Oceanographer of the Navy, the Naval Oceanographic Office, the Warfighting Support Center, and the Naval Reserve Meteorology and Oceanography Activity (966). Without the support and assistance from these individuals, this symposium and the resulting report would not have been possible.

Contents

Executive Summary

The value of oceanographic information for planning and executing naval operations has been recognized by the Navy for decades. Consequently, the Office of Naval Research has been a leading funder of academic oceanographic research for many years. In an effort to improve the academic ocean science community's understanding of the operational demands placed on units involved in Naval Special Warfare (NSW), the National Research Council's Ocean Studies Board (OSB), through the support of the Office of Naval Research and the Office of the Oceanographer of the Navy, convened a symposium on oceanography and NSW in February 1997.

NSW encompasses some of the most unique and arduous challenges facing naval personnel in combat situations. Real-time decision making is crucial, and the need for adequate and accurate environmental data on small scales is paramount for minimizing uncertainty and reducing risk. Mission success and human lives often depend on the availability of accurate environmental information. Consequently, the symposium (and this report) examined three components: (1) the mission and personnel assigned to NSW, (2) the present capability of the Navy's oceanographic community to support NSW, and (3) the potential for research to expand that capability.

NAVY OCEANOGRAPHIC CAPABILITIES

The U.S. Navy provides environmental support for NSW by means of an infrastructure that includes both the operational oceanography community and an underlying science and technology (S&T) base. The Office of the Oceanographer of the Navy (N096) oversees the day-to-day operational aspects, and the Office of Naval Research (ONR) manages the S&T program.

Generally, the Oceanographer and his Command are responsible for understanding the effects of the natural environment on the planning and execution of naval operations and interpreting atmospheric and ocean phenomena for the fighting forces. Meeting the meteorological and oceanographic (METOC) needs of NSW are an increasingly important aspect of this mission as the focus of naval warfare continues to move toward the littoral zone, defined as the oceanographic region encompassing the continental shelf and slope and the adjacent deep water.

The long-term success of the Navy's METOC community in satisfying the particular needs of NSW depends, to a large degree, on research and technology efforts coordinated by ONR. ONR's primary role in the Navy's METOC support infrastructure is to provide a technology base for the development and fielding of the next generation of METOC capabilities that support warfighters—including NSW.

As the Navy continues to adjust from the conditions of the Cold War to a "New World Order" in which the likelihood of smaller-scale naval operations nearshore increases, operational oceanography has had to confront a new set of challenges associated with understanding and predicting natural environments that change much more rapidly in time and space than the deep ocean settings of the past. This, in turn, is causing a sweeping reexamination of traditional METOC approaches. The coastal regions and adjacent hinterlands are a particular focus for NSW. Consequently, improved characterization of the littoral zone should be especially useful in supporting new NSW needs.

ROLE OF RESEARCH

NSW-related research challenges are formidable. NSW operational needs create spatially and temporally difficult requirements for environmental models and observations. Models and observations that were successfully used in support of anti-submarine warfare cannot be easily adapted to support NSW operations. The problem is one of both scale and environmental complexity. NSW operations require localized environmental information (at a resolution on the scale of hundreds of meters), in many different types of environments (shelf, inner shelf, nearshore, inlet, harbors, rivers). In addition, for mission planning purposes, estimates of environmental parameters (e.g., surf conditions, water clarity, atmospheric visibility), or the time scales upon which they vary, need to be available five to seven days in advance.

The Navy has acknowledged that new, creative approaches to collecting, assilimating, and providing environmental information should be considered if NSW is to be adequately supported. The complexity of the environment, the required resolution of information, and the demand of the mission timeline make it impossible for most parameters to be predicted or modeled using a single approach. Leaders of the METOC community recognize the need to develop and deploy hybrid platforms with different types of sensors for local and regional observations. As envisioned, these platforms would use model results to improve their sensing of the environment and the models would use the platform data to improve their predictions.

EXPANDING THE CAPABILITY

At the symposium, Navy and academic scientists, NSW boat operators, SEAL team members, and representatives of the various organizations that make up the Navy's METOC infrastructure met in plenary and working group sessions. Discussions centered on ways to improve or augment information on bioluminescence, hazardous marine organisms, waves and surf, currents and tides, bathymetry, humidity and EM-ducting, atmospheric visibility, underwater acoustics, underwater optics, and water temperature. The primary function of the symposium was to bring together individuals of diverse backgrounds and interests to examine an interdisciplinary issue. The steering committee was not charged with identifying specific recommendations for how the sponsors or the research community should attempt to act upon suggestions made during the symposium discussions or otherwise expand the existing capability to support NSW. The steering committee, however, did identify a number of salient points made during the symposium:

- The changing geopolitical context that the U.S. Navy operates in is forcing greater emphasis on littoral operations.
- Littoral warfare in general, and NSW in particular, call for higher resolution data and predictions than those needed by more traditional open ocean naval operations.
- Greater understanding of ocean processes can help decision makers identify the best mix of predictive capability and real-time observations for unfamiliar settings.
- Significant information and relevant technology already exists in academia or other research sectors.
- Making that knowledge more readily available to NSW and other Navy users will require greater understanding of both the Navy's needs and the nature of current ocean science knowledge.

1

Introduction

The value of oceanographic information for planning and executing naval operations has been recognized by the Navy for decades. Consequently, the Office of Naval Research has been a leading funder of academic oceanographic research for many years. In an effort to improve the academic ocean science community's understanding of the operational demands placed on naval units, the Ocean Studies Board (OSB), through the support of the Office of Naval Research and the Office of the Oceanographer of the Navy, convened four previous symposia on tactical oceanography (NRC 1991, 1992, 1994, 1996). These symposia have become an important vehicle for facilitating dialogue between academic scientists and the warfighters. These exchanges constitute a valuable mechanism to facilitate more efficient use of naval research funds and to help academic scientists identify areas of research of high value to the Navy.

Naval Special Warfare (NSW) encompasses some of the most unique and arduous challenges facing naval personnel in combat situations. Real-time decision making is crucial, and the need for adequate and accurate environmental data on small scales is paramount for minimizing uncertainty and reducing risk. A thorough understanding of surf conditions; the nature of the coastline; the variability of seabed stability; and even the concentration of local marine life, large predators, and natural or man-made toxins can help ensure mission success.

The OSB's fifth symposium on tactical oceanography examined the present state of knowledge and predictive capability relevant to NSW. Emphasis was placed on discussion of issues of shared interest between warfighters and scientists (see Box 1-1). A total of 104 attendees from the operational Navy, the Navy research and development community, and academia participated.

The symposium included, but was not limited to, discussion of the processes (e.g., gravity and infragravity waves) that control the transport of momentum and material in the region from roughly 1 km offshore, inward to the seasonal high-tide mark (roughly, water of 40 m and shallower depths). By describing the dynamic relation of the fluid, sediment, and biota, with effects on visibility and boundary stability, the meeting reviewed existing approaches used to monitor and predict changes in physical parameters and other environmental factors important for conducting special warfare operations in nearshore settings. The effects of marine boundary-layer and water column visibility on remote sensing capabilities and operations were also included.

The NRC appointed a symposium steering committee consisting of two OSB members and two additional ocean scientists. This steering committee (1) worked with appropriate Navy personnel to identify specific topics to be covered, (2) identified the most appropriate speakers to address symposium attendees, (3) identified members

Box 1-1: Statement of Task

This symposium is designed to bring together members of the academic community, the U.S. Navy (warfighters, meteorologists, and oceanographers), and scientists, technologists, and managers from naval warfare centers and defense programs to:

- address timely operational problems, fleet mission needs, and other areas in which oceanographic research and development solutions need to be expanded;
- enhance communication among the basic and applied research communities, as well as with naval forces engaged in Naval Special Warfare; and
- enable an extended group of researchers to become familiar with challenging naval issues related to the use of oceanographic information in Naval Special Warfare.

of the academic community who should be encouraged to attend, and (4) authored this unclassified symposium summary report.

SPECIAL OPERATIONS FORCES: AN OVERVIEW

Making use of information about the various environments in which NSW personnel operate, will require that scientist and warfighter understand (1) the constraints faced by the operator in the field and (2) the limitations placed on the scientist's knowledge by the complexity of processes that operate in such settings. Understanding the methods of operation of a group that prides itself on being able to routinely conduct clandestine operations is a unique challenge. Consequently, an examination of the nature of special operations in general may provide some insights germane to understanding Naval Special Warfare.

Special Operations Forces (SOF, sometimes referred to as Special Forces) are military personnel who receive demanding and specialized training in order to conduct a variety of unique missions for which most of the more conventional military units are not adequately suited. Many nations, including Great Britain, Australia, the Russian Federation, and the United States, have designated Special Operations Forces within their military structure. Most of these units have long and distinguished histories and are descendants of a variety of unconventional forces involved in a number of conflicts. Some of the most commonly recognized units include the Special Air Service (SAS) and Special Boat Service (SBS) (Great Britain), the Green Berets (U.S. Army), Spetsnaz (Russian Federation), and the SEALs (Sea, Air, and Land teams; U.S. Navy).

These SOF units have been referred to as "necessity's children" (White, 1992) and perform a wide variety of unique tasks, including reconnaissance and surveillance patrols, guerrilla and assault commando missions, and combat rescue. In addition, these forces are commonly used as instructors in each nation's efforts to train allied forces in less developed nations. Perhaps the best-trained and equipped forces within this group of elite warfighters from around the world are members of the U.S. Special Operation Forces (US SOF) under the U.S. Special Operations Command (USSOCOM).

US SOF are military personnel who provide the National Command Authorities a highly-trained, rapidly-deployable joint force capable of conducting special operations anywhere in the world. US SOF may support and enhance the capabilities of conventional forces by serving as a force multiplier, or US SOF may provide an independent capability that can be applied across the full range of military operations. Political sensitivities, in some cases, may render SOF as the only available military option. US SOF are valuable instruments of national policy, because they provide an array of capabilities to meet a myriad of operational requirements (Office of the Undersecretary of Defense, 1996).

U.S. SPECIAL OPERATIONAL FORCES AND USSOCOM

Activated on April 16, 1987, USSOCOM is an umbrella organization intended to provide command, control, and training for all U.S. Special Operations Forces (US SOF). Some 47,000 active, National Guard and reserve personnel are included in USSOCOM. USSOCOM headquarters is located at MacDill Air Force Base, Florida. Component SOF commands within USSOCOM include the Joint Special Operations Command, Fort Bragg, North Carolina; the U.S. Army Special Operations Command, Fort Bragg, North Carolina; the Air Force Special Operations Command, Hurlbert Field, Florida; and the Naval Special Warfare Command (NAVSPECWARCOM), Coronado, California.

Box 1-2: Principal Missions of U.S. Special Operations Forces

- **Counterproliferation**—The activities of the Department of Defense across the full range of U.S. government efforts to combat proliferation of weapons of mass destruction, including the application of military power to protect U.S. forces and interests; intelligence collection and analysis; and support of diplomacy, arms control, and export controls. As appropriate, accomplishments of these activities may require coordination with other U.S. government agencies.
- **Special reconnaissance—**Conduct reconnaissance and surveillance actions to obtain or verify information concerning the capabilities, intentions, and activities of an actual or potential enemy or to secure data concerning characteristics of a particular area.
- **Psychological operations—**Induce or reinforce foreign attitudes and behaviors favorable to the originator's objectives by conducting planned operations to convey selected information to foreign audiences to influence their emotions, motives, objective reasoning, and ultimately the behavior of foreign governments, organizations, groups, and individuals.
- **Direct action—**Conduct short-duration strikes and other small-scale offensive actions to seize, destroy, capture, recover, or inflict damage on designated personnel or material.
- **Foreign internal defense**—Organize, train, advise, and assist host nation military and paramilitary forces to enable these forces to free and protect their society from subversion, lawlessness, and insurgency.
- **Civil affairs**—Facilitate military operations and consolidate operational activities by assisting commanders in establishing, maintaining, influencing, or exploiting relations between military forces and civil authorities, both governmental and nongovernmental, and the civilian population in friendly, neutral, or hostile areas of operation.
- **Combating terrorism**—Preclude, preempt, and resolve terrorist actions throughout the entire threat spectrum, including anti-terrorism (defensive measures taken to reduce vulnerability to terrorist acts) and counter-terrorism (offensive measures taken to prevent, deter, and respond to terrorism), and resolve terrorist incidents when directed by the National Command Authorities or the appropriate unified commander or requested by the Services or other government agencies.
- **Information warfare/command and control warfare**—Actions taken to achieve information superiority by affecting adversary information, information-based processes, information systems, and computer-based networks while defending one's own information, information-based processes, information systems, and computer-based networks.
- **Unconventional warfare**—Organize, train, equip, advise, and assist indigenous and surrogate forces in military and paramilitary operations normally of long duration.

Continued

Box 1-2: Continued

SOF Collateral Activities

- **Coalition support—**Integrate coalition units into multinational military operations by training coalition partners on tactics and techniques and providing communications.
- **Combat search and rescue—**Penetrate air defense systems and conduct joint air, ground, or sea operations deep within hostile or denied territory at night or in adverse weather to affect the recovery of distressed personnel during wartime or contingency operations.
- **Counterdrug (CD) activities—**Train host nation CD forces on critical skills required to conduct small unit CD operations in order to detect, monitor, and counter the production, trafficking, and use of illegal drugs.
- **Countermine (CM) activities—**Reduce or eliminate the threat to noncombatants and friendly military forces posed by mines, booby-traps, and other explosive devices by training host nation forces in the location, recognition, and safe disposal of mines and other destructive devices, as well as CM program management.
- **Humanitarian assistance—**Provide assistance of limited scope and duration to supplement or complement the efforts of host nation civil authorities or agencies to relieve or reduce the results of natural or manmade disasters or other endemic conditions such as human pain, disease, hunger, or privation that might present a serious threat to life or that can result in great damage to, or loss of, property.
- **Security assistance—**Provide training and assistance in support of legislated programs which provide U.S. defense articles, military training, and other defense-related services by grant, loan, credit, or cash sales in furtherance of national policies or objectives.
- **Special activities—**Subject to limitations imposed by Executive Order and in conjunction with a Presidential finding and congressional oversight, plan and conduct actions abroad in support of national foreign policy objectives so that the role of the U.S. government is not apparent or acknowledged publicly.

In addition, US SOF personnel can conduct other activities as determined by the President of the United States or the Secretary of Defense. Counterterrorism and unconventional warfare are strictly special operations. US SOF units share the other seven specific responsibilities with conventional forces, but because low-visibility, low-cost special operations techniques are distinctly different, they expand the range of options open to U.S. defense decision makers.

Source: Office of the Undersecretary of Defense, 1996

MISSIONS OF SPECIAL OPERATIONS FORCES

Special operations are characterized by the use of small units in direct and indirect military actions focused on strategic and operational objectives. These actions require units with combinations of specialized personnel, equipment, training, and tactics that go beyond the routine capabilities of conventional military forces. In support of national military strategy, US SOF are currently organized and trained in nine principal mission areas. Based on their unique capabilities, US SOF are also frequently tasked to participate in other activities that are not principal US SOF missions. These collateral activities tend to shift in response to the changing international environment.

US SOF may conduct several principal missions and collateral activities at the same time in a single campaign. Whenever US SOF are tasked by the National Command Authorities, a joint force commander, a U.S. ambassador or country team, or any other government agency to perform a mission for which US SOF are best suited among the available forces—or perhaps are the only force available—the focus becomes the tasked mission, even if it is not a principal US SOF mission or a collateral activity (Office of the Undersecretary of Defense, 1996).

SOF units are employable where high-profile conventional forces appear to be politically, militarily, or economically inappropriate. Small, self-reliant, readily deployable units that capitalize on speed, surprise, and deception may sometimes accomplish missions in ways that minimize risks of escalation and concurrently maximize returns compared to orthodox applications of military power, which normally emphasize mass (Collins, 1994). Aircraft, artillery, or combat engineers, for example, might demolish a critical bridge at a particular time, but SOF units could magnify the physical and psychological effects considerably. Conventional land, sea, and air forces normally patrol specified sectors intermittently, whereas SOF forces may remain in hostile territory for weeks or months at a time collecting information that otherwise would be unobtainable. Severe misfortunes, of course, may accompany failure. Large enemy conventional forces can easily overwhelm small SOF units that they manage to corner during clandestine operations, and they may be tempted to treat survivors harshly. Adverse political repercussions can be far-reaching (Collins, 1994).

NAVAL SPECIAL WARFARE: "ELITE OF THE ELITE"

Like many naval forces around the world, units involved in Naval Special Warfare (NSW) have evolved in response to constant changes in the tactical and strategic environment in which the U.S. Navy operates. NSW units can trace their heritage back to World War II when formal training of the Naval Combat Demolition Units (NCDUs) began in the spring of 1943 (Kelly, 1992). These units distinguished themselves at Utah and Omaha beaches during the D-Day landing at Normandy. In the Pacific, NCDUs were consolidated into Underwater Demolition Teams (UDTs) that saw action during MacArthur's island-hopping campaign. These units drew volunteers from the Navy's Scouts and Raiders (a small group of what were then referred to as amphibious commandos), Naval Constructions Battalions (Sea-Bees), or even civilians with experience in ordnance disposal. After World War II, these units and the SEAL teams they evolved into saw action in Korea, Vietnam, Grenada, Panama, and the Persian Gulf war (Kelly, 1992).

Today's NSW units, including the SEALs, still exhibit the hallmarks of excellence that characterized their predecessors. Perhaps two aspects of NSW distinguish it from activities conducted by other US SOF assets—NSW is truly force projected from the sea, and SEALs most commonly operate in the maritime environment at squad or platoon strength. Thus, stealth and an ability to direct maximum fire power from a small force when needed characterize NSW operations.

SETTING AND STRUCTURE OF THE SYMPOSIUM

The symposium was held at the Naval Amphibious Base, Expeditionary Warfare Training Group Pacific, Coronado, California, on February 17-20, 1997. Discussions and presentations also took place at the nearby Naval Special Warfare Center and the Naval Pacific Meteorology and Oceanography Facility located at North Island Naval Air Station.

As mentioned earlier, the symposium series was developed, in large part, to facilitate interaction between the scientist and the warfighter. Therefore, Day 1 of the symposium emphasized interaction with SEAL team members. Small groups of attendees participated in a series of activities, including interactive demonstrations designed and led by SEAL team members, to increase awareness of the challenges involved in NSW.

Day 2 introduced the attendees to the mission needs of typical NSW operations. Small groups participated in interactive mission-planning exercises and concurrent working groups to identify the types of environmental data needed and to gain an understanding of the means presently available to collect and disseminate such data.

The final day focused on lessons learned and on the identification of ways to increase the ability of the ocean science community to support NSW operations. Attendees were organized into topical working groups to provide an opportunity for colleagues to participate in a dialogue directed at problem solving.

SCOPE OF THIS REPORT

This report is intended to help make the nature and substance of the symposium available to a wider audience than the limited number of individuals who were able to attend. Based in large extent on declassified meeting notes, the report summarizes discussions that took place during plenary and working group meetings. This material was supplemented by discussions held during a post-meeting review at which the steering committee and members of various Navy units discussed the informational material provided to attendees, the declassified symposium notes, and attendee evaluation forms. This report, therefore, is more than a simple record of the symposium itself. It is intended (1) to help educate both the scientist and the warfighter about the unique challenges each faces and (2) to focus attention on specific aspects of the symposium that, in the opinion of the committee, are most germane to Naval Special Warfare.

2

Naval Special Warfare

ORGANIZATION AND PERSONNEL

The best known component of the Navy's special warfare capability are the SEAL (Sea, Air, and Land) teams. The SEALs, however, represent only a portion of the Naval Special Warfare Command (NAVSPECWARCOM), which was commissioned on April 16, 1987, at the Naval Amphibious Base in Coronado, California. This command includes two major groups, with one group each located on the U.S. Pacific and Atlantic coasts (Fig. 2-1). Naval Special Warfare Group 1 (NAVSPECWARGRU 1), located in Coronado, California, oversees three SEAL Teams and one SEAL Delivery Vehicle (SDV) Team. Special Boat Squadron 1 oversees the Special Boat Units (SBUs) and Patrol Craft (PCs). NAVSPECWARGRU 2, located in Little Creek, Virginia, performs the same function for the Atlantic fleet. NSW forces deployed "in-theater" receive support from permanent NSW units located in Rodman, Panama; Panzer Kaserne, Germany; Roosevelt Roads, Puerto Rico; Bahrain, Saudi Arabia; Rota, Spain; and Guam.

SELECTION AND TRAINING

Individuals interested in joining the SEALs or other NSW units, whether in the military or not, must meet minimum mental and physical requirements, including a minimum score on the Armed Services Vocational Aptitude Battery (ASVAB). Only men 28 years of age or younger are eligible. All candidates must complete the Basic Underwater Demolition/SEAL (BUD/S) training program at the Naval Special Warfare Center (NSWC) at Coronado, California. The rigorous training offered and the structure of the program (officers and enlisted personnel train side by side) make BUD/S training unique among military training programs.

BUD/S First Phase (Basic Conditioning)

The first Phase of BUD/S training is eight weeks in length. Continual physical conditioning, including running, swimming, and calisthenics grow progressively more demanding over the first four weeks of training. Students participate in weekly, four-mile timed runs in boots, navigate timed obstacle courses, and swim (wearing fins) distances up to two miles in the ocean. In addition, small boat seamanship skills are developed.

The first four weeks of the first phase are intended to prepare students for the fifth week, known as "Hell

FIGURE 2-1 (NAVSPECWARCOM) organizational chart depicting the relations among various units in the Naval Special Warfare Command. NOTE: CNSWC—Commander, Naval Special Warfare Command; DEVGRU—NSW Development Group, SBU—Special Boat Unit; SDV—SEAL Delivery Vehicle, PC—Patrol Craft. SOURCE: Naval Special Warfare Center, Coronado, California.

Week." During this week, students participate in five and one-half days of continuous training, with a maximum of four hours of sleep. This week is designed as a test of each trainee's physical and mental motivation. Hell Week includes strenuous physical activities that require teamwork, many of which are executed under extreme forms of psychological stress (including weapons firing blank ammunition to simulate live fire and simulated grenade explosions). Dropout rates during this phase of training commonly reach 50 percent or higher. BUD/S trainees are not eliminated, they are simply forced to continue the exercise until they request to be dropped from the program. This intense training is viewed by many in the NSW community as the key to the simultaneous development of military spirit and self-reliance. The remaining three weeks of BUD/S first phase training are devoted to developing various skills including an introduction to methods of combat and hydrographic reconnaissance.

BUD/S Second Phase (Diving)

After completion of the first phase, BUD/S trainees are considered ready for more in-depth training. The second phase lasts seven weeks. During this period, both the physical and the technical training become more rigorous. Second phase instruction concentrates on combat SCUBA (self-contained underwater breathing apparatus). Students are trained in two types of SCUBA: open circuit and closed circuit. Training is centered around a progressive dive schedule that emphasizes the basic combat swimmer skills needed to qualify as a combat diver. These skills, which separate SEALs from all other Special Operations Forces (SOF), are intended to enable successful students to tactically insert and complete their combat objective.

BUD/S Third Phase (Land Warfare)

The third phase of training emphasizes demolition, reconnaissance, weapons, and tactics and is ten weeks long. In addition to continued physical training, the third phase concentrates on teaching land navigation, small-unit tactics, rappelling, use of military land and underwater explosives, and weapons training. The final four weeks of third phase are spent on San Clemente Island, where students apply the techniques they have acquired in a practical environment.

Post-BUD/S Schools

BUD/S graduates receive three weeks of basic parachute training at the Army Airborne School, Fort Benning, Georgia, prior to reporting to their first SEAL/SDV team. Navy corpsman who complete BUD/S and basic airborne training also attend two weeks of Special Operations Technicians Training at the Naval Special Warfare Center, Coronado. In addition, they participate in an intense course of instruction in diving medicine and medical skills referred to as 18-D (Special Operations Medical Sergeant Course). This 30-week course provides training in treatment of burns, gunshot wounds, and other trauma.

After assignment to a SDV or SEAL Team and successful completion of a six-month probationary period, qualified personnel are awarded the Naval Special Warfare Insignia. New combat swimmers serve the remainder of their first tour (2-3 years) in either a SEAL Delivery Vehicle (SDV) or a SEAL team. Follow-on orders for a SEAL may be to complete additional training before reporting to another SDV or SEAL team. Advanced courses include sniper, diving supervisor, language training, and SEAL tactical communications. Shore duty opportunities are available in research and development, instructor duty, and overseas assignments.

CLANDESTINE INFILTRATION AND EXFILTRATION

Successful completion of many NSW missions requires that infiltration and exfiltration of a SEAL unit be conducted in such a manner that hostile forces are not aware of its presence until the last possible moment. In other instances, strategic or tactical implications of the mission may require that SEAL units conducting an NSW mission be able to enter and leave an area under the control of a hostile force totally undetected. The following discussions of various clandestine infiltration and exfiltration methods commonly employed by the SEALs (with the help of other NSW units) are intended to provide scientists with a reference frame that may help them understand the impact environmental factors can have on these missions.

Airborne Infiltration

Although Naval Special Warfare is best characterized as force projected from the sea, SEAL teams are often inserted using a variety of airborne platforms. Infiltration can be accomplished by parachuting from various aircraft or by fast roping from helicopters. Parachuting is a prerequisite for special operations, and BUD/S graduates attend jump school at Army Airborne School, Fort Benning, Georgia. However NSW personnel are delivered to the target area, they exhibit the same military discipline and employ many of the tactics and techniques for which the SEALs are widely regarded (White, 1992).

Static Line Parachuting

Static line parachuting was once one of the most common means of infiltration used by SOF worldwide. SEALs typically jump from a variety of fixed-wing aircraft (such as the C-130 Hercules or C-141 Starlifter) and helicopters, using a static line parachute with a reserve. The relatively slow speeds of aircraft dropping static line parachutists into enemy-held drop zones make these aircraft vulnerable to antiaircraft defenses and enemy fighter aircraft. Similarly, once the static line parachute is opened, the warfighter is a visible target and is relatively helpless until reaching the ground. Consequently, static line parachuting is commonly used at night and for drop zones at sea (White, 1992).

LALO Parachuting

To reduce the SEALs' exposure during static line parachuting, jumps can be made using a technique referred to as Low Altitude Low Opening (LALO) parachuting. LALO descents involve the parachutist leaving the aircraft at 500 feet. Consequently, the parachutist is visible for a relatively brief period, minimizing the time available for enemy ground troops to react (White, 1992).

HALO and HAHO Parachuting

In an effort to decrease the risk from ground fire and increase the clandestine nature of many infiltrations, greater use of aircraft flying at high altitudes as parachute platforms has been made (White, 1992). Parachutists jump from aircraft at altitudes up to 36,000 feet employing two techniques—High Altitude Low Opening (HALO) or High Altitude High Opening (HAHO) parachuting. In both techniques, parachutists are exposed to subzero conditions (at altitudes exceeding 13,000 feet) and must make use of supplemental oxygen systems. Because of the danger of hypoxia and other free-fall related hazards, parachutists employ an automated pressure-activated rip cord (referred to as an FF2). SEALs employing free-fall HALO techniques achieve terminal velocities of 120-170 miles per hour (mph) and can fall undetected through enemy radar defenses. By using the Ram Air steerable parachute, SEAL team members can navigate quietly and land in a relatively small area (White, 1992). HAHO parachuting poses other unique challenges and requires tremendous experience, especially when SEAL team members are dropped in groups. Navigating during the long descent at night is particularly challenging. Consequently, global positioning systems (GPS) and other navigation aids are extremely important for successful HAHO infiltrations (White, 1992).

Helicopters

Helicopter infiltrations using fast ropes are extremely effective methods of getting small groups of men into the target area. During these operations the helicopter approaches the landing zone (LZ) at low altitude to minimize radar detection. When the helicopter arrives, ropes are dropped and the entire squad or platoon can be on the ground and in an established defensive position in less than 90 seconds. This technique is extremely effective for helicopter visit board searches and seizures (referred to as HVBSS, these actions involve rapid transport of SEALs onto vessels underway at sea) or close quarters combat (CQC) missions (where SEAL squads or platoons can bring tremendous fire power to bear on a single position in a rapid and unexpected manner).

Seaborne Infiltration and Exfiltration

Although air infiltration can be performed in a number of situations where rapid deployment to remote locations is called for, seaborne infiltration is still a SEAL specialty. NSW units can be deployed in a variety of situations using a wide range of dedicated vehicles (see Table 2-1).

SEAL Delivery Vehicle MK VIII

The SEAL Delivery Vehicle (SDV) MK VIII is a "wet" submersible, designed to carry combat swimmers and their cargo in fully flooded compartments. Submerged operators and passengers are sustained by the onboard air system as well as closed-circuit breathing apparati. Operational scenarios for the SDV include reconnaissance missions, ship attacks, and over the beach operations.

The SDV is propelled by an all-electric propulsion subsystem powered by rechargeable silver-zinc batteries. Buoyancy and pitch attitude are controlled by a ballast and trim system; control in both the horizontal and the vertical planes is provided through a manual control stick to the rudder, elevator, and bow planes. A computerized Doppler navigation sonar displays speed, distance, heading, altitude, and other piloting functions. Instruments and other electronic units are housed in dry, watertight canisters. The special modular construction provides easy removal for maintenance.

