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# AN EXPERT SYSTEM FOR DESCRIBING AND PREDICTING THE COASTAL OCEAN ENVIRONMENT

Tactical oceanography can be described as the military use of archival and contemporaneous oceanographic information to gain tactical advantage. Ensuring that tactical oceanographic support is provided to deployed fleet units often reduces to a problem of information acquisition, interpretation, and management. This article explores the suitability of expert system technology to the tactical oceanographic problem. It summarizes ongoing efforts to apply this technology to the autonomous description and continuous refinement of the coastal environmental scene in a form suitable for applications in tactical oceanography.

## INTRODUCTION

The changing focus in maritime strategy from a major-power Cold War confrontation perspective to a forward-deployed maritime expeditionary force concept[1] places new significance on seizing control of the "littoral" sea early in a postulated military operation (littoral refers to that part of the coastal ocean extending from the deep offshore waters to the coast itself). Recent experience (for example, Desert Storm and the humanitarian operations in Somalia) suggests that future military expeditionary operations may occur in nontraditional littoral areas where locations cannot be predicted. Such operations in coastal and shallow waters will present significant challenges to the delivery of oceanographic support to the on-scene tactical decision maker.

Coastal ocean areas are inherently complex. The complexity arises from the interactions between the ocean and the atmosphere along the sea–landmass boundary, a variable coastal geomorphology, and coupled coastal and deep-water ocean circulation dynamics. Figure 1, showing NOAA-10 satellite infrared imagery of the Sea of Japan in May 1991, illustrates the complexity typical of many coastal seas. In this image, cold surface temperatures are shown as light grays or dull whites, and warm temperatures are shown as dark. The bright white features in the lower right quadrant are clouds. The Tsushima current, entering the Sea of Japan from the south, provides warm water (shown in the figure as the dark, convoluted gray plume in the lower left-hand corner) through the Tsushima Strait between Japan and the Korean peninsula. The transition from the warmer waters in the eastern region of the Sea of Japan to the cold coastal waters off Korea and China occurs through a complex series of eddies and thermal fronts (high horizontal temperature gradient zones) fully extending across the sea. Such naturally occurring littoral variability presents a challenge not only to tactical decision makers who are striving to tune the capabilities of their in-water sensor and weapons systems to the prevailing environmental conditions, but also to ocean forecasters trying to support ships at sea.

We view tactical oceanography primarily as a problem in information management, that is, acquiring, interpreting, and disseminating environmental information about local oceanographic and atmospheric conditions to the tactical decision maker in a readily usable form. Ideally, environmental information is provided in terms specifically relevant to the operation of the available sensors and weapons systems.

Historically, specially trained naval oceanographic and meteorological personnel (either located on-scene or assisting from detached supporting commands) have

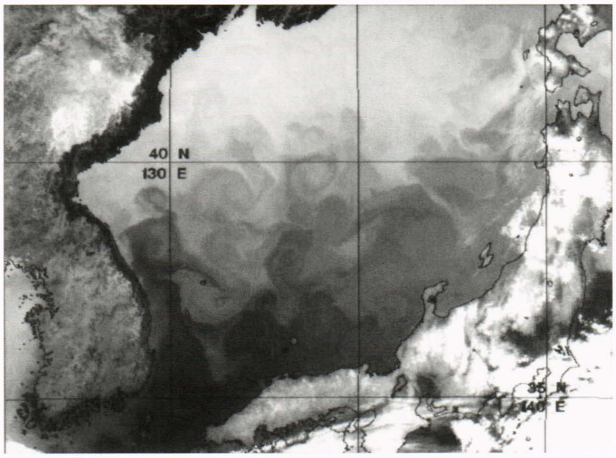


**Figure 1.** Infrared imagery of the surface of the Sea of Japan in May 1991, obtained by the NOAA-10 satellite. The nearly cloud-free image, taken in late winter, shows the remarkable complexity in the thermal structure within the transition from the warm water temperatures (represented by the dark shades) in the eastern portion of the sea to the colder waters (shown by the light shades) to the west. (Courtesy of the U.S. Naval Oceanographic Office, Operational Oceanography Center, Stennis Space Center, Miss.)

provided tailored environmental data to the tactical decision maker concerning environmentally sensitive aspects of major at-sea and shore operations. Naval Oceanography Command shore facilities generated atmospheric and meteorological forecasts that were communicated to the forward-located analysts, who then merged that information with locally derived environmental data. The result was then distributed by the analyst for tactical decision support. Various approaches have been used for this information delivery process. Today, analysts (traditionally located on major combatant ships such as aircraft carriers) use a dedicated environmental computer workstation called TESS (Tactical Environmental Support System[2]), which provides area environmental forecasts, satellite imagery, and *in situ* data assimilation and interpretation products. Platforms not equipped with TESS (which usually have no analyst on board) rely primarily on a blend of TESS-generated environmental analysis products received from the operational command ship and locally derived *in situ* data. Whatever additional analysis is performed to tailor the environmental analysis products to the ship's specific tasks and location is normally left to the ship's crew.

Given current trends in military force levels, the future availability of trained, professional analysts at the local decision-making level is uncertain. Forward-deployed platforms such as submarines and antiair defense frigates will increasingly have to rely on their own oceanographic measurement, interpretation, and decision-aid resources. The increased emphasis on the littoral regions of the world will create additional demands for local environmental assessment capabilities. The availability of oceanographic data for many littoral regions is spotty because of the historical focus of oceanographic research on the mid- to high-latitude deep-water ocean. Moreover, oceanographic research is just beginning to develop an understanding of shallow-water coastal characteristics and physical processes.

