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ENVIRONMENTAL FACTORS AFFECTING MILITARY OPERATIONS IN THE LITTORAL BATTLESPACE

The changing world situation is causing the Navy to shift from open-ocean warfighting to joint operations conducted in the littoral battlespace. This battlespace encompasses a complex coastal environment with highly dynamic oceanographic and meteorological processes that can affect military operations in ways not seen in the open ocean. The coastal environment and its effects on the military can be described as a complex series of interactions between bathymetry, oceanography, meteorology, and man-made influences. Specific examples are given of important features and their effect on the various phases of an amphibious operation. The article concludes with a discussion of several new methods of measuring and predicting these features that are being developed and applied by the Navy.

INTRODUCTION

The world is rapidly changing, forcing the Navy and other services to rethink their roles and missions. The strategic direction envisioned for the Navy is a shift away from open-ocean warfighting toward joint operations conducted from the sea with the Marines, Air Force, Army, and Coast Guard. The new littoral battlespace has two regional components: a seaward segment, comprising the area from the open ocean to the shore, that must be controlled to support operations ashore; and a landward segment, comprising the area inland from the shore, that can be supported and directly defended from the sea.[1]

This littoral battlespace encompasses an extremely complex coastal environment. In coastal regions, the proximity of the land, the shallow water depths, and the influence of rivers and weather systems combine to produce significant environmental changes in both the oceanography and meteorology. These changes occur over much shorter spatial and temporal scales than those seen in the open ocean. The interaction between the land and the ocean also creates features in the coastal environment that have no counterpart in the open sea.

Coastal variability can both help and hinder military operations. The purpose of this article is to provide an overview of the complexity of these environmental interactions in the littoral zone and their potential effect on military operations. Our intent is not to provide a detailed treatment of the physics of the coastal environment; instead, we emphasize representative coastal features and processes and their consequences on military operations.

We will further restrict attention to Navy support of amphibious operations rather than address the full range of important military actions that might occur in the littoral battlespace. Key components of this amphibious assault would be preliminary data gathering, mine clearing, the amphibious landings, and maintenance of air and sea superiority in the battlespace surrounding the operation. Maintaining sea superiority also includes antisubmarine warfare (ASW) to prevent attack of the support fleet by enemy submarines. Special warfare operations before the landing could also be part of the activity.

The coastal environment will be discussed in four major sections, each limited to a few key, representative processes and the influence of those processes on amphibious operations. The first section examines coastal bathymetry, followed by sections on some significant oceanographic and meteorological features unique to the coastal regime. The fourth section considers anthropogenic or man-made influences. We conclude the article by examining means of measuring and predicting important features of the coastal environment.

BATHYMETRY

The presence of land and shallow water depths near the coast are directly responsible for much of the environmental variability occurring in the coastal region. The extent of this region is best seen in Figure 1, which shows the worldwide coverage of the continental shelf in red, extending out from the coast to a depth of 200 m. The yellow region shows the area of the adjacent continental slope where the ocean depths then rapidly fall to 2400 m, leading into the deep ocean basins.

In many areas (e.g., off the coast of China), the continental shelf can extend hundreds of miles offshore. In such areas, the littoral battlespace could be confined entirely to shallow water. A more typical littoral battlespace, however, has both shallow- and deep-water areas, such as the northern Arabian Sea and the entrance to the Persian Gulf, shown in the expanded view of Figure 2. A task force could easily be sited in the deep water of the northern Arabian Sea to support mine-clearing operations in the shallow entrances of the Persian Gulf.

In general, the coastal ocean floor is not a gently sloping, homogeneous surface but often shows a rapid change from one type of material to another with a wide variety of relief. Figure 3 shows the range of bottom types that occur in the Strait of Sicily, with regions characterized by

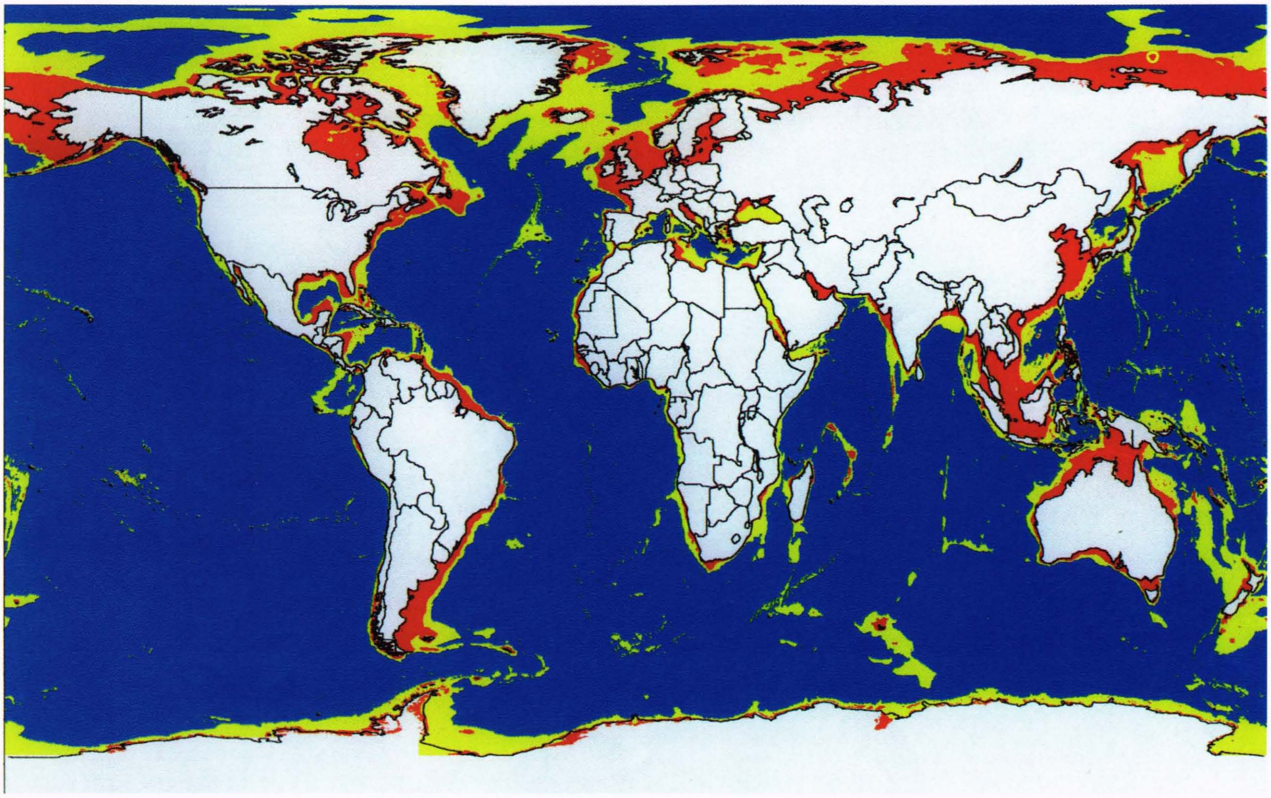

Figure 1. Worldwide distribution of ocean depth regimes. The continental shelf is shown in red, corresponding to depths shallower than 200 m. The continental slope covers the depth band from 200 to 2400 m and is shown in yellow. Areas with depths greater than 2400 m are shown in blue.