Dry Deck Shelter

The Dry Deck Shelter (DDS) gives a submarine (host ship) the capability of participating in special operations involving the SDV. The DDS allows launch and recovery of the SDV while the host ship is submerged. The DDS can also be used to release SEAL combat swimmers directly, without the use of an SDV, through a maneuver known as a Mass Swimmer Lockout (MSLO). The DDS is installed on the host ship immediately before the mission and removed when the mission is completed. The host ship can carry one DDS or two DDSs mounted side by side.

The DDS consists of three pressure modules constructed as one integral unit: a hangar in which the SDV and other system equipment are stowed, a transfer trunk to allow passage between the modules and the host ship, and a hyperbaric chamber for decompression and recompression treatment of divers. The DDS provides a working environment at 1 atmosphere for the mission team during transit and has structural integrity to the diving test depth of the host submarine. The DDS can be provided with a hangar door that opens to starboard or to port.

Combat Swimming

U.S. Navy SEALs have three SCUBA systems available for the conduct of NSW operations: open-circuit compressed air, closed-circuit (100 percent oxygen) LAR V Draeger UBA, and MK 15 semi closed-circuit (mixed gas) UBA.

Open-Circuit Systems: In the open-circuit system, air is breathed from a supply tank and exhausted directly into the surrounding water. The supply tank(s) can be worn on the diver (SCUBA), or the diver can breathe from air supplied from tanks mounted aboard an SDV. Personnel may use SDV-supplied air for long offshore transits and switch to closed-circuit systems in hostile areas. Open-circuit systems are limited in duration by the capacity of the air supply, depth, and dive work rate. Long-duration deep dives may require diver decompression following the U.S. Navy Standard Air Decompression Table.

Closed-Circuit Oxygen UBA: The LAR V Draeger UBA is a self-contained closed-circuit, 100-percent-oxygen, underwater breathing apparatus, designed for clandestine operations in shallow water. The LAR V is worn on the diver's chest. With this closed-circuit system, the diver breathes 100 percent oxygen and his exhaled

TABLE 2-1 Characteristics Of Some Dedicated NSW Watercraft

Craft	Length	Beam	Weight	Draft	Speed	Range	Crew/SEALs
MK IV	68 feet	18 feet	49.5 tons	3.5 feet	30-plus knots	Not available	8/20
MK V SOC	81 feet	17 feet	57 tons	5 feet	45 knots	500 nautical miles	5/16
PBR	32 feet	11 feet, 8 inches (including guardrails)	8.75 tons	2 feet	30-plus knots	Not available	4/
PBL	25 feet	8 feet, 7 inches (max beam/height)	6,500 lbs. (fully loaded)	18 inches	30-plus knots	In excess of 150 nautical miles	4/6
RIB	24 feet	9 feet	9,300 lbs. (fully loaded)	2 feet	25-plus knots	In excess of 170 nautical miles	3/6
RIB	30 feet	11 feet	14,700 lbs. (fully loaded)	3 feet	30-plus knots	In excess of 145 nautical miles (fully loaded)	2/12
RIB	10 meters (32.8 feet)	3.8 meters (12.5 feet)	8,400 kilograms (9.25 tons) (fully loaded)	.8 meter (approximately 32 inches)	35-plus knots	In excess of 200 nautical miles (fully loaded)	2/12
MATC	36 feet	13 feet (including guardrails)	12.5 tons	2 feet	25-plus knots	In excess of 200 nautical miles	2/14
CRRC	15 feet, 5 inches	6 feet, 3 inches	265 lbs	2 feet	18-plus knots	In excess of 60 nautical miles	1/8
PC	170 feet	24.9 feet	323.5 tons	7.6 feet	35 knots (max)	In excess of 1250 nautical miles	28/9

breath is recirculated in the diving apparatus. The LAR V allows SEAL combat swimmers to approach targets in a clandestine manner by eliminating the familiar bubble trail associated with conventional SCUBA. The divers exhaled breath passes through a chemical filter that removes carbon dioxide, replenishing the oxygen that is consumed. Depth, water temperature, and oxygen consumption rate all affect the duration of the LAR V Draeger.

Closed-Circuit Mixed Gas UBA: The MK 15 UBA is a self-contained mixed gas underwater breathing apparatus. Similar in function to the LAR V Draeger, this unit utilizes oxygen mixed with a dilutent gas (normally air) to maintain a preset partial pressure of oxygen (PPO_2) level. By maintaining the preset PPO_2 level, the MK 15 increases the depth and duration capability of a SEAL swimmer compared to the 100 percent oxygen system of the LAR V. The duration of the MK 15 is limited by the carbon dioxide scrubber system it uses. SEAL swimmers executing long-duration, deep dive profiles may be required to undergo diver decompression as stipulated by the U.S. Navy MK 15 decompression tables.

Dedicated Surface Vehicles

Patrol Boat MK IV: The *Sea Spectre* 68-foot PB MK IV was designed as an improved version of the recently retired 65-foot PB MK III. It is capable of carrying a variety of U.S. or foreign weapons in a number of alternate configurations. A modular payload concept was incorporated, allowing the craft to be adapted to a variety of missions in deep rivers and harbors as well as coastal or open sea environments. These boats are also used in a variety of missions, including coastal patrol and interdiction, fire suppression of onshore and floating targets, and infiltration or exfiltration of NSW units. The MK IV was designed to support 25 and 40 mm machine gun mounts and an 81 mm mortar mount.

The *Sea Spectre* MK IV is powered by three high-power, lightweight diesel engines. The engines were designed to decrease the acoustic noise level, and the all-aluminum hull was designed with a low silhouette to reduce its radar profile cross section. The craft has a fuel, personnel, and storage capacity to remain at sea and conduct unsupported operations for up to five days. The vessel has a multi-frequency communications capability and is equipped with a surface search radar. Due to its size and displacement, the craft and its crew of 8 can operate in combined seas up to 10 feet.

MK V Special Operations Craft (MK V SOC): The primary mission of the MK V SOC operating system is to provide medium range infiltration and exfiltration (MRI) support for NSW personnel in a low to medium threat (offshore/coastal) environment.

These boats are used in a variety of missions, including coastal patrol and interdiction, fire suppression of onshore and floating targets, and infiltration or exfiltration of NSW units. The MK V SOC was designed to support 4 universal gun mounts for .50-caliber machine guns, M60 machine guns, and 40 millimeter grenade launchers.

River Patrol Boats (PBR): The PBR is designed for high-speed riverine patrol operations in contested areas of operations, and infiltration or exfiltration of SEAL team elements. More than 500 units were built when it was first introduced in the Vietnam conflict in 1966, and the current inventory of 24 craft is used exclusively by SEAL reserve units. Capable of being transported by aircraft (e.g., the C-5 Galaxy), the PBR is heavily armed and vital crew areas are protected with ceramic armor. The PBR can be configured with both single and twin .50-caliber machine gun mounts and 40 mm grenade launchers. The PBR reinforced fiberglass hull and two Jacuzzi-type waterjet propulsion pumps allow the unit to operate in shallow, debris-filled water. The craft is highly maneuverable and can turn 180 degrees and reverse course within the distance of its own length while operating at full power. Engine noise-reducing techniques have been incorporated into the design and improved over the years. The combination of relatively quiet operation and its own on-board surface search radar system make this unit an excellent all-weather picket as well as a shallow water patrol and interdiction craft.

Light Patrol Boat (PBL): The PBL is a lightly armed Boston Whaler-type craft with no armor. The PBL is constructed of fiberglass with reinforced transom and weapons mount areas. It is powered by dual outboard motors and is highly maneuverable making it useful for intercepting a lightly armed adversary. It functions effectively in harbor control, diving and surveillance operations, riverine warfare, drug interdiction, and other offensive or defensive efforts where it is unlikely to engage a heavily armed or well-organized hostile force. The PBL can be configured with .50-caliber heavy machine guns or 7.62 mm machine guns mounted on 180-degree mounts, providing effective weapon employment in any direction. The unique hull design of the PBL is excellent for the riverine environment, allowing it to operate in virtually any water depth. The PBL displaces 6,500 pounds fully loaded and is transportable via its own trailer, helicopter sling, or C-130 aircraft.

Rigid Hull Inflatable Boat (RIB): The RIB is a high-speed, high-buoyancy, extreme-weather craft with the primary mission of infiltration or exfiltration of SEAL tactical elements from enemy-occupied beaches. The RIB is constructed of glass-reinforced plastic with an inflatable tube made of a new hypalon neoprene/nylon-reinforced fabric. There are three types of RIBs currently in the inventory—a 24-foot RIB, a 30-foot RIB, and a 10-meter RIB. For other than heavy-weather coxswain training, operations are limited to 10-foot combined seas and winds of 35 knots or less.

Mini-Armored Troop Carrier (MATC): The MATC is a 36-foot all-aluminum hull craft designed for high-speed patrol, interdiction, and combat assault missions in rivers, harbors, and protected coastal areas. The MATC has a large area for transporting combat-equipped troops, for carrying cargo, or for gunnery personnel operating its seven weapons stations.

The MATC internal water jet propulsion system is similar to that of the MK IV PBR. This type of propulsion is especially appropriate for beaching NSW units. A hydraulic bow ramp is designed to aid the infiltration and exfiltration of troops and equipment. The craft has a low radar silhouette that makes it difficult to detect in all speed ranges; it is extremely quiet, particularly at idle speeds. An on-board high-resolution radar and multiple communications suite, provide all-weather surveillance and a command and control presence for interdiction and anti-smuggler operations.

Combat Rubber Raiding Craft (CRRC): The mission of the CRRC is clandestine surface infiltration and exfiltration of lightly armed SEALs. The CRRC is typically equipped with a 35-55 horsepower engine and is capable of surf passages. It can be launched by air (rubber duck or helo-cast), or by sea craft. (It may also be launched from a submarine, either submerged and on the surface.) It has a low visual electronic signature and is capable of being cached by its crew once ashore.

Patrol Coastal Class (PC): The primary mission of the PC is coastal patrol and interdiction, with a secondary mission of NSW support. The PC has two 3350 horsepower engines, and is capable of launching and recovering two CRRCs. NSW operational missions include long range SEAL insertion/extractions, tactical swimmer operations, intelligence collection, operational deception, and coastal/riverine support.

3

Navy Support of NSW: An Overview

The U.S. Navy provides environmental support for its Naval Special Warfare (NSW) units by means of an infrastructure that includes both the operational meteorological and oceanographic (METOC) community and an underlying science and technology (S&T) base. The Office of the Oceanographer of the Navy (N096) oversees the day-to-day operational aspects, and the Office of Naval Research (ONR) manages the S&T program.

Generally, the Oceanographer and his staff are responsible for understanding the effects of the natural environment on the planning and execution of naval operations and for interpreting atmospheric and oceanic phenomena for the fighting forces. The two main objectives are (1) to ensure the safety of the fleet and the shore establishment in the face of adverse ocean and weather conditions and (2) to provide warfighters a decisive tactical advantage through exploitation of METOC processes. The METOC needs of NSW are an increasingly important aspect of this mission as the focus of naval warfare continues to move toward the littoral zone.

The long-term success of the Navy's METOC community in satisfying the particular needs of NSW depends, to a large degree, on research and technology efforts coordinated by the Office of Naval Research (ONR). Most ONR-sponsored ocean research and technology development relevant to NSW is conducted within the Ocean, Atmosphere and Space Science and Technology Department (ONR 32). The mission of ONR 32 is to provide the scientific and technological base that will maintain and expand the operational superiority of the Navy and the Marine Corps in the ocean, atmosphere, and utilization of space. ONR regards this core area as helping the Navy to "win the environment." Conducting research and developing technology to help U.S. naval forces obtain a tactical operational advantage is a major focus for ONR. This effort includes all areas of ocean science and engineering, from sensing and systems to processes and prediction.

In an attempt to minimize the length of time needed to see tangible benefits (many operational Navy needs have recently been addressed by the results of basic research begun as much as 20 years ago), divisions within ONR have recently been vertically integrated to facilitate the transition of basic and applied research from the "lab bench," through exploratory and advanced development to the "marketplace," which for the Navy is the Fleet. ONR is expanding its efforts to involve science and technology team leaders in the operational exercises of the Fleet, providing an opportunity for ONR staff to gain a better understanding of the needs of their primary customers. This is also facilitated by teaming the federal funding category 6.3 (advanced development) managers with the 6.1 (basic research) and 6.2 (applied research) managers (NRC, 1996).

ONR 32 only rarely provides equipment, models, data, or methodologies directly to the operating components of NSW. Rather, its primary role in the Navy's METOC support infrastructure is to provide a technology base for the development and fielding of the next-generation of METOC capabilities for the infrastructure that supports warfighters including NSW. In a sense, ONR 32 supports N096, and N096 in turn supports NSW.

As the Navy continues to adjust from the conditions of the Cold War to a "New World Order" in which the likelihood of smaller-scale naval operations nearshore is a primary concern, operational oceanography has had to confront a new set of challenges. This, in turn, is causing a sweeping reexamination of traditional METOC approaches and a new accommodation to natural environments that change much more rapidly in time and space than deep ocean settings. The coastal regions and adjacent hinterlands are a particular focus for NSW. Consequently, recent emphasis placed on characterization of the littoral zone should be especially useful in supporting NSW needs.

In an effort to inform the academic research and military communities about the potential challenges facing the naval METOC and research communities, a series of presentations were made by key individuals from both the Office of the Oceanographer of the Navy and the Office of Naval Research (see Appendix A). Dr. Edward Whitman, Technical Director of the Office of the Oceanographer of the Navy, described the concept of operations (CONOPS) that underlies the existing informational infrastructure and a vision for the future. The following discussion is summarized from Dr. Whitman's presentation.

SUPPORTING NSW IN A CHANGING WORLD

The traditional top-level concept of operations that has evolved in the METOC community for assimilating observational data into ocean-atmosphere numerical models and generating tactical products for dissemination to the fleet is shown in Figure 3-1. Synoptic-scale guidance products are produced at two large supercomputer centers ashore: the Naval Oceanographic Office (NAVOCEANO; Stennis Space Center, Mississippi) and the Fleet Numerical Meteorology and Oceanography Center (FNMOC; Monterey, California). Both centers gather sensor data from a variety of sources and run large-scale numerical prediction models on a daily, scheduled basis. The model outputs are passed down the chain (normally as gridded fields of parameter estimates) for use as numerical guidance in more focused regional forecast centers at Norfolk, Virginia; Pearl Harbor, Hawaii; Rota, Spain; and Guam. These regional centers add local value and produce forecast products tailored directly for afloat units and staffs in their areas of responsibility. In turn, at the tactical level, on-scene METOC staffs on command and aircraft-capable ships receive and display weather imagery from both Department of Defense (DoD) and National Oceanic and Atmospheric Administration (NOAA) satellites. On-scene personnel produce local area forecasts for direct fleet support and processed data for infiltration into tactical decision aids. Both land-line and satellite communications links are used to tie this infrastructure together, and increasing use is being made of wide-band digital networks, for example, the Internet-like NIPRNET and SIPRNET.

This tiered approach to fleet METOC support, beginning with a shore-generated, synoptic view and proceeding down the chain through successive stages of increasingly local focus, has served the Navy well in the deep ocean, Cold War scenarios of the past. For NSW (and for expeditionary warfare generally), however, the Navy's capabilities will have to expand.

The Office of the Oceanographer envisions a shift in CONOPS in which the rapid assimilation of more densely spaced observations is the key to predicting warfighting conditions on the temporal and spatial scales of the smaller, more rapid operations typically conducted by NSW units. Essentially, the existing Cold War infrastructure will be refocused further forward, with rapid environmental assessment (REA) as a primary goal. REA comprises detailed and timely METOC characterization of a limited objective area, keyed to much closer and more timely support of the warfighters. Correspondingly, there is a growing dependence on the display and interpretation of direct observations, with less emphasis on numerical prediction models.

There are several key aspects under development. First is the transition to a much denser grid of local area observations and correspondingly more highly resolved data bases, both oceanographic and atmospheric. Second is a growing emphasis on local or "in-stride" capabilities for direct assimilation of both raw and processed data into tactical decision aids in near real time, with continual adaptation to changing conditions. Finally, there is a need

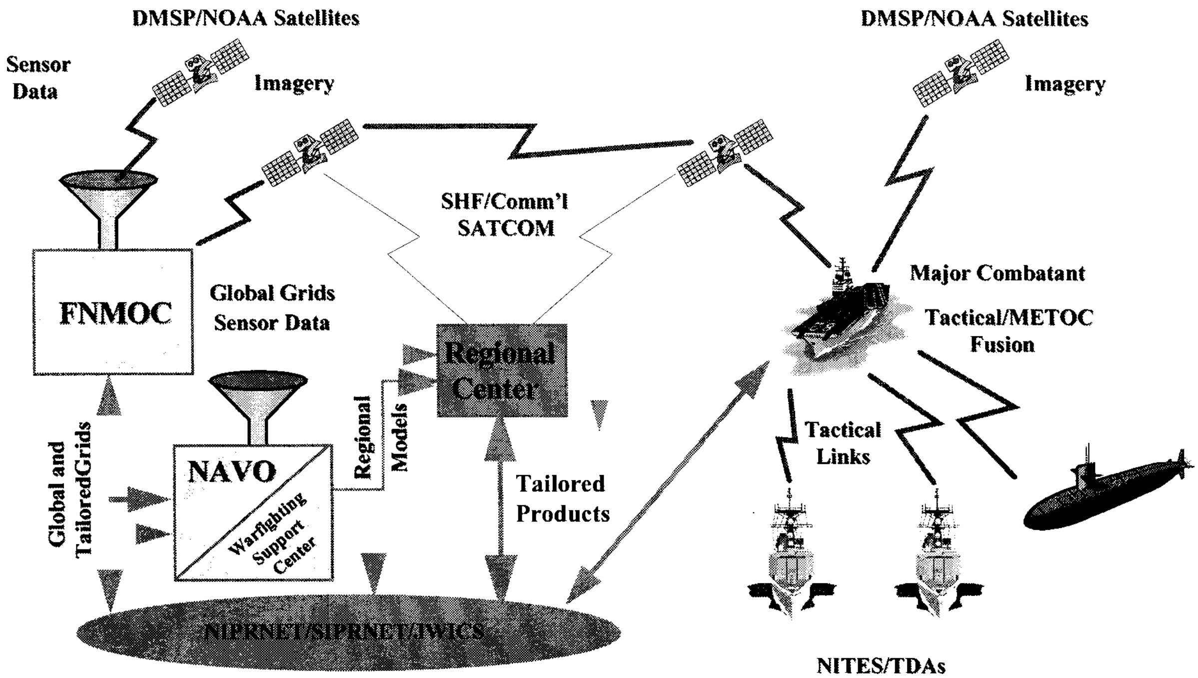


FIGURE 3-1 Schematic depiction of the concept of operations that underlies the Navy's existing infrastructure for supplying environmental data to its combat units at sea. NOTE: DMSP—Defense Meteorological Satellite Program; SHF—Super High Frequency; NAVOCEANO—Naval Oceanographic Office; NOAA—National Oceanic and Atmospheric Administration; JWICS—Joint Worldwide Intelligence Communications Systems; SATCOM—Satellite Communications; TDAs—Tactical Decision Aids. SOURCE: Office of the Oceanographer of the Navy.

for a more responsive information infrastructure that targets warfighters (not METOC specialists) directly. NAVOCEANO, in particular, with its Warfighting Support Center (WSC), is already fielding a unique capability for the integration or "fusion" and detailed analysis of all-source oceanographic, satellite, and imagery data and the quick turnaround of highly focused, multidisciplinary products, such as the Special Tactical Oceanographic Information Chart (STOIC; Plate I—in rear pocket) and annotated imagery (Plate II). NSW components have been among the WSC's key customers from the beginning.

The more forward-leaning REA focus described above and its associated proliferation of sensor systems will require new concepts of operation and a new support architecture, both at sea and ashore. As illustrated in Figure 3-2, a number of architectural implications are identifiable, including the need to "close the decision loop" for REA as far forward as possible. This will, in turn, necessitate that more powerful tactical METOC fusion capabilities be deployed with the operators, along with access to the local grid of tactical METOC sensors, guidance products from the ashore infrastructure, satellite imagery, and other space-based observations. Sufficient computer power is needed for assimilating these data into tactical-scale fusion and analysis models whose outputs are directly usable as warfighting decision aids. Eventually, many of these capabilities will become available at the NSW tactical level.

Although the scope of today's METOC support to NSW is unprecedented, the underlying paradigm has been inherited largely from the experiences of the Cold War. Recent contingencies in Somalia, Haiti, and the Adriatic have already defined new needs for which naval oceanography is only partially prepared. Significant changes are currently in progress as the Navy rises to the new challenges of small-scale wars (and operations short of war), near hostile and unknown coasts. In the words of N096, the METOC community will move the "center of gravity" forward toward the "tip of the spear," enabling better support for Naval Special Warfare.

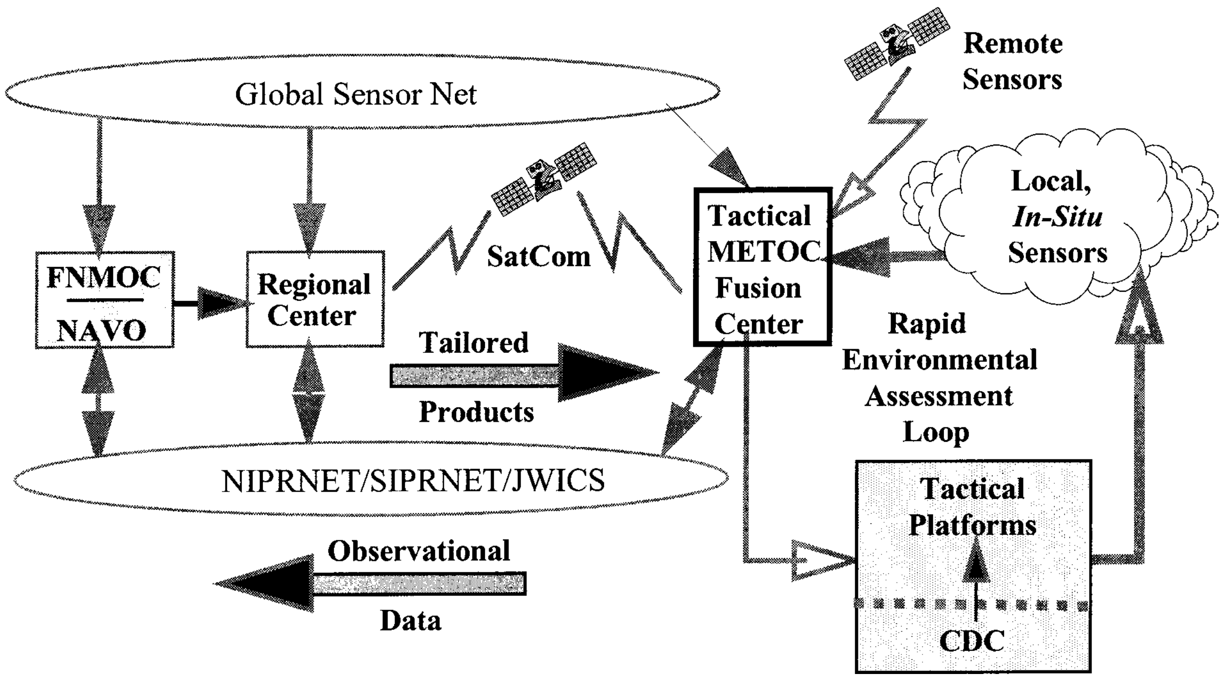


FIGURE 3-2 Schematic depiction of the concept of operations underlying N096's vision for the future. The infrastructure depicted for supplying environmental data to naval combat units at sea would emphasize forward-deployed and enhanced observational capabilities. NOTE: SATCOM—Satellite Communications; CDC—Combatant Data Collection; JWICS—Joint Worldwide Intelligence Communications Systems. SOURCE: Office of the Oceanographer of the Navy.

ONR SUPPORT OF NAVAL SPECIAL WARFARE

ONR supports the science and technology needs of Naval Special Warfare (NSW), and the Navy as a whole, through an integrated program of basic and applied research and through advanced development activities. NSW needs are expressed in formal requirements documents that typically call for relatively short time-scale completion (e.g., 2 to 3 years). NSW long-range requirements can be expressed in less formal long-term assessments and speculations on the future directions of NSW. ONR directs its basic and some applied research activities at these over-the-horizon needs. The latter activities are performed, whenever possible, in concert with the related activities of the Office of the Oceanographer. Many of ONR's basic and applied research programs involve close cooperation with academia and industry, reflecting the Navy's commitment to continue to develop strong ties to the nonmilitary private sector (NRC 1994, 1996).

As discussed previously, the main source of METOC support for NSW within ONR is the Ocean, Atmosphere, and Space Science and Technology Department (ONR 32) through a number of component programs and program officers (Appendix D). ONR also manages S&T projects for NSW in areas other than METOC, including materials, robotics, and hydrodynamics (Appendix D).[1] The Ocean Engineering and Marine Systems Program collaborates with program officers throughout ONR, and its team leader is therefore an appropriate point of contact for non-METOC NSW support.

[1]Information obtained from http://www.Onr.Navy.Mil/sci_tech/ocean/onrpgahf.htm, October 10, 1997.

ONR 32 consists of two divisions, **Sensing and Systems** and **Processes and Prediction**. The divisions manage integrated programs in the naval focus areas of battlespace environments; undersea warfare (antisubmarine and mine); expeditionary warfare (including amphibious operations); maritime intelligence, surveillance, and reconnaissance, and space exploitation; joint explosive ordnance disposal; and Naval Special Warfare.

Sensing and Systems Division

This division supports scientific inquiry and technology development through a number of programs, including Ocean Acoustics; Remote Sensing and Space; Sensing Information Dominance; Coastal Dynamics; Sensors, Sources, and Arrays; Ocean Engineering and Marine Systems; Undersea Signal Processing; and Tactical Sensing Support. The division's interests directly relate to Navy and Marine Corps operations including undersea, expeditionary, and special warfare in littoral environments. In addition, the division manages the operation and maintenance of Navy research facilities, research ships, and other platforms. Programs within the division of specific interest to NSW are Remote Sensing and Space, Coastal Dynamics, and Ocean Engineering and Marine Systems.

Remote Sensing and Space—This program investigates physical and chemical processes that govern active and passive electromagnetic spectrum scattering from the Earth's surface and propagation through the upper atmosphere and the near space environment. Of particular interest for surface effects is short water wave roughness modulation mechanisms; surfactant effects; intermittency in wave breaking; and non-linear water waves. Research is directed toward improving the knowledge base for development of mechanistic EO/EM (electrooptical/electromagnetic) clutter models and automatic target recognition, and to investigate techniques that invert sensor information for the development of algorithms for assimilation into environmental models. Additional interests include electromagnetic scattering theory, microwave properties, scattering surface characterization, and wave and flux modulation mechanisms.

Space research interests include improved specification of the global ionosphere and studies of ionospheric irregularities which impact radio frequency propagation at all frequencies up to and including those used by the GPS (Global Positioning Satellite) system. Investigations of space weather phenomena are directed toward improved understanding and forecast of solar, heliospheric, and magnetospheric disturbances which destroy or degrade Naval space assets. Investigations of upper atmospheric composition and dynamics are supported to improve specification of satellite drag and other space applications. Additional research interests include precise time and time interval, Earth orientation, and astrometry for autonomous navigation and synchronization of Naval systems.[2]

Coastal Dynamics—This program includes aspects of the fluid and sediment mechanics of the coastal ocean. At present, three areas are emphasized: (1) nearshore processes—the fluid mechanics, sediment mechanics, and morphological response in the nearshore where waves begin to break because of shoaling (Fig. 3-3); (2) shelf dynamics—the fluid mechanics of the continental shelf, particularly the inner shelf, seaward of the surf zone but where surface and bottom boundary layers encompass much of the water column; and (3) surface wave mechanics and prediction over the continental shelf. There are collaborations with other programs to address issues such as coastal meteorology, littoral remote sensing, ocean models, and mine burial and migration.

A nearshore processes experiment, Sandy Duck 97, will be held at Duck, North Carolina, during summer and fall 1997; additional information is located on the World Wide Web at http://www.frf.usace.army.mil/SandyDuck/OverviewSandyDuck.html. A surface wave mechanics experiment is planned for the shelf off North Carolina in 1998 and 1999.

Ocean Engineering and Marine Systems—The goals of this program are to improve the knowledge base of fluid-structure interactions for engineering designs and to develop and demonstrate new technologies for expedi-

[2]Information obtained from http://www.Onr.Navy.Mil/sci_tech/ocean/onrpgahf.htm, October 12, 1997.