The problem, then, is how optimally to exploit the available sparse data and incomplete coastal ocean environmental information to support naval expeditionary force operations in the littoral regions. Advanced information management technologies may play an important role in mitigating potential shortcomings; a knowledge-based systems approach is a promising candidate. This article describes an embodiment of such an approach, termed the Ocean Expert System (OES), being developed at APL.

## INTRODUCING KNOWLEDGE-BASED SYSTEMS TECHNOLOGY

Expert systems are computer-based systems that support, or perform automatically, cognitive tasks in a narrowly defined problem domain. Such tasks are typically carried out by human experts who employ their personal skills, domain-specific technical expertise, and judgment learned over time.[3] Expert or knowledge-based systems technology is one of the most widely applied developments to emerge from the broader field of artificial intelligence, regarded to have begun in the late 1950s.

Artificial intelligence research initially focused on general-purpose problem-solving strategies, theorem proving, and game playing. Although some interesting results were achieved (such as the General Problem Solver,[4] the Logic Theorist,[5] and Samuel's checker-playing programs[6]), the focus on general-purpose techniques resulted in systems that were limited to puzzle solving and game playing, and seemed less well suited to more complex problems.

A major change in the artificial intelligence research perspective occurred when researchers realized that the true power in artificial intelligence-based systems lay in the knowledge embedded in the system, and not necessarily the reasoning process or procedures used. Knowledge engineering, a term generally attributed to Edward Feigenbaum (an expert system pioneer), came to represent the process by which one acquires expertise from human experts and reproduces it in knowledge-based systems. Specifically, it is not the problem-solving method that distinguishes human experts from novices but rather the amount of task-specific knowledge the expert possesses (frequently represented by heuristics or rules of thumb) and has culled from an extensive base of experience, largely without conscious effort.

Following this realization, research in artificial intelligence focused on capturing human expertise in narrow, well-defined domains, and the field of expert systems was born. Three early and landmark knowledge-based system applications were Dendral,[7] Mycin,[8] and Prospector.[9] Dendral encompasses the analytical expertise of two Nobel prize winners and uses mass spectrogram and nuclear magnetic resonance data to determine the structure of complex organic molecules. Dendral demonstrated performance equal to some human experts, and subsequently produced molecular analyses that were published in the peer-reviewed scientific literature as original research results.[10] Mycin captures the expertise of physicians to diagnose and recommend treatment for infectious blood diseases. Prospector is an "expert geologist" system that has been used successfully to locate several commercially viable mineral deposits.

These early successes generated tremendous interest in knowledge-based systems. Later efforts produced systems supporting various interpretation, prediction, diagnosis, design, planning, monitoring, debugging, repair, instruction, and complex system-control tasks. Knowledge-based or expert systems have since found use in such diverse fields as agriculture, chemistry, electronics, engineering, geology, law, manufacturing, medicine, meteorology, military science, physics, process control, and space technology.[11]

## COMPARING KNOWLEDGE-BASED AND CONVENTIONAL SOFTWARE SYSTEMS

Expert systems differ from conventional computer programs in four critical aspects: goal, focus, approach, and output. The goal of conventional software is to implement algorithms, whereas expert systems seek to capture and distribute expertise. Typically, conventional programs focus on data (primarily numerical), take an algorithmic data processing approach, and produce a calculated result. Expert systems, on the other hand, focus on knowledge (primarily symbolic), take a heuristic reasoning approach, and generate one or more decisions or analyses. (This distinction is a generalization and is drawn as a sharp contrast for clarity. Increasingly, knowledge-based approaches are being integrated with conventional data processing in hybrid software systems.) A symbolic, knowledge-centered approach to the characterization of the coastal ocean scene parallels that of the human-expert oceanographic analyst and offers potentially significant advantages over numerical data-centered approaches to analysis and interpretation.

## Data versus Knowledge

Data refers to fairly static, simple descriptive facts, whereas information refers to the reduction of uncertainty in a situation; knowledge refers to the capacity to correctly use data and information in the execution of intelligent behavior.[12] Consider the remote sensing of sea-surface temperature via satellite sensors (Fig. 1). Individual temperatures (either image pixel or derived engineering unit values) could be classified as data. The association of temperature values with specific geographic regions constitutes information, a synthesis of the two data sets. Knowledge, then, would refer to the ability to identify organized features such as fronts or eddies in a satellite image, the ability to predict the future evolution of such features on the basis of a time series of satellite images or personal familiarity with the region, and the ability to assess and exploit the tactical implications of such features.

The process of identifying organized features such as ocean fronts or eddies and explicitly representing them as separate feature entities or objects transforms the reasoning from pixel-based numerical data processing (as in edge detection algorithms) to more abstract symbolic manipulation. For example, an elliptical eddy could be represented symbolically by a name and a set of associated parameters (e.g., location of the center, length of major and minor axes, swirl velocity, etc.). The eddy feature object captures the information content of the individual sea-surface temperature values at the pixel level and abstracts it in a higher-level representation. This symbolic representation more closely parallels the manner in which a human expert would conceptualize the information contained in the image. A symbolic representation allows expert knowledge of the likely propagation of such an eddy to be captured in rules that predict the future values of the various eddy parameters.