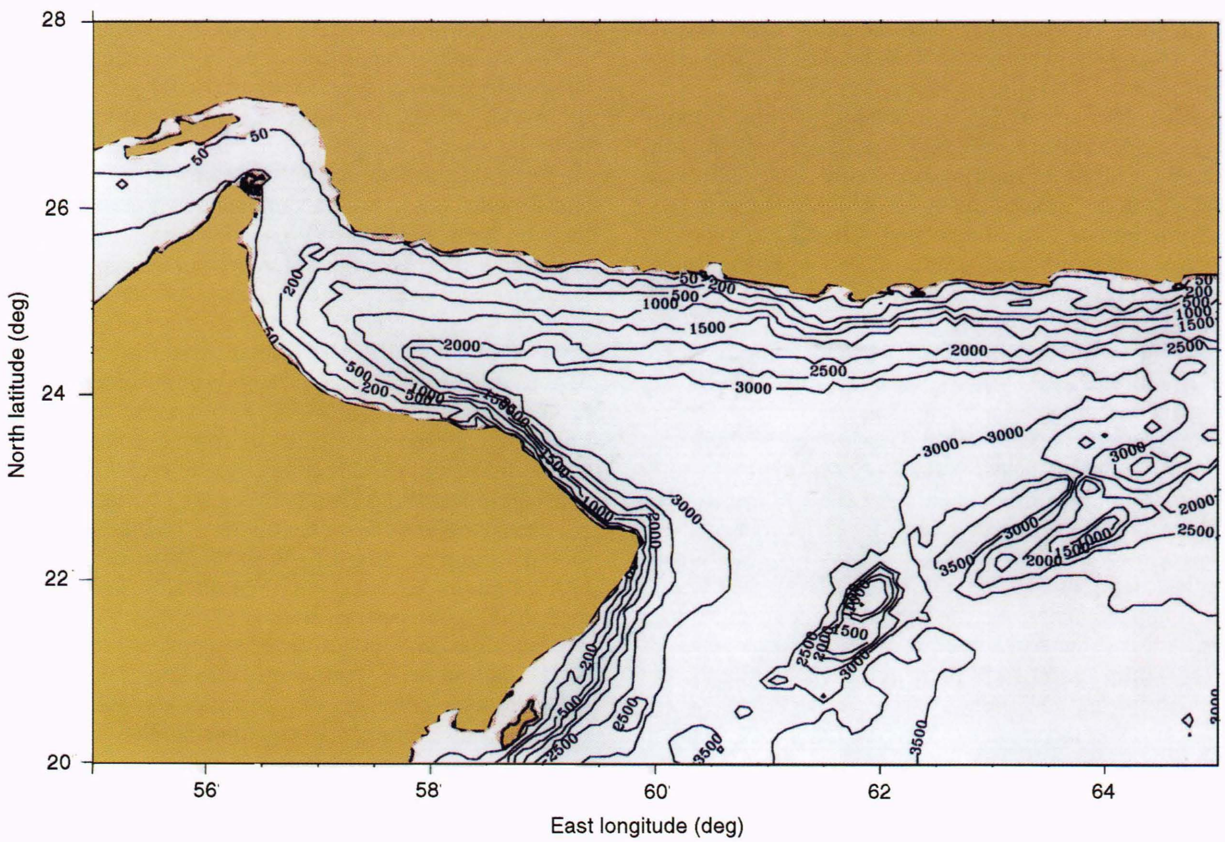

Figure 2. Bathymetric chart of the Gulf of Oman and the northern Arabian Sea. Depth contours are in meters. This region encompasses both deep-water areas and extensive shallow areas in the Strait of Hormuz (upper left).

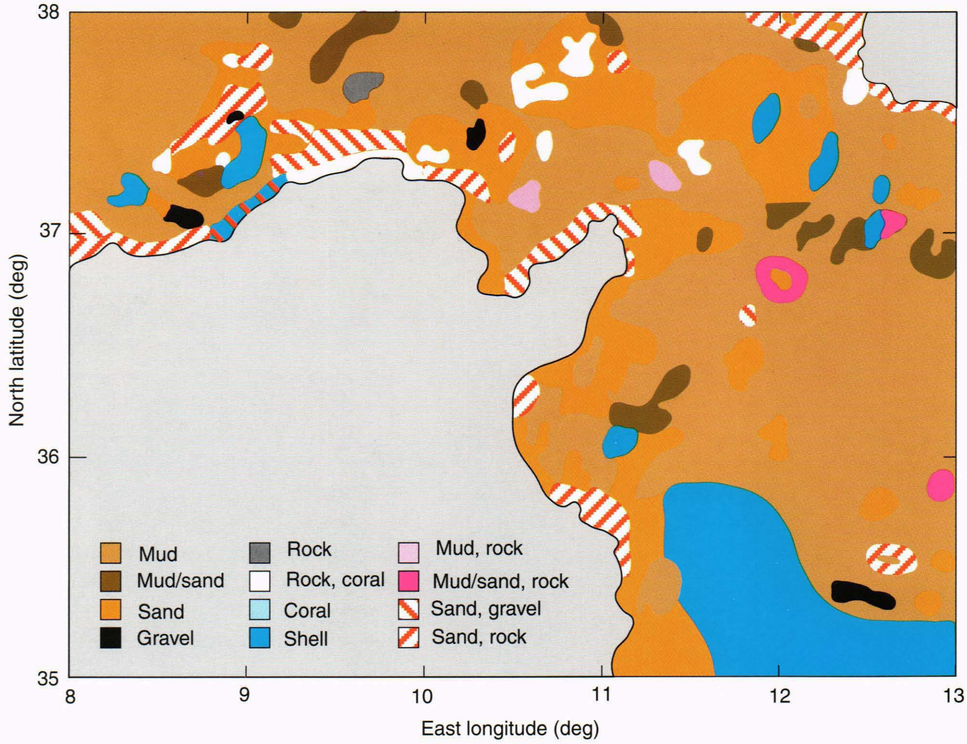

Figure 3. Bottom composition and distribution in the Strait of Sicily (courtesy of the U.S. Naval Oceanographic Office).

a mud composition rapidly changing to regions characterized by sand or sand and gravel. Similar variability in composition is frequently seen in many other coastal areas around the world, with soft, muddy bottoms adjacent to sandy, gravelly, or rocky regions.

Such bottom variability can complicate mine-hunting operations, which are a necessary prelude to amphibious operations. Bottom mines can easily sink into soft, muddy bottoms, concealing them from mine-hunting systems that rely on optical detection. Conversely, on rocky bottoms, variable bottom scattering can significantly degrade the performance of mine-hunting sonars. In shallow, sandy areas, wave motion and currents may cover many bottom mines with a layer of sand, again reducing the effectiveness of optical mine-hunting systems. An additional complication in shallow, sandy areas is wave breaking on the beach, which may suspend enough sand and fine sediment in the water column to significantly reduce visibility, further degrading the performance of optical mine-detection systems for both bottom and moored mines. In regions with a highly variable bottom composition, a single mine-hunting technique or system may be inadequate to provide a mine-free route from deep water to the landing zone. A detailed knowledge of bottom composition and a depiction of the bottom would be essential in identifying optimum routes to clear and in determining the best bottom mine-hunting systems to use.

The shallow water depth and highly variable bottom composition also complicate the ASW problem of protecting the battleforce from enemy submarines, and degrade the performance of weapons systems such as torpedoes. Shallow water depth can cause high levels of bottom scattering in active sonars, and the acoustic loss associated with bottom-interacting paths will cause high transmission loss in both active and passive sonar systems.

The variable composition of the bottom can also cause large changes in sonar performance in only short distances. In addition, the proximity of the bottom to the surface creates a sound channel that results in an optimum frequency for acoustic propagation (see the article by Boyles and Biondo, this issue). Examples of shallow-water effects on sonar performance are shown in Figures 4 and 5. Figure 4 illustrates the differences in transmission loss that can occur over short distances. Differences of 10 to 20 dB are evident for paths separated by only 10° or 20° in the southwest quadrant. Similar variability occurs with bottom scattering. Figure 5 shows bottom-scattering levels at a single location (40°N, 72°W) in 57 m of water. Each trace is the composite of four separate acoustic beams emitted in the directions shown. Differences of 15 to 20 dB in scattering level between the two sets of beams are clearly evident, associated with a change in average look direction of only 45°. With this kind of variability in transmission loss and bottom scattering, accurate prediction of sonar performance is extremely difficult, requiring large amounts of detailed geoacoustic data.

The shallow-water bathymetry also affects nonacoustic systems. The presence of magnetic anomalies in the Earth's crust generally results in much higher noise levels in MAD (magnetic anomaly detection) sensor systems in shallow water. These MAD noise levels can also vary significantly from one shallow-water area to another. Current flowing past bottom features that extend near the surface (e.g., underwater hills) can also produce hydrodynamic disturbances such as internal waves, which may

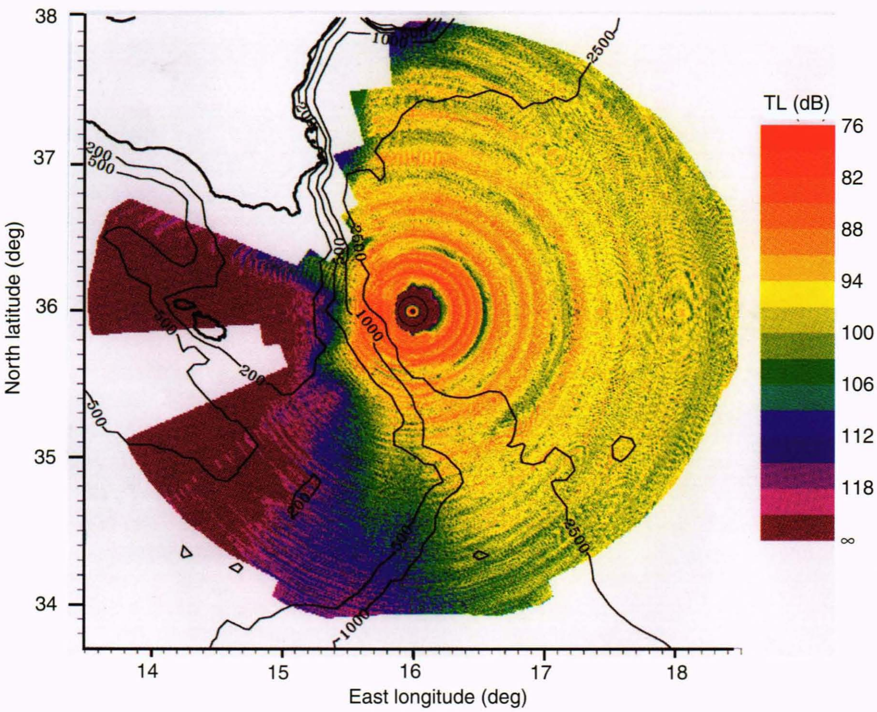

Figure 4. Shallow-water transmission loss (TL) from source to target southeast of Sicily in the Mediterranean during January using historical oceanographic data. (Source frequency = 250 Hz, source depth = 183 m, and receiver depth = 91 m. Depth contours are in meters.)