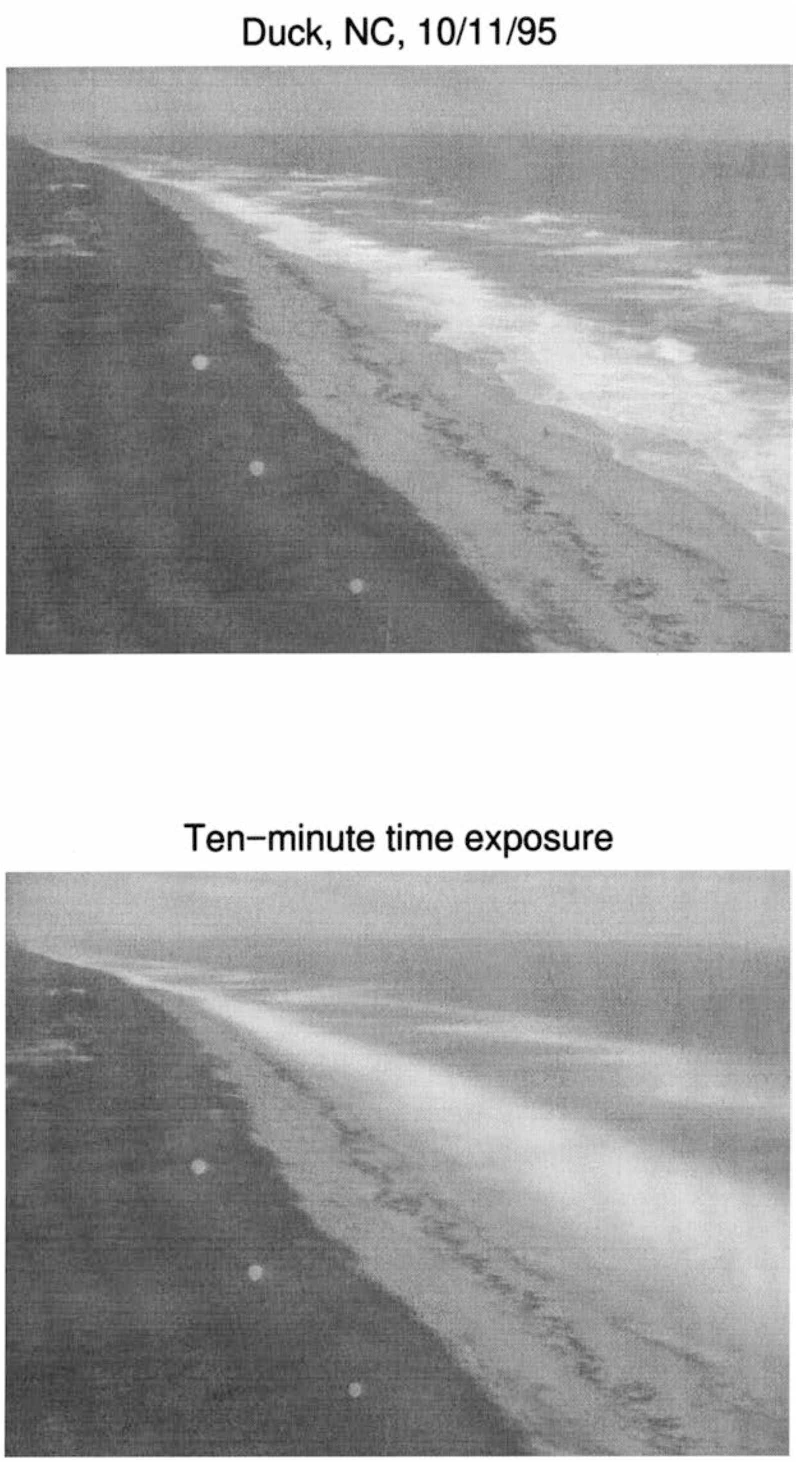


FIGURE 3-3 Black and white images taken by the ARGUS video monitoring system located near Duck, North Carolina. Position of breaking surf visible on short time exposure (a) is controlled by location of submerged bars. A ten-minute time exposure of the same section of beach (b) results in an image with useful information about the geometry and distribution of these offshore features. Photo courtesy of the Office of Naval Research.

tionary operations and special warfare. The investigators conduct multi-disciplinary science and technology efforts in the behavior of ocean systems in general as well as specifically for the Marine Corps, NSW units, and Navy Explosive Ordnance Disposal units. The basic research program focuses on fluid forcing and structural response mechanisms and the coupled nonlinear interactions of fluids with generic structural components and unmanned platform systems. Technology development efforts are primarily in the areas of detection and imaging technologies applicable to underwater and buried objects, technologies for neutralization of explosive devices, underwater life support technologies, surface and subsurface transport systems for NSW, autonomous search and surveillance system technologies, and technologies leading to a capability for rapid wide-area clearance of mines and obstacles from the surf zone.

Processes and Prediction Division

This division concentrates on improving the Navy and Marine Corps' understanding of environmental variability and change, the assimilation of data, and the limits of predictability. It plans, fosters, and encourages an extensive program of scientific inquiry and technological development through a number of programs, including Biological and Chemical Oceanography, Marine Meteorology and Atmospheric Effects, Marine Geology and Geophysics, and High-Latitude Dynamics. In addition, the division supports programs of particular relevance to NSW, including: Environmental Optics, Physical Oceanography, and Ocean Modeling and Prediction.

Environmental Optics—The goal of this program is to further our understanding of how light interacts with the ocean, including the ocean boundaries (the sea surface and the ocean floor) and the atmosphere within tens of meters of the ocean surface. Funded basic research generally falls into one or more of the following categories:

- Radiative Transfer Modeling—developing and testing state-of-the-art numerical models of radiance propagation within the ocean.
- Instrument Development—developing the devices and techniques required to measure the inherent optical properties of ocean water and the ocean floor.
- Optical Process Studies—quantifying the effects of light in the ocean regarding physical, biological, and chemical ocean processes.

The products of this research are generally to support the development or application of ocean prediction models, new ocean remote sensing systems and the associated image analysis algorithms. Applied research is funded in areas of underwater imaging and hyperspectral remote sensing in support of mine warfare and special operations (Plate III) and LIDAR in support of submarine warfare.[3]

Physical Oceanography—This program supports process oriented and hypothesis driven science and technology in the area of physical oceanography. In response to post-Cold War Naval strategy and tactics, increased emphasis is now given to the littoral. Attention still remains on open ocean processes with particular focus given to those processes that couple the open ocean with the littoral. Approximately 1/3 of the program is directed toward littoral processes, 1/3 toward open ocean processes, and 1/3 toward processes, tools, and techniques which have application to both the open ocean as well as to the littoral. Processes under study include western and eastern boundary currents, fronts, intrusions, eddies, air/sea fluxes of heat, mass, momentum, surface and internal waves, the upper surface mixed layer, the bottom boundary layer, fine structure, and microstructure.

Research continues in open ocean processes, particularly those that foster understanding of analogous processes in the littoral environment. However, special emphasis is now being made in marginal and semi-enclosed seas and in straits. High priority is given to the dynamic linkage between these processes, their relationship to atmospheric forcing and boundary conditions, and their degree of predictability. Strong emphasis is given to their

[3]Information obtained from http://www.Onr.Navy.Mil/sci_tech/ocean/onrpgahk.htm, October 12, 1997.

role in biological, geological, atmospheric, acoustic, and optical processes, particularly with respect to their impact on current and planned Navy operational systems and models. The program fosters transition of research products such as numerical and theoretical models, analysis algorithms, in situ data, and sea-going instrumentation and platforms into operational Navy systems.[4]

Ocean Modeling and Prediction—This program seeks to develop accurate representations of the ocean system as it evolves in time and space. Underlying fundamentals include ocean field estimation, scale interaction and boundary interaction which are now applied toward nowcast and forecast skill, subgrid scale parameterization, ocean-atmosphere and ocean-bottom coupling and nested domains. The system includes acoustic and electromagnetic propagation models linked to hydrodynamic models. The goal of enhanced predictability is achieved through research on better dynamical formulations, improved numerical methods, and optimal data assimilation through adaptive sampling. Basic and applied research are pursued jointly with environmental information and to motivate new understanding by operational experience.[5]

[4]Information obtained from http://www.Onr.Navy.Mil/sci_tech/ocean/onrpgabv.htm, October 12, 1997.
[5]Information obtained from http://www.Onr.Navy.Mil/sci_tech/ocean/onrpgahm.htm, October 12, 1997.

4

Oceanography and Naval Special Warfare

As discussed earlier, the nature of Naval Special Warfare (NSW) operations makes understanding the environmental factors that NSW units may face an important aspect of mission planning and execution. Consequently, the symposium was organized to provide attendees with a good introduction to the capabilities and challenges facing NSW (including the Sea, Air, and Land [SEAL] teams) and the meteorological and oceanographic (METOC) community that supports them.

The Naval Special Warfare Mission Planning Guide identifies a number of environmental parameters, including lunar illumination, water temperature, bathymetry, wave height, water clarity, humidity, current direction and speed, that must be considered throughout mission planning and execution. These factors affect many aspects of mission planning, including transportation and communications.

The symposium was organized to maximize interaction between NSW operators and the attending scientists, while focusing attention on important environmental parameters. The first two days emphasized operational requirements while the third day allowed colleagues of similar backgrounds and interests to discuss lessons learned and identify potential future research ideas related to NSW needs. Attendees were therefore organized into five working groups: Bioluminescence and Marine Toxins, Waves and Surf, Currents and Tides, Electromagnetic and Infrared “Above Surface” Signal Propagation and Winds, and Electrooptical and Acoustic “Below Surface” Signal Propagation. The following chapter includes both a discussion of how environmental factors may affect mission planning and execution and a summary of the discussions that took place during the meeting of the five working groups.

NAVAL SPECIAL WARFARE MISSION PLANNING

The method used by NSW personnel to develop a mission profile has been evolving since the mid 1980s and is referred to as a phase plan. Each member of the SEAL platoon takes part in designing a set of highly orchestrated actions. These actions are tied to a detailed and rigorous time line that describes the role of each team member as he is transported to and enters the mission area, performs one or more assigned missions, and returns. Options and backup contingency actions are explicitly planned to ensure the highest probability of success and the greatest team safety.

The planning cycle typically includes a 96-hour work-up phase to allow sufficient time for personnel and resources to be made available. However, this can be compressed in a national emergency or at the direction of the National Command Authority. Until recently, mission plans were literally hand drawn. Recent efforts have been made to develop automated mission planning software for use on a personal computer. Automation promises to allow better and faster plan modification, especially if technological advances allow environmental and intelligence data to be updated more efficiently.

Although the environment plays an important role in any military operation, missions conducted by special operations forces in general, and NSW forces in particular, are extremely environmentally sensitive. Environmental conditions are an important consideration in mission planning as demonstrated by the importance placed on them in the NSW Mission Planning Guide (prepared by the Naval Special Warfare Center). Accurate and reliable information about a range of environmental conditions can make the difference between NSW personnel obtaining a tactical advantage or having the mission's success severely and negatively impacted and personnel placed in unnecessary danger. Compromise is the best option in certain instances where ambient environmental conditions present some operational advantage as well as a hindrance. For example, a moonless night assists by decreasing the possibility of detection of the SEAL team but also increases the degree of difficulty it will encounter in finding the assigned target. Similarly, low winter air temperatures may be advantageous when they reduce the efficiency of a sentry guarding a targeted harbor facility; however, cold water temperatures can cause a SEAL swimmer to breathe faster and more rapidly consume the oxygen supply in his closed-circuit diving support system.

Mission planning and execution involves an ongoing series of choices in response to a constantly changing set of environmental and tactical conditions. Consequently, a series of meteorological and oceanographic (METOC) critical thresholds has been developed, as part of the NSW Mission Planning Guide, to help mission planners and the operators make reasonable decisions about when and how to take environmental factors into consideration. The NSW Mission Planning Process addresses the potential impact of a range of environmental parameters on various mission phases. As discussed in Chapter 3, the Naval Oceanographic Office (NAVOCEANO) provides NSW personnel with environmental information in a variety of forms. Much of the most relevant environmental information is conveyed to NSW personnel from the Warfighter Support Center through a STOIC (Special Tactical Oceanographic Information Chart) similar to the example included as Plate I.

The following sections describe the general structure of a hypothetical, yet typical, SEAL mission and discuss the impact of a variety of environmental factors on mission planning and execution. This discussion is intended to provide some context for the remaining sections of the chapter, which deal with the wide range of parameters discussed in the NSW Mission Planning Guide.

Environmental Factors and Mission Success

Although describing any SEAL mission as typical is probably an oversimplification, the typical mission can generally be divided into five components: (1) insertion, (2) infiltration, (3) action at the objective, (4) exfiltration, and (5) extraction. Due to logistical considerations, the boundaries between insertion and infiltration, or exfiltration and extraction, can be indistinct but significant. NAVSPECWARCOM does not typically possess platforms capable of transporting SEAL units long distances in a maritime environment. Therefore, insertion is defined as that phase when a variety of platforms (typically non-NSW submarines, surface craft, or aircraft) are used to transport NSW personnel and equipment to a location from which smaller, shorter-range NSW platforms can be used to begin infiltration (extraction is similarly defined as the boarding and tactical transport of NSW personnel and equipment away from a location reached during exfiltration). Due to the need to coordinate the use of non-NSW platforms during insertion and extraction, the infiltration and exfiltration phases of a mission must be planned to provide maximum flexibility.

The following sections describe the impact that environmental factors can have on each phase of a hypothetical SEAL mission to destroy a number of ships docked in a foreign and hostile harbor. As discussed in Chapter 2, NSW personnel carry out an extremely varied range of missions. The example described here thus represents a fairly specific mission profile and is included simply to demonstrate the reliance NSW planners and operators place on environmental information. Other SEAL missions would, by necessity, require more or less emphasis on certain environmental factors discussed in the NSW Mission Planning Guide. The use of SEALs in this situation would indicate that stealth and minimal collateral damage were important considerations in the decision to undertake this mission.

Insertion and Infiltration

The mission profile calls for use of a SEAL squad transported to waters well offshore from the harbor by a Navy submarine equipped with a Dry Deck Shelter (DDS) and the SDV. Based on a range of mission considerations, infiltration by a SEAL Delivery Vehicle (SDV) was chosen (Table 4-1). In planning the mission, SEAL swimmers and the SDV team considered the potential impact of various environmental factors during the last stage of insertion—lockout (during which the SEALs make the transition from the DDS to the flooded SDV) and the infiltration phase. For this mission, infiltration includes (1) the transportation of the SEALs to the enemy harbor aboard the SDV, and (2) the SDV's approach to, and preparation to enter, the enemy harbor. During infiltration, the SDV may have to avoid unexpected underwater obstacles and wait while unanticipated harbor traffic subsides. Preserving the clandestine nature of the mission is a high priority, especially once the SDV enters the harbor.

Actions at the Objective

Once inside the harbor, the SDV will make its way to the pier where the target vessels are docked (Table 4-2). Navigating within a foreign harbor is complex because the SDV must avoid both unknown obstacles and detection by craft entering, exiting, or patrolling the harbor. Successful navigation can be made more complicated since the SDV is flooded and turbidity can adversely affect the SDV operator's ability to read displays on the console. Once the SDV has reached the appropriate position, SEAL swimmers must exit it successfully, find the correct ships, and attach explosive charges at specific locations to ensure that the targets are crippled or destroyed. Successful completion of this delicate phase of the mission will require that SEALs work quickly and accurately while avoiding detection from both enemy personnel and civilians working on piers or on board various vessels in the harbor.

Exfiltration and Extraction

Many of the factors that can impact execution of the insertion (lockout), infiltration, and action at the objective phases of the mission are relevant during the exfiltration and extraction (lock in) phases (Table 4-3). However, due to the length of time elapsed and the complex nature of SEAL activities during the first two phases of the mission, the potential impact of these factors can be magnified by the effects of fatigue. Although detection during this phase may not allow the enemy time to prevent destruction of the target, it can place the SDV and the SEALs at risk and may even jeopardize the safety of the submarine (and its crew) that waits to complete their extraction.

The hypothetical SEAL mission discussed above is intended to provide some idea of how a variety of environmental factors may impact mission planning or execution. Because NSW missions can be highly varied and complex, this one hypothetical example cannot fully demonstrate the potential impact of all the environmental factors discussed in the NSW Mission Planning Guide on the breadth of potential NSW missions. Consequently, summaries of working group discussions that took place during the symposium (i.e., Bioluminescence and Toxins Working Group, Waves and Surf Working Group, Currents and Tides Working Group, EM/IR "Above Surface" Signal Propagation and Coastal Winds Working Group, EO/Acoustic "Below Surface" Signal Propagation Working Group) have been edited and augmented by the steering committee (working with naval personnel, symposium working group leaders, and other symposium participants) to provide a detailed discussion of a significant number of the environmental factors that may play a role in NSW mission planning and execution.

Each of the following sections attempts to discuss the way these individual factors or processes can play a role in NSW operations, to review the present approaches and capabilities used to address these factors, and to identify some of the salient points raised by attendees during the symposium. As with any gathering in which emphasis is placed on attendee participation, this symposium was designed to allow the participants to take the discussion into areas of mutual interest. Therefore, not all of the topics identified in the NSW Mission Planning Guide received equal treatment. The following sections are intended solely to summarize discussions that took place during the symposium. The steering committee did not attend all working group sessions and was not constituted to review their technical content. The inclusions of proposed solutions or future research agendas suggested by meeting participants should not be interpreted as an endorsement by the steering committee or the National Research Council.

TABLE 4-1 SDV-Ship Attack Mission Phases (Infiltration)

Insertion/ Infiltration	Environmental Effects	Impact On Mission	Possible Operator Compensation
Lockout	Bioluminescence	Increases risk of detection	Conduct lockout farther from shore (can increase fatigue risk)
	Water temperature	Low temperatures increase risk of hypothermia	Use dry suit versus wet suit (reduces manual dexterity)
	Currents	Development of vertical shear creates SDV maneuver difficulties, leading to operator fatigue, danger of injury	Plan for longer subsurface interval, or conduct lockout closer to target to reduce travel time, or move to island lee to avoid current
	Sea swell	Creates SDV and submarine maneuver difficulties	Plan for longer subsurface interval, conduct lockout closer to target to reduce travel time or move to island lee into swell shadow zone
Transit	Bioluminescence	Increases risk of detection	Change depth or speed of SDV
	Water temperature	Low temperatures increase risk of hypothermia	Use drysuit versus wet suit (reduces manual dexterity)
	Turbidity	Creates navigational difficulties when high, increased risk of detection when low	Change water depth or otherwise avoid areas of high turbidity
	Currents	Can increase travel time, contributing to operator fatigue	Change depth or speed, or infiltration route to avoid current
	Sea swell	Creates SDV maneuver difficulties	Change depth and speed, plan for longer subsurface interval
Harbor Entrance	Bioluminescence	Increases risk of detection	Change depth or speed of SDV
	Tidal currents	Can increase travel time, contributing to operator fatigue	Plan for longer subsurface interval
	Bottom composition	Contact with muddy or silty bottom can lead to high turbidity creating navigational difficulties or increased risk of detection, contact with hard bottom can damage SDV	Avoid contact with bottom
	Turbidity	Creates navigational difficulties when high, increased risk of detection when low	SDV pilot and navigator plan for low-visibility conditions, use predetermined signals and procedures
	Water temperature	Low temperatures increase risk of hypothermia	Switch to dry suit (reduces manual dexterity)
	Lunar phases	High illumination increases risk of detection	Plan infiltration route time to avoid back lighting by moon in event SDV must surface

TABLE 4-2 - SDV-Ship Attack Mission Phases (On-Site)

Actions at the Objective	Environmental Effects	Impact On Mission	Possible Operator Compensation
Target: Ship At Pier	Bioluminescence	Increases risk of detection	Change depth or speed of SDV
	Bottom composition	Contact with muddy or silty bottom can lead to high turbidity, creating navigational difficulties or increased risk of detection; contact with hard bottom can damage SDV	Avoid contact with bottom
	Biological fouling of pier or ship	Biofouling on pier or ship can pose threat to swimmers or SDV; biofouling on ships can create problems with placement of ordnance (e.g., magnetic mines)	Plan alternative methods of attaching ordnance
	Tidal currents	Create SDV maneuver difficulties, especially in close proximity with pier or ship	Plan arrival at target to avoid tidal currents
	Turbidity	Creates navigational difficulties for SDV pilot when high, increased risk of detection when low	SDV pilot and navigator use predetermined signals and procedures for low visibility
	Toxins	Create hazard for SDV pilot or navigator	Brief operators on possible effects, alter route if possible to avoid sewage or river runoff

TABLE 4-3 SDV-Ship Attack Mission Phases (Exfiltration)

Exfiltration/ Extraction	Environmental Effects	Impact On Mission	Possible Operator Compensation
Harbor Exit	Bioluminescence	Increases risk of detection	Change depth or speed of SDV
	Tidal currents	Complex current regime can create SDV maneuver difficulties and increase travel time (contributing to operator fatigue)	Plan for longer subsurface interval, or change time line of operation to avoid head-on tidal induced currents
	Bottom composition	Contact with muddy or silty bottom can lead to high turbidity, creating navigational difficulties or increased risk of detection; contact with hard bottom can damage SDV	Avoid contact with bottom
	Turbidity	Creates navigational difficulties when high, increased risk of detection when low	SDV pilot and navigator use predetermined signals and procedures
	Water temperature	Low temperatures increase risk of hypothermia	Switch to dry suit (reduces manual dexterity)
Transit	Bioluminescence	Increases risk of detection	Change depth or speed of SDV
	Water temperature	Low temperatures increase risk of hypothermia	Switch to dry suit (reduces manual dexterity)
	Turbidity	Creates navigational difficulties when high, increased risk of detection when low	Change water depth or otherwise avoid areas of high turbidity, change depth or speed
	Currents	Can increase travel time, contributing to operator fatigue	Change depth and speed, plan for longer subsurface interval
	Sea swell	Creates SDV maneuver difficulties	Change depth and speed, plan for longer subsurface interval
Lock-In	Bioluminescence	Increases risk of detection	Conduct lock-in farther from shore (can increase fatigue risk)
	Water temperature	Low temperatures increase risk of hypothermia	Switch to dry suit (reduces manual dexterity)
	Currents	Consequent development of vertical shear creates SDV maneuver difficulties, leading to operator fatigue	Plan for longer subsurface interval, conduct lock-in closer to target to reduce travel time, change pickup time or location (e.g., move to island lee)
	Sea swell	Creates SDV and submarine maneuver difficulties	Plan for longer subsurface interval, conduct lockout closer to target to reduce travel time, change pickup time or location (e.g., move to island lee)

BIOLUMINESCENCE

Bioluminescence is an environmental factor that can significantly impact the vulnerability and efficiency of Navy personnel involved in NSW. The critical threshold of bioluminescence is defined militarily as any condition that allows visible detection of an SDV or swimmer submerged to 10 feet under ambient light conditions.

Mission Influence

NSW personnel rely on stealth in all aspects of the associated logistics and communications to accomplish their mission objectives. Clandestine insertion of personnel and manned or unmanned vehicles through defended, denied, littoral waters requires that no inherent visible indicator betray the presence of NSW forces at night. Littoral waters are most often nutrient rich due to upwelling and terrestrial discharges (such as storm water runoff) and have been shown to support high concentrations of dinoflagellates (as well as other bioluminescent organisms) on a seasonal basis. Consequently, coastal waters can accumulate large populations of bioluminescent organisms above the thermocline, making transit of personnel and vehicles through this zone susceptible to detection by the unaided eye and light-intensified devices. There is an operational need for monitoring and predicting conditions in which coastal bioluminescence may hamper night operations.

Operationally, the occurrence of bioluminescence is readily apparent. The challenge is to recognize the potential at the planning stage or immediately preceding the mission or exercise. Currently, the primary sources of data on bioluminescence are Naval Oceanographic Office (NAVOCEANO) products, such as Special Tactical Oceanographic Information Charts (STOICs; see Plate I), Mine Warfare Pilots, and Submarine Insertion Loitering Area Charts (SULACs). (Many of these products should be examined critically before basing operational decisions on them as the abundance and distribution of most marine organisms responsible for bioluminescence vary seasonally.) In addition, there are several university studies that are site specific and limited in scope. Given the extreme variability of bioluminescence in the coastal zone, as well as the very limited number of researchers who are collecting field data in this environment, the attendees recognized that additional field data would be needed to identify sources of variability in levels of bioluminescence.

Research Issues

Long Term Goals—Signature Reduction

To adequately address the problem of detection or vulnerability of divers and undersea vehicles, two types of activities were initiated in 1991 at Naval Research and Development (NRaD), San Diego, following a request for supporting research in this area from the Naval Special Warfare Center (NSWC). The first attempted to measure the long-term variability of bioluminescence in settings with similar conditions to sites where NSW missions can be expected to take place. The second attempted to conduct a series of exercises with combat swimmers, MK VIII SDV, and a sea-truthing survey craft to collect oceanographic data on bioluminescence intensity, seawater temperature and clarity, and on species abundance. The objective of these activities was to develop threshold levels for visual detection of combat swimmers and SDVs during nighttime operations, because of bioluminescence. The threshold level would be used to determine the probability of visual or light-amplified detection of swimmers and their vehicles by the production of luminous wakes at night. Exercises conducted at Naval Research and Development (NRaD) and Camp Pendleton, California from 1991 to 1997 have shown that visual detection ratio (VDR) (VDR represents the optical relationship between measured bioluminescent intensity and sea water clarity threshold) determination is useful for determining the probability of visual or light-amplified detection of swimmers and their vehicles in coastal waters during any season.

Several possibilities exist for reducing military signatures associated with bioluminescence. Near-term opportunities may exist to minimize the bioluminescence signature of slow-moving platforms as much as 50 percent by shielding “hot spots” such as propellers. This might not be as successful for high-speed craft. Bioluminescent wakes extending one full hull length and more behind a vessel have been reported. Covering emissions by shielding flashes and cloaking points of high turbulence could be made available as field expedients or modification kits. Signature measurements are needed for the boats and vehicles used by NSW units.

Environmental conditions will also affect the signal-to-noise ratio and hence the threat of detection from bioluminescence through the addition of ambient light. For example, moon glitter will reduce the signal to noise ratio by adding ocean surface glitter. Therefore, mission planners should consider the beneficial aspects of moonlight from a signature reduction viewpoint. Another environmental condition that can affect the signal-to-noise ratio is sea state. Rough weather has two effects: surface breaking waves (whitecaps) increase surface glitter. High sea state also promotes mixing of organisms down into the water column and may dilute surface concentrations of organisms and hence the magnitude of the signature. Water turbidity and absorption can attenuate the observable signal caused by submerged divers or vehicles, therefore mission planners concerned about bioluminescence should consider moonlight, atmospheric conditions, prior and current sea state, and water optical properties.

The fundamental oceanography training provided in Basic Underwater Demolition/SEAL (BUD/S) training was discussed at the symposium. Some attendees suggested that bioluminescence could be evaded through changes in depth, course, and/or speed. These techniques should be implemented if a reconnaissance swimmer observes bioluminescence or other reliable reports are available. Current NRaD experiments indicate that surveys of inshore areas can provide an excellent opportunity to identify patterns of bioluminescence with both horizontal location and depth. Natural occurrences such as the turbulence produced by waves breaking over a reef or obstacle could also be exploited. Effective training would address obtaining data from activities of the Naval Meteorology and Oceanography Command (NAVMETOCCOM), as located in San Diego, Norfolk, and other fleet centers or naval air stations. These facilities provide ready access to NAVOCEANO data bases and products. NRaD is currently supplying swimmer detection ratios to NAVMETOCCOM and NAVOCEANO during planned exercises.

Current Understanding and Technology

Bioluminescence intensity varies widely among the more than 500 marine genera that produce light. Wavelengths cover the spectrum of visible light and in several rare cases even extend into the ultraviolet (UV) and the infrared (IR). However, in the marine environment, bioluminescence is confined primarily to blue and blue-green emissions. Low light-level TV cameras or image intensifiers can be carried by ships or aircraft to detect bioluminescence, and potentially, the outline of the physical disturbance at a threshold that is slightly better than the fully dark-adapted human eye. These and other sensing techniques may offer a means to measure bioluminescence rapidly and to identify otherwise dark and undetectable objects.

Bathyphotometers measure light beneath the ocean surface. In general, such instruments are designed to draw water that contains organisms through a light-tight chamber where a light detector measures the bioluminescence stimulated by some turbulence-generating mechanism, such as an impeller, constriction, or grid. Since some bioluminescent organisms produce only a single flash whereas others produce multiple flashes and flash durations vary from less than 100 milliseconds to many seconds, the values measured by different bathyphotometer designs are generally instrument specific. In other words, the photon flux that is reported depends on such factors as the detection chamber volume, the flow rate through the chamber, the method of stimulation, and the amount of pre-stimulation that occurs due to light baffling. Some of this variability is evident in the different units used to report measurements of stimulated bioluminescence (see Table 4-4).

Primary among these units have been photons per unit volume and photons per second per unit volume. Units of photons per unit volume are used when the residence time of the bioluminescent organism in the detection chamber is long enough for a whole flash to occur. Under such circumstances the average photon flux measured by the light detector is a function of the concentration of bioluminescent organisms, the total photons per flash, and the volumetric flow through the detection chamber. In these cases the average photon flux (photons/per second) is divided by the volumetric flow (volume/per second) and the results are reported in photons per liter. Alternatively, when the residence time in the detection chamber is short compared to the duration of the flash, then the

TABLE 4-4 Bathyphotometer Measurements of Bioluminescence per Liter in Different Oceans

Location	Depth[a] (m)	Bioluminescence[b,c]
Sargasso Sea	0-100	1×10^{10}
Greenland Sea	0-150	1.1×10^{10}
Pacific Ocean (Alaska to Hawaii)	Surface	$1\text{-}5 \times 10^{10}$[c]
North Atlantic Ocean (MLML)	12-80	$0.7\text{-}2.8 \times 10^{10}$
Caribbean Sea	0-120	4.5×10^{10}
Beaufort Sea (NRaD)	0-60	$5 \times 10^{8}\text{-}1.2 \times 10^{11}$[c]
Vestfjord, Norway (NRaD)	0-100	$0.9\text{-}2.7 \times 10^{11}$[c]
Arabian Sea (NRaD)	0-70	$2\text{-}9 \times 10^{11}$[c]

NOTE: MLML = Mixed Light Marine Layer Project (ONR)

[a]Depth of bathyphotometer profiles over which bioluminescence in next column was averaged.