A sample analyzed version of the image in Figure 1 is shown in Figure 2, where the data-dense continuous gray-scale representation of the sea surface (often consisting of up to 2048 × 1024 individual pixels) is replaced by feature lines that identify the significant horizontal temperature gradients in the image. In this example, gradients of the largest magnitude are shown in red and are viewed by the analyst as being potentially more operationally significant than the other gradients shown in black. By representing the original image as feature objects, the analyst reduces the volume of data to be considered while maintaining the essential informational elements of the original image. The reduced data set is more easily manipulated and compared with other information than the image-based representation. Analysis involves an information extraction and condensation process that forms the basis for the analyst's interpretation. The original data are converted into an abstracted and condensed data set that takes on significant meaning. This representation draws upon the analyst's experience and previous examples. It is this valuable expertise (knowledge or skill developed through experience) that expert systems strive to capture and distribute.

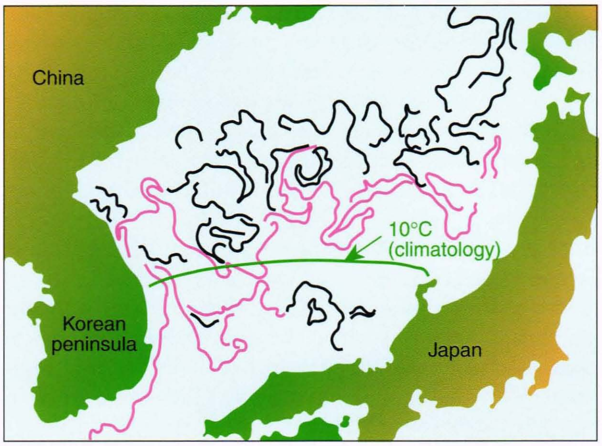


**Figure 2.** Sea-surface temperature gradient analysis of the infrared image in Figure 1. The original sea-surface imagery is replaced by an oceanographic feature analysis of the locations of the significant temperature gradients in the image. The gradients (red depicting a strong temperature difference and black a weak gradient) often represent the surface expression of the water mass features (e.g., water mass boundaries, or fronts, and separated eddies) in the image. The complexity in the imaged water mass structure is evident by comparison with the mean climatological location of the 10°C sea-surface isotherm shown in green, which is often taken as the indicator of the northern boundary of the Tsushima current. The analyst captures the essential elements of this complexity in an oceanographic feature-oriented analysis, thus reducing the volume of data that must be handled in subsequent analyses and facilitating automated interpretation of the image.

## Conventional versus Knowledge-Based Information Processing Systems

Since knowledge-based systems focus on highly abstracted symbolic reasoning rather than on numerical data processing, they can handle problems that would be difficult or impossible to address using conventional approaches. For example, knowledge-based systems can readily deal with uncertain, incomplete, and even inconsistent data. The problem of describing and predicting the coastal ocean scene is particularly appropriate to a knowledge-based system analysis approach. Oceanographic data acquired in real time rarely resolve completely the full extent of the measured field; ocean prediction models cannot easily represent small-scale processes that are important in coastal regions when significant real-time data are lacking. The limited data sets and associated uncertainty in coastal oceanography would be difficult to handle using conventional data processing approaches.

Another feature of knowledge-based systems is their ability to formulate analyses (or beliefs) and to revise them as new information becomes available. This ability is critical when the goal is to develop and continuously refine an environmental scene description as local information develops. The iterative analytical approach parallels that taken by a human analyst in, for example, water mass analysis, shown in Figure 3. Human analysts are adept at reconciling the usefulness of new information in the context of both their expectations (often based on an understanding of the underlying physics) and previous experience. In the absence of information, the analyst might assume a coastal ocean region to consist of a single water mass, that is, one having internally uniform characteristics. The initial field estimate is revised iteratively as evidence accumulates that substantiates or contradicts the initial assumptions. An autonomous analytical system such as OES would be able to emulate the human analyst's approach in interpreting a continuous stream of new data and updating the estimate of the local scene description as new information becomes available.

Another benefit accruing from the symbolic nature of knowledge-based systems is the ability to provide an explanation of the decision-making process. This feature has high utility in the estimation of oceanographic fields where different estimates may have significantly different kinds of information supporting them.[13] Since the targeted user of OES in not an oceanographic expert, the ability to provide an explanative basis for the presented analysis is a critical requirement. Finally, knowledge-based systems differ from conventional software systems in the development approach. The algorithmic nature of conventional systems lends itself to a linear or serial waterfall model for software development (Fig. 4). In such a model, the requirements are spelled out in detail in advance of code development, and testing occurs after the module development and integration have been completed. Knowledge-based system development, on the other hand, is well-suited to a spiral model (see, e.g., Ref. 14) of software development (Fig. 5). In this model, successively refined prototypes are cyclically developed and tested. A significant advantage of the spiral development method is that it enables rapid development of an initial prototype using a limited subset of the problem-domain knowledge as a proof of concept. The initial prototype is then used as a tool for acquiring additional domain knowledge and functional requirements for future development.

Given the superior utility of symbolic knowledge over conventional data, as well as the other advantages of knowledge-based systems just outlined, such systems seem promising. But although some successes have been achieved, attempts to universally apply knowledge-based system technology have met with mixed results. In fact, the president of one artificial intelligence company estimated that only 10% of medium- to large-size expert systems eventually succeed.[15] Knowledge-based or expert system technology, like much of artificial intelligence, has consequently suffered; early success has been overpromoted and has bred unrealistically high expectations.