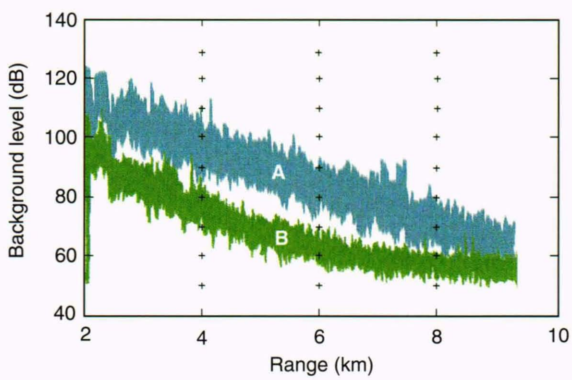

Figure 5. Bottom scattering at 40°N, 72°W. Trace A corresponds to the overlay of four acoustic beams on the bearings of 245°, 255°, 265°, and 275°. Trace B corresponds to the overlay of four acoustic beams along the bearings of 200°, 210°, 220°, and 230°.

mask or simulate some submarine signatures. Often tidal flow over underwater features such as shelves has produced large trains of internal waves, which in turn produce highly visible surface disturbances.

The ocean bathymetry relief near the coast produces its own effect on military operations. In many regions, the continental shelf is not a smooth, gently sloping bottom, but rather has numerous furrow-like cuts, often called "submarine canyons," that can extend into quite shallow water.[2] The coastline itself can contribute to an uneven topography; headlands and promontories jut out and intermix with shallow bays and coastal indentations. These coastal features translate into a subsurface relief of ridges and valleys running out from the shore that tend to focus or defocus ocean-surface waves approaching the beach. Since surface waves slow down as they enter shallow water (where the depths are comparable to their wavelength), the waves will refract toward the subsurface ridges and away from the subsurface canyons and valleys. This focusing results in higher sea states near the headlands and lower sea states in the shallow bays and coastal indentations, as shown in Figure 6. This focusing may affect the preferred landing zones for amphibious operations or for covertly putting special forces ashore.

Perhaps the most visible effect of the coastal bathymetry is manifested through the tides. Regions with a large tidal range and shallow, sloping, offshore bathymetry will have a long distance between the low- and high-water points. Some areas may have offshore obstructions such as coral reefs that are too shallow for landing craft at low tide. Accurate tide prediction is critical in planning amphibious operations under such conditions. Tidal heights are affected by the actual bathymetry, currents, winds, surf, and so on. For example, strong onshore winds or heavy surf can increase the expected tidal levels in a region, whereas strong offshore winds can have the opposite effect.

Inaccurate tidal predictions or incomplete knowledge of underwater obstructions can leave untracked landing craft stranded a long distance from the beach, resulting in unnecessary additional exposure of troops and materiel to enemy fire. This problem is accentuated when a region has both a small tidal range and underwater obstructions close to the surface, offering a small margin for clearance. Such a problem occurred during the Marine landings at Tarawa in the Pacific Ocean during World War II; many of the larger landing craft were stranded on coral reefs 300 yards from the beach, resulting in additional casualties.[3]

OCEANOGRAPHY

Oceanographic behavior in the coastal zone is characterized by several physical mechanisms that show great variability in spatial and temporal scales. These scales range from fairly local effects such as beach erosion and currents in the surf zone, which vary over periods of hours, to large-scale effects such as interactions with the open ocean along the edge of the continental shelf, which vary over periods of days and longer. The environmental features that most affect military operations such as ASW or mine-clearing involved in an amphibious landing, however, are the sound-velocity profile (SVP) structure of the water column, water clarity, and coastal currents. The following discussion will concentrate primarily on some key processes that affect these parameters.

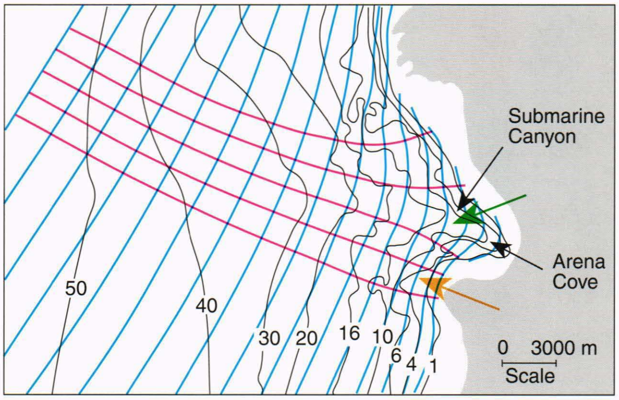

Figure 6. Bathymetric refraction of surface waves approaching a coast, with the wave refracted toward the coastal headlands and away from the coastal embayments. Depth contours (black curves) are in meters. Red lines are the propagation direction of wave fronts coming from an offshore direction for 12-s waves. Blue lines represent the corresponding wave fronts. Green arrow shows an area in which a divergence of the propagation direction produces low waves. Orange arrow shows an area in which convergence of the propagation direction produces high waves. (Reproduced from Bowditch, N., *American Practical Navigator,* H. O. Publication No. 9, Government Printing Office, Washington, D.C., 1966.)

A major feature of the coastal environment is the influx of fresh water from rivers and marshes. About 3.6×10^{13} m^3 of fresh water, equal to a cube 18 nmi on a side, flows into the coastal zone around the world per year.[4] Depending on the volume of river flow, this fresher water usually does not spread out uniformly but forms a plume as it enters the coastal environment, with portions pinching off to form lenses of fresher water dispersed through the coastal water.[5] This fresh water can significantly affect the SVP as it spreads out over the saltier coastal water, producing a shallow surface duct over the top 5 or 10 m of the water column. Such effects are particularly noticeable near large rivers during the spring melt runoff. In northern coastal areas, the inflowing fresh water is often much colder than the coastal water, further affecting the SVP.

Rivers also carry large loads of suspended sediment into the coastal zone, which can significantly reduce the optical clarity of the water column. Currents parallel to the coast, including tidal currents, can carry these river outflows up or down the coast, distributing their effect over large segments of the coastal regime. Figure 7 shows a shuttle photographic image in the visible band of the sediment plume associated with the Po River in Italy.