[b]Units of Photons l^{-1}. Measurements were made with HIDEX-BPs

[c]Units of Photons $s^{-1}\ l^{-1}$ for short residence time bathyphotometers

average photon flux measured by the light detector is a function of detection chamber volume rather than volumetric flow. Under these circumstances the photon flux measured by the detector is divided by the chamber volume, rather than the volumetric flow, and the results are reported as photons per second per unit volume.

NAVOCEANO is currently using a recently developed bathyphotometer design that measures the full output of the first stimulated flash from an organism and measurements are reported as photons per unit volume. In this bathyphotometer, bioluminescence is stimulated by hydrodynamically calibrated flow through a turbulence generating grid at the entrance to a large cylindrical detection chamber. An array of optical fibers embedded in the walls of the detection chamber collects light and directs it to the light sensor. A variable-speed pump draws water through the detection chamber at pumping rates from 20 ls^{-1} to 44 ls^{-1} (Widder et al., 1993; Case et al., 1993). This bathyphotometer is known as the HIDEX-BP (High Intake Defined Excitation Bathyphotometer) and was designed to standardize bioluminescence measurements. HIDEX-BP design principles have also been incorporated into a towed system (TOWDEX) and a moored system (MOORDEX). The basic HIDEX-BP design is such that direct comparisons can be made of measurements from these various systems. Although frequently designed to be lowered or towed, bathyphotometers can also be fixed to a submersible. Some exploratory developments include floating bathyphotometers and expendable sensors. Bioluminescence measurements obtained by automated, unmanned vehicles, both airborne and underwater, were also discussed. It was pointed out that the number of researchers engaged in making bioluminescence measurements varies with available funding, but this is not presently a large field. In the past, research emphasis has been placed on open ocean rather than coastal environments. The examples of bioluminescence measurements made from different oceans (see Table 4-4) clearly indicate a trend of low bioluminescence in open ocean, nutrient-poor waters to higher bioluminescence in more productive, coastal environments. It is possible that predictive models could identify regions of lower bioluminescence potential and yield graphics useful in guiding nearshore operations.

Solutions

Plankton such as dinoflagellates, radiolaria, ostracods, and copepods living near the surface are the dominant organisms that reveal boat wakes, outline boats or swimmers, and highlight SDVs. Some organisms such as the ostracods and copepods may secrete clouds of luminescence, whereas others such as dinoflagellates and radiolaria produce an intrinsic luminescence (i.e., light-emitting chemicals are retained within the organism). In general, luminescent plankton are not spontaneous emitters but require a mechanical stimulus to initiate light emission. Even though bathyphotometers routinely use turbulent flow to excite bioluminescence, the stimulation threshold actually occurs in laminar flow. The minimum threshold stimulus required to excite bioluminescence in dinoflagellates occurs at a shear stress of 1 dyne/cm^2, which is sufficient to deform the cell membrane, and within 0.02 seconds produces a flash of light that lasts for 0.1 to 0.5 seconds. Turbulent flow increases bioluminescence by stimulating more organisms due to a thicker boundary layer, increased mixing, and greater rates of entrainment. The vast majority of bioluminescent organisms are capable of multiple flashes in response to repeated stimuli. In coastal environments, bioluminescence intensity may vary over several orders of magnitude seasonally, as well as on time scales of only hours (e.g., during the exponential growth phase of a dinoflagellate bloom, or through tidal current concentration) and on spatial scales of meters (e.g., across a frontal system produced by nutrient runoff). There is also vertical patchiness in bioluminescence due to nonhomogeneous depth distributions of the organisms. This patchiness renders modeling bioluminescence, at least in the near-term, impractical in coastal zones.

To determine the relationships between environmental conditions and bioluminescence, a program for time series measurements at several representative coastal locations could be expanded. The field program would quantify the correlation of bioluminescence with environmental parameters such as wind, waves, nutrients, temperature structure (i.e., thermocline), rainfall and runoff, and amount of solar illumination.

Because luminescent organisms are present during the daytime, it may be possible to estimate nighttime bioluminescence from daytime measurements taken hours (as opposed to days) before the mission begins. Research should explore the development of diagnostic tools that allow operational teams to test seawater samples for potential bioluminescence. If feasible, such tools, when used in conjunction with existing technology, would give mission operators the means to verify predictions or reports of bioluminescence conditions on a variety of time scales.

Suggestions and Summary

Several working group members suggested the use of training items on coastal and littoral processes for both NSW and METOC personnel. The bioluminescence and toxins group recognized the need for greater two-way information flow, specifically the greater need for "brief-back" of bioluminescence observations in NSW exercises and operations. Presumably NSW after-action reports are analyzed and archived at an appropriate facility. A standardized environmental report form could separate those METOC conditions to be directed to littoral warfare data bases useful to NSW and other military units. More specifically, discussions centered on conducting field exercises that address detection of combat swimmers and their vehicles, using swimmers to determine detection at various depths.

Overall, eight specific suggestions were offered by symposium participants to limit the adverse impacts of bioluminescence on NSW operations:

- Characterize optical signatures at night for SEAL vehicles such as Combat Rubber Raiding Craft (CRRC), zodiacs, and ribbed vehicles. Although these vehicles produce a surface signature, in contrast to swimmers and SDVs, a series of similar exercises could be conducted emphasizing on-board instrumentation for a "real-time" threat assessment to visual detection. Shrouding the propeller may also reduce the most obvious source of stimulated bioluminescence and dampen an optical signature.
- Provide a reasonably simple model for operational planning, and develop a suite of sensors capable of measuring bioluminescence and transmittance to further the development and use of VDRs. Sensors could be mounted in patrol craft, SDVs, and moorings (short term, long term). For example, miniaturized bioluminescence systems developed at NRaD could be mounted in autonomous unmanned vehicles (AUVs) and SDVs that will access in real time the vulnerability of vehicles and personnel to detection within coastal and near-coastal areas. This kind of instrumentation could be used in newer and larger SDVs now in the planning stages. Miniaturized sensors could be deployed in forward areas days, weeks, and months before a planned operation, giving SEALs real-time data on what to expect in vulnerability from bioluminescence. Subsurface moored detectors can transmit nightly bioluminescence intensities and project VDRs if desired.

- Conduct time series studies in the littoral zone that examine the relationship between bioluminescence and environmental parameters.
- Institute a bioluminescence brief-back mechanism for NSW operations.
- Standardize a report form for bioluminescence information.
- Develop a Web site with input from leading researchers in bioluminescence that can serve as a reliable source of information on the subject.
- Create a NSW training item on bioluminescence.
- Develop a seawater test kit that will allow nighttime bioluminescence predictions from daytime measurements.

HAZARDOUS MARINE ORGANISMS

NAVOCEANO and other Navy environmental information products typically contain relevant information on three categories of hazardous marine life: (1) venomous—organisms capable of injecting venom, (2) wound-inflicting—organisms capable of inflicting non-venomous wounds (includes marine predators), and (3) poisonous—organisms possessing toxic compounds capable of producing various degrees of systematic poisoning when ingested as food (Fig. 4-1). In addition to these three general categories of hazardous marine life, symposium attendees identified a fourth category of hazardous marine organisms: microorganisms capable of transmitting infectious diseases. The following section includes a summary of discussions that took place during the symposium as well as some additional material intended to provide more background on this topic.

Large marine predators will pursue other animals in the water if they are threatened or are seeking prey. These animals are generally not aggressive toward humans, although they can, in some situations, harass and harm swimmers. Many marine organisms produce toxins that are used to protect them against predators. Venomous and stinging animals generally do not actively pursue prey but can inflict venomous stings when disturbed. As discussed, some marine organisms are toxic only when consumed. The toxins produced vary but include some of the most lethal neurotoxins known.

Perhaps the most widespread of this group of toxin-producing organisms are the dinoflagellates and diatoms associated with harmful algal blooms. These organisms produce potent toxins that generally have neurological or gastrointestinal effects that in some cases are severe enough to be life threatening (Table 4-5). These toxic organisms are consumed by other marine animals that then accumulate the toxins (Shumway, 1990). Human health is impacted when these marine animals are consumed, as the high concentration of toxins they contain can lead to illness and even death.

NSW personnel are routinely inoculated against a wide variety of potential diseases; however, it is not possible to inoculate against all potential diseases. Exposure to infectious disease can occur by consuming shell fish from, or swimming in, waters that have been polluted by human waste. This is most likely to occur when swimming near areas where untreated sewage flows directly into coastal waters. In addition, some recent evidence suggests that outbreaks of certain infectious diseases, such as cholera, may be associated with algal blooms. It was not clear, based on the limited discussions at the symposium, in what specific ways additional research on infectious diseases could be made to benefit NSW operations.

Mission Influence

The Navy attempts to provide information on a variety of biological threats (Fig. 4-1). Missions can be adversely impacted by the death or illness of mission personnel. In the case of harmful marine algal blooms the impact can occur in two ways. If seafood is consumed that has accumulated toxic algae, illness can occur. This is most likely to take place during long missions when nutrition is gleaned from local sources. There is a lower probability of contracting an illness from harmful algal blooms by consuming some quantity of seawater during routine marine activities. In addition, brevetoxins can become aerosolized because *Gymnodinium breve*, unlike other harmful algal bloom species, is an unarmored form and may lyse (experience cell disruption) under wave

DANGEROUS MARINE LIFE

NAME	SIZE	HABITAT	DANGER
JELLYFISH			
SEA WASP	BELL 38 CM (15 IN) IN DIAMETER.	FREE-FLOATING.	STINGING CELLS ON TENTACLES.
SEA NETTLE	BELL 0.3 M (1 FT) IN DIAMETER.	FREE-FLOATING.	STINGING CELLS ON TENTACLES.
BLUE	BELL 36 CM (14 IN) IN DIAMETER.	FREE-FLOATING.	STINGING CELLS ON TENTACLES.
PORTUGUESE MAN-OF-WAR	FLOAT 0.3 M (1 FT) IN DIAMETER; TENTACLES EXTENDING TO 15 M (50 FT) BELOW FLOAT.	FREE-FLOATING.	STINGING CELLS ON TENTACLES.
SKATES AND RAYS:			
SOUTHERN YELLOW, ATLANTIC, ROUGHTAIL, BLUNTNOSE, SPINY, BUTTERFLY, BULLNOSE, COWNOSE, SPOTTED EAGLE, STINGRAYS	TO 2.4 M (8 FT) LONG; MORE COMMONLY LESS THAN 1.5 M (5 FT).	FREE-SWIMMING; COMMON IN NEARSHORE SAND AND MUD BOTTOMS; WILL BURY IN SOFT SEDIMENTS.	BARBED SPINE ON TAIL WITH POSSIBLE VENOM DISCHARGE.
EYED ELECTRIC, ATLANTIC TORPEDO, MARBLED ELECTRIC, LESSER ELECTRIC	TO 2 M (6.5 FT) LONG.	FREE-SWIMMING; LESSER ELECTRIC COMMON IN OFFSHORE WATER, REST	ELECTRIC ORGANS.
SHARKS:			
BIGEYE THRESHER, BLACKTIP, BLUE, DUSKY, GREAT WHITE, SCALLOPED HAMMERHEAD, SILKY, SPINNER, TIGER	TO 8 M (26 FT) LONG; MORE COMMONLY LESS THAN 3.6 M (12 FT).	COASTAL AND OFFSHORE; PELAGIC; GREAT WHITE AND SILKY FOUND OFFSHORE IN SUMMER AND NEARSHORE IN WINTER; GREAT WHITE MAY TRAVEL IN PAIRS; DUSKY MAY ENTER RIVERS AND ESTUARIES.	SHARP TEETH; CAPABLE OF SEVERE BITE.
LONGFIN, MAKO, OCEANIC WHITETIP, SHORTFIN MAKO, SMOOTH HAMMERHEAD	TO 5 M (16 FT) LONG; MORE COMMONLY LESS THAN 3 M (10 FT).	PELAGIC; ALSO IN OFFSHORE WATERS; SHORTFIN MAKO COMMON IN SUMMER.	SHARP TEETH; CAPABLE OF SEVERE BITE.
BULL, BONNETHEAD, FINETOOTH, GREAT HAMMERHEAD, SAND TIGER	TO 5.5 M (18 FT) LONG; MORE COMMONLY LESS THAN 3 M (10 FT).	PELAGIC; FOUND IN NEARSHORE WATERS; MAY ENTER ESTUARIES AND BAYS ON OCCASION; MAY FORM LARGE SCHOOLS.	SHARP TEETH; CAPABLE OF SEVERE BITE.
BARBFISH	TO 0.3 M (1 FT) LONG.	FOUND IN NEARSHORE WATERS TO CONTINENTAL SLOPE.	VENOMOUS FIN SPINES; SHARP TEETH.
SCORPIONFISH	TO 0.9 M (3 FT) LONG.	FOUND IN NEARSHORE WATERS; BOTTOM-DWELLING.	VENOMOUS FIN SPINES; SHARP TEETH.
BARRACUDA	TO 3 M (10 FT) LONG.	NOT COMMON, FOUND NEAR CORAL PATCHES DURING SUMMER.	SHARP TEETH.

FIGURE 4-1 Table describing hazardous marine organisms possibly occurring in waters off New River Inlet, North Carolina, taken from Plate I. STOIC courtesy of the Warfighting Support Center, Naval Oceanographic Office (NAVOCEANO), Stennis Space Center, Mississippi.

action. Although reports of severe respiratory distress caused by inhalation of toxins transported by aerosols around the surf zone have largely been confined to people with chronic respiratory problems; even healthy individuals such as SEALs may experience coughing, sneezing, eye irritation and respiratory distress when exposed.

Venomous and stinging marine animals can jeopardize missions by incapacitating personnel. Reactions to venomous stings can be severe and in some cases immediately fatal. However, most stings and venoms are

TABLE 4-5 Health Impacts Associated with Harmful Algal Blooms

Health Syndrome	Species	Toxin	Health Risks
Amnesiac shellfish poisoning	*Pseudonitzchia* sp.	Domoic acid	Nausea, intestinal distress, seizure, memory loss, possible death
Ciguatera fish poisoning (CFP)	*Gambierdiscus toxicus* *Prorocentrum* sp. *Ostreopsis* sp. *Coolia monotis* *Thecadinium* sp. *Amphidinium carterae*	Ciguatoxin Maitotoxin	Diarrhea, vomiting, abdominal pain, neurological dysfunction; paralysis and death in rare instances, but not usually fatal
Diarrhetic shellfish poisoning	*Dinophysis* sp.	Okadaic acid	Incapacitating diarrhea, nausea, vomiting, abdominal cramps, and chills—full recovery within three days
Neurotoxic shellfish poisoning	*Gymnodinium breve*	Brevetoxins	Gastrointestinal and neurological distress similar to CFP, but less severe and never fatal
Paralytic shellfish poisoning	*Alexandrium* sp. *Gymnodinium catenatum* *Pyrodinium bahamense*	Saxitoxins	Diarrhea, vomiting, abdominal pain, neurological distress, which in its most severe form results in respiratory arrest and death

irritating and therefore do not pose a serious health risk. Conversely, large predatory animals can incapacitate personnel. Severe lacerations and ensuing mortality have been reported. These occurrences are unpredictable but are relatively rare. Infectious disease transmission in most cases will not jeopardize missions unless they are long in duration. Many diseases have an incubation time in excess of 24 hours, however, this is not uniformly true. Furthermore, although the impact of most of these diseases can be limited by appropriate vaccination of personnel (as discussed earlier), attendees surmised that greater education and awareness would be beneficial (especially to mission planners).

Research Issues

Research that leads to improved prediction and awareness of hazardous marine organisms will mitigate their negative impacts. Harmful marine algal blooms appear to be increasing in regional distribution, number, and intensity (Smayda, 1992). Consequently, incidences of human illness and death from consuming contaminated seafood have increased. The increase in blooms may be the result of increasing pollution and nutrient input to coastal waters, long-term climatic trends, and introduction of exotic species. The forecasting of blooms would be beneficial so that mission planning can take such events in account. To improve prediction, research is needed both to identify the environmental conditions that regulate the distribution, abundance, and impact of harmful algal blooms and to improve identification methods and protocols for early detection of blooms. In addition, flexibility in mission planning could be improved if data bases were developed that include bloom incidence, mass mortality events, and epidemiology. For all other hazardous organisms, a data base could be developed that documents the distribution of hazardous organisms, their habitat, and treatment protocols.

Solutions

The impact of venomous animals on missions can be reduced primarily by training of personnel and improvement of data bases that document the incidence of these organisms. Special Forces personnel already receive training that addresses general issues about some hazardous marine organisms. The distribution of toxins and dangerous marine animals is addressed in standard NAVMETOCCOM products as well as services from the Warfighting Support Center (WSC; Fig. 4-1) and inputs to the Special Operations Forces Planning and Rehearsal System (SOFPARS). Based on discussions with NSW personnel during the symposium, harmful algal blooms may not be treated adequately during training, and information about the types and distribution of hazardous marine organisms in areas where personnel have not been previously deployed for extended periods does not appear to be adequate. Knowledge that indicates the potential presence of hazardous marine organisms in the area of operation is usually available from academia or in published literature. Usefulness of this information could be improved by providing more detailed and uniform data that describe the habitat of the organisms more specifically and forecast their abundance and distribution (i.e., the abundance and distribution of many marine organisms vary seasonally).

WAVES AND SURF

Ocean waves and surf directly influence NSW and SEAL insertion and recovery operations and SEAL hydrographic reconnaissance missions. The ingress and egress routes of these operations place NSW in several environmentally distinct domains of wave dynamics and kinematics: the surf zone, the inner shelf offshore of the surf zone, inlets, and harbors.

Wave characteristics that are relevant to NSW operations in wave domains are:

- heights (distance from trough to crest of the waves),
- periods (time between crests),
- wavelengths (distance between crests),
- direction,
- steepness (height-to-wavelength ratio) and skewness (local steepness),
- breaker type (plunging, spilling, or collapsing), and
- wave groupiness (temporal modulation of wave heights).

The surf zone, the region in which waves break continuously from offshore to the shoreline, should be distinguished from offshore regions of wave breaking, for example, shoals and reefs on the shelf or inner shelf. The surf zone can span distances anywhere from several meters (on beaches with steep depth profiles and small wave heights) to several kilometers (on beaches with low-sloping depth profiles and large wave heights).

The inner shelf is the region in which waves are strongly influenced by local bathymetry. Its extent offshore from the breaker location depends on the period of the waves but typically extends out to depths of 15 m. In this region, waves can be strongly refracted by the local bathymetry. In addition, shoals, migrating bars, and reefs in this domain can be shallow enough to cause local wave breaking.

The kinematics of waves in the inlets to bays and harbors are affected by the ebb and flood currents of the tides through the inlets, by the unique bathymetry at the mouth of the inlet (e.g., sand shoals and channels), and by breakwaters that define an inlet. Harbors are protected regions of low wave energy and little or no wave breaking. However, wave energy does propagate into this region. The amount of wave energy and the nature of the energy depend both on the wave conditions outside the harbor and on the geometry of the inlet and harbor. Significant wave energy at long periods (swell and infragravity waves) are commonly observed.

Mission Influence

The direct influences of waves and surf on NSW infiltration and exfiltration operations are many. For instance, critical thresholds for wave height are listed for every platform in the Critical Threshold Values for NSW Operations of the NSW Mission Planning Guide. Ingress and egress routes pass through the inner shelf and through either a surf zone or an inlet and harbor. Advance knowledge of wave characteristics along the route through these distinct wave domains is needed for mission planning and can be critical to mission success. As seen on the NAVOCEANO STOIC included as Plate I, information on waves and surf can be limited.

In mission planning, the choice of both the platform and the timeline of operation are affected by wave characteristics. The speed of transit of a patrol boat or a rigid-hull inflatable boat can be affected by the wave steepness and the propagation direction of the waves relative to the ingress or egress route. In the outer regions of the inner shelf and deeper water, wave steepness (the height-to-wavelength ratio) is determined by the height and period of the waves. However, in shallower water, the wavelength of the wave is shortened. The resulting increase of wave steepness may affect transit speeds.

In the inner shelf region, wave refraction by the local bathymetry may result in the focusing and defocusing of inshore waves. The resulting pattern of high and low wave heights can affect optimum routes and timelines. In addition, waves are highly nonlinear in this region, especially near the surf zone. Steepening wave crests and broadening wave troughs evolve in a sawtooth pattern as waves enter the surf zone.

The type of breaker is to a large extent determined by the wave steepness compared to the steepness of the underlying bathymetry. Beaches with moderately sloping depth profiles (e.g., greater than 1:50) and moderately steep waves (e.g., greater than 1:50) will have spilling breakers. However, with less steep waves the breakers will be plunging or, for extremely low wave steepness, collapsing. Thus, the type of breaker varies with the wave climate. However, the underlying bathymetry determines the range of variability of the breaker type and the most common type for that beach. Surf zone width, the distance over which significant depth-caused breaking occurs, affects mission tranist times and exposure to breaking waves.

When a mission route passes through the surf zone, not only are the height and period of the waves critical to mission planning and personnel safety but so are the type of breaker and the groupiness of breaking waves. Plunging breakers are more dangerous than spilling breakers. If the incoming waves are groupy (i.e., possess varying periods so that they tend to come in groups), windows of opportunity open up for passage through otherwise impassable breakers.

Wave groupiness depends on the proximity of wave-generating storm conditions. Waves from distant storms commonly provide groupy wave heights, whereas more local generation yields waves that are less groupy.

Ingress and egress through inlets presents unique, local wave conditions. Currents out of the inlet during ebb tide have the same effect on waves as rapidly shoaling water depths and cause extremely localized refraction (wave focusing) and wave steepening. In addition, the mouths of inlets often have sand deposits that are large enough to cause localized bathymetric refraction and wave steepening. Given the wrong set of conditions, there can be localized wave breaking at the mouth of an inlet. An inlet can at times be as hostile an environment as the surf zone.

The geometry of inlets and harbors significantly reduces the amount of wave energy that can propagate into a harbor. Waves with periods on the order of 10 seconds are reduced significantly in height. However, in the presence of local strong winds, a harbor geometry with a long axis parallel to the wind direction can have short, choppy (on the order of 3-second periods) waves with heights of 1 m. In addition, harbors and inlets are not typically designed to block long-period waves such as long swell (e.g., 25-second period) and infragravity waves (e.g., 100-second periods). As a result, these waves often enter a harbor with little reduction in height. Because swell and infragravity waves have long wavelengths and moderate heights, they have low steepness and do not break. However, they can pump energy into the natural harbor resonance, generating large seiching, and like harbor seiche, these low-steepness waves can have large sea surface oscillations that hamper operations near ship docks.

The discussion thus far has focused on the direct influences of waves on NSW operations. The most significant indirect influence is the role of waves in the generation of currents on the inner shelf and in the surf zone. On the inner shelf, both wind and waves play important roles in the generation of currents. A greater discussion of the importance and characteristics of currents can be found later in this chapter.

Research Issues

Research on waves propagating over the shelf and inner shelf has, until recently, focused on linear models of refraction and diffraction effects of the underlying bathymetry and currents. Field studies have been used to test and verify these wave propagation models, and they are now being transferred to the operational Navy (e.g., REF/DIF—refraction and/or diffraction wave propogation model). With knowledge of the underlying bathymetry and the wave directional climate offshore, these models are capable of making good predictions of the heights of waves over a large area (breaker heights at beaches, island shadowing effects, etc.), having resolution on a par with the input bathymetry resolution (O'Reilly and Guza, 1993). However, fundamental research questions still exist, for example, the aberrant dissipation of waves, and concomitant reduction in wave height, across a shelf.

As waves propagate into the surf zone, their dynamics become influenced by nonlinearities. The unique dynamics of waves, currents, and sediments on the inner shelf have only recently been a research focus. The Duck '86, '90, '94, and '97 field experiments are examples of recent efforts to better understand the inner shelf wave nonlinearities and currents on the East Coast (Birkemeier, 1989, 1991), while the Nearshore Sediment Transport Study (NSTS) addressed processes on lower-sloping California beaches (Seymour, 1987).

The refraction and diffraction models mentioned above assume a linear wave field. Therefore, nonlinear effects such as wave crest steepening and trough broadening are not predicted by these models. Therefore, the flux of momentum that drives currents and sea surface elevation changes in the inner shelf and surf zone is not predicted well with these linear models. Several approaches for the modeling of nonlinear wave propagation are under study. Each approach has a set of assumptions that serves to define a set of manageable equations (the assumption of a linear wave field yields the simplest set of equations). Models that are being used to study waves propagating over the inner shelf fall into three categories: nonlinear shallow water, Boussinesq, and boundary element. Of these three, the most thoroughly tested for random wave fields on natural beaches is the Boussinesq approach (Freilich and Guza, 1984), which provides accurate prediction of harmonic growth, skewness, and asymmetry for nonbreaking waves in shallow water.

Nonlinearities within groups of incident waves also generate long-period motions called infragravity waves in the nearshore (Holman, 1981; Guza, 1985; Herbers et al., in press). Infragravity waves have longer periods and wavelengths than wind waves, and their amplitudes are an order of magnitude smaller than wind waves on the inner shelf but can be larger than wind waves in the surf zone. Understanding infragravity wave dynamics is an ongoing research topic. Past research has demonstrated the ubiquitous presence of these waves; present research is studying and modeling the generation and kinematics of these waves and the bathymetric effects on their dissipation and scattering.

In the surf zone, the primary wave research topics are the study of infragravity waves and their influence on the underlying bathymetry and the study of wind wave breaking. Models are now being developed to simulate the dynamics of spilling breakers. These are being attached to wave propagation models to allow them (e.g., the Boussinesq time-domain wave model) to propagate a wave from the shelf to the shoreline (through the surf zone). Model-field and lab studies are now being considered to test the modeled spilling breaker dynamics. However, the study and understanding of plunging breaker dynamics is still in its infancy. Very recently, there has also been an increasing focus on the detailed dynamics of swash (the interactions of waves with the beach face; [Holland et al., 1995; Raubenheimer et al., 1995]).

The study of wind waves propagating through, around, and over breakwaters and inlets has a rich history in ocean engineering research. However, the study of infragravity waves through these inlets and into harbors is a relatively new topic (Okihiro and Guza, 1996).

Solutions

Wind-wave climate information in a shallow water operational region can be obtained from:

- model predictions with knowledge of the underlying bathymetry and the offshore wave conditions,
- direct observation using in situ sensors, and
- indirect observation using remote sensing platforms and concomitant transfer function models.

NSW operations place stringent requirements on these methods, requiring small-scale (100 m) local wave climate. These three basic methods are discussed below. This discussion illustrates why any one method is insufficient. However, data assimilation of direct and remote observations integrated with wave propagation models looks promising.

Model Predictions: Model predictions require initial and boundary conditions (input about the offshore wave climate, bathymetry along the propagation path, and/or wave kinematics along the boundaries of the area of interest). The model predictions are only as good as the initial and boundary conditions. Often, the input offshore wave conditions are incomplete, and neglect wave energy that may be too small to be significant in deep water, but are nonetheless significant in shallow water because of the propagating wave dynamics. In addition, wave propagation can be sensitive to details of nearshore bathymetry. Thus, the spatial resolution of available bathymetry data is often insufficient to permit accurate small-scale, local model predictions of the wave climate. These problems are particularly evident if the wave climate on a local beach is to be predicted from offshore (deep water) wave conditions and bathymetry across the shelf to the surf zone. Such a wave-climate modeling scenario could benefit from integration with in situ and remotely sensed wave-climate data, employing a real-time correction to the model for inadequacies in the initial and boundary conditions.

Direct Observation: Direct observation will provide the best local wave-climate information possible. Modern technology provides the capability to build expendable pitch and roll buoys that can measure wave heights, periods, and directions and can store the data locally and/or transmit information back to ship, sub, or satellite (Earle et al., 1994). The pitch and roll buoy wave direction information is not the highest resolution obtainable from in situ instrumentation; a spatially distributed coherent phase array of sensors provides the greatest possible accuracy and resolution of the wave climate. However, the latter requires accurate placement of more sensors (greater expense) on the ocean bottom (more difficult logistics) and is effective only in waters less than 15 m deep.

The complexity of the bathymetry on the inner shelf limits the applicability of local wave-climate measurements to other locations; wave-climates can change dramatically over as little as 100 m because of refraction and diffraction of waves by bathymetry and currents. However, using the local wave climate measurements with wave propagation models and bathymetry data can alleviate this inherent limitation.

Remote Observation: Indirect, remote (satellite or airborne) observation has distinct advantages over in situ measurement because of the spatial coverage possible. However, because wave dynamics and kinematics are complex on the inner shelf and in the surf zone, the transfer function between the sensing platform direct observation and the wave climate is also complex. A wave propagating across the inner shelf can change wave form from nearly sinusoidal to strongly skewed and asymmetric (sharp, tilted peaks and broad troughs) over tens of meters. Therefore, the resolution of the remotely sensed data must necessarily be on the order of tens of meters. Encouragingly, the changes in wave kinematics are predictable from the nonlinear wave propagation models mentioned in the previous section. Therefore, remote sensing of waves on the inner shelf has excellent possibilities if these models are incorporated in the definition of the sensing platform's transfer function. However, the accuracy of these models, and therefore the transfer function, is again constrained by the accuracy and resolution of bathymetry data.