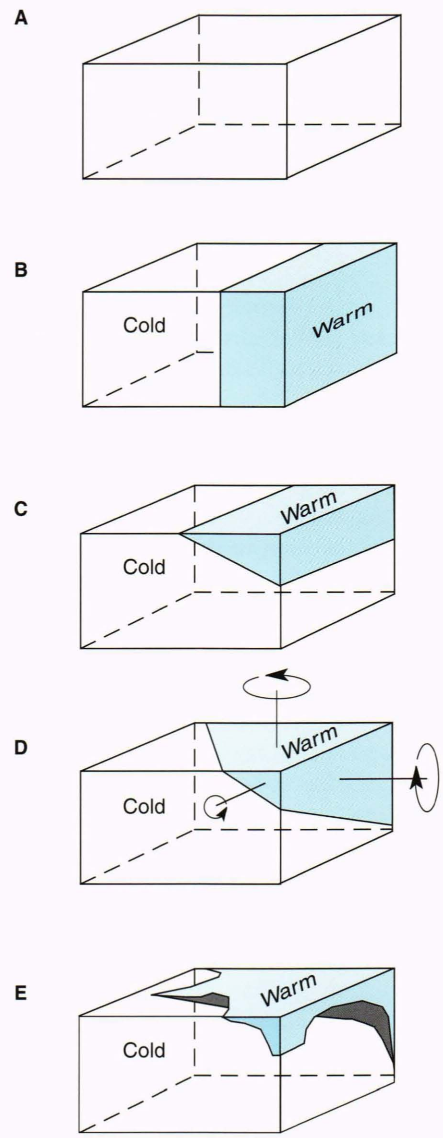


**Figure 3.** Simple conceptual model for oceanographic water mass analysis frequently used by a human analyst. **A.** Without evidence (data or information) to the contrary, the analyst initially estimates the water mass characteristics in a region to be singular and uniform. **B.** After receipt of information indicating that two different water masses coexist in the region, the analyst attempts to locate the boundary between the water masses. **C** and **D.** The boundary location and shape are subsequently modified as the analyst reviews new information (e.g., *in situ* measurement, satellite imagery, ocean forecast data) and reconciles that with both personal experience in the specific geographic area and personal understanding of the dynamics (or physics) of water mass boundaries (or ocean fronts) in general. **E.** The oceanographic scene description becomes progressively more well defined as additional information and insight are gained.

The single most common reason for the failure of expert system technology is the attempt to apply it in domains where it is not appropriate or not likely to succeed. In considering the application of knowledge-based system technology, then, we must understand the

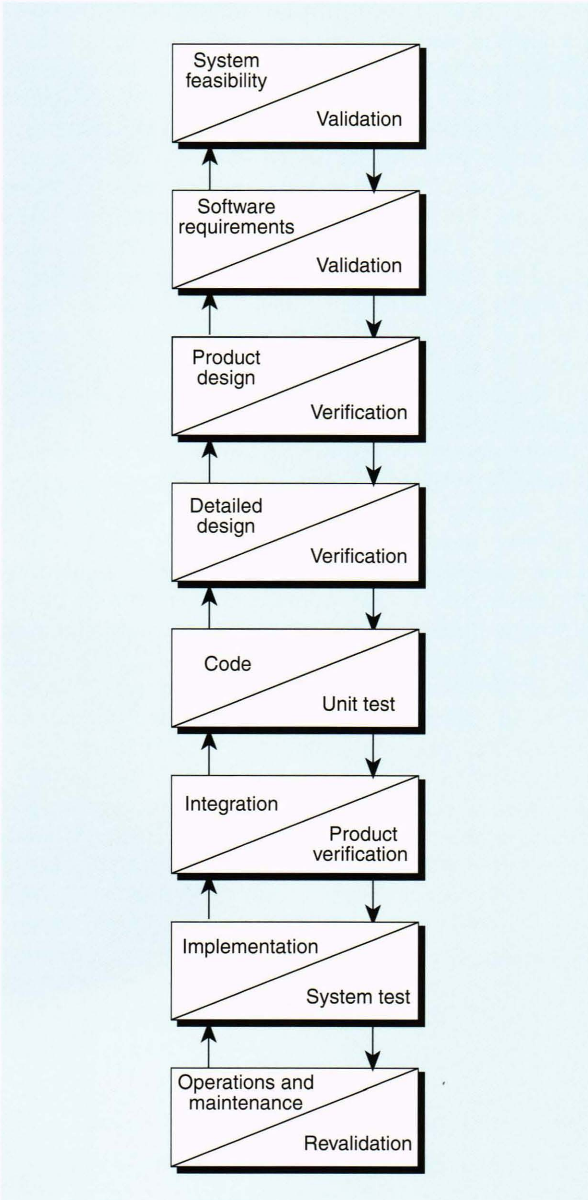


**Figure 4.** The algorithmic nature of a conventional software system lends itself to a linear waterfall software developmental approach. In such a developmental method the requirements are specified in advance, and system testing occurs after software module development and integration.

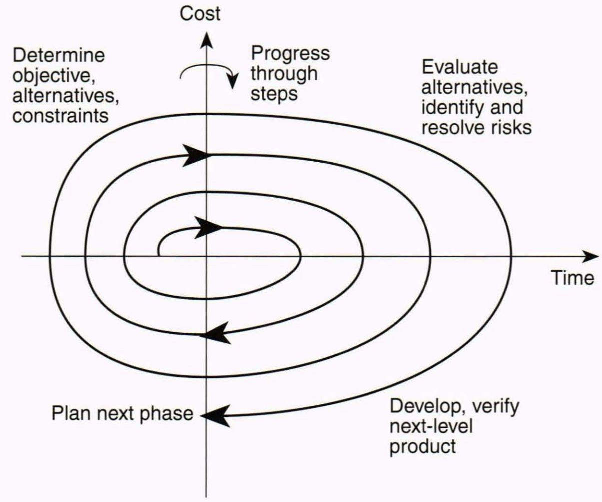


**Figure 5.** Knowledge-based system development is well-suited to the spiral model of software development, wherein successive prototypes are developed and tested cyclically as problem-domain knowledge is acquired.

characteristics of a problem domain where knowledge-based system technology would be appropriate and successful.