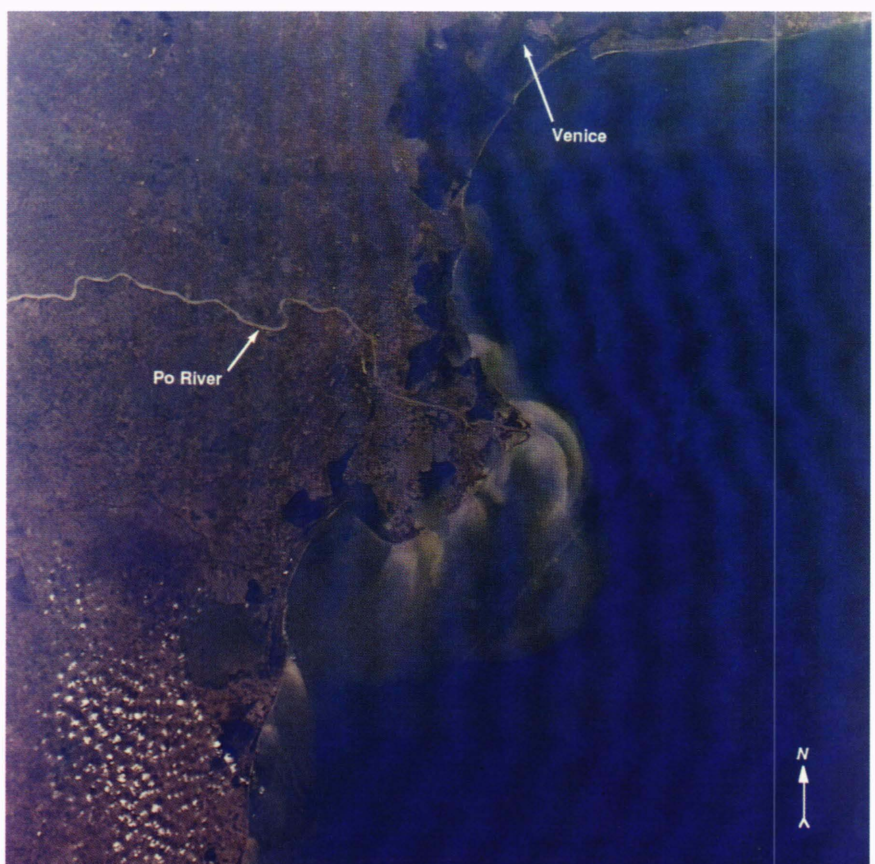

Figure 7. Sediment plume from the Po River, Italy, carried south by the coastal current. The distance from the mouth of the Po River to Venice is 35 miles. (Reproduced from *Oceanography from Space*, Office of Naval Research, Washington, D.C., Jul 1989.)

Currents in the coastal environment are driven by many processes depending on geographic location, such as wind patterns or interactions with offshore current systems like those in the Gulf Stream off the East Coast of the United States. One common source of near-coastal currents is the tidal cycle, which can produce strong tidal currents (up to several knots), depending on interactions with the coastal topography. Such tidal currents play an important role in the mixing and advection of different water masses within the coastal regime. Depending on their strength, such currents can affect the landing or recovery of special forces before an invasion, slowing the progress of small, manually propelled craft or carrying them down-current from the desired landing or recovery site.

Another major feature of the coastal regime is cold, deeper ocean water brought to the surface by upwelling. The upwelling process typically results when the wind blows along the coast and comes about by interactions between the wind-driven water currents and the Earth's rotation. In the Northern Hemisphere, the open ocean must lie to the right of the direction in which the wind is blowing (the reverse holds in the Southern Hemisphere). The Coriolis force produced by the Earth's rotation acts on the wind-generated water currents to force the surface waters in the upper 20 to 40 m to flow to the right, out to sea, as shown in Figure 8. These surface waters are then replaced by colder, deeper water upwelling to the surface, typically from depths of 100 to 200 m.

Since nutrient levels (e.g., nitrogen and phosphorus) are generally higher in these deeper waters, increased phytoplankton growth frequently occurs in coastal upwelling zones, causing reduced visibility and higher biological levels relative to the open sea.[6] The increased phytoplankton levels, in turn, support a greatly increased biological population in the coastal zone, ranging from small zooplankton up through fish and marine mammals.

The increased phytoplankton levels and associated reduction in water clarity that occur in coastal upwelling zones can be seen in Figure 9. Figure 9A shows the increased chlorophyll levels in the upwelling zone off Somalia, taken from the Coastal Zone Color Scanner on the Nimbus-7 satellite in July 1979. Figure 9B shows the resultant increase in the diffuse attenuation coefficient K_d (a measure of light attenuation in the water column) associated with these higher phytoplankton levels. In general, the optical detection depth in the ocean for remote passive and active optical systems is inversely proportional to K_d. Figure 9B indicates that the depth of optical penetration is reduced by a factor of more than 2 as one moves into the region of upwelling from the clearer offshore waters.

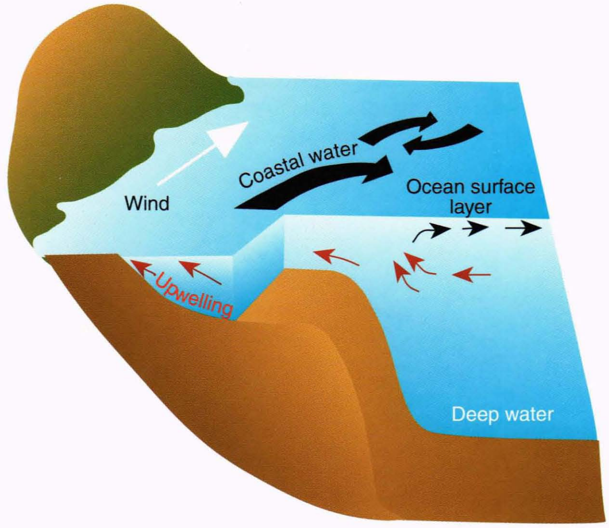

Figure 8. Hydrographic flow during an upwelling event in the Northern Hemisphere. The Coriolis force displaces surface water to the right of the wind direction. This surface offshore flow is replaced by deeper water upwelled from depths of a few hundred meters. In the Southern Hemisphere, the directions are reversed, and the surface water is forced to the left of the wind direction.

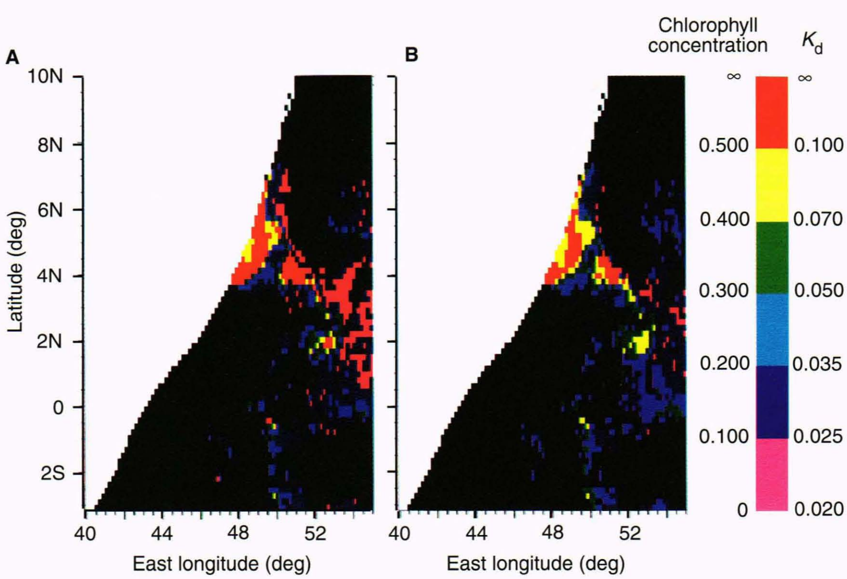

Figure 9. The effect of upwelling on ocean chlorophyll concentrations and optical diffuse attenuation off Somalia during July 1979, based on Coastal Zone Color Scanner satellite measurements. **A.** Near-surface chlorophyll concentrations (mg/m^3). **B.** Corresponding diffuse attenuation coefficient, K_d (m^{-1}).

Upwelling can occur anywhere when the winds blow in the appropriate direction along the coast for sufficient time, typically a few tens of hours. Some regions of the world are particularly noteworthy for upwelling, however. Because of global wind patterns, upwelling occurs frequently along the eastern boundaries of major ocean basins (e.g., along the western coast of the United States or the western coast of Africa). The northern Arabian Sea is particularly well known for the strong upwelling that occurs during the summer as the monsoon winds blow from the southwest along the coasts of Somalia and the Arabian Peninsula. Upwelling is not strictly a coastal phenomenon, but can also occur in the open ocean under appropriate wind patterns.

River influx and upwelling processes are among a few of the many processes occurring in the coastal environment that cause increased variability in the coastal zone. The mixing of different water masses results in the formation of many frontal zones in coastal areas that are characterized by rapidly varying temperature, salinity, and SVP's. Figure 10 shows the wide variation that can occur in SVP's over only short distances in the Barents Sea (with typical depths less than 200 m). Typical SVP's for the upper ocean at various locations are shown by the small insets. The horizontal axis shows sound speed in feet per second, in accordance with the Navy convention. The difference in sound speed between major ticks is 10 ft/s (3.05 m/s). The vertical scale shows depth in meters, with the range adjusted to the local water depth. For example, the depth scale for the upper left-hand inset goes down to 1500 m, whereas the depth scale for the upper right-hand inset only goes to 100 m. The depth range for most of the SVP insets is 250 to 350 m. The wide variation in SVP shapes, like the bottom composition variations discussed previously, makes the prediction of acoustic performance for ASW systems or torpedoes extremely difficult in the coastal environment.