In the surf zone, attempts to remotely sense breaking waves in an effort to define the breaking wave climate are not as easily handled as remote sensing of the offshore wave climate. The surf zone is confused with temporal and spatial coherent scales much smaller than offshore. This reduced coherence and the present basic lack of understanding of breaking wave dynamics and kinematics make remotely sensing the surf zone wave climate formidable. However, wave propagation models, with good high-resolution bathymetry and accurate offshore wave climate as input (from in situ or remote sensors or both), can yield good estimates of breaker location, height, groupiness, and type.

CURRENTS AND TIDES

Currents and tides affect many aspects of NSW activities, ranging from decisions on whether or not to begin the process to insert or extract a team to decisions of where to conduct operations and how. Accurate knowledge and predictions of currents and tides are essential for any mission in shallow water since currents and tides are prevalent contributors to time-varying, spatially complex nearshore flows. Consequently, NAVOCEANO products typically contain a variety of information on currents and tides (Plate I). In contrast with deep water situations, where space and time scales of variability are relatively large and long, littoral operations are conducted in environments where rapid change is the norm. The predictability of currents and tides in this shallow water environment is thus more complex than in deep water.

The term "currents" includes motions within the littoral on a variety of different time scales. In littoral usage, the term "waves" typically designates motions associated with wind and gravity processes. Periods of waves range typically from a few or tens of seconds for wind waves and swell to several minutes for infragravity waves. The lower-period (higher-frequency) limit of waves usually is set at turbulent time scales, whereas the upper-period limit (lower-frequency limit) is more poorly defined. At longer time scales than waves, the current regime is typically assumed to commence.

Using the above definition, currents are long time-scale fluid flows arising from a wide variety of processes. Tidal forces create currents; the combination of wind action and the earth's rotation provides other forcing mechanisms for currents. Winds and river flows create currents that influence the littoral surrounding the river's mouth. Because of the complex interactions among the different forcing mechanisms that cause currents, warfighters must assimilate a net effect of currents without the benefit of understanding what contributes to these complex structures. Therefore, METOC analysis prior to an NSW mission must be sophisticated enough to understand the complexities of the forces that cause currents, determine whether these mechanisms are reinforcing or counteracting, and understand both their scales of variability and how these factors may combine to affect the mission profile.

Mission Influence

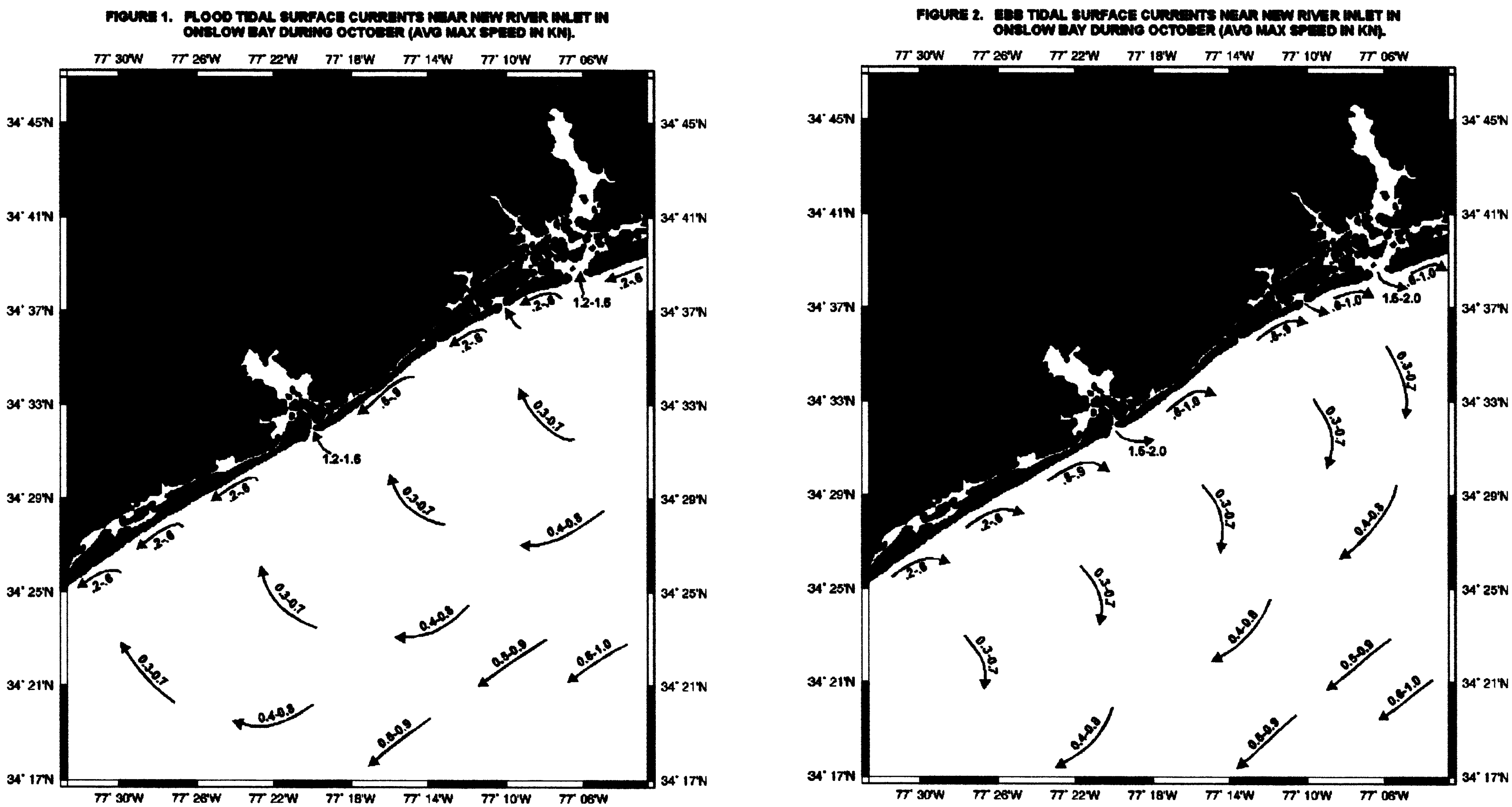
Currents are complex in the littoral zone, reflecting the shelf flows in deeper waters, shallow water alterations of tides, and wave-driven currents within the surf zone (Figs. 4-2 and 4-3). The complexity of nearshore currents implies that accurate prediction requires knowledge of the physical environment of the entire operating arena, not just the 1 km stretch of coastline where operations are taking place. Several questions arise during attempts to predict the nature and distribution of currents in the littoral zone: (1) what is the spatial scale of the basin in which the operation is taking place?; (2) what are the natural modes of oscillation of the basin, and what effect do these modes have on the currents (e.g., within a semi-enclosed sea, gulf, and harbor)?; (3) what is the exposure of the beach to prevailing winds and seas?; and (4) what is the geometry of the river or estuary, and how are tides modified by river flow and geometry within these systems?

Research Issues

Surf Zone Currents

Mean flows in the surf zone are driven by nonlinearities of the incident waves. In the cross-shore direction, these nonlinearities force an undertow, or in the presence of longshore structure in the bathymetry, they can drive a horizontal circulation pattern with strong rip currents (Bowen, 1969; Tang and Dalrymple, 1989). Currents flowing in the alongshore direction can be driven by obliquely incident waves or can form in regions where there are longshore variations in wave height, perhaps due to nonuniform bathymetry (Longuet-Higgins, 1970).

The presence of these surf zone currents can have a variety of impacts on NSW operations. Undertow and rip currents can complicate surf zone transit and induce errors in hydrographic reconnaissance, where kick count is



(A) (B)

FIGURE 4-2 Maps of flood tidal surface currents (a) and ebb tidal surface currents (b) near the New River Inlet, Onslow Bay, North Carolina, taken from the WSC STOIC included as Plate I. STOIC courtesy of the Warfighting Support Center, Naval Oceanographic Office (NAVOCEANO), Stennis Space Center, Mississippi.

NEARSHORE ONSLOW BAY OCTOBER CURRENT TABLE

	OFFSHORE	NEARSHORE
SURFACE		
NON-STORM		
PREVAILING	PRIMARY OFFSHORE FLOW TOWARD SW ON THE SHELF AND TOWARD THE NE IN THE GULF STREAM SPEED 0.6-4.2 KN.	COASTAL CURRENTS PARALLEL SHORELINE PRIMARILY TOWARD NE OR ENE. SECONDARY TOWARD SW SPEED 0.2-1.5 KN.
TIDAL	ROTARY OFFSHORE AVG. MAX. SPEED 0.3-0.7 KN.	REVERSING NEAR LAND, FLOOD SW, EBB NE. PERIOD OF 12.4 HR. DIRECTION PARALLEL TO CHANNEL IN NEW RIVER INLET. PEAK FLOOD TOWARD NW OFF THE COAST PEAK EBB TOWARD SE OFF THE COAST AVG. MAX. SPEED 0.6-2.0 KN.
LONGSHORE		0-1.4 KN. PARALLEL TO SHORELINE FLOW TOWARD NE OR SW 0-2.8 KN. SEAWARD
RIP		SPEED 0-1.8 KN.
STORM	DIRECTION SAME AS STORM WIND SPEED 2% OF WIND SPEED MAX. SPEED 4.0-6.0 KN.	CURRENTS IN STORM IN DIRECTION OF WIND STORM WINDS ALTER FLOW PATTERN AVG. MAX. SPEED 2.0 KN.
SUBSURFACE		
UPPER 5 M (16 FT)	SAME AS SURFACE	SAME AS SURFACE
BELOW 5 M (16 FT)	DIRECTION SAME AS SURFACE OR IN TIDAL DIRECTION DURING MODERATE WINDS. SPEED DECREASES WITH INCREASING DEPTH.	DIRECTION SAME AS SURFACE OR IN TIDAL DIRECTION DURING MODERATE WINDS. SPEED DECREASES WITH INCREASING DEPTH.
NEAR-BOTTOM		
NON-STORM	OFFSHORE DIRECTIONS SAME AS SUBSURFACE SPEED 0.0-3.0 KN.	DIRECTION SAME AS SUBSURFACE SPEED 0.2-1.4 KN. LONGSHORE SPEED 0-1.0 KN. RIP SPEED 0-1.8 KN.
STORM	OFFSHORE DIRECTIONS SAME AS SUBSURFACE SPEED 0.5-4.5 KN.	DIRECTIONS SAME AS SUBSURFACE AVG. MAX. SPEED 1.4 KN. LONGSHORE SPEED 0-2.2 KN. RIP SPEED 0-4.0 KN.

NOTE: SATELLITE IMAGERY ACQUIRED DURING OR NEAR THE TIME OF AN OPERATION MAY LOCATE THE LOCATION OF THE GULF STREAM. THIS LOCATION MAY REVEAL WHERE THE CURRENTS SWITCH FROM A SOUTHWEST DIRECTION ON THE SHELF TO A NORTHWEST DIRECTION IN THE GULF STREAM.

LOCAL WINDS GENERATE CURRENTS THAT OVERRIDE AND ALTER THE PATTERNS SHOWN IN FIGURES 1 AND 2.

SPACING BETWEEN RIP CURRENTS RANGE FROM 1 TO 8 TIMES THE WIDTH OF THE SURF ZONE. RIP CURRENT LOCATIONS SHIFT WHEN WAVE REGIMES CHANGE.

CAUTION: STORM SURGES, TSUNAMIS, AND COASTAL SEICHES ARE RARE EVENTS THAT CAN GENERATE DANGEROUS AND UNPREDICTABLE CURRENTS, ESPECIALLY NEAR LAND.

CAUTION: TRANSIENT EDDIES ALTER CURRENT SPEEDS AND DIRECTIONS.

CAUTION: MIXED TIDES CAUSE PEAK TIDAL CURRENT SPEEDS TO VARY FROM TIDE TO TIDE.

WARNING: WHEN CURRENTS DRIVEN BY DIFFERENT MECHANISMS FALL IN LINE IN THE SAME DIRECTION, TRANSIENT CURRENT PULSES DISPLAY SPEEDS EXCEEDING THOSE SHOWN IN THE ABOVE FIGURES AND TABLE.

CAUTION: THIS CHART GIVES A "SNAPSHOT" VIEW OF THE CURRENTS.

WARNING: A STRONG EBB CURRENT OUT OF THE NEW RIVER INLET CAUSES INCOMING WAVES TO BECOME UNSTABLE AND BREAK OVER THE INLET'S BAR, AND IS ESPECIALLY SEVERE IN SOUTHEAST WINDS.

FIGURE 4-3 Description of current field for Onslow Bay, North Carolina, taken from the WSC STOIC included as Plate I. STOIC courtesy of the Warfighting Support Center, Naval Oceanographic Office (NAVOCEANO), Stennis Space Center, Mississippi.

often used to determine horizontal location. Smaller, untethered mines will be redistributed by currents into patterns that may include both relatively safe and dangerous lanes.

The predictability of current regimes in the surf zone and very nearshore settings depends on the nature of the bathymetry. On low-sloping beaches, longshore currents can be described as simple models, whereas current behavior on beaches with well-defined sandbars has remained more elusive and is not well predicted at present. Moreover, longshore currents on barred beaches develop instabilities with periods of several minutes, called shear waves (Oltman-Shay, et al., 1989). Because of this variability, estimation of current strength based on sampling for less than five minutes can be substantially in error. Both cross-shore and longshore current strengths are quite dependent on details of the nearshore bathymetry.

River or Harbor Tides and Currents

Commonly, the ultimate objective of NSW missions is industrial or military sites located along a navigable estuary or river or involving significant transit along an estuary or river. Adverse or unexpected currents can seriously impact total transit time or can exhaust air or fuel supplies, whereas known current patterns can be a significant tactical aid by facilitating transport. Likewise, unexpected or intense turbidity may interfere with the location of an objective, whereas moderate turbidity can beneficially conceal a SEAL team. Thus, the direct needs of NSW include better understanding and predictability of tidal and estuarine circulation and their influence on turbidity levels.

To understand and predict currents and turbidity better in rivers, harbors, and estuaries, academic research should focus on the interaction of tides, basin, and channel geometry; river flow; mixing; and density-driven circulation. For example, in small harbors, slack water is associated with high, and low tide, whereas along estuaries and rivers, peak currents can occur at low, high, or mean water, depending on depth and along-channel geometry. Strong variations in the strength and phase of tidal currents occur across a channel as a function of local water depth. Stratification and density-driven estuarine circulation are also related to local channel depth, along-channel constrictions, and stage of the spring neap cycle. In contrast to typical academic research of the past, future efforts should focus on broadly generalized dynamics rather than highly site-specific processes.

Making knowledge available in academia more accessible could rapidly improve the planning of NSW operations. Existing STOIC charts (Plate I) could be updated, for instance, in areas of rivers and harbors, simply by adding information on nonlinear tidal behavior to predict timing of flow reversals, time delays, and amplitude changes in surface tides. Whereas present STOIC charts now rely on tidal information from the nearest coastal point, improved understanding of large-phase and large-amplitude changes within the estuary, as well as the relative phase between tidal height and tidal currents (which differ strongly from the linear tidal case), could improve the capabilities of NSW operations (including SDV operations).

Current-Wave Interaction at River Mouths and Inlets

NSW operators would benefit from an increased ability to recognize the potential hazards associated with, as well as the possibility of, exploiting the effects of strong currents on the behavior of waves at the entrance to rivers and inlets. Ebb currents can make otherwise benign waves dangerous, whereas flood currents can make rough seas benign. Full coupling of nonlinear, high frequency (e.g., waves) and low frequency (e.g., tides) changes in water depth in shallow water settings must be accomplished for conditions of complex and time-varying bottom morphology. Strong spatial gradients in waves, currents, and tides exist at river mouths, which will affect NSW operations.

Several research opportunities exist: (1) numerical modeling of wave propagation and breaking on currents, ground truthed by laboratory modeling and field measurements at inlet and river mouths; (2) characterization of the river or inlet mouth as a low-pass filter, so that waves interior to the mouth can be characterized; and (3) understanding inlet stability processes to predict the location and morphology of inlets under different wave, tidal, and riverine flow conditions.

Integrate Hydrological Models to Understand Rivers and Harbors

NSW operators and mission planners would benefit from enhanced capability to anticipate and develop tactics for SDV and swimmer operations in harbors and rivers affected by episodes of rainfall throughout the local watershed. Variable river discharge affects the buoyancy compensation, structure (vertical shear), and strength of the current system, as well as the water visibility encountered in the target river or harbor.

Opportunities exist for research into both the computational architecture and the physics of stratified hydraulics. River hydrology modeling is ideal for geographic information system (GIS) adaptation and presents challenging nested-grid and multitiered time-splitting techniques when merged with coastal circulation models at the harbor or river mouth. Physics-based challenges are associated with the stratified hydraulics of the time-varying river flood hydrography and resulting fresh water plume. Harbor and river mouth geometry likely exert a strong influence on possible hydraulic states. The hydraulic states will localize mixing of the fresh water plume in the neighborhood of the harbor or river mouth. These mixing effects will be modified by the sediment load which is a product of the flood hydrography. Major research opportunities exist in the areas of modeling, nonlinear tidal hydrodynamics, river sedimentation, stratified flows, and turbidity maxima.

Improved Circulation Models for Tides, Winds, and Buoyancy Forcing

There is a need for skillful, high-resolution local models in support of special warfare operations in both the planning and the execution phases of a mission. These models should be easily configurable, robust, and able to be run with minimum spin-up time. Model products should be able to be ingested in easily used post-processing software so that the results are made available to NSW personnel in a clear, concise fashion, preferably in a time variable, fully three-dimensional visualization package.

In response to this need, there appears to be research opportunities in the following areas: (1) model configuration improvements over all scales of interest; (2) development of easy-to-use analysis and post-processing tools; and (3) integration at all phases with three dimensional visualization packages. With respect to model configuration, improvements would include the use of rapid environmental assessment (REA; for greater discussion see Chapter 3) products, an easy-to-use grid data base of all bathymetric data and forcing fields, and the transition of these models to computers capable of being used in the field. With respect to postprocessing and analysis, tools should include those areas specific to Special Warfare missions, such as salinity gradients in the vertical and horizontal, tidal velocity vectors, and wind fields. With regard to visualization packages, all model products should be visualized in a useful 3-D fashion to present these results in a fashion that is immediately and easily understood by NSW personnel not conversant in scientific issues. This 3-D visualization would communicate spatial and temporal features clearly. An animation capability must also be included. These models should be applied to three to five selected systems to demonstrate predictive performance for a variety of estuarine, harbor, and bay types (e.g., well-mixed, partially mixed, stratified, sill or fjord). Careful assessment should be made of a model's predictive skills. The model should address the vertical structure problems associated with sigma/leveled gridding systems.

BATHYMETRY

NSW operations take place in the inner littoral zone between intermediate depths, perhaps several tens of meters, and the dry beach and backshore. For the purposes of understanding the role of the environment within this region, SEAL operations can be considered to be of two generic types. Ingress or egress operations simply need to transit the nearshore to and from some target in a safe and stealthy manner. On the other hand, special reconnaissance operations require the collection of data on nearshore bathymetry and obstacles from within the nearshore (Fig. 4-4). SEALs are specifically tasked with bathymetry reconnaissance for depths less than 6.5 meters (21 feet, 3.5 fathoms; Box 4-1).

The spatial and temporal variations of depth in the nearshore (shoreline to nominally 20 m depth) lead to many

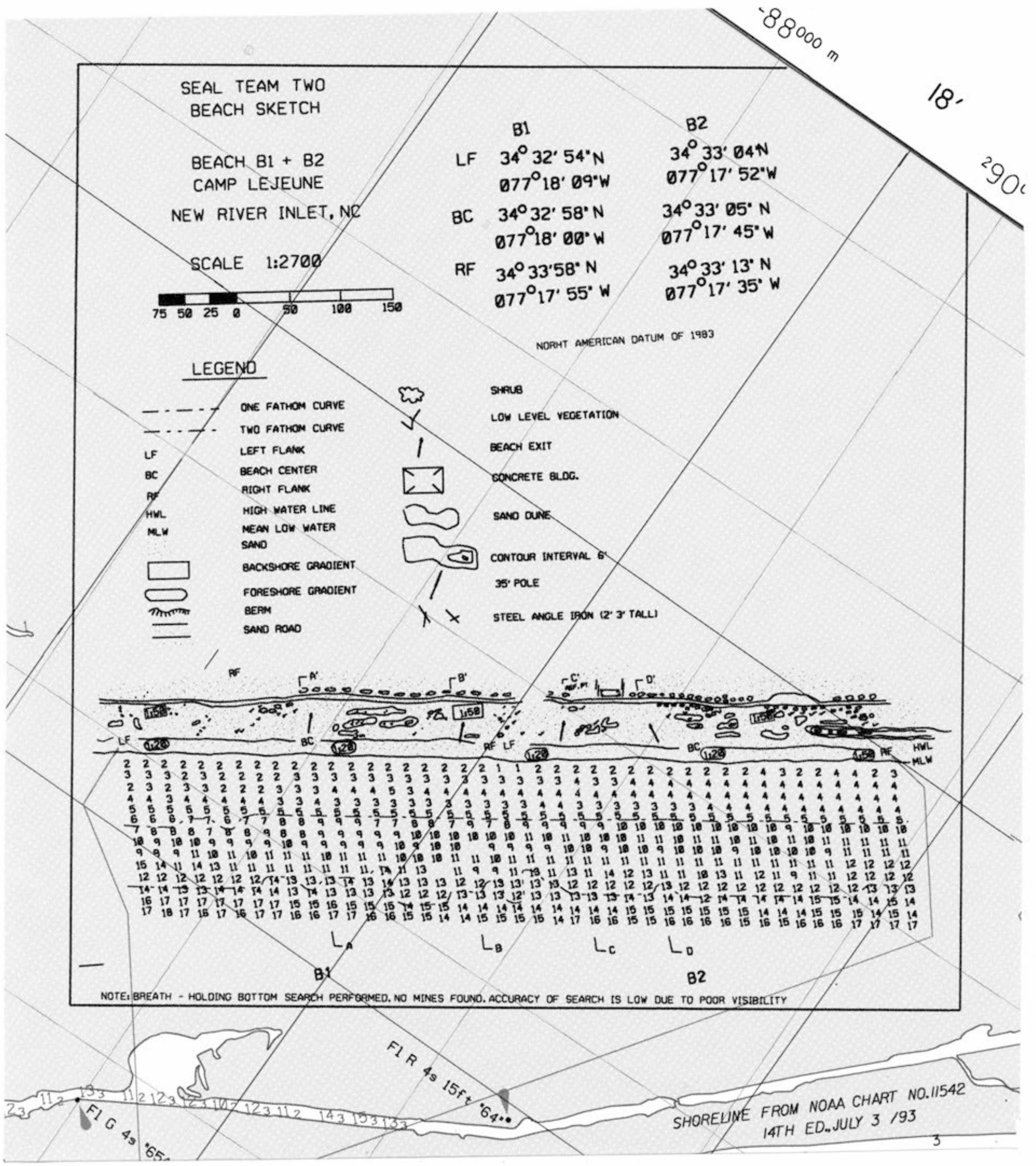


FIGURE 4-4 Beach sketch map prepared by the WSC from data collected by SEAL Team Two for a section of beach near New River Inlet, North Carolina, and taken from Plate I. STOIC courtesy of the Warfighting Support Center, Naval Oceanographic Office (NAVOCEANO), Stennis Space Center, Mississippi.

complications in NSW operations. These include direct complications such as unexpected shallow water over sandbars or reefs or unexpected deep water over troughs and channels. Indirect effects can be the bathymetric influence on the location and height of breaking wind waves and on the location, direction, and strength of the currents.

Nearshore bathymetry issues can be divided into two regional categories: surf zone and offshore of the surf zone (inner shelf). Once measured, the inner shelf bathymetry can be assumed to be reasonably known; the changes to inner shelf bathymetry caused by sediment suspension and transport by waves and currents is small. However, in the surf zone of sandy beaches, changes in depth associated with sediment transport can be sufficient either to directly affect a mission (development of a bar or rip channel) or to provide an important indirect effect, substantially changing current or wave patterns. For ocean beaches, this division between surf zone and inner shelf occurs in depths on the order of 5 m. For purposes of this discussion, the former region will be called the inner shelf whereas the latter will be referred to as the surf zone (although wave breaking may occur in only a fraction of the region).

BOX 4-1: SEAL Team Hydrographic Reconnaissance

SEAL combat teams are used for reconnaissance of beaches for amphibious landing practice, landing troops on relatively safe beaches, and landing troops on unsafe beaches. There are three basic hydrographic reconnaissance methods employed by the SEAL teams:

- perpendicular reconnaissance (administrative reconnaissance for amphibious landing practice),
- parallel reconnaissance (combat reconnaissance of a relatively safe beach), and
- underwater reconnaissance (clandestine reconnaissance of an unsafe beach).

SEAL teams are responsible for reconnaissance of a beach from the 21-foot depth contour to the shore. All methods map the hydrography (i.e., bathymetry) on a 25 x 25-yard grid. The survey width of a beach is nominally 500 yards.

Perpendicular Reconnaissance

Perpendicular reconnaissance is an overt, daytime beach reconnaissance used primarily for amphibious landing practices. As illustrated in the figure (a) below, a platoon or more (16 to 24) of surface swimmers lines up perpendicular to shore. The team member farthest offshore holds position above the 21-foot depth contour while the rest of the platoon swims inshore pulling a line (rope) marked at 25-yard intervals. They align themselves perpendicular to the beach using a pair of markers on the beach. After team members measure the water depth with a line and lead weight, search the area for debris, and log each depth, they move alongshore 25 yards, aligning themselves with another pair of markers on the beach.

Parallel Reconnaissance

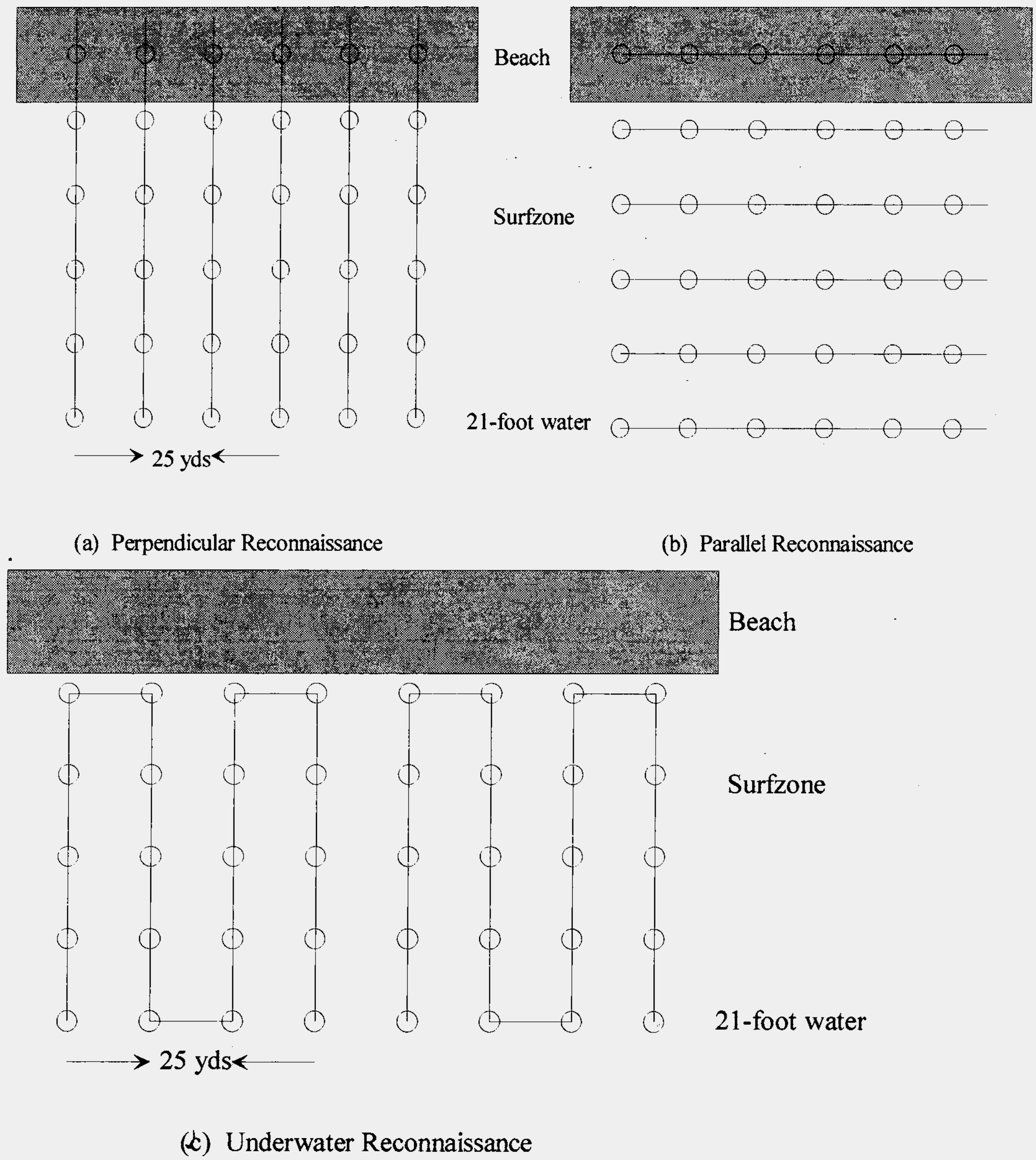
Parallel reconnaissance is used in a combat situation on a relatively safe beach. A platoon swims on the surface to the 21-foot depth contour and lines up parallel to this contour or to the beach, spaced at roughly 25 yards (b). After the depth measurement, the platoon logs the depth, searches the area for debris, and advances 25 yards toward the beach. When team members have repositioned themselves, they make another depth measurement. This is repeated until they are all near or onshore.