## CHARACTERISTICS OF A DOMAIN SUITABLE FOR EXPERT SYSTEM TECHNOLOGY

Slagle and Wick,[16] building on the work of Prerau,[17] have developed a taxonomy of essential and desirable domain characteristics for which the application of expert system technology would be likely to succeed. The characteristics can be classified into one of three groups: (1) the users and their management, (2) the task, and (3) the expert.

### The Users and Their Management

Of primary concern to the expert-system developer is the need for the customer to agree that the payoff is high. The customer must have realistic expectations of the system's scope and limitations. In particular, the user must recognize that an expert system might not always give correct answers and cannot be expected to be better than a limited version of the human expert.

### The Task

Expert system development should target those problems where traditional methods are inadequate for performing the application task. The task itself should be knowledge-intensive and heuristic, thus allowing the expert system to exploit the intrinsic strengths of knowledge-based systems. The application should be definable and self-contained (i.e., limited in scope). Applications requiring commonsense reasoning should be avoided, since experience has shown that representing broad-based commonsense knowledge has proved to be quite difficult and time-consuming. For example, it is common sense that successful gardens require "rich" soil. The exact characteristics of what is meant by rich depends on many elements, leading to a prohibitively complex knowledge domain concerning plants and soil chemistry. Expert systems require explicit knowledge. Furthermore, the task should be of the appropriate difficulty. It should have characteristics such that experts could develop a solution in a reasonable time (minutes to hours), whereas nonexperts could not achieve equally good solutions or would require much more time to do so. Finally, the problem domain of the task should be stable. That is, once the knowledge is extracted from human experts, it should be usable without substantial modification for an extended period of time.

## The Expert

An expert with considerable, explicit experience in the problem domain must actually exist. The strength of knowledge-based system technology is in its ability to capture expert knowledge, but such knowledge must exist in order to be captured. The expert must be committed to the project for its duration, must be cooperative, and must have good communication skills for the knowledge to be captured. Other indicators of likely success include the degree to which the expert uses symbolic reasoning when performing the task and the extent to which the expertise can be transferred to another human. Finally, the expert's creativity should not be needed in solving the problem since creativity is poorly understood and nearly impossible to capture in a computer-based system.

# THE OCEAN EXPERT SYSTEM CONCEPT

The OES concept evolved from a recognition of the difficulty that forward-deployed naval units might have in accessing and interpreting local oceanographic information during littoral operations, and the potential that knowledge-based systems might have in improving that access. The OES is a knowledge-based system whose principal function is the autonomous generation and continuous updating of a description of the local environmental scene for use at sea by tactical decision makers. A developmental goal is to demonstrate that significant human-expert knowledge relating to the management and use of environmental information for the development of the local scene description can be captured in a knowledge-based system. Such knowledge capture would make available to a deployed combatant important environmental analytical skills that otherwise would have had to be provided by a human expert. The OES does not negate the need for trained human analysts. Rather, OES is targeted at extending the availability of those skills autonomously and thereby providing a bridge from the expert to the nonexpert user. The functional goals for OES are to have significant environmental-scene developmental skills over a wide range of available environmental information; to demonstrate autonomous real-time oceanographic feature recognition skills for those platforms having a continuous *in situ* measuring system; to provide a geographic rendering of the estimated scene description and significant events; and to provide interpretation and explanatory assistance to the nonexpert user.

The process by which the human analyst develops an environmental scene description is putatively straightforward. Relevant oceanographic data in the particular geographic area of interest are identified, quality-controlled, and then merged with available supporting information to develop as complete a description of the oceanographic scene as possible. The scene interpretation process involves the extraction and review of task-relevant subsets from the merged data sets. Review occurs in the context of the analyst's professional expertise and previous experience. The different steps in the analytical process, developed as a result of interviews with selected oceanographic analysts, are summarized in Table 1. The specific human expert tasks relevant to OES development are to collect available information, quality check that information, extend where possible the individual data sets into regions not having good data coverage, develop a common

**Table 1.** Environmental field analytical procedure.

| Analytical process | Description | Examples relevant to Ocean Expert System development |
|---|---|---|
| Collect information | Assemble relevant data that may be appropriate to the task | Assemble relevant data for area (e.g., previous forecasts, recently acquired local data, climatologies, ocean model forecast data) |
| Check | Evaluate quality of available data | Estimate noise and bias in local sensor data (e.g., ship track sea-surface temperature [SST] data)<br>Verify previous forecast with current data to identify anomalies |
| Extend | Extend the existing data through gaps in the data coverage | Extend sea-surface temperature contours through data voids (e.g., satellite IR imagery)<br>Combine separate SST track data to joined data set |
| Adjust | Adjust individual data sets to a common reference | Interpolate bathythermographic temperature data to a reference depth surface (e.g., 200 m)<br>Adjust ocean model forecast data with satellite IR imagery to accommodate for differences between image/forecast reference times |
| Compile | Combine individual, adjusted data sets to a standard presentation | Combine expendable bathythermographic and ocean forecast data to provide a single estimate of subsurface thermal structure |
| Interpret | Determine significance of the compiled, adjusted data sets | Identify probable locations of high horizontal temperature gradients in the ocean region of interest<br>Identify water mass boundaries or fronts<br>Estimate sound velocity profiles within each water mass region |

reference across the different data sets so that a unified set can be compiled, and then interpret the compiled information.