The increased turbidity of the coastal water can degrade the performance of optical systems used for ASW as well as detection of bottom and moored mines. Many zooplankton and other invertebrates, however, may be bioluminescent, which may enhance submarine or

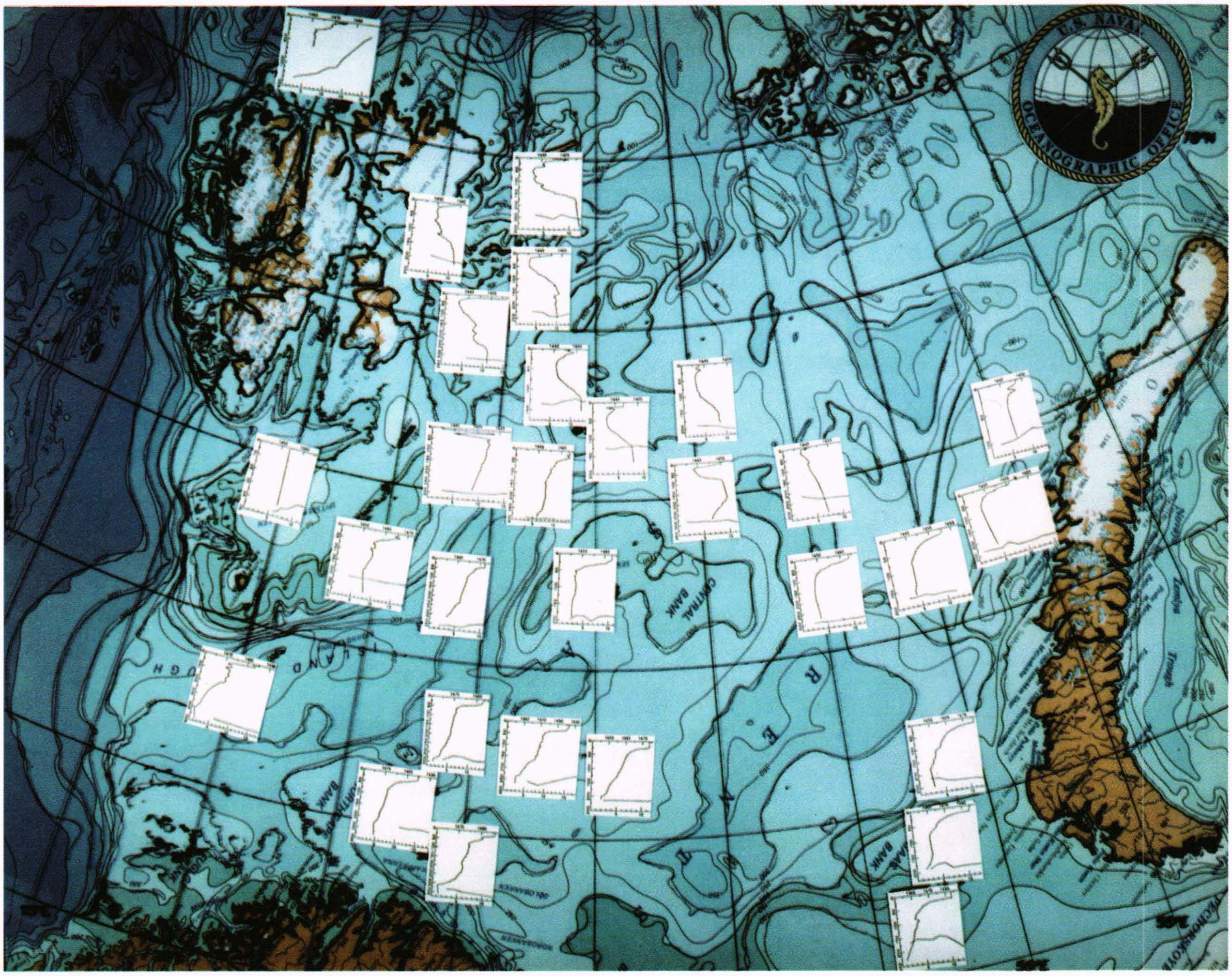

Figure 10. The spatial variability of near-surface sound-velocity profiles in the Barents Sea. The vertical depth range varies with location, but is generally 300 m; the horizontal axis shows sound velocity in the range of 1450 ft/s, with increments of 10 ft/s (3.05 m/s). The horizontal trace at the bottom of each inset shows the bottom bathymetry at that location. The profiles in the lower region are characteristic of the inflowing water from the Norwegian Sea; the profiles in the center and upper regions are characteristic of mixing between the inflowing water from the Norwegian Sea and the cold Arctic water (courtesy of the U.S. Naval Oceanographic Office).

swimmer detection under dark, nighttime conditions. The increased biology associated with upwelling zones also results in higher levels of ambient acoustic noise from the biological sources. In addition, in the shallow coastal region, many biological sources of acoustic noise exist that have no open-ocean counterparts (e.g., snapping shrimp, bottom-dwelling fish). The larger populations of zooplankton and fish in the coastal environment, particularly around upwelling zones, can cause increased levels of volume scattering, thus degrading the performance of active sonars and particularly torpedo and mine-hunting sonar systems.

In short, we face in the coastal environment considerable challenges to clearing mines, landing troops, and conducting ASW against enemy submarines that might threaten the landing force. These same conditions, however, can be used by our own submarines to increase their stealth while operating in coastal areas.

METEOROLOGY

Meteorological processes in the coastal zone are strongly affected by interactions between the land and the ocean, and these effects often show up in the wind patterns. Some processes, such as a sea breeze and land breeze, result directly from the land-sea interaction and occur only where that interaction takes place.

The basic mechanisms creating a sea breeze and land breeze are shown in Figure 11. As the land heats during the day, the warm air rises, drawing in cooler air from the water, which results in the sea breeze. In tropical regions, this sea breeze may set in by late morning and continue through the day, weakening and beginning to disappear by sunset. The seaward extent of the sea breeze is on the order of 10 nmi, and velocities can reach 4 to 7 m/s.[7]

The sea breeze can affect amphibious operations in several ways. The onshore wind will generate higher sea states; the waves propagate toward the coast, creating higher sea clutter for shore-based radars looking seaward. Thus, an optimum time for submarine periscope and mast exposure for data gathering along a coast might be during this period of higher sea states generated by the sea breeze, since the increased sea clutter may degrade the enemy's radar performance. When mountainous terrain lies near the coast, the sea breeze may be forced to rise as it flows inland. If the air is sufficiently moist, the cooling associated with its forced rise can lead to cloud formations inland, obscuring targets and enemy movements. This land effect is generally contained within 20