Underwater Reconnaissance

At unsafe beaches, underwater reconnaissance is performed by several swimmer pairs; the number of pairs depends on the beach width to be surveyed. The swimmer pairs spread out parallel to the beach at 50- to 200-yard intervals on the 21-foot depth contour. Their separation is the estimated beach width that a pair can survey, which depends on the estimated beach slope, the time to swim and make observations, and the maximum time that the swimmers can remain in the water. As shown in the figure (c), a zigzag pattern is used. Each pair swims toward shore while watching for debris and counting kicks to estimate 25

(continued)

yards, measures the water depth, and enters the data in a logbook. The time to repeat this cycle is estimated to be 2 minutes per depth measurement. When the team reaches water depths of 2 or 3 feet, it turns and swims 25 yards parallel to the shore for the next measurement. The swimmers turn again and swim directly offshore, logging the depth at 25-yard intervals until they reach or pass the 21-foot depth contour. If time is available, they advance 25 yards alongshore and start a new pattern.



Basic beach hydrography methods used by SEAL teams. NOTE: Circles denote the depth measurement location; lines show either the alignment of the SEAL team for a synchronous depth sampling (a, b) or the survey pattern of a swimmer (c).

Mission Influence

Bathymetry is a pervasive issue for Naval Special Warfare. On the inner shelf, the direct influences are limited primarily to undetected obstacles. However, the indirect influences are many. Ocean waves begin to be influenced by the shoaling bathymetry in these depths. Although direct shoaling effects in these depths are usually small, refraction over banks can lead to substantial wave height changes due to focusing (Pawka, 1982). Conversely, "quiet" regions can develop landward of "holes." Adequate models exist now for wave shoaling prediction, but these models depend on accurate knowledge of the bathymetry.

The inner shelf can also be a region of complicated physical oceanography. Unlike deeper water, the bottom and surface boundary layers begin to merge due to the shallowing of the inner shelf. The smaller scale of processes makes the current and density fields more complicated to model. Sea level anomalies up to 1 m are not uncommon due to the shoaling of larger-scale physical oceanography structures onto the inner shelf (Baron et al., monthly reports). In addition, acoustic propagation is complex on sloping bathymetric surfaces.

In the surf zone, sandbars and adjacent shoreward troughs are very common. A shallow bar can provide a direct obstacle for boats, whereas the landward trough may be a meter or more deeper and can have strong currents. Channels cut through the bar usually trap rip currents and can provide a handy exit for egress. Waves undergo a strong shoaling in this region and usually break over a sandbar, making the bar crest a region that is both harsh and exposed. Egress back through breaking waves on a sandbar can be very difficult. Rip currents, longshore currents, and undertow are all strongly associated with nearshore topography and can easily affect a mission. Finally, the movement of sand in this region can affect the distribution of small mines or can cause the burial or scouring out of tethered mines. Sands recently accreted onto the beach are often soft and lead to trafficability problems.

Research Issues

In the inner shelf region, bathymetry itself does not constitute a research issue. However, the dependence of many indirect processes on the details of bathymetry is very relevant. Most notable is the sensitivity of wave field focusing to bathymetric anomalies. Examples from the Southern California Bight show strong focusing and defocusing due to bathymetric features that are distant from the nearshore (Pawka, 1982). Bathymetric anomalies can also influence tides and larger-scale shelf currents, especially near the mouths of estuaries or other sources of density variation. The principle research issue lies in understanding the sensitivities of models to the bathymetry.

Bathymetry in the surf zone is substantially more complicated. Depths no longer change monotonically but usually show one or more sandbars out to depths as great as 6 m. Toward the region of wave breaking, the bathymetry becomes quite variable in the longshore direction, with the development of rip channels and a variety of features offshore of the bar and in the trough. These features appear to be related to a feedback between the wave and current fields and the topography, and they can change rapidly. In addition, recent work suggests that the distribution and lithology of various underlying geological units can control bathymetry in a manner similar to the way differential weathering and erosion of varying geological units can result in unique and predictable geomorphic landscapes in terrestrial settings. Furthermore, subaqueous erosion of some lithologies can produce significant amounts of locally derived sediment. These two factors may also play a role in the distribution of submarine vegetation, "hard grounds," and other features of the sea floor. Bathymetric changes, whether related to migrating subaqueous dunes or to the erosion of the underlying geologic framework, in turn drive substantial changes in the overlying waves and currents.

Although research is ongoing, at this time there is no known model that successfully predicts the evolution of a preexisting beach topography due to waves and currents or underlying geologic framework. In addition, the time scale over which topography undergoes significant change is not well known. Thus, the "shelf life" of a measured topography is unknown, although in the surf zone and on the beach face, operationally important changes have been observed over periods as short as one day and are commonly observed over one week (Sallenger et al., 1985). This time scale of change is clearly a function of location in the profile, with rapid changes possible on the shoreline and slower changes over a deeper sandbar. In addition, we are only beginning to be able to model the wave and current fields over complex nearshore topography and do not yet have a good feel for the sensitivities of model results to details in topography.

Finally, it appears that beaches around the world can manifest quite different behavior. For instance, the observed fluid dynamics and sandbar structures on an Oregon beach appear different from those on a steeper barrier island beach of North Carolina. Yet all sites operate under the same physics. Understanding how the same laws of physics yield such different manifestations of behavior is a key objective of nearshore research.

Solutions

There are four possible solutions to the problem of knowing the bathymetry in a region of operations: (1) direct measurement (the current approach), (2) in-situ remote sensing, (3) overhead remote sensing, and (4) modeling.

Direct Measurement

The two direct measurement methods presently utilized by the Navy are hydrographic reconnaissance (from shoreline to 21 foot depth) by a SEAL team and the Laser Airborne Bathymetry System (LABS). The bathymetry survey methodology employed by the SEALs is described in Box 4-1. Some work is in progress to assess the accuracy of these methods, both as a yardstick to compare to alternative future hydrographic techniques and to allow sensitivity tests to be run for nearshore models. LABS is another direct measurement technique available to the Navy. The active laser system of LABS can operate in waters from 1 to 40 m depth, depending on clarity of the water. For instance, it cannot penetrate regions of breaking waves such as the surf zone.

In situ Remote Sensing

Several in situ techniques may become available. Offshore of the surf zone, new types of AUVs are becoming available that can measure bathymetry and could potentially search for obstacles and mines. Toward the surf zone, the Beach Probing System (BPS) offers the potential for using inner shelf instrument packages to estimate surf zone bathymetry based on wave signals that propagate out from nearshore.

Overhead Remote Sensing

A substantial amount of work has gone into using remote sensing approaches to estimate bathymetry from overhead assets. The primary approach is based on the known relationship between the celerity (speed of propagation) of waves and the local depth, known as the dispersion relation (Lamb, 1932). The progression of a wave phase is quite apparent to the eye and to various sensors, so that wave celerity can be measured and inverted for depth. The problem reduces primarily to one of signal processing, trying to extract robust estimates from somewhat sparse data. However, preliminary results are promising.

Work is also being done on the use of hyperspectral techniques to infer depth from the changing color content of light reflected from the bottom. Unlike lidar, which can penetrate to 6 times the optical extinction depth due to its active pulse nature, this passive technique is limited to shallower depths in clear water. Moreover, the optical clarity of the water must either be known or be measured to calibrate the results. Finally, some work is being done on the use of stereography to estimate the depths of submerged features. Removal of or compensation for surface waves remains a problem.

Modeling

Modeling of a predicted nearshore bathymetry without knowledge of a pre-existing bathymetry is beyond the current capability of the research community. The problem is daunting. To start with, since the evolution of the bathymetry is driven by wave and current fields, and in some instances the distribution of the underlying geologic units, these must be modeled to a reasonable accuracy—a task that is still beyond current production capabilities. Second, since the bathymetry drives the dynamics of the wave field and the wave field drives changes in the topography, there is substantial feedback in the system. This makes the nearshore a nonlinear dynamic system. In comparison with other such natural systems, a richness of unexpected behavior is expected, and observed. The problem is analogous to the prediction of weather. With research, models will be developed that provide some skill in predicting short-term evolution of the bathymetry, perhaps as long as a week or more. However, like weather forecasting predictions beyond this horizon will remain of climatological value only. For the foreseeable future, in situ or remote measurements of the nearshore bathymetry are the only viable tools.

Summary

Although not considered a critical mission parameter, the importance of determining bathymetry pervades NSW operations. For ingress and egress, bathymetry may represent an obstacle in the form of a sandbar and adjacent deeper trough in the nearshore or perhaps some unknown bathymetric obstruction. However, the secondary effects of bathymetric shoaling are strong. These include wave shoaling and breaking as surf, the generation and channeling of strong currents, and the potential introduction of wave height anomalies through refractive focusing or defocusing caused by progression over offshore shallow banks. Also, determination of bathymetry in waters shallower than 3.5 fathoms is a designated special reconnaissance mission of the SEALs.

In waters deeper than 5-6 m, bathymetry can be assumed to be unchanging, and surveys can be carried out in advance of an anticipated need. In shallower waters of sandy beaches, bathymetry is continually changing and profile data must be recent (within a few days for surf zone work) to be useful. The evolution of a pre-existing profile currently cannot be modeled and therefore must be determined either by direct measurement (e.g., using SEAL teams, airborne lidar, remotely sensed measurements). Both in situ and overhead remote sensing approaches are being explored and appear promising.

EM-DUCTING

NSW and SEAL operations take place in marine and coastal areas where rapidly changing and complex atmospheric conditions are common. Special reconnaissance and other clandestine operations require the collection of data on nearshore bathymetry, obstacles from within the nearshore, and targets and/or defenses on land in the coastal zone. In many situations, onshore NSW units must maintain radio communications with Naval forces offshore. These radio communications, under certain atmospheric conditions, can jeopardize the clandestine nature of the mission, and in some instances, jeopardize the lives of both the onshore and offshore units.

The term “EM-ducting” refers to anomalous refraction of electromagnetic (EM) waves by the atmosphere leading to enhanced (over-the-horizon) radar detection ranges and communications channels. Reduced radar detection and communications may also occur for slightly elevated propagation angles (referred to as a “radar hole”). The term “anomalous propagation” is used when refraction effects are significantly greater than the standard atmosphere. If the downward curvature of an EM ray exceeds the curvature of the earth, then a radar “duct” is said to exist. The curvature of the rays is a function of the index of refraction of the atmosphere, which depends on the pressure, temperature, and moisture content in a well-known manner. A duct that results from the strong gradient in the atmosphere near the sea surface is usually referred to as an “evaporation duct” because of the strong vertical gradient of moisture near the sea surface. The height above the surface where the gradient of refractive index is reduced to the critical value (i.e., the ray curvature exactly equals the curvature of the earth) is the duct thickness or duct height. Ducts caused by the presence of a temperature or humidity gradient not associated with the surface are referred to as elevated ducts; these are most commonly associated with the temperature inversion at the top of the marine boundary layer (heights on the order of a kilometer).

Mission Influence

EM-propagation affects most aspects of SEAL operations on or above the sea surface associated with transportation to and from the mission area and execution of the mission. EM propagation does not affect most SEAL operations below the sea surface (i.e., most SEAL subsurface activities do not produce a radar-detectable surface signature) but is relevant to communications by submerged minisubs or to possible radar detection of a periscope. EM-propagation effects can be broken down into two parts: (1) radar detection and (2) communications. These issues may be looked at from both directions. Radar detection of enemy threats *by* SEALs or their supporting units, and radar detection *of* SEALs or their supporting units are relevant. EM-ducting may provide enhanced ranges to improve communications *by* SEAL units but also will increase the probability of detection *of* SEAL units by local enemy forces. Ducting may also affect tactics in support of SEAL units. For example, an electronic countermeasure (ECM) aircraft might approach the coast undetected by flying above an evaporation duct and then descend into the duct to turn on jamming signals to mask a SEAL egress. This jamming might affect enemy radar or communications.

Research Issues

To deal with EM-propagation effects, SEALs need a specification of the propagation conditions in the operational area as a function of time and location for the duration of the operation. For mission planning purposes, this specification is required well before the actual mission—in other words a *forecast* of propagation conditions is necessary, with continual updates and evaluations through the planning and execution of the mission. During execution of the mission, SEALs may need an evaluation *nowcast* of propagation conditions for tactical purposes (i.e., use one type of radio if ducting conditions exist and another type if they do not). Forecasting of propagation conditions requires forecasting the profiles of pressure, temperature, and humidity in the operations area (both over sea and over land) and forecasting of the surface wave conditions; this information is used as input for the computation of propagation properties with a mathematical model. The surface wave field affects both the propagation of ducted signals (by multiple scatter from the surface) and the detectability of SEAL surface units and/or low-flying airborne units (i.e., radar detection is a signal-to-noise problem and sea clutter is a source of noise). Because NSW operations are conducted primarily in the coastal zone, strong horizontal variations in meteorological and propagation conditions are expected. To summarize, forecasting of ducting requires an environmental forecast model of local meterological conditions to which we apply a propagation model; nowcasting may involve in situ determination of environmental data (with application of the propagation model) or some other method to infer propagation conditions directly (e. g., observations of radar sea clutter intensity as a function of range from supporting ship or aircraft).

The U.S. Navy operational forecast models in the United States operate in the classic mode: a set of data is collected, gridded at some horizontal and vertical resolution, analyzed, and used to establish an initial state of the atmosphere or ocean. The dynamic equations of the system are integrated in time on this gridded volume from the initial state to form the forecast and to derive variables that are not actually measured as part of the initial state. For global models, the data grid has about the same resolution as the grid for the model computations (except for some big holes over the oceans). For regional-scale models covering thousands of square kilometers (e.g., the continental United States), the surface data have about the same resolution as the model (with each grid cell typically covering a few hundred square kilometers), but the atmospheric profiles are much sparser—perhaps 20 model grid points for each rawinsonde. A high-resolution mesoscale model run on a coastal domain might have no operational data in its entire grid space. Such models must be nested within regional or global models that effectively provide data as evolving boundary conditions. Such high-resolution models cover a few tens of square kilometers and provide a reasonable representation of local conditions only to the extent that these conditions are dominated by the larger-scale context (e.g., nesting in the larger-scale model) and the driving force of local surface properties (surface fluxes, terrain, etc.). Synoptically driven fronts and land-sea breeze cycles are examples of phenomena that tend to be well described with this approach. To the extent that local processes are not well captured by synoptic forcing and local surface conditions, local data are needed in the mesoscale model.

Local jets, squall lines, gravity wave interactions, small orographic eddies, rainbands, fog banks, isolated thunderstorms, roll vortices, and other intermittent mesoscale phenomena are examples of processes that cannot be forecast without first ingesting local data. Even for phenomena that are well described in general without explicitly local initialization, the exact timing or structure of these events may still be too uncertain unless some local measurements are incorporated. For example, if a sea breeze switches to a land breeze three hours earlier than anticipated, ducting conditions over the ocean may be changed radically. The land-sea breeze cycle is driven by the temperature contrast between the sea and the land. The land surface temperature is critically related to soil moisture, vegetation, and cloud cover. These values represent complicated physical processes that must be accounted for correctly to obtain an accurate forecast. Furthermore, the internal parameterizations of the model must account for the uniquely inhomogeneous conditions encountered in coastal domains. This is a major issue in attempting to use models optimized for much coarser resolution.

Data from a variety of sources are required. For example, satellite data could be used but they must, by necessity, be derived from sensors with kilometer-scale horizontal resolution. Examples of potentially useful satellite sensors are IR or microwave sea surface temperature radiometers, synthetic aperture radar (SAR), and scatterometers. These data may be used in atmospheric, oceanic, or coupled ocean-atmosphere models. For example, it may be impossible to forecast a land-sea breeze transition accurately without an accurate forecast of upwelling (which can significantly alter the sea surface temperature pattern in 12 hours). The fundamental problems faced by researchers can be simply stated: What improvements in present models are necessary to realistically handle the coastal domain at such high resolution, and can such unconventional data be incorporated into an operational mesoscale model? More specific questions include the following: can conventional closure models yield reasonable coastal boundary layers in a variety of conditions; how can the basic data be processed to extract the maximum amount of information; which variables are most useful for data assimilation; how can data fields be processed for optimum incorporation into models; how can the models be modified to utilize these data fields; and what are the minimum temporal and spatial resolutions that still yield significant improvements in model analyses and forecasts?

Solutions

Planning NSW missions requires forecasts and nowcasts in the highly variable coastal region where local in situ measurements are very difficult to obtain. The solutions to this problem involve (1) improved environmental forecast models of local atmospheric conditions (especially horizontally stratified conditions such as humidity); (2) more sophisticated and more accurate signal propagation models (i.e., models that can handle horizontal inhomogeneities); and (3) innovative measurements of local atmospheric conditions.

The U.S. Navy now runs operational global (NOGAPS) and regional (NORAPS) forecast models, and these are known to be of limited value for forecasting ducting conditions in coastal areas. The Navy has an experimental high-resolution coupled ocean-atmosphere model (COAMPS) that is under development but is not operational. This model is expected to include wave forecasts. Although this is the only realistic approach to solving the NSW's ducting forecast problem, it is a long way from meeting NSW requirements. Propagation models must be able to deal with surface sea clutter and coastal terrain. Information is needed on radar scattering signatures of NSW vessels and their wakes. The working group considered the merits of a new field of research using diverse forms of information to nowcast ducting conditions (e.g., GPS [global positioning system] methods, radar or communications statistics, inverse methods).

ATMOSPHERIC VISIBILITY

Naval Special Warfare operations involve both the water and the land portions of the littoral zone. Atmospheric visibility is of crucial importance for the success of ingress or egress operations and reconnaissance. Electro-optical (EO) devices operating in the visible region (including the human eye) and the infrared are affected strongly by the propagation environment. Of special importance is the nearshore region some 10 miles either way from the shoreline, which is influenced strongly by both land and water regimes.

Mission Influence

Visibility is crucial to most aspects of NSW operations. Poor visibility can be both detrimental and beneficial, the latter especially if the enemy does not have the technology to operate under such conditions. The primary atmospheric parameter affecting visibility is aerosols. Commonly, aerosols are water droplets formed around a nucleus, but they also could be dust or smoke particles. Molecular absorption is usually not a problem in the visible wavelength band but must be considered for devices operating in the infrared bands. Turbulence and refraction can affect laser and imaging systems. Depending on the local circulation, offshore conditions should be more horizontally homogeneous and temporally stable than in-shore conditions which might be dominated by nonuniform aerosol sources, terrain-induced circulation, and solar heating. Visibility can be of special concern in the surf zone where breaking waves and wind may generate large near-surface aerosols. Usually, spatial scales of interest for EO devices are less than a few tens of kilometers. Temporal variability can be quite high and may be as short as minutes between visibility extremes. This temporal and spatial variability poses a formidable challenge to mesoscale model development.

Research Issues

Understanding and modeling of near-surface aerosols is incomplete and needs further attention. Surf aerosols close to the ocean surface are difficult to measure and are a function of both surf and wind. The chemical composition of aerosols in coastal environments is often a complex mixture of marine and continental aerosols, including industrial pollution. In aerosol models, the origin of the aerosol has to be known, which requires better characterization and parameterization of air mass characteristics.

Remote sensing techniques for aerosol extinction need to be further developed. Lidar techniques have been used to infer aerosol extinction but have not yet resulted in operationally useful instruments. Various lidar techniques for sensing aerosol extinction have to be investigated further. Satellite remote sensing techniques for inferring marine boundary-layer and extinction characteristics should also be developed.

High-resolution (e.g., models using 1 km grid sizes) mesoscale models need to address parameters important for EO propagation, such as drop size distributions and particle transport. Such mesoscale models should be part of data assimilation systems that can accept conventional (e.g., surface observations, radiosonde data) as well as unconventional (e.g., spectral moments from ground and satellite remote sensors) data.

Since NSW operations routinely take place in denied areas, satellite-sensed data are often the only real-time data sources. Over water, multi-spectral upwelling radiance can be used to infer optical depth and boundary-layer aerosol properties. Satellite sensing techniques for similar information over land should be investigated.

Sea and land background radiances must be sensed, modeled, and integrated into EO tactical decision aids for performance assessment of infrared imaging devices and night vision goggles.

Solutions

It is not possible to measure accurately the spatially and temporally variable operational environment. Even if it were, a reliable forecast capability is also needed. A data assimilation system capable of accepting a wide variety of directly and remotely sensed data with improved mesoscale and large eddy simulation (LES) models and techniques capable of integrating measured and modeled information appear to represent the best chances to improve predictions. More emphasis should be placed on predicting EO parameters in the numerical modeling area. The models need higher-resolution data input, increased ability to accept non-traditional inputs, and the ability to work over land, surf, and sea. Development and incorporation of expert systems would assist the data fusion task.

Satellite sensors provide data globally and for denied areas. For a variety of reasons, information from geostationary satellites is not fully exploited for shipboard use. With the increasingly convenient access to geostationary satellite data through the net (e.g., SIPRNET) it is possible to utilize cloud type and motion to characterize prevailing conditions and make short-term forecasts. Polar orbiters (Defense Meteorological

Satellite Program [DMSP] and, in the future the National Polar Orbiting Environmental Satellite System [NPOESS]) carry a number of profilers. Their present resolution and the impact of higher resolution on improved EO predictions should be examined. Data bases on ground cover, soil type, albedo, snow cover, rain rates, and so forth should be assembled, and techniques should be investigated to use polar orbiter sounder data in data assimilation systems. In addition to the operational military and National Weather Service satellites, the National Aeronautics and Space Administration (NASA) has existing and planned satellites that carry special sensors (one example is aerosol lidars). Data from these NASA satellites should be examined carefully for use and recommendations for future operational environmental satellites. Finally, unmanned airborne vehicles (UAVs) and covert in situ sensors may be used to sense temperature, humidity, and aerosols in denied areas.

UNDERWATER ACOUSTICS

Underwater acoustics is a pervasive issue for NSW underwater missions, especially those that take place in very shallow water. The littoral regime is a dynamic, acoustically harsh environment characterized by high reverberation, high ambient noise, and volume micro-inhomogeneities. The performance of NSW acoustic systems for detection, localization, imaging, navigation, and communications is severely affected by reverberation, attenuation, and distortion of the acoustic signals by the environment.

Mission Influence

During infiltration or exfiltration, the environment significantly affects the operation and performance of SDV obstacle avoidance and navigational sonar. Additionally, the performance of diver-held acoustic “tools” (e.g., imaging sonar) used to conduct underwater missions depends greatly on environmental conditions.

The primary navigation and detection sensor on the SDV is a high-frequency forward-looking obstacle avoidance sonar. The operation of this sonar can vary greatly, depending on the operating environment, with operating ranges typically less than design specifications. Existing mine countermeasures shallow water sonar performance prediction models could be used to provide SDV teams with a range-of-the-day prediction for mission planning. Although such models provide a rough measure of performance, they are limited by the fidelity of environmental acoustic models describing boundary interactions at high frequencies. Specific METOC products required for sonar “range-of-the-day” predictions include wind speed, bottom type, and sound velocity profile.

NSW capability to detect, classify, localize, and identify underwater threats is severely limited. These threats are usually either volume or bottom sea mines and obstacles. Bottom mines may become completely or partially buried. Currently SEAL swimmers conduct their missions using either the MK-10 magnetic locator or the AN/PQS-2A diver-portable sonar. The MK-10 has detection capability against ferrous mines, a short detection range, and no stand off localization capability. The diver must swim directly over the mine to ensure its detection. The diver-portable sonar requires the diver to discern the sonar’s aural output, and the detection performance is greatly dependent on the diver’s training, experience, and level of fatigue. Once a target is detected, the diver must swim to it for visual identification. In areas of low visibility, the diver must physically touch the object to identify major features.

The Office of Naval Research (ONR) is currently supporting the development of technology that addresses these acoustic detection deficiencies. A video representation of the AN/PQS-2A aural signals has recently been developed that offers improved detection performance. Although this has provided a quick fix to noted operational deficiencies for exposed or partially buried objects, the sonar operates in the upper end of the frequency spectrum for buried object detection, and performance against completely buried objects may be poor.

Additionally, many years of basic research in piezoelectric materials and manufacturing techniques are leading to the development of technologies that could enable fabrication of a portable underwater two-dimensional acoustic array imager. The goal is to develop a hand-held underwater device capable of at least 15 frames per second with 0.5 cm resolution at 5 m stand off ranges for positive identification and detection ranges up to 50 m.

Research Issues

NSW operations are typically conducted in shallow water littoral environments. Due to the proximity of boundaries (sea surface, seafloor) in very shallow water, underwater acoustic research issues most relevant to NSW missions include both small-scale characterization of the boundaries and the development of models for acoustic boundary interactions at high frequency.

Sea Surface Scattering

Although surface roughness and wind-generated bubbles are relevant to acoustic surface interactions, improvements to modeling the acoustical effects of bubbles constitute the most important research issue. The upper ocean boundary layer is a distinct acoustical environment in which the active hydrodynamics of the wave zone combines with the surface bubble layer to scatter, attenuate, and refract high frequency acoustic signals. Existing models for forwardscattering and backscattering treat the bubble field as a homogeneous nonrefracting surface layer. The ability to generate useful models for the prediction of high-frequency acoustic systems near this environment is limited by knowledge of the temporal and spatial size distributions of bubbles near the air-sea interface.

Bottom Scattering

Reverberation from the seafloor is often the limiting factor for detecting acoustically small targets on the seafloor. Experiments have shown considerable variability in bottom characteristics ranging from millimeter to kilometer scales and temporal variability ranging from seconds to years. In most operational cases, deterministic modeling of the acoustic scattering based on temporal and spatial variations in sediment characteristics is unrealistic. It is therefore an important research issue to determine the statistical characterization of seafloor properties and roughness that is required for physics-based modeling of acoustic scattering. Present theory and modeling techniques do not adequately allow for the heterogeneity that has been observed in seafloors.

Low Grazing Angle Penetration of Sound into the Seafloor

The acoustic detection of buried mines depends critically on the transmission of acoustic energy into the seafloor. Accurate prediction of the intensity level and spatial coherence in sediments is therefore important to the design and prediction of performance of buried mine detection systems. Some measurements have shown anomalously high penetration of sound into the seafloor for signal incident at grazing angles below the critical angle. The mechanism responsible for the observed anomalous penetration at low grazing angles is an open research issue. Hypotheses for this include generation of a Biot slow wave, scattering by roughness in the water-sediment interface, and scattering of the evanescent wave by volume inhomogeneities.

Solutions

Surface Scattering

To improve the existing understanding of issues related to acoustic surface interactions, improved descriptions of the spatial and temporal nature of the bubble field are needed. Symposium attendees identified a need for a stochastic, space-time description of the bubble field that is sufficiently complete to form the basis for acoustic surface scattering model development. For this purpose, an adequate understanding of the important environmental descriptors, in addition to wind speed, that determine the properties of the bubble field, must be developed.

Low Grazing Angle Penetration of Sound into the Seafloor

Field experiments are needed to understand the anomalously high penetration of sound into the seafloor at grazing angles below the critical angle. These experimental investigations will require burial of receivers and sources that allow for the identification and measurement of compressional, Biot slow, and shear waves.

It is essential that these acoustic experiments include sedimentologic and oceanographic measurements necessary to understand the physics of both propagation and scattering. Sedimentologic and oceanographic measurements required for understanding acoustic behavior include stereophotography of the seafloor for measuring roughness, acoustic profilers for determining layering and variability over a wide range of spatial scales, and measurements for determining sediment physical composition and behavior such as porosity, density, permeability, gas content, and shear and compressional wave velocities and attenuation.

Bottom Scattering

A promising approach to improving the accuracy of bottom reverberation modeling would be the ability to infer the relevant bottom parameters using acoustic remote sensing. However, before inverse techniques can be used reliably to rapidly determine the seafloor environment, the forward problem has to be investigated further. Contributions to scattering by roughness, volume inhomogeneities, and bubbles have not been adequately isolated and related to measured properties of the environment.

UNDERWATER OPTICS

Water clarity is a key parameter listed in the NSW Mission Planning Guide and is of concern for underwater visibility. Clear water may allow detection by sentries; highly turbid water may impede the mission through minimizing underwater line of sight or the ability to see navigational aids or dive meters. Scientific study of underwater optics focuses on spectral absorption and scattering coefficients that can be related to visibility via theory. These parameters are called inherent optical properties and are independent of the external illumination field. The inherent optical properties of the water depend on the composition of the material (phytoplankton concentration and type, organic and inorganic particles, soluble material). NSW mission planning needs for thresholds of visibility over a specified distance relate to human underwater visual perception. Visibility is related not only to the inherent optical properties but also the external illumination field; such parameters are called apparent optical properties. Details of underwater optics and its theory have been reviewed by Kirk (1994) and Mobley (1994).