## Conceptual Design

The OES embodies the human analytical process outlined in the preceding discussion and rests on a central concept: the interpretation of data obtained by local *in situ* measurements and data provided from off-board (nonlocal) sources in a context of the regionally expected climatologies, physical processes, and previous analyses for the geographic area in question. The provisional system design is shown in Figure 6. Local data include measurements of the ocean's vertical temperature or sound-speed profile that the ship obtains with expendable instruments and continuous measurements of temperature or other parameters at the sea surface or at depth using towed or hull-mounted sensor arrays. Off-board-generated data include forecasted environmental fields provided by TESS, analyzed satellite imagery, atmospheric and oceanic forecast products, and interpreted data products relayed from other ships in the area.

As data become available to the system, they are checked to determine their relevance and acceptability against established task-related and quality-assurance criteria. Task-related criteria include relevance tests against specific user-defined tasks. For example, data in forecast fields not relevant to the local operational region would be culled out. The quality-assurance criteria include consistency with both established climatologies and with the underlying physics that influence the processes occurring in the coastal environment. Information is weighted relative to its consistency evaluation and with regard to expectations derived from previously estimated environmental scene descriptions. Data not meeting the evaluation criteria are not completely rejected, but are stored as "unresolved" samples, allowing for future reexamination as new information becomes available. The embedded knowledge bases represent the core of the system and provide the context for both conventional data processing and reasoning within the OES system.

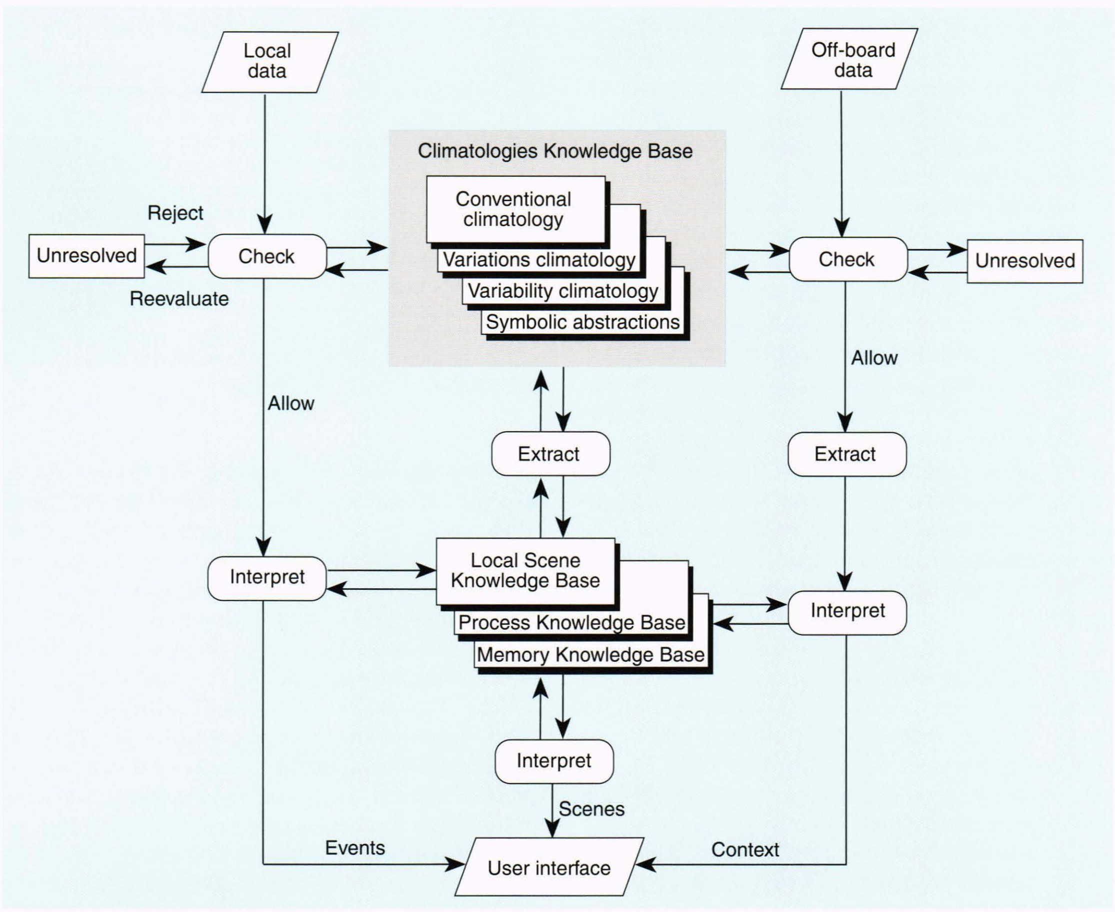


**Figure 6.** Conceptual design for the Ocean Expert System (OES). The goal of the system is to produce a best estimate of the oceanographic scene description, given the information that might be available at any given time. Information external to the system is derived from local oceanographic and atmospheric measurements as well as from information communicated to the system from off-board sources. A key aspect of the OES is the integration of embedded knowledge bases that allow (1) the evaluation of available oceanographic information in a context of conventional algorithmic tests (such as statistical variability) in addition to previous experience in the area and (2) a physics-based representation of coastal dynamics that cannot easily be captured in a conventional computer-based system. The estimated scene description provides information concerning significant environmental events, the mapping of those events to the local area, and estimates of the larger-scale context within which the scene is to be interpreted.