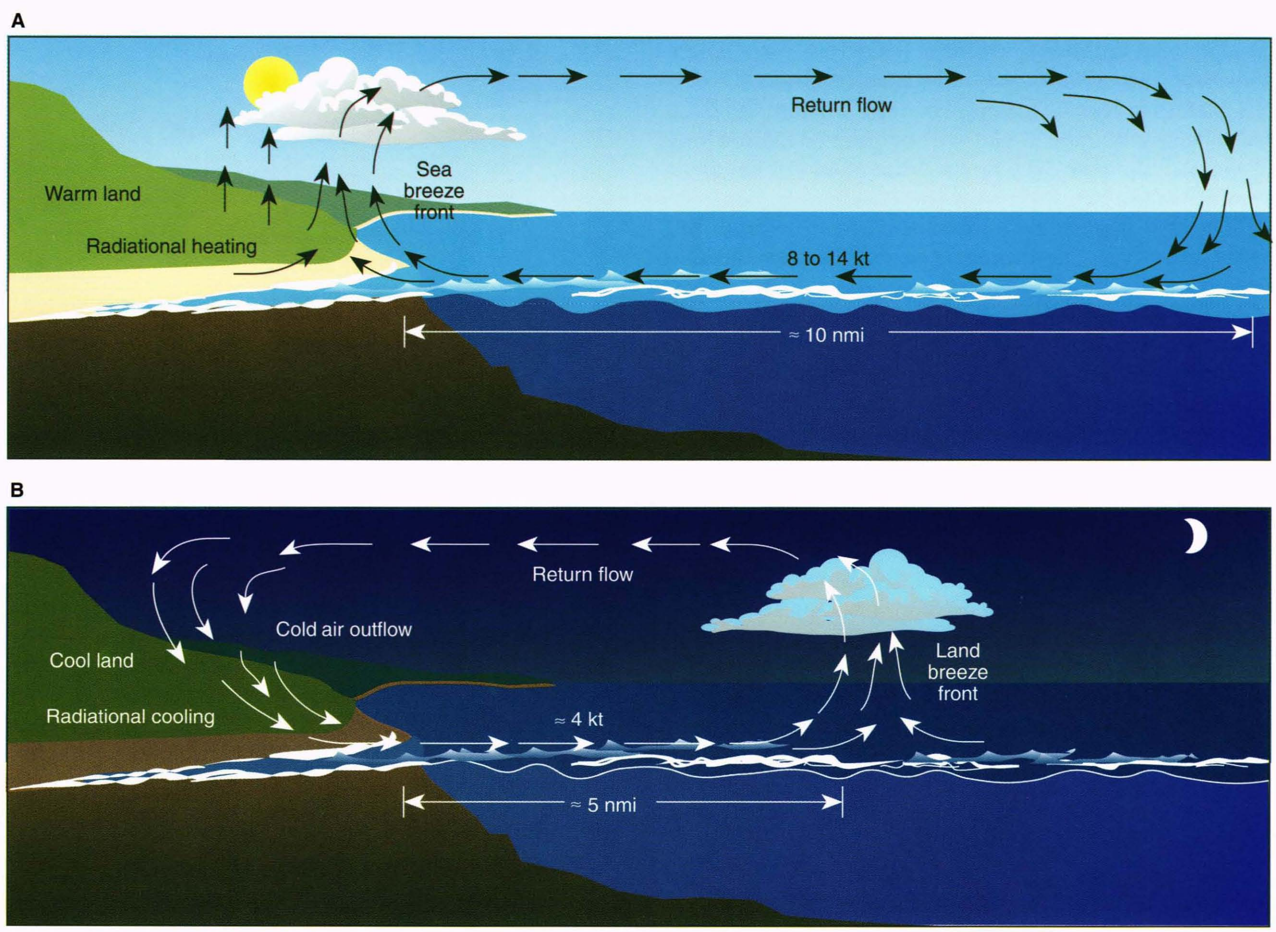

Figure 11. Circulation cells with wind direction and speed for a land breeze and sea breeze. **A.** The stronger sea breeze is driven by solar heating of the land, beginning about midmorning and continuing until sunset. **B.** The land breeze is driven by cooling of the land, which begins during the early evening and continues through the night, disappearing around sunrise.

to 50 miles inland of the coast and, under appropriate conditions, can obscure wide areas of the inland region near the coast.[8] As a result, the effectiveness of aerial attacks or reconnaissance during the late afternoon in these regions may be degraded.

The land breeze forms in a reverse fashion from the sea breeze. As the land cools in the evening and early night, the heavier air falls and flows out over the ocean as a land breeze. This breeze generally sets in during the evening and disappears around sunrise. Compared with the sea breeze, land breeze velocities are generally lower, on the order of 2 m/s, and the circulation generally does not extend more than a few miles off the coast. Perhaps the primary military effect of the land breeze is that it can carry things like land fog or smoke out over the coastal operating area. Land fog, produced by radiational cooling at night, can mask special warfare operations (e.g., landing small teams or clearing landing beaches of mines and obstructions) from enemy observation and increase the chances for success of the operation. Stronger winds blowing out from the land can also carry sand and dust over the coastal area, reducing visibility and potentially causing failure in equipment such as aircraft engines.

Evaporative radar ducts at the ocean surface are also common in the coastal regions of tropical and subtropical climates, although they can occur farther to sea and at higher latitudes as well. These ducts result when the index of refraction in the atmosphere, determined by the temperature and humidity profiles, decreases with height above the sea surface over a distance on the order of a few meters to tens of meters. For radars within the duct, radar energy is trapped and will be propagated for long distances within the duct, on the order of tens or hundreds of miles (Fig. 12).

In coastal regions, two different mechanisms can lead to the formation of surface radar ducts.[9] The first, heating from below, occurs when an offshore wind carries cooler air out over warmer seawater. The warmer seawater almost always produces a humidity gradient that results in a duct, typically 5 to 15 m thick. This first mechanism is fairly common in tropical regions where the seawater is quite warm and often occurs when an offshore breeze, such as a land breeze, carries out air that was cooled over the land during the night.

The second mechanism, cooling from below, may occur when warmer air is carried out over cooler seawater. This cooler water produces a temperature inversion (temperature increasing with altitude), but duct formation depends on a variety of other factors such as the humidity profile in the air column. When ducts form as a result of this mechanism, however, they can have thicknesses of many tens of meters and can extend offshore for tens of miles.[9] The lower sea-surface temperatures associated with upwelling zones in coastal regions (discussed previously) may result in the formation of such ducts when the wind conditions are right.

Several military implications are associated with these surface radar ducts. Since ducts increase the radar horizon for low-sited radars or radar targets located within the duct, the detectability of submarine mast or periscope exposures during data-gathering missions prior to an invasion may be increased during ducting conditions. This increased detectability may be offset somewhat by the higher levels of sea clutter caused by radar scattering from the sea surface. Surface radar ducts also pose problems for the task force supporting an amphibious operation. The shallow radar ducts can shield incoming sea-skimming missiles from detection by ship radars located above the duct. Ship radars located within the duct can have an increased number of false targets caused by ground clutter returns from the nearby coast, greatly complicating discrimination of real targets from the background.

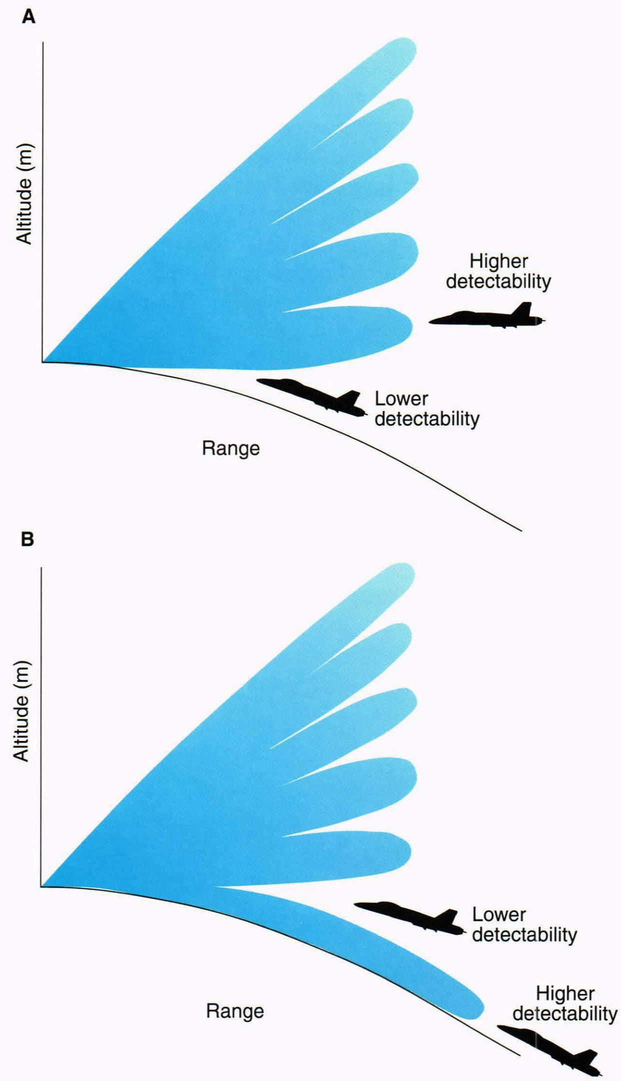

Figure 12. Effect of a radar surface duct on radar coverage for a transmitter located within the duct. **A.** With no duct, radar energy is directed upward, leaving a coverage gap near the ocean surface. **B.** For a transmitter within a surface duct, in addition to the upward refracted energy, some radar energy is captured within the duct and carried along the ocean surface beyond the horizon.

MAN-MADE EFFECTS

Man-made effects in the coastal environment also affect amphibious operations. Although humans influence the coastal environment in many ways, ranging from pollution to over-fishing, only a few nonmilitary activities have significant military consequences.

Coastal shipping densities can be high along many coasts, both over the continental shelf and just seaward in deeper water, depending on the direction of ocean currents. The higher biological productivity of the coastal waters also supports an active fishing fleet in many areas. These ships and fishing vessels can contribute greatly to acoustic background noise in the near-coastal environment, and they represent an additional source of false alarms when the movements of enemy surface craft are being monitored. Also, coastal shipping noise can be used by our own submarines on intelligence-gathering missions to enhance their stealth.

Coastal regions often have many sunken wrecks resulting from shipping accidents, storms, and earlier military activity, particularly near major ports (such a wreck posed a problem in the recent landings in Somalia). In conducting ASW operations to protect an amphibious operation, these wrecks can be a frequent source of acoustic and nonacoustic false alarms. Magnetic anomaly detection systems in particular are sensitive to sunken ships, which can be difficult to distinguish from diesel/electric submarines sitting on the bottom.