Significant work has been accomplished in characterizing the various optical properties of relevant constituents that govern water clarity; in developing instrumentation for measurement of essential parameters; and in the development of models based on radiative transfer theory that can use inherent optical properties as input to predict apparent optical properties such as water clarity. The operational capability of the METOC community to support NSW operations with accurate, time-varying, local information on nearshore optics is very limited. Gross climatologies are available but cannot be adjusted at local scales or in response to wind, wave, tide, or river flow events. Expendable diffuse attenuation meters have been developed and are available for real-time assessment of local-scale optical properties. Although significant research capability, including instrumentation and modeling, is now available, the local operations of SEAL units depend primarily on reconnaissance by swimmers to assess the water clarity of targets.

Mission Influence

The mission of NSW units can be influenced strongly by the clarity of the water. In general, water clarity and visibility at the target site are of concern; the offshore visibility at the mother ship or insertion point is not of great concern and will not be discussed in detail. The critical mission thresholds included in the NSW Mission Planning Guide indicate that swimmer or SDV operations should not be conducted when water clarity allows the swimmer or SDV to be observed at depths greater than 10 feet by an individual located on the shore or on an adjacent pier or ship. Although detection in clear water is of great concern, operations conducted underwater in very turbid conditions can be adversely impacted by low visibility. NSW operators mentioned issues of visibility of the SDV control panel where extreme turbidity prevented the pilot from being able to read its speed or direction. Such circumstances could adversely impact the mission. Also, near coastal waters, rivers, and estuaries can have strongly absorbing dissolved material, even if there are few suspended particles. Such circumstances could impair the ability of an operator to discern different colors, such as colored electronic wires. Thus, knowledge of the time-varying changes in underwater optical properties could be an excellent asset in mission planning and execution.

Nearshore, Riverine, and Estuarine Optics

Water clarity can vary rapidly in the near coastal zone, within rivers, estuaries, or bays, as a consequence of tidal changes, river flow, surf action, and watershed rainfall. Furthermore, the types of optical constituents found in the nearshore region are more diverse than those offshore, because heavier sediments may remain suspended due to the greater turbulence characteristic of nearshore settings. In addition, the water column in nearshore settings typically contains higher concentrations of sediments or dissolved material from nearby terrestrial sources. Knowing the type of sediment in the surf zone, or being carried by rivers or tidal flow, is critical to defining the optical properties of the water column. For example, heavy sands may intensely scatter light but settle out quickly, whereas fine silts often have significant organic components with strong spectrally dependent absorption and can remain suspended for longer periods of time. In addition, the contribution of dissolved material to light absorption is highly variable in coastal waters. Thus, the littoral region in which NSW units operate is the most difficult part of the marine environment for making predictions about water clarity.

Research Issues

Climatologies of optics can be improved by augmenting actual ship-based optical measurements with existing ocean color satellite imagery from instruments such as the coastal zone color scanner (CZCS; Acker, in press) to get basic background information on coastal optics and their variations over time and space. Ocean color sensors on satellites or aircraft can provide estimates of the spectral attenuation coefficient, which can be related to water clarity. Unfortunately, the CZCS sensor had relatively low spatial resolution (1 km at nadir), poor temporal coverage (10 percent duty cycle over the six-year lifetime), and strong effects from bright target adjacency (e.g., land targets adjacent to water targets). Therefore, the CZCS will prove of limited use in developing refined climatologies of the nearshore, riverine, or estuarine domains of greatest interest to NSW operations. A combined use of ship observations, satellite archives (including the recent 8-month global OCTS [Ocean Color and Temperature Scanner] mission launched by the National Space Development Agency of Japan [NASDA] and the recently launched Sea-viewing Wide Field-of-view sensor [SeaWiFs] mission launched by the National Aeronautics and Space Administration [NASA]; Acker, in press), and selected deployment of aircraft sensors in regions of greatest interest would contribute to a better data base from which optical climatologies can be developed.

During actual NSW operations, existing tools developed in recent years could be utilized. Small, portable, spectral absorption, attenuation, and reflectance meters, useful for defining detailed in situ optical properties at the local scale, including vertical profiles, are available. Expendable attenuation meters have been developed by the Navy. Aircraft-mounted sensors have the advantage of higher spatial and spectral resolution and flexibility of deployment at the regional or local scale. They could be appropriate for broader surveys but retrieve only surface information. Laser-based systems can be used to estimate backscatter of aquatic particles, and the fluorescence induced by these systems allows for estimates of chlorophyll and soluble organic matter concentrations. Such systems are limited to surface measurements along the flight line and have very restricted ability to resolve vertical profiles. If deployed via aircraft, they would provide survey lines of important parameters. These systems can be flown in day or night and under clouds, a flexibility that passive ocean color sensors do not have. Combined with optical models, this suite of measurement tools could be used to provide local-scale information on the vertical and horizontal variability of water clarity, and other features of significance to NSW (Plate III). If hydrodynamic models of the region of interest were available, the optical data and models could be incorporated to provide time-dependent predictions of the region. These potential capabilities require collaboration of scientists from different disciplines (e.g., optical, biological, and physical oceanographers and modelers).

Solutions

Various disciplines have been developing advanced measurement tools and models of relevance to predicting the time and space mission-critical parameters included in the NSW Mission Planning Guide. Furthermore, advances in battery systems, submarine propulsion, and microelectronic control systems have resulted in underwater vehicles that are now capable of executing underwater surveys. The technology exists and the modeling ability is evolving rapidly. It is therefore possible to envision the development of prototypes, within several years, of multi-sensor remote vehicles, which would be capable of providing detailed optical and hydrographic surveys of a region without jeopardizing NSW personnel. Ultimately, networks of such systems might be deployed within a region to provide real-time data that can be used in data assimilation schemes and models. This type of system holds the promise for real-time prediction of the suite of parameters that are of critical concern to NSW operations.

WATER TEMPERATURE

Except in very rare circumstances, the temperature of the ocean decreases with depth. This decrease is often fairly rapid near the surface, where sea surface temperature (SST) can be influenced strongly by solar radiation (Weller and Taylor, 1993). A typical depth-versus-temperature plot shows a surface layer on the order of a few meters to a few tens of meters thick. This layer is commonly referred to as the mixed layer because surface winds tend to keep the waters in this interval well mixed and essentially isothermal (Knauss, 1978). The base of this mixed layer is referred to as the thermocline. Conditions in the mixed layer can vary drastically from those within the water column beneath the thermocline. In waters above the continental shelf (where terrestrial influences are most pronounced), turbidity, salinity, and the number and types of marine organisms can vary drastically across the thermocline.

Mission Influence

Water temperature can have direct effects on NSW operations since low water temperatures can degrade diver performance and lead to hypothermia. Consequently, operators are instructed to wear dry suits in water temperatures less than 60^{o} (Fahrenheit). Because of the effects of water temperature and the location of the thermocline on a variety of important mission parameters, understanding the thermal structure of a water body in which a mission is to take place is of extreme importance (Fig. 4-5).

Research Issues

As indicated in Tables 4-1 through 4-3, SEAL operators need access to reliable information about SST and the depth and nature of the thermocline. In coastal settings where the mixed layer extends to the seafloor, SST measurements are of greatest value. Historic data incorporated into static climatologies can give mission planners and operators some indication of the conditions in which they may have to work (Fig. 4-5). However, these climatologies may be insufficient to meet all mission planning needs, especially in situations where temperature can influence a number of other parameters, such as bioluminescence, or where turbidity or other values vary greatly across the thermocline. At present, NSW mission planning needs may be met by remote sensing capabilities when these assets are available. Water temperature (surface and at depth) can be measured using a combination of satellites, ship-mounted thermisters, surface moorings (in some locations), and drifters (in some settings;

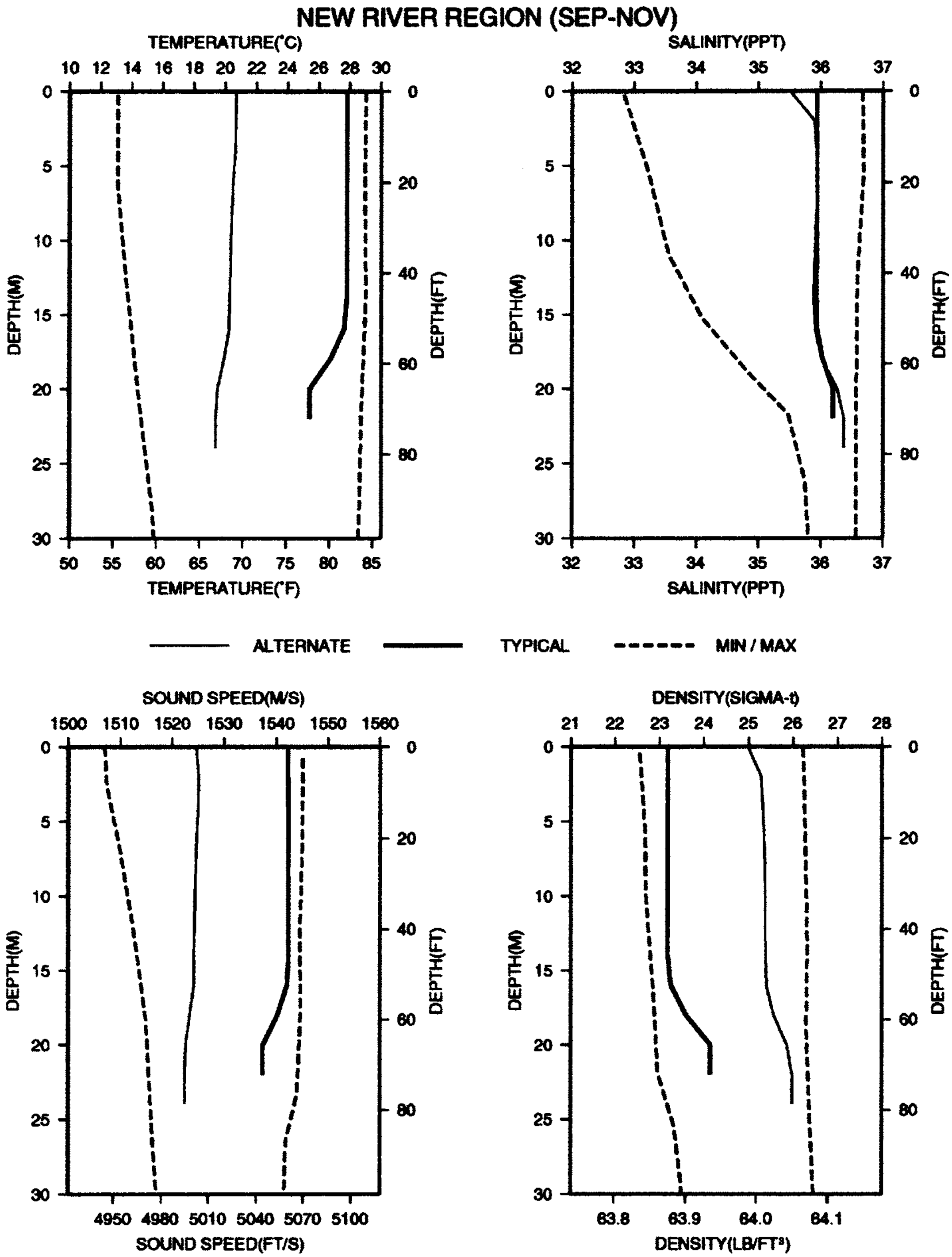


FIGURE 4-5 Water temperature, salinity, sound velocity, and density plots for waters off New River Inlet, North Carolina taken from Plate I. STOIC courtesy of the Warfighting Support Center, Naval Oceanographic Office (NAVOCEANO), Stennis Space Center, Mississippi.

Weller and Taylor, 1993). However, limitations exist in terms of both the length of time required to collect adequate data and the spatial resolution possible by any subset of the methods listed. Predictive capabilities are also limited by the validity of the initialization parameters (e.g., errors in the input data can be propagated through the model) and the spatial resolution of the model. Local and often unknown variations in bathymetry and other input variability can drastically affect the reliability of any predictive method.

5

Summary and Discussion

Researchers can best support Naval Special Warfare (NSW) by increasing the knowledge and understanding of the environment in which NSW personnel operate. Only through such research efforts can much-needed predictive models and observational techniques for the environment be developed. The environmental parameters that directly affect NSW operations are discussed in the NSW Mission Planning Guide or the Naval Oceanographic Office (NAVOCEANO) Special Tactical Oceanographic Information Chart (STOIC) included as Plate I. The symposium provided a unique opportunity for researchers to understand the impact of these environmental parameters on NSW operations, discuss the present capabilities to predict and observe these parameters, and explore future possibilities.

In addition to identifying many specific research challenges, participants in the various working groups also discussed NSW personnel as potential users and collectors of environmental information. For example, as combat decision making is transferred farther forward and increasingly requires near-real time data processing, analysis, and synthesis (e.g. the Rapid Environmental Assessment loop diagrammed in Fig. 3-2), it follows that NSW personnel will require more thorough understanding of these processes. Similarly, SEALs and other NSW personnel (if properly trained) could make observations of important environmental variables at the spatial and temporal scales needed to parameterize boundary conditions and initial conditions for high-resolution models with very little sophisticated equipment. Indeed, by making these measurements a part of NSW training exercises now, it seems that a wealth of information from a variety of well-known coastal locations could be compiled in the near-term, which would rapidly advance understanding of littoral processes. It was not clear to the steering committee to what extent such education is presently incorporated into BUD/S training or what opportunities exist to incorporate greater education about relevant natural processes into what is already a very rigorous training regimen. Perhaps enhancing educational opportunities through a program of continued training within the NSW organization would be more practical.

Table 5-1 summarizes the symposium committee's evaluation, based in part on symposium discussions, of the present, near-term, and far-term capabilities for reasonably delivering the type, accuracy, and lead time needed for each of the environmental parameters. Research capability implies a predictive model or a measurement method available to researchers but not yet used for Navy operations. Whether a capability could make the transition to operational use or how long that transition would take is not addressed. Instead, Table 5-1 lists research capabilities that are presently in place or will be in place within one year ("now"); capabilities that can reasonably be

TABLE 5–1 Environmental Support Capabilities

Parameter	Current METOC Capability To Support NSW	Research Capability Now	Research Capability Next	Research Capability Future
Lunar illumination	S	S	S	S
Water temperature				
Surface	S	S	S	S
At depth	I	A	A	S
Bathymetry				
Offshore	A	A	S	S
Nearshore	I	I	A	A[a]
Waves	A	A	S	S
Tides	A	A	S	S
Cloud ceiling	A	A	S	S
Bottom composition	A	A	S	S
Surf	A	A	A	S
Currents				
Offshore	A	A	A	S
Nearshore	I	A	A	S
Visibility	A	A	A	S
Toxins, dangerous animals	A	A	A[b]	A[b]
Lightning	I	A	S	S
Internal waves	I	A	S	S
Winds	I	A	A	S
Precipitation (liquid)	I	A	A	S
Water clarity (turbidity)	I	A	A	S
Humidity[c]	I	A	A	S
Biofouling	I	A	A	S[b]
Beach trafficability	I	I	A[b]	S[b]
Bioluminescence	I	A	A	A

Note: I = inadequate; A = adequate; S = satisfactory
[a] = Mission specific; [b] = Not currently being pursued; [c] = Impact on communications as related to ducting or vulnerability.

expected to be developed by researchers, for researchers, in two to three years (“next”); and models and measurement capabilities that will be developed in three to five years or longer (“future”). The superscript “a” identifies scores that are mission and environment specific; for example, support may be adequate in some ocean environments but not in others. For instance, the required resolution of bathymetry measurements for NSW support is different for platforms traveling across the inner shelf than it is for platforms crossing the surf zone. In the former scenario, the platform is affected by the presence of shoaling banks (scales of kilometers) that may modify local currents and wave heights. In the latter scenario, the platform is affected by the presence of sand bars and troughs (scales of several tens of meters) that may stop a boat abruptly in mid surf zone. Superscript “b” indicates research topics that do not appear to be pursued currently by ONR-funded scientists. The parameters assigned to the satisfactory category under future research capabilities shows the optimism of the symposium committee about research gains, given adequate effort.

The minimal support historically given for research in direct support of NSW is evident in Table 5-1. Only the present capabilities to provide lunar luminescence and surface water temperature were obviously satisfactory for present NSW needs. The present capability to provide nine important parameters was seen as adequate but not optimal, and the present capability to provide twelve other parameters was seen as inadequate. In many instances, the knowledge or technologies needed to improve the METOC capability to provide needed information already exists.

Table 5-2 provides information about the types of technologies that are or could be available to METOC personnel supporting NSW operations. This table, also organized by environmental parameter, lists the NSW platforms that are affected along with the NSW Mission Planning Guide's critical threshold value (above which a platform should not be used in the mission). Listed on Table 5-2 under the heading "Current METOC Capability to Support NSW" are technologies currently available to Navy METOC personnel to predict and observe each parameter. For instance, the METOC capability to provide surface water temperature seen as adequate to meet NSW needs (Table 5-1), is based on IR satellites and surface buoys. Alternatively, the current METOC capability for predicting and observing bioluminescence (coming from sparse, historical, climatological records) was viewed to be inadequate (Table 5-1).

The NSW-related research challenge is to identify deficiencies in the basic knowledge and address approaches that can build upon that knowledge to yield both improvements and new approaches to the prediction and observation of environmental parameters critical to NSW operations.

IMPORTANT CHALLENGES

NSW-related research challenges are formidable. NSW operations place spatially and temporally difficult demands on environmental models and observational systems. Models and observations that were successfully used in support of anti-submarine warfare (ASW) operations cannot be easily ported to support NSW operations. The problem is both one of scales and environmental complexity. NSW operations require environmental information on a local scale (resolution on the scale of hundreds of meters), through many different types of environments (shelf, inner shelf, nearshore, inlet, harbors, rivers). In addition, for mission planning purposes, the environmental parameters need to be predicted five to seven days in advance. In many situations, the choice of infiltration and exfiltration routes and platforms cannot change hours or even days before deployment.

The Navy has acknowledged that new, creative approaches to collecting, assilimating, and providing environmental information should be considered if NSW is to be adequately supported. The complexity of the environment, the required resolution of information, and the demand of the mission timeline make it impossible for most parameters to be predicted or modeled using a single approach. Leaders of the METOC community recognize the need to develop and deploy hybrid platforms with different types of sensors for local and regional observations. As envisioned, these platforms would use model results to improve their sensing of the environment and the models will need to use the platform data to improve their predictions. Fortunately, many of NSW needs appear to be shared by other communities within the operational Navy. For example, previous symposia in this series have identified a need for enhanced capabilities to predict coastal conditions such as clouds and visibility, humidity, and nearshore sea state for strike warfare (NRC 1992, 1996) and a greater understanding of littoral processes for coastal ASW and amphibious operations (NRC 1992, 1994). These common needs suggest that by supporting basic and applied research in a number of areas relevant to NSW, enhanced capabilities could be achieved that would benefit a wide spectrum of end users within the Fleet.

Listed under the research capabilities (now, next, and future) in Table 5-2 are the types of technology that the committee believes, based on the symposium discussions and their own experience, are presently available to researchers, or that will be available to researchers in two to three years, or in three to five years or longer. This table provides an educated guess as to how research may evolve. The outlook is promising. However, how well the NSW challenge is met will depend on the Navy's focus and the researcher's appreciation and understanding of that focus.

TABLE 5.2 Mission-Sensitive Environmental Parameters

Parameter	Platform (mission critical threshold)	Current METOC Capability To Support NSW
Bathymetry	Pervasive	• Databases • Charts • Echo-sounders • Hydro recon • Airborne laser (LABS) • AUV side-scan (soon)
Bioluminescence	• SDV, swimmers (10-ft in water visibility, in ambient light)	• Sparse climatology
Currents	• SDV (>2.5 kt) • Swimmers (>1 kt)	• Tide Charts • X-T surf-zone long-shore currents (Surf Manual) • Feature tracking of SAT images • Coastal models
Waves and surf	• SDV (>3 ft) • CRRC, parachute (>4 ft) • Swimmer (>5 ft) • MATC, PBL, PBR (>6 ft) • RIBS, PB, HSB, MK V (>10 ft) PC (>8-12 ft)	• Global WAM • Regional WAM • Laser wave heights (airborne) • Breaker type (Surf Manual) • SAT wave-height fields (>10 km scales) • SAT wave-directions (deep wtr) • SAT surf-zone patterns
Tides	• SDV (>2 ft range, if LW depth <8 ft	• Tide charts • X-T models • Expendable tide gauge (soon)
Water temperature	• SDV, swimmer (<60^0 F)	• SAT IR (surface) • Tailored, local summaries (based on models, data, etc.) • XBT • Sensors on operational platforms • Drifting buoys
Winds	• Parachute (>13-40 kts, height dependent) • PB, MATC, PBL, PBR, RIBS, PC, MK V (>35 kts)	• NORAPS/AMPS • Mobile teams • SAT winds (clouds, SSMI) • T-DROP (soon) • AEGIS Tactical Wx Radar (soon)
Precipitation (liquid)	• Parachute (>0.1 inch per hour)	• NOGAPS/AMPS • Direct observations • Weather radars • AEGIS Tactical Wx Radar (soon)

Research Capability Now	Research Capability Next	Research Capability Future
• Jet skis • AUV sensing	• Hyperspectral inversion of depths • Wave celerity-based inversions • SAR-pattern based inversions • U/W rem sensing (i.e., BPS)	• Data-fused celerity-based inversions • SAT versions of airborne methods
• HIDEX (also at NAVOCEANO) • Direct measurements of emission	• Short-term temporal predictability • AUV sensors	• Spatial predictability • AUV networks
• HF radar (shore) • Drifters • Moored Doppler • X-T nearshore models over complex bathymetry	• Interferometric SAR • HF radar (ships) • VHF radar • AUV survey • Extended feature tracking (e.g., ARGUS, SATs) • U/W rem sensing (i.e., BPS) • Data assimilation • X-Y-T nearshore models	• Hi-res littoral models • Hi-res direct measurements • X-Y-Z-T nearshore models
• REF/DIF • Expendable pitch-roll buoys	• Bousinesq models • Data assimilation	• Combined air-sea-waves models (currents, waves) • Hi-res littoral models
• TOPEX-based offshore models • X-Y-T nearshore models driven by offshore	• X-Y-Z-T nearshore models driven by offshore • Photo-grammetric interpretation of imagery	• Hi-res littoral models
• Coastal circulation models • Small temp sensors • Airborne IR • AUV sensors	• Closer-to-shore models • AAV IR • Subsurface inferences from SAT-based data fusion	• Hi-res littoral models • AUV networks
• NSCAT directional winds • On-site hi-res sensors	• Drifters w/wind • COAMPS, ETA, MM5, etc. (coupled air-sea models)	• Higher resolution, but local coverage • SAT polarmetric winds • Patterns from SAR
• AEGIS radar	• TRMM • AEGIS extensions • COAMPS, ETA, MM5, etc. (coupled air-sea models)	• Hi-res models, assimilating • SAT and radar improvements

(continued)

TABLE 5.2 Continued

Parameter	Platform (mission critical threshold)	Current METOC Capability To Support NSW
Thunderstorms and lightning	• Parachute (closer than 1 mi)	• Direct observations (EM, visible)
Visibility	• Parachute (<3 nmi horizontally) • Mission accomplishment (e.g., target lasing)	• Vis/aerosol models • Direct observations (instrument, eye)
Cloud ceiling	• Parachute (variable needs; aircraft height dependent)	• Laser ceilometer • NOGAPS/AMPS
Internal waves	• SDV (existence in operational area)	None
Water clarity (turbidity)	• SDV, swimmer (>10 ft visibility from surface, in ambient light)	• Climatology • Expendable k-meter (XKT)
Lunar illumination	• SDV, CRRC, swimmer (full moon, clear sky)	• Ephemeris • SAT cloud observations
Humidity	• CRRC (surface ducts for E-M)	• T-DROP • NOGAPS/AMPS • SAT water vapor • COAMPS (soon)
Bottom composition	• SDV • Mission related	• Sparse climatology • Geological inferences • In situ observations
Beach trafficability	• Mission related	• Sparse climatology • Geological inferences • In situ & remote observations (SAT) • USMC/USA expertise/input
Biofouling	• Mission related	• Sparse climatology
Toxins, dangerous marine organisms	• SDV, swimmers (not known)	• Climatology for some regions

NOTE: AAV = autonomous airborne vehicle; AUV = autonomous underwater vehicle; BPS = Beach Probing System; COAMPS = coupled ocean-atmosphere model; CRRC = Combat Rubber Raiding Craft; EM = electromagnetic; EOS = Earth Observing System; HF = high frequency; HIDEX = High-Intake Defined Excitation System; HSB = High Speed Boat; IR = infrared; LABS = Laser Airborne Bathymetry System; LW = low water; MATC = Mini-Armored Troop Carrier; NAVOCEANO = Naval Oceanographic Office; NOGAPS/AMPS = Navy Operational Global Atmospheric Prediction System; NORAPS/AMPS = Navy Operational Regional Atmospheric Prediction System;

Research Capability Now	Research Capability Next	Research Capability Future
None	None	• EOS lightning sensors
• Laser refractometers, transmissometers	• Improved visibility models	• Hi-res littoral models
None	• COAMPS, ETA, MMT, etc. Coupled air-sea models)	None
• In situ or remote measurements • Statistical climatologies • X-Z-T generation models	• Regional databases • X-Y-Z-T generation models	• Regional prediction models • Hi-res littoral models
• Ocean color (rem sensing) • In situ transmissometer (moored, profiled)	• AAV hyperspectral • AUV transmissometer	• SAT hyperspectral • Hi-res littoral models • AUV networks
Same	Same	Same
• Hi-res radiosondes	• COAMPS	• Hi-res models, assimilating • Advanced SAT sensors, for model assimilation
• Direct measurement • Acoustic inversions	• Inferences from fused geological and other data (acoustic, multi-spectral) • Acoustic inversions from operational platforms	• Predictive models • AUV-based acoustic inversions • Data fusion and inversion
• Airborne observations	• Inferences from fused geological and other data (EM, SAR, multi-spectral) • Geological inferences fused with nearshore oceanographic climatology	• Inferences from SAT/airborne SAR, hyper-spectral sensing, etc., fused with geological, and oceanographic information • Expert system for estimates, inferences
• Direct measurement • Uncollated data	• Tailored estimates from ambient conditions • Collated data	• Expert system for estimates, inferences
• Direct measurement • Uncollated data	• Tailored estimates from ambient conditions • Mitigation strategies • Collated data	• Expert system for estimates, inferences

NSCAT = NASA Scatterometer; PB = Patrol Boat; PBL = Light Patrol Boat; PBR = River Patrol Boat; PC = Patrol Craft; REF/DIF = refraction and/or diffraction; RIBS = Rigid-Hull Inflatable Boats; SAR = synthetic aperture radar; SAT = satellite; SDV = SEAL Delivery Vehicle; SSMI = Special Sensor Microwave Imagers; TOPEX = Ocean Surface Topography Experiment; TRMM = Tropical Rainfall Measuring Mission; T-DROP = Tactical Dropsond; USA = U.S. Army; USMC = U.S. Marine Corps; U/W = underwater; VHF = very high frequency; WAM = Wave Model; XBT = expendable bathythermograph

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APPENDIXES

APPENDIX A

Symposium Program

SYMPOSIUM ON OCEANOGRAPHY AND NAVAL SPECIAL WARFARE

Naval Amphibious Base
Coronado, California
February 17-20, 1997

Monday, February 17

Symposium registration and security check-in

1600 - 1900: Security Check-In and Registration
Lobby, Bachelor Officers Quarters (BOQ), Building 504

Tuesday, February 18

The Symposium series was developed, in part, to facilitate interaction between the scientist and the warfighter. Therefore, Day 1 of the Symposium emphasizes interaction with SEAL team members. Small groups of attendees, led by SEAL team members, will participate in a series of activities designed to increase awareness of the challenges involved in Naval Special Warfare (including interactive demonstrations).

0700 - 1200: Security Check-In and Registration (for late arrivals)
Lobby, Bachelor Officers Quarters (BOQ), Building 504

0700 - 0745: Continental Breakfast
Club Coronado

0745: Buses depart for Special Boat Squadron 1

PLENARY SESSION I - INTRODUCTION AND OVERVIEW

Special Boat Squadron 1 Classroom

0800 - 0810: Welcome and Administrative Remarks

0810 - 0850: Commander, Naval Special Warfare Command (CNSWC) Command Brief, *Building 209*

SEAL DEMONSTRATIONS/DISCUSSIONS

ALPHA and BRAVO Platoons

0900 -1005: SEAL Static Display and Basic Underwater Demolition/SEAL (BUD/S) Training Demonstration, *Combat Training Tank*

CHARLIE and DELTA Platoons

0900 - 1005: MK-V and Rigid Hull Inflatable Boat (RHIB) Display and Demonstrations *Special Boat Squadron 1 Pier*

ALPHA and BRAVO Platoons

1015 - 1115: MK-V and Rigid Hull Inflatable Boat (RHIB) Display and Demonstrations *Special Boat Squadron 1 Pier*

CHARLIE and DELTA Platoons

1015 - 1115: SEAL Static Display and BUD/S Training Demonstration *Combat Training Tank*

1130: Buses depart from Combat Training Tank and Special Boat Squadron 1 for *Club Coronado*

1145 - 1245: Lunch, *Club Coronado*

PLENARY SESSION II - Operational Examples of METOC Needs

Auditorium, Expeditionary Warfare Training Group Pacific, Building 401

1300 - 1630: **NSW Guest Speakers:**
CDR Toohey, *NSWG-2*
LCDR Dietz, *ST-5*
LT Deluna, *SBU-12*
SKCM Favor, *SBU-20*
LT McNabb, *NSWDEVGRU*

1750: Buses depart from BOQ to *Beach Pavilion*

ICEBREAKER

1800 - 2000: Catered Reception, *Beach Pavilion*

2015: Buses return to BOQ

WEDNESDAY, FEBRUARY 19

Day 2 introduces the attendees to the mission needs of typical SEAL operations. Small groups will participate in interactive mission-planning exercises and concurrent working groups to identify the types of environmental data needed and gain an understanding of the means presently available to collect and disseminate that data.