## Resident Knowledge Bases

Several types of resident knowledge are provided within the OES: knowledge concerning the climatology of the region that might be related to the interpretation of regionally specific locally generated and off-board-generated information, knowledge related to previous analyses of the local scene, and knowledge related to coastal-specific physical oceanographic and atmospheric processes that have been shown to influence local water mass characteristics.

The Climatologies Knowledge Base comprises a library of geographically oriented information about previous experience in the local region. Its organization reflects an implicit hierarchy from large spatial- and temporal-scale (and essentially more statistically stable) characteristics to successively smaller-scale (and less stable) regional characteristics. Such knowledge consists of both conventional (primarily statistics-based) climatological information and knowledge related to specific dynamical or physical processes that might at times (but not always) influence the observed environmental conditions of the local region. The Climatologies Knowledge Base will support a variety of consistency checks of the incoming information over a broad range of physical scales. It is also central to the recognition of regionally specific environmental phenomena that could affect sensor or weapons performance and the extension of limited observational data sets to larger regions using feature analysis.

The Conventional Climatology Knowledge Base contains information related to the expected environmental conditions in the area and parallels the type of information found in conventional environmental decision-aid systems. Information in this knowledge base includes, for example, monthly mean environmental parameter values in the region of interest, the most frequently encountered (modal) values, and the associated variances. An example of a conventional climatological presentation is shown in Figure 7, which illustrates the mean surface temperatures in the Sea of Japan region. Additional knowledge bases include ocean bathymetry, coastline and coastal topography databases, and meteorological databases. The conventional climatology can also support initialization of the systems scene description in the absence of any previous analysis.

The Variations Climatology Knowledge Base provides knowledge relating to first-order departures from the mean climatology. For example, the monsoonal atmospheric cycle strongly influences the strength and direction of coastal currents in Southeast Asia (Fig. 8). Although the monthly mean climatology suggests that the winter monsoon generally ends in late March, with the summer monsoon well established by late June, the actual onset of the seasonal monsoon will vary each year. The Variations Climatology Knowledge Base in the OES provides information supporting the recognition of expected significant variations in environmental conditions from the mean climatology for a particular region. Typically, these variations include regionally coherent, shorter-scale variations in conditions that may occur. This climatology supports additional data interpretation and quality-assurance checks. Incoming information that is potentially inconsistent with, for example, the Conventional Climatologies Knowledge Base is examined for the presence and interpretation of these smaller-scale variations. In this way, information that might represent a real departure from the conventional climatology of a region, and which might have been discounted as being atypical in a conventional analytical approach, can be examined in a more realistic interpretative context within OES.

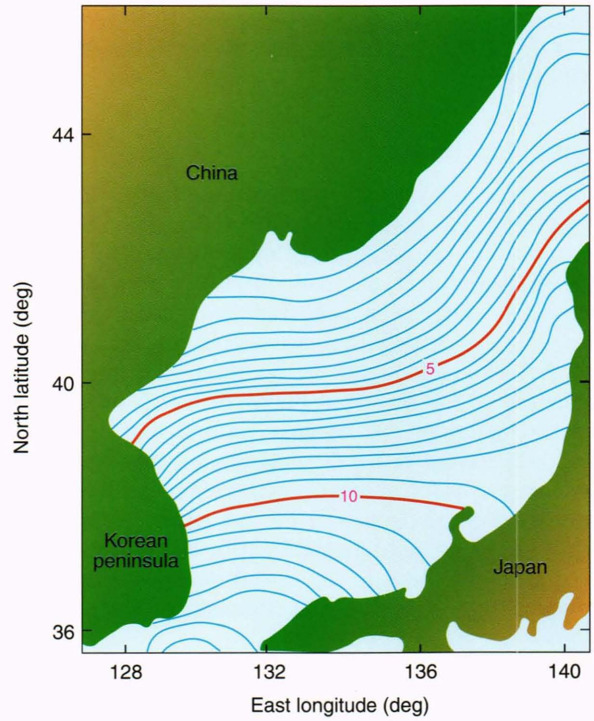


**Figure 7.** An extract from a "conventional climatology" showing the mean sea-surface temperature isotherms in the Sea of Japan. The isotherms (in degrees C) are shown to vary smoothly (an artifact of the large spatial- and temporal-scale averaging process used to obtain the mean isotherm values and locations) with little evident structure across the region. This common representation contrasts markedly with the structure shown in the Sea of Japan in Figure 1. Conventional climatologies, by their very nature, tend to underestimate the true complexity of the ocean's structure but are useful as input regarding initial estimates of a region's ocean-thermal structure. (Adapted from Robinson, M. K., *Atlas of the North Pacific Ocean Monthly Mean Temperatures and Mean Salinities of the Surface Layer*, U.S. Naval Oceanographic Office, Washington, D.C., p. 26, 1976.)