Another characteristic of coastal regions is the large amounts and variety of trash (e.g., tires, refrigerators, small wrecks, other metallic scrap, and scrap building materials) that have been dumped on the bottom over the years, particularly near ports and along coastal shipping routes. These items can generate false alarms for bottom mine-hunting sonar systems. In clearing Q-routes (mine-free routes) for shipping, side-scan sonars can be particularly useful in identifying and locating these objects.

MEASUREMENTS AND PREDICTIONS OF THE COASTAL ENVIRONMENT

The preceding discussion shows that naval operations in the coastal environment are sensitive to the effects of that environment over a variety of time and space scales. Many oceanographic parameters, such as bottom depth and geoacoustic characteristics, are important from deep water up the continental slope, across the continental shelf, all the way in to and up on the beach for supporting the many facets of expeditionary operations.

Databases for most oceanographic parameters, especially at the high spatial resolutions necessary in coastal areas, are lacking in all but a very few regions of the world. For example, for bathymetry alone, about 70% of the coastal areas of the world are inadequately surveyed to support naval operations. A major effort would be needed just to obtain adequate bathymetric data in the highest priority regions. Because of this and the need to collect various types of data worldwide, traditional oceanographic surveys up to the surf zone would, in general, be economically impractical and often politically infeasible. This situation raises the question of how to practically and economically measure or predict oceanographic conditions with sufficient resolution to support naval or expeditionary forces operating in the littoral regime. The problem is being addressed by the Navy. Some approaches being taken will be described in what follows. In these approaches, the Navy is coordinating its efforts with activities underway in other nations and with civilian agencies having similar interests in coastal mapping and oceanography.

To meet the needs for precise bathymetric data, airborne techniques and remotely operated vehicles (see the article by Shotts and McNamara, this issue) are showing great potential to augment more traditional coastal hydrographic survey methods from ships. The use of airborne lasers for collecting coastal bathymetry has been under development for many years; however, only within the last few years has the technique been fully developed, and it is just now becoming operational and available in several countries. An airborne laser system flown from fixed- or rotary-wing aircraft provides a cost-effective, rapid means of collecting high-density survey or reconnaissance bathymetric data. Airborne laser bathymetric systems can collect data in clear waters to about 50 m and in exceptionally clear waters to depths of perhaps 70 m. These systems can cover about 50 km^2/h and provide high spatial resolution with an accuracy of about 0.3 m down to depths on the order of 30 m. They are obviously limited by water clarity, but flying at speeds of about 150 kt and coupled with Global Positioning System navigation, they provide a viable alternative for rapid data collection in support of naval operations in uncharted waters.

A second technique for airborne bathymetric data collection involves using an electromagnetic system flown from a helicopter at a speed of about 85 kt. It can be used to measure water depths exceeding 30 m. The method is based on measuring the electromagnetic induction in seawater and the seafloor sediments and has the advantage that it is independent of water clarity, surface agitation, bottom vegetation, and sunlight intensity. It can even map bathymetry through ice. The technique was developed for mineral prospecting during the 1950s, and since then has evolved into a sophisticated, multifrequency system that has provided the basis for evaluating its utility for bathymetric applications. The airborne bathymetric system is still being developed by the Navy, but it has shown the potential to provide a flexible and rapid means of collecting bathymetric data with an accuracy of about 0.6 m during field tests.

Another potential means of collecting information on shallow-water bathymetry is through the use of synthetic aperture radar (SAR) from space or aircraft. Bathymetric features were observed in space-based SAR imagery obtained from the Seasat satellite; however, although bottom features that correlate well with bottom charts have been identified, we cannot yet determine actual depth information from the SAR images. Such space-based SAR images may offer the ability to locate obstacles, which could then be verified by more traditional means or by the techniques previously described. In addition, by observing wave refraction patterns often seen in SAR images, we can identify shoaling water and may be able to estimate water depth by measuring the properties of the refraction pattern. Although use of SAR imagery is more limited than either the airborne laser or the electromagnetic technique, it nonetheless may provide a rapid reconnaissance method for locating good and bad landing sites for amphibious or special operations in uncharted waters.

A totally different approach to augmenting ship-collected bathymetric data involves the use of a remotely operated vehicle together with a high-resolution multibeam sonar. Figure 13 shows a recent innovation being developed by the Canadian Hydrographic Service that the Navy is currently evaluating. The approach involves using the Dolphin underwater vehicle, together with Global Positioning System satellites and a multibeam echo sounder system. With an appropriate handling system, the Dolphin concept can be used aboard ships of opportunity or in conjunction with traditional hydrographic survey vessels. The Dolphin vehicle can be operated at speeds of 12 kt for up to 26 h. This system shows great promise at a reasonable cost for obtaining bathymetric, side-scan, and geoacoustic data.[10]

Building a high-resolution database on geoacoustic parameters is particularly challenging. Such data are required for obtaining accurate acoustic predictions for ASW systems, optimizing mine-hunting system performance and corridor selection, and clearing bottom mines. The structures of near-surface sediments can change over periods of hours to years, and the time scales of change depend on local conditions. For example, the outflow of rivers is a source of sediment deposits and will change after floods and storms. Likewise, waves and currents move the sediments around and provide a mechanism for continuous change. In addition, partially buried mines may be lifted off the bottom during severe storms by "wave-induced breakout." With the potential for dynamic bottom conditions, techniques must be available for routine bottom surveys and measurements of critical bottom parameters.

In very shallow, clear water areas, satellite multichannel optical methods may be useful for obtaining information about bottom type.[11] Traditional acoustic echo sounders, coupled with new processing devices, can be used for sediment classification and can provide the subbottom structure. Recent advances, such as with chirp sonar, offer ever greater resolution of subbottom structure and sediment classification.[12]

Even with the potential for improving measurements to obtain essential information on bathymetry and bottom properties, we still face formidable challenges to convert the systems just described into reliable survey systems, and even more significant challenges if the data must be obtained covertly. Measurements of the oceanographic and optical properties of the water, however, are more amenable to proven survey and satellite techniques coupled with emerging coastal ocean forecasting models. In fact, it is easy to envision a coastal warfare environmental

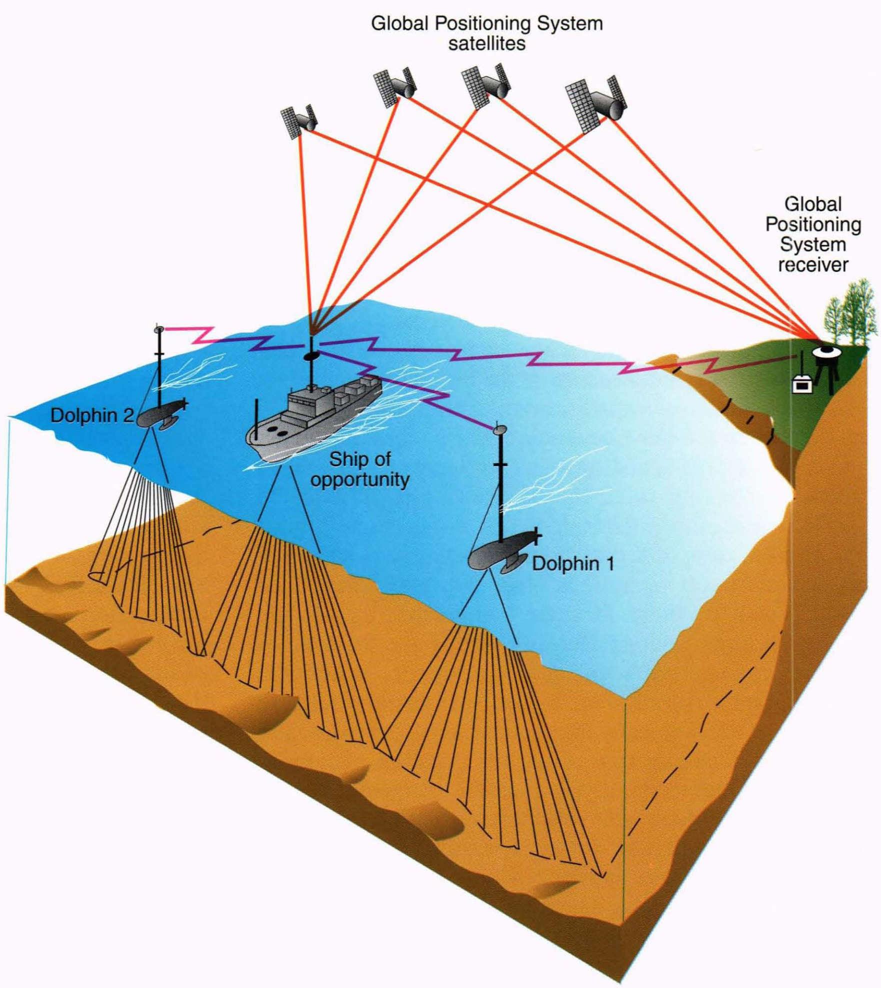

Figure 13. Dolphin underwater vehicles augmenting a hydrographic survey ship or ship of opportunity. This is a unique and revolutionary cost-effective system for conducting seafloor mapping surveys (courtesy of Geo-Resources, Inc., St. John's, Newfoundland, Canada).

support system that combines historical databases, *in situ* measurements, satellite sensors, and ocean prediction models. Although such a system does not exist today, all of the components are available or will soon be available and are waiting to be integrated into a complete system.