0700 - 0745: Continental Breakfast, *Club Coronado*

PLENARY SESSION III - Naval Special Warfare and Meteorology and Oceanography (METOC)

Auditorium, Expeditionary Warfare Training Group Pacific, Building 401

0800 - 0825: Navy Basic Research Supporting METOC
Dr. T. Kinder
0825 - 0850: Navy Basic and Applied Research Supporting NSW
Dr. T. Swean
0850 - 0915: The Oceanographer's Program in Support of Nearshore Warfare
Dr. E. Whitman
0915 - 0940: Littoral Remote Sensing
Dr. F. Herr
0940 - 1005: NAVOCEANO Warfighting Support Center
CAPT T. McPherson
1005 - 1030: Coffee Break

1030 - 1130: **Mission Planning Overview**

1030 - 1100: Mission Planning Overview
Mr. Steve Wells, *CNSWC Training Officer*
1100 - 1110: Swimmer Delivery Vehicle (SDV) Mission Planning Brief
LT McKinney, *NSWG-2*
1110 - 1120: Special Boat Unit (SBU) Mission Planning Brief
LT Deluna, *SBU-12*
1120 - 1130: SEAL Mission Planning Brief
CWO2 Kelz, *ST-1*

1145 - 1245: **Lunch - *Club Coronado***
Science and Nearshore Warfare Since World War II
Dr. Douglas Inman, *Scripps Institution of Oceanography*

1250: Buses depart Club Coronado for Special Boat Squadron One &
North Island Naval Air Station (NAS)

MISSION PLANNING AND METOC SUPPORT EXERCISES

ALPHA and BRAVO Platoons

1300 - 1530: **Mission Planning Exercise**
Mr. Steve Wells, *CNSWC Training Officer*
Special Boat Squadron One, Bldg. 209

1545: Buses depart Special Boat Squadron One for North Island NAS

1600 - 1830: **METOC Support Exercise**
CDR Tim McGee, *Commanding Officer NAVPACMETOCFAC*
Naval Pacific Meteorology & Oceanography Facility, North Island

1845: Buses depart North Island for BOQ

CHARLIE and DELTA Platoons

1300 - 1530: **METOC Support Exercise**
CDR Tim McGee, *Commanding Officer NAVPACMETOCFAC*
Naval Pacific Meteorology & Oceanography Facility, North Island

1545: Buses depart North Island NAS for Special Boat Squadron One

1600 - 1830: **Mission Planning Exercise**
Mr. Steve Wells, *CNSWC Training Officer*
Special Boat Squadron One, Bldg. 209

1845: Buses depart Special Boat Squadron One for BOQ

THURSDAY, FEBRUARY 20

The final day focuses on lessons learned and the identification of ways to increase the ability of the ocean science community to support Naval Special Warfare. Attendees will be re-organized into topical working groups to provide an opportunity for colleagues to participate in a dialogue directed at problem solving. By identifying research priorities, the attendees can help shape the future of oceanographic and meteorological support for this elite fighting force.

0700 - 0745: Continental Breakfast, *Club Coronado*

MISSION PLANNING PLATOON WORKING GROUPS (CONCURRENT)

Expeditionary Warfare Training Group Pacific, Building 401

0800 - 0930: **Mission Brief Backs - *Lessons Learned***
- Assess critical “requirements”
- Identify challenges for Technical Working Groups

0930 - 1000: Coffee Break

PLENARY SESSION IV - PLATOON WORKING GROUP REPORTS

Auditorium, EWTGP, Building 401

1000 - 1130: Introduction to Critical Topics for Technical Working Groups

1145 - 1245: Lunch, *Club Coronado*

CRITICAL ISSUES TECHNICAL WORKING GROUPS (CONCURRENT)

Expeditionary Warfare Training Group Pacific, Building 401

1300 - 1545: **Response to the Challenge - *Future Paths***

- Bioluminescence & Toxins
- Currents & Tides
- EM/IR “Above Surface” Signal Propagation and Coastal Winds
- EO/Acoustic “Below Surface” Signal Propagation
- Waves & Surf

PLENARY SESSION V

Auditorium, EWTGP, Building 401

1600 - 1730: Reports from Technical Working Groups and Symposium Wrap-Up

1730: **ADJOURN**

APPENDIX B

Participants

Robert Arnone, Naval Research Laboratory, Stennis Space Center, Mississippi
Joseph Atangan, U.S. Naval Observatory, Washington, D.C.
David Aubrey, Woods Hole Oceanographic Institution, Massachusetts
H.G. (Jim) Bancroft, U.S. Special Operations Command, MacDill AFB, Florida
Reginald Beach, Oregon State University, Corvallis
Stephen Boss, University of Arkansas, Fayetteville
Melbourne Briscoe, Office of Naval Research, Arlington, Virginia
Rodney Buntzen, Spectral Information Tech Applications Center, Fairfax, Virginia
Kendall Carder, University of South Florida, St. Petersburg
Casey Church, Naval Research Laboratory, Stennis Space Center, Mississippi
Tony Clark, North Carolina State University, Raleigh, North Carolina
M. Elizabeth Clarke, Ocean Studies Board, National Research Council, Washington, D.C.
Joan Cleveland, Office of Naval Research, Arlington, Virginia
Daniel Crute, Coastal Systems Station, Panama City, Florida
Peter Dahl, Applied Physics Laboratory, University of Washington, Seattle
William Dally, Florida Institute of Technology, Melbourne
Robert Dean, University of Florida, Gainesville
Don DelBalzo, Naval Research Laboratory, Stennis Space Center, Mississippi
Ken Demoyse, Joint Special Operations Command/WX, Fort Bragg, North Carolina
Scott Dixon, Naval Air Station, New Orleans, Louisiana
Thomas Drake, North Carolina State University, Raleigh
John Dudinsky, Coastal Systems Station, Panama City, Florida
Michael Duensing, Commander, Naval Special Warfare Development Group, Virginia Beach, Virginia
Billy Edge, Texas A&M University, College Station
Stephen Elgar, Washington State University, Pullman
Chris Fairall, National Oceanographic and Atmospheric Administration Environmental Technology Laboratory, Boulder, Colorado
Gary Faltinowski, CNMOC, Stennis Space Center, Mississippi
Mark Favor, SKCM, Special Boat Unit 20, Norfolk, Virginia

Anthony Fraser-Smith, Stanford University, California
Carl Friedrichs, College of William and Mary, Gloucester Point, Virginia
Richard Gasparovic, Applied Physics Lab, Johns Hopkins University, Laurel, Maryland
Mark Geiger, Naval Oceanographic Office, Stennis Space Center, Mississippi
Ralph Goodman, Pennsylvania State University, State College
Morgan Gopnik, Ocean Studies Board, National Research Council, Washington, D.C.
Gus Grussendorf, Naval Surface Warfare Center, Dahlgren, Virginia
Robert Guza, Scripps Institution of Oceanography, La Jolla, California
Ken Hamilton, U.S. Special Operations Command, MacDill AFB, Florida
Richard Hayes, U.S. Naval Observatory, Washington, D.C.
Frank Herr, Office of Naval Research, Arlington, Virginia
Richard Hodur, Naval Research Laboratory, Monterey, California
Robert Holman, Oregon State University, Corvallis
Thomas Hopkins, North Carolina State University, Raleigh
Douglas Inman, Scripps Institution of Oceanography, La Jolla, California
Scott Jenkins, Scripps Institution of Oceanography, La Jolla, California
Bruce Johnson, Naval Explosive Ordnance Disposal Technology Division, Indian Head, Maryland
David Jones, FLENUMMETOCCEN, Monterey, California
Henry Jones, Naval Postgraduate School, Monterey, California
James Kaihatu, Naval Research Laboratory, Stennis Space Center, Mississippi
Timothy Keen, Naval Research Laboratory, Stennis Space Center, Mississippi
Thomas Kinder, Office of Naval Research, Arlington, Virginia
David Koebel, Special Boat Unit 22, Naval Support Activity, New Orleans, Louisiana
Jeff Ladouce, CNMOC, Stennis Space Center, Mississippi
David Lapota, Naval Research and Development, San Diego, California
Thomas Lippmann, Scripps Institution of Oceanography, La Jolla, California
William Little, U.S. Pacific Fleet, Pearl Harbor, Hawaii
Joseph Lopes, Coastal Systems Station, Panama City, Florida
Steve Martin, U.S. Naval Observatory, Washington, D.C.
Sheryl McCarthy, U.S. Naval Observatory, Washington, D.C.
Jack McDermid, Naval Research Laboratory, Stennis Space Center, Mississippi
Tim McGee, Naval Air Station, North Island, San Diego, California
Robert McNabb, Commander, Naval Special Warfare Development Group, Virginia Beach, Virginia
Terry McPherson, Naval Oceanographic Office, Stennis Space Center, Mississippi
Chiang Mei, Massachusetts Institute of Technology, Cambridge
Gregory Mitchell, Scripps Institution of Oceanography, La Jolla, California
Peter Mitchell, Spectral Information Technical Applications Center, Fairfax, Virginia
Curtis Mobley, Sequoia Scientific, Mercer Island, Washington
Bruce Morris, Naval Special Warfare Command, San Diego, California
Edward Mozely, Naval Research Laboratory, Stennis Space Center, Mississippi
Stewart B. Nelson, Consultant, New Windsor, Maryland
Greg Neuschafer, Office of Naval Research, Arlington, Virginia
Joan Oltman-Shay, University of Washington, Seattle
Rich Paulus, NCCOSC, San Diego, California
Steve Payne, Office of Naval Research, Arlington, Virginia
Lawrence T. Peter, Commander, Naval Special Warfare Development Group, Virginia Beach, Virginia
David C. Pitcher, U.S. Special Operations Command, MacDill Air Force Base, Florida
Steve Ramberg, Office of Naval Research, Arlington, Virginia
Mike Richardson, Naval Research Laboratory, Stennis Space Center, Mississippi
Jeff W. Rish, Coastal Systems Station, Dahlgren Division, Panama City, Florida

Angel R. Rivera, Naval Oceanographic Command, Stennis Space Center, Mississippi
Tim Schnoor, U.S. Naval Observatory, Washington, D.C.
Clara Shockley, National Security Office, National Research Council, Washington, D.C.
Rob Simmons, Naval Explosive Ordnance Disposal, Tech Division, Indian Head, Maryland
Malcolm L. Spaulding, University of Rhode Island, Narragansett
Richard W. Spinrad, Consortium for Oceanographic Research and Education, Washington, D.C.
Richard W. Sternberg, University of Washington, Seattle
Mike Stewart, CNMOC, Stennis Space Center, Mississippi
John M. Stroud, Naval Special Warfare Command, San Diego, California
Ib A. Svendsen, University of Delaware, Newark
Tom Swean, Office of Naval Research, Arlington, Virginia
Edward Thornton, Naval Postgraduate School, Monterey, California
Ron Tipper, Office of Naval Research, Arlington, Virginia
Paul E. Tobin, Oceanographer of the Navy
Doug Todoroff, Office of Naval Research, Arlington, Virginia
John Vesecky, University of Michigan, Ann Arbor
Linwood Vincent, Office of Naval Research, Arlington, Virginia
Phil Vinson, Office of the Oceanographer of the Navy, Washington, D.C.
Christopher Von Alt, Woods Hole Oceanographic Institution, Massachusetts
Dan Walker, Ocean Studies Board, National Research Council, Washington, D.C.
Keith Ward, Office of Naval Research, Arlington, Virginia
Douglas D. Warner, USS Typhoon, Fleet Post Office, Ammunition Ship (AE)
Glen H. Wheless, Center for Coastal Physical Oceanography, Norfolk, Virginia
Edward Whitman, Office of the Oceanographer of the Navy, Washington, D.C.
Edith A. Widder, Harbor Branch Oceanographic Institution, Fort Pierce, Florida
Kevin Williams, Applied Physics Lab, University of Washington, Seattle
Jody Wood, Coastal Systems Station, Panama City, Florida

Appendix C

Acronyms and Units

AAV	autonomous airborne vehicle
ACTD	Advanced Concept Technology Demonstration
ASVAB	Armed Services Vocational Aptitude Battery
AUV	autonomous underwater vehicle
BPS	Beach Probing System
BUD/S	Basic Underwater Demolition/SEALs
CFP	ciguateria fish poisoning
CNSWC	Commander Naval Special Warfare Command
COAMPS	coupled ocean-atmosphere model
CONOPS	concept of operations
CRRC	Combat Rubber Raiding Craft
CQC	close quarters combat
CZCS	coastal zone color scanner
DA	direct action
DDS	Dry Deck Shelter
DMSP	Defense Meteorological Satellite Program
DoD	Department of Defense
ECM	electronic countermeasures
EM	electromagnetic
EO	electro-optical
EOD	Explosive Ordnance Disposal
EOS	Earth Observing System
ERDAS	Earth Resources Data Analysis System
FF2	automated pressure-activated rip cord
FNMOC	Fleet Numerical Meteorology and Oceanography Center
GIS	Geographic Information System
GPS	global positioning system
HAHO	high altitude, high opening (parachute)
HALO	high altitude, low opening (parachute)

HF	high frequency
HIDEX-BP	High-Intake Defined Excitation Bathyphotometer
HSB	High Speed Boat
HYDICE	Hyperspectral Digital Imagery Collection Equipment
IBT	Internet-based training
IR	infrared
LABS	Laser Airborne Bathymetry System
LALO	low-altitude, low-opening (parachute)
LES	large eddy simulation
LIDAC	Littoral Data Consolidation
LRS	littoral remote sensing
LW	low water
LZ	landing zone
MATC	Mini-Armored Troop Carrier
METOC	meteorology and oceanography
MSLO	Mass Swimmer Lockout
MLML	Mixed Light-Marine Layer & Project
MOORDEX	Moored Excitation System
N096	Office of the Oceanographer of the Navy
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
NAVMETOCCOM	Commander Naval Meteorology and Oceanography Command
NAVOCEANO	Naval Oceanographic Office
NAVSPECWARCOM	Naval Special Warfare Command
NAVSPECWARGRU	Naval Special Warfare Group
NCDU	Naval Combat Demolition Unit
NEC	Naval Enlisted Classification
NIPRNET	Navy Internet Protocol Router Network
NOAA	National Oceanic and Atmospheric Administration
NOGAPS	Navy Operational Global Atmospheric Prediction System
NORAPS	Navy Operational Regional Atmospheric Prediction System
NPOESS	National Polar Orbiting Environmental Satellite System
NRAD	Naval Research and Development
NRL	Naval Research Laboratory
NSCAT	NASA Scatterometer
NSTS	Nearshore Sediment Transport Study
NSW	Naval Special Warfare
NSWC	Naval Special Warfare Center
OCTS	Ocean Color and Temperature Scanner
ONR	Office of Naval Research
ONR 32	ONR's Department of Ocean, Atmosphere and Space Science and Technology
ONR 321OE	ONR's Ocean Engineering and Marine Systems Program
OSB	Ocean Studies Board
PB	Patrol Boat
PBL	Light Patrol Boat
PBR	River Patrol Boat
PC	Patrol Coastal
REA	rapid environmental assessment
REF/DIF	refraction and/or diffraction wave propogation model
REMUS	Remote Environmental Monitoring Units

RHIB	Rigid-Hull Inflatable Boat
S&T	science and technology
SAR	synthetic aperture radar
SAS	Special Air Service
SAT	satellite
SBS	Special Boat Service
SBUs	Special Boat Units
SCUBA	self-contained underwater breathing apparatus
SDV	SEAL Delivery Vehicle
SeaWiFs	Sea-viewing Wide Field-of-view Sensor
SEALs	Sea, Air, and Land (teams)
SIPRNET	Secure Internet Protocol Router Network
SOF	Special Operations Forces
SOFPARS	Special Operations Forces Planning and Rehearsal System
SR	Special Reconnaissance
SSMI	Special Sensor Microwave Imagers
SST	sea surface temperature
STOIC	Special Tactical Oceanographic Information Chart
SULAC	Submarine Insertion Loitering Area Chart
TENCAP	Tactical Exploitation of National Capabilities
T-DROP	Tactical Dropsond
TOPEX	Ocean Surface Topography Experiment
TOWDEX	Towed Excitation System
TRMM	Tropical Rainfall Measuring Mission
UAVs	unmanned aerial vehicle
UBA	underwater breathing apparatus
UDTs	Underwater Demolition Team
USA	United States Army
USMC	United States Marine Corps
USSOCOM	United States Special Operations Command
UUVs	Unmanned Underwater Vehicle
UV	ultraviolet
UW	unconventional warfare
VDR	visual detection ratio
VHF	very high frequency
VSB	visit board searches
WAM	Wave Model
WHOI	Woods Hole Oceanographic Institution
WSC	Warfighting Support Center

Appendix D

Office of Naval Research Program Contacts

ONR Program	ONR Team Leader	Phone	Email
Primary Support			
Coastal Dynamics	Dr. Tom Kinder	703-696-1206	kindert@onr.navy.mil
Ocean Engineering and Marine Systems	Dr. Tom Swean	703-696-4025	sweant@onr.navy.mil
Secondary Support			
Biological and Chemical Oceanography	Dr. Ron Tipper	703-696-4415	tipperr@onr.navy.mil
Environmental Optics	Dr. Steve Ackleson	703-696-4732	ackless@onr.navy.mil
Marine Geology and Geophysics	Dr. Joe Kravitz	703-696-4070	kravitj@onr.navy.mil
Marine Meteorology and Atmospheric Effects	Dr. Scott Sandgathe	703-696-0802	sandgas@onr.navy.mil
Ocean Modeling and Prediction	Dr. Tom Curtin	703-696-4119	curtint@onr.navy.mil
Physical Oceanography	Dr. Lou Goodman	703-696-4112	goodmal@onr.navy.mil
Remote Sensing and Space	Dr. Bob McCoy	703-696-8699	mccoyr@onr.navy.mil
Tactical Sensing Support	Dr. Randy Jacobson	703-696-4121	jacobsr@onr.navy.mil
Pizoelectric Materials	Dr. Wally Smith	703-696-0284	smithw@onr.navy.mil
Autonomous Robotics	Dr. Tom McKenna	703-696-4503	mckennt@onr.navy.mil
	Dr. Teresa McMullen	703-696-3163	mcmullt@onr.navy.mil
Neural Networks	Dr. Tom McKenna	703-696-4503	mckennt@onr.navy.mil
Hydrodynamic Impact Theory	Dr. Ed Rood	703-696-4305	roode@onr.navy.mil
Biomaterials	Dr. Keith Ward	703-696-0361	wardk@onr.navy.mil
Micro-Porous Polymer Membranes	Dr. Hal Guard	703-696-4311	guardh@onr.navy.mil
Phase-Change Materials	Mr. Joe Brumfield	703-696-4319	brumfij@onr.navy.mil
Manufacturing Technology	Mr. Steven Linder	703-696-8482	linders@onr.navy.mil

SEAL team members discuss the various roles they fill and the equipment they use during an interactive briefing for symposium attendees. Photo courtesy of the Office of the Oceanographer of the Navy.

BUD/S trainees practice drownproofing skills during exercises intended increase their confidence in the water. Photo courtesy of the Office of the Oceanographer of the Navy.

BUD/S trainees involved in a series of training activities at the Combat Training Tank, Naval Amphibious Base, Coronado, California. Photo courtesy of the Office of the Oceanographer of the Navy.

Symposium attendees prepare to board a Mark V Special Operation Craft (SOC) at the Special Boat Squadron docks, Coronado, California. Photo courtesy of the Office of the Oceanographer of the Navy.

Symposium attendees enjoy a tour of the interior of a Mark V SOC. Photo courtesy of the Office of the Oceanographer of the Navy.

Symposium attendees prepare for a “boat ride” aboard a 30 m rigid hull inflatable boat (RIB) at the Special Boat Squadron docks, Coronado, California. Photo courtesy of the Office of the Oceanographer of the Navy.

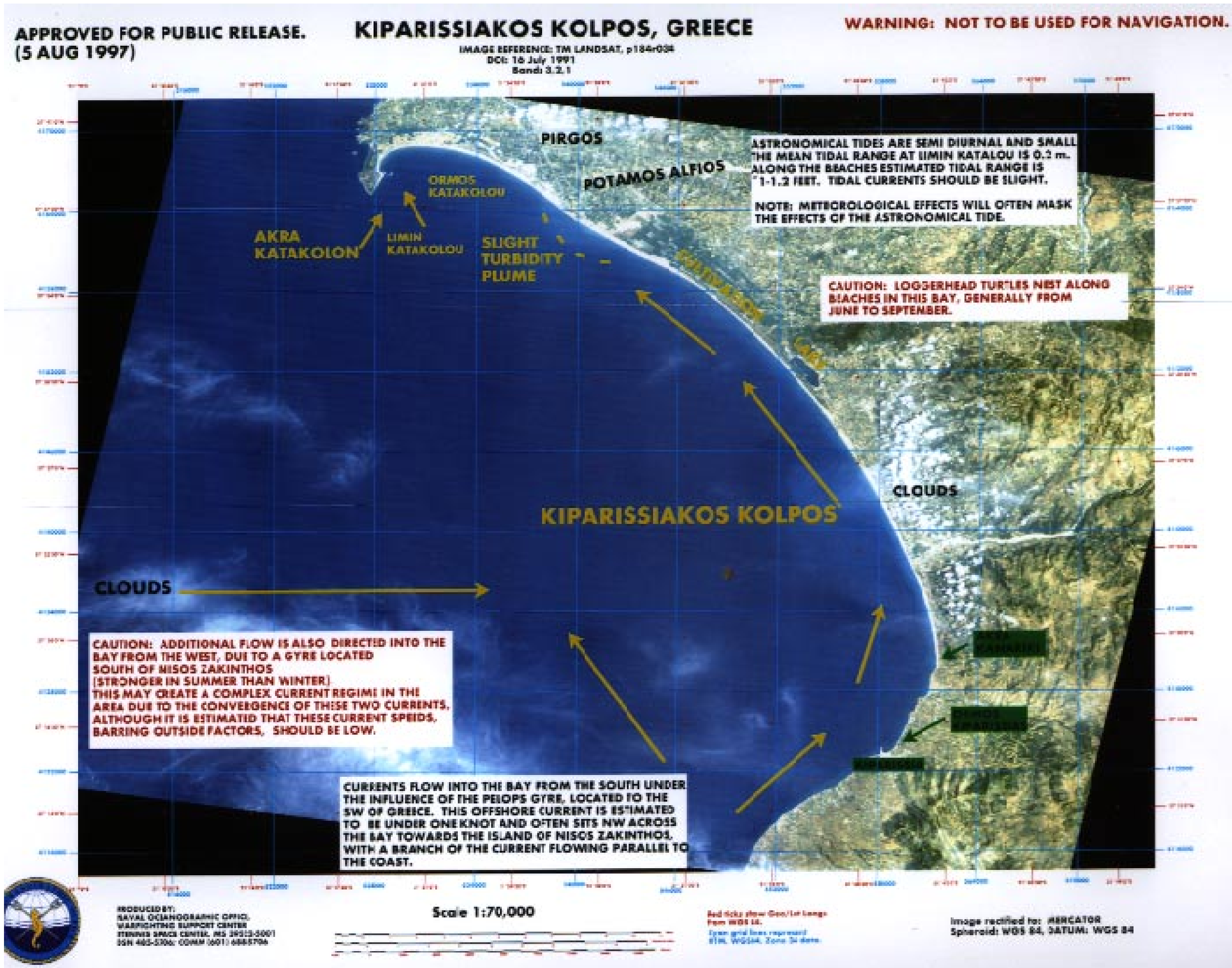

Plate II LANDSAT image of Kiparissiakoas Kolpos, Greece annotated by the Warfighting Support Center for use as an example of the type of remotely sensed information commonly supplied NSW mission planners. Image courtesy of the Warfighting Support Center, Naval Oceanographic Office (NAVOCEANO), Stennis Space Center, Mississippi.

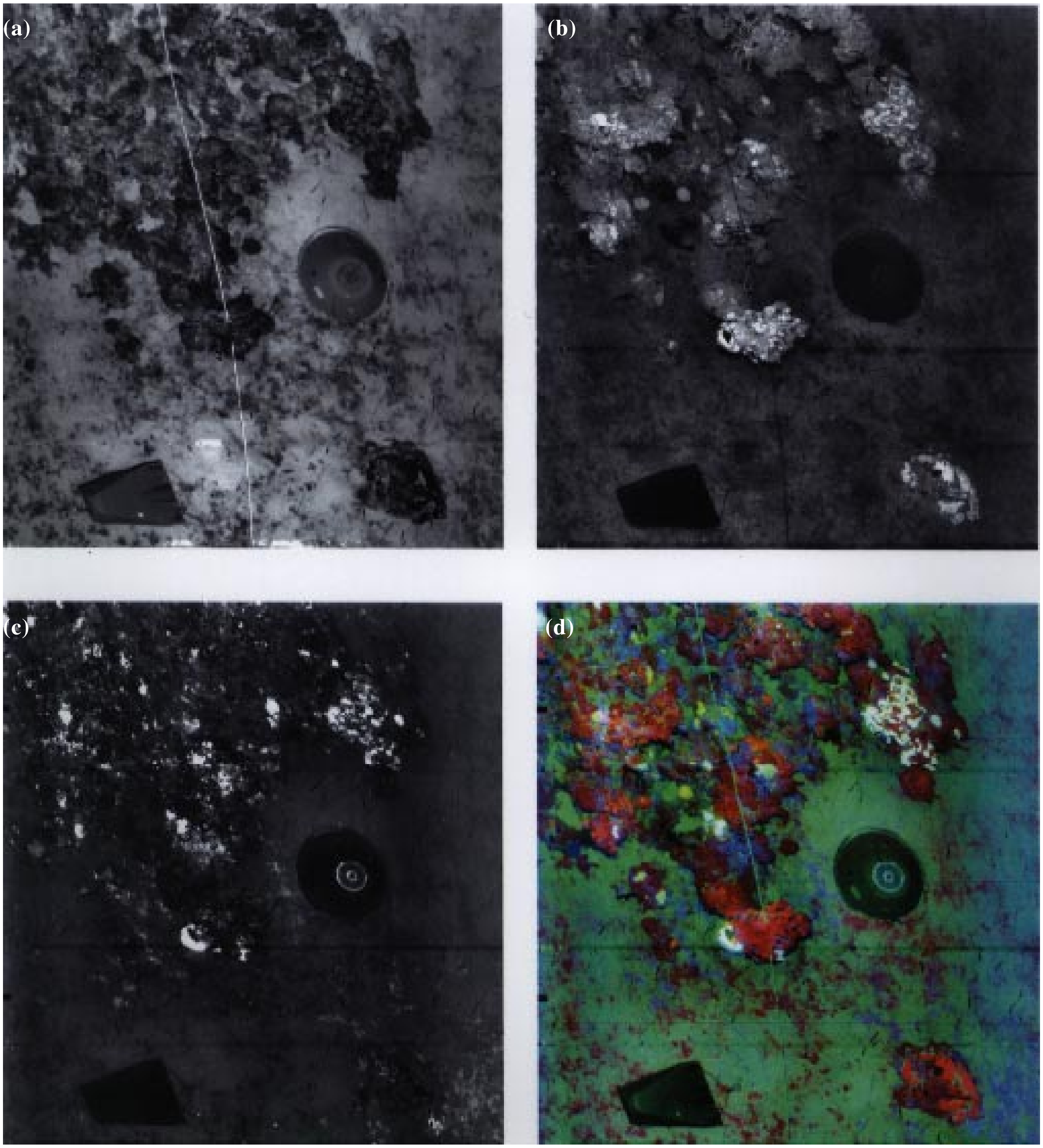

Plate III Comparison of four images (scale is 1:25) of a section of sea bed using (a) open channel (elastic scattering) imaging, (b) red fluorescence imaging, (c) yellow fluorescence imaging, and (d) pseudocolor fluorescence imaging. The elastic scattering image simulates the results of a standard monochromatic laser line scan. In the three fluorescence images, the color and sand fluoresce strongly, while the man-made objects block the fluorescence signal and appear dark. Consequently, the fluorescence signal has greater utility for discriminating between natural materials (suach as sand or coral) and man-made materials (such as antipersonnel mines). Images courtesy of the Naval Special Warfare Center, Coastal Systems Station.