Expendable drifting buoys, deployed from either ships or aircraft, have been or are being developed to measure air and seawater temperature, winds, air pressure, and acoustic ambient noise. They have extended lives of months and contain single sensors or even strings of sensors over variable depths. Data can be relayed to shore or ship receivers via satellite, while constant monitoring of the buoy location provides information on drift and local currents. Satellite data obtained using a variety of different sensing techniques, such as infrared and microwave imaging, can provide information on sea-surface temperature, fronts, eddies, winds, waves, upwelling, and river discharge. Late in 1993, the SeaWiFS (Sea-viewing Wide Field-of-view Sensor) satellite will be launched, which will provide the ability to obtain data on water clarity (attenuation length), chlorophyll and biological productivity, and sediment discharge. SeaWiFS is a follow-on to the successful Coastal Zone Color Scanner flown by NASA in the 1980s and is an important adjunct to the other sensors. It has particular importance for use in measuring water clarity in real time to support laser detection and bathymetry systems.

The satellite and real-time data obtained from drifting buoys or ships are combined with the Navy's climatological databases to yield the best available description of the three-dimensional ocean environment. The Navy's "standard" databases include information on bathymetry, temperature, salinity, sound speed, shipping noise, wind speed, ice roughness, acoustic volume scattering, acoustic bottom reflection, and electromagnetic propagation. These traditional deep-water databases are being expanded to include new coastal regions and to increase their spatial and temporal resolution in these regions. The result will be expanded, high-resolution, gridded data fields in coastal regions or tailored descriptions for local areas of interest.

Those data fields, coupled with satellite imagery, form the basic input for a new family of operational coastal ocean prediction models that are under development to forecast ocean currents and thermal structure in near-shore regions and semienclosed seas. These models, part

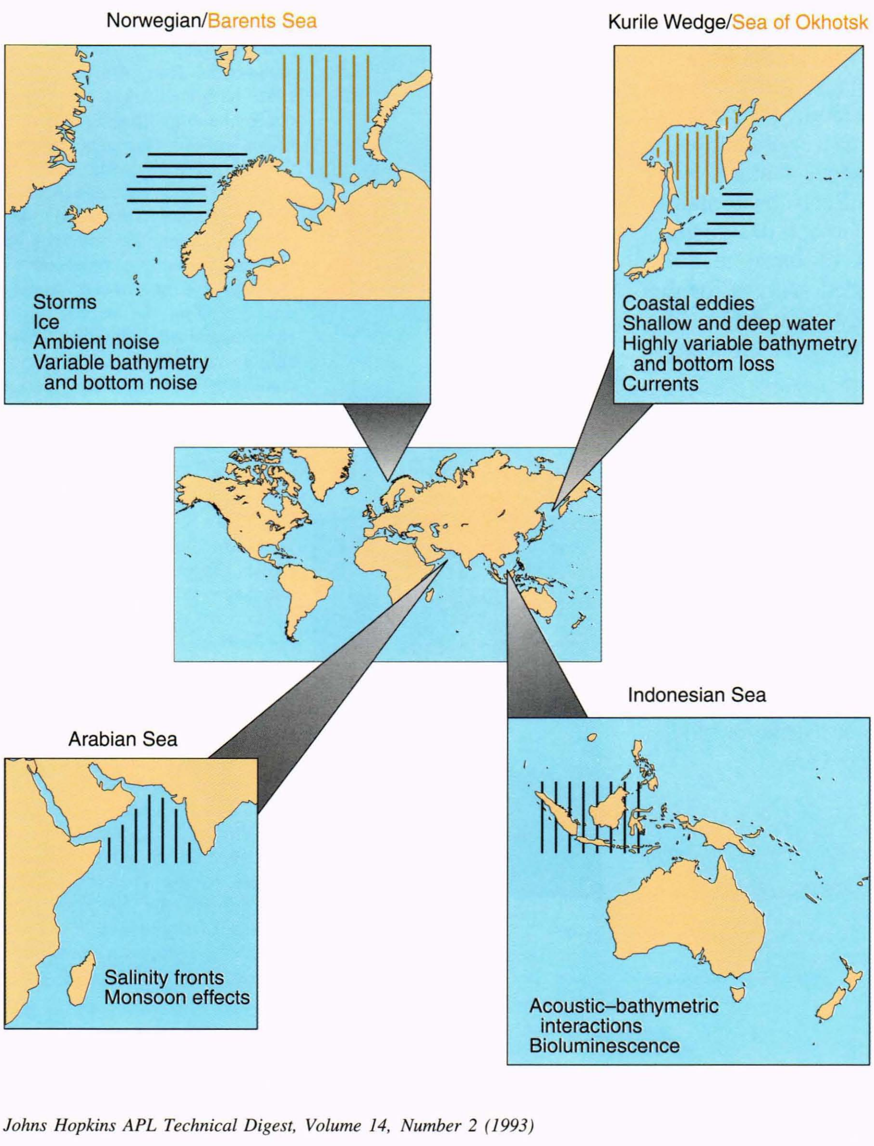

Figure 14. Geographic variability of the key environmental parameters in various littoral zones. The color-keyed hatching indicates the regions of interest in each area. The parameters shown indicate some of the militarily important features of those regions.

of the Navy's overall ocean modeling program, are also coupled to open-ocean models and use the Navy's meteorological forecast system to provide forcing information. The Persian Gulf was the first area in which a coastal, regional forecasting system was implemented. Operational implementation of the Persian Gulf model began in November 1990, but the system has continued to evolve and undergo additional testing. Other areas under development include the Mediterranean Sea, the Red Sea, and the Sea of Japan. To date, however, the operational use of regional models has been limited to the prediction of near-surface current speeds. Such predictions are important for drifting mines; in fact, the Persian Gulf model was used in Desert Storm for predicting mine and oil spill drift.[13]

SUMMARY

The coastal environment, determined by complex interactions between land terrain, underwater bathymetry, meteorology, and oceanography, can affect all aspects of a military amphibious operation, including initial covert intelligence gathering, mine clearing, landing operations, and protection and support of the subsequent military operations, both seaward and landward.

Unlike the open ocean, where meteorological and oceanographic conditions are often uniform over large areas, the coastal environment shows significant variability over a wide range of scales, sometimes down to meters and hours. Because of its extreme variability, the coastal environment may be better described as a combination of different physical processes that produce features with varying effects on military operations. Such an alternative description suggests that a survey approach designed to track and characterize the behavior of these features might be more appropriate than girdded surveys for the coastal regime. This view also suggests that future surveys should include more closely correlated meteorological and oceanographic measurements.

We have discussed many features characteristic of the coastal environment. No one coastal region has all of them, and their relative importance varies from region to region. For example, Figure 14 shows some distinctive characteristics of four different coastal regions.

We have presented only some of the most important of the many processes occurring in the coastal environment, and restricted the discussion of their military effects to some key steps in an amphibious operation. The coastal environment is much more complex than suggested in this article, and it influences other military operations in the littoral zone such as forward strike or blockades in additional ways not discussed here.

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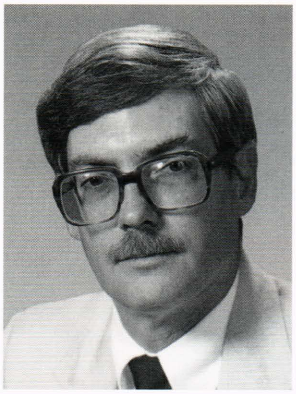

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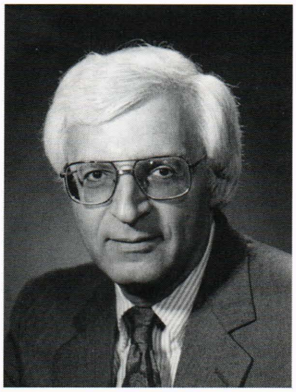

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