The Variability Climatology Knowledge Base provides knowledge of specific small-scale, geographically coherent environmental features or processes within the area of interest, and relates those features to measurable parameters. Processes represented in the initial prototype system will include coastal upwelling, tidal mixing, regionally specific winds events, and selected others. For example, Byun and Seung[18] observed that the water conditions off the southeastern coast of the Korean peninsula are locally sensitive to the prevailing winds (Fig. 9). Under the influence of southerly winds, cooler water moves in along the coast as a result of local upwelling and the advection of cool water from the north. The OES will examine available geomorphological, oceanographic, and atmospheric data for evidence of tendencies for

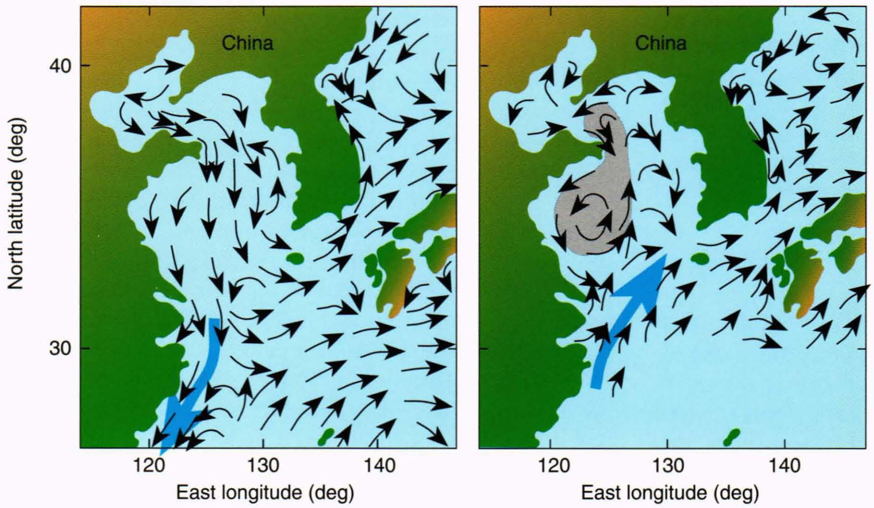


**Figure 8.** An example of the information that might be contained in a "variations climatology." During the northwest monsoon (left), the Chang Chiang current flows southwestward along the China coast. The flow reverses to the north (right) after the onset of the summer (southeast) monsoon. The southeast monsoon also sets up a cool counterclockwise Huanghai gyre (shaded area) between China and the Korean peninsula. (The Chang Chiang flow is represented by the blue arrows.) The Ocean Expert System contains the information in the Variations Climatology Knowledge Base to identify shorter-term variations in oceanographic conditions not resolved by conventional climatologies. (Adapted from *U.S. Navy Marine Climatic Atlas of the World, Vol. II, Northern Pacific Ocean*, U.S. Government Printing Office, Washington, D.C., pp. 365 and 367, 1977.)

such locally generated phenomena and modify the evaluation of the incoming data and the resulting scene description accordingly. The ability to conduct a physics-based evaluation of the environmental data permits identification of features not resolved by regional forecast models alone, improves the use of locally acquired data, and offers the prospect of extending the environmental scene description into contiguous areas in a physics-based extrapolation not afforded by conventional analytical systems.

The Symbolic Abstractions Knowledge Base provides for the representation of complex environmental features through feature models. Glenn et al.[19] have shown that the essential characteristics of complex oceanographic features such as ocean eddies can be represented in compact form using feature models. Rather than explicitly mapping the characteristics of the feature in detail, the feature model captures the essential eddy characteristics (e.g., shape, size, strength, and movement). The OES will extend the feature model concept to represent the feature's influence on the surrounding water mass properties as well. Feature models, then, can serve as an abstraction of multiple data sets into a single, compact representation, simplifying the tracking and mapping of those features while retaining the essential characteristics. Feature models serve as an information compression technique and as a tool to facilitate the rapid construction of a time-dependent environmental scene description.

The OES reasoning draws on additional knowledge bases as well. A Local Scene Knowledge Base contains the current version of the scene description. A Memory Knowledge Base provides access to previous scene descriptions to support time-dependent reasoning and to enable tracking the evolution of the environmental scene. A Process Knowledge Base contains knowledge concerning significant oceanographic processes and features

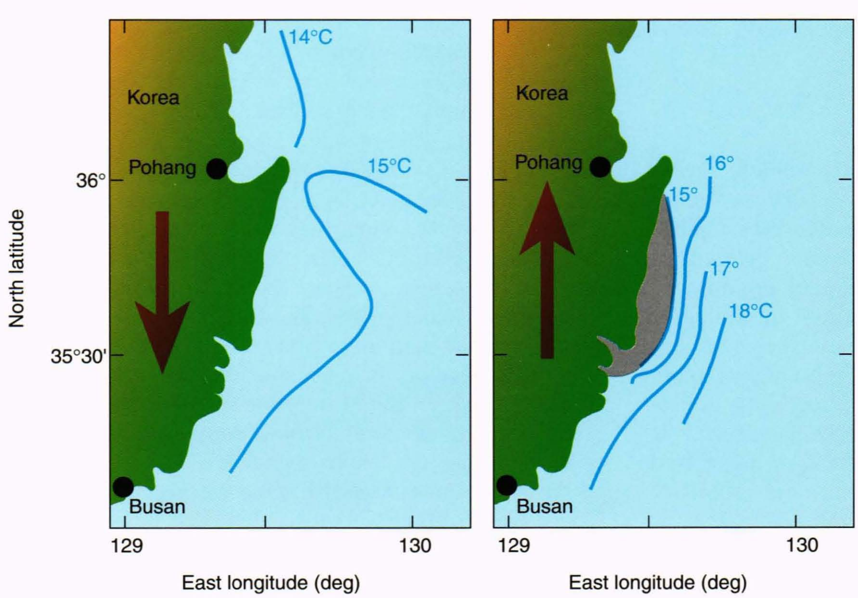


**Figure 9.** The "variability climatology" provides information concerning specific time-dependent physical processes observed in a particular geographic region, which may not be present permanently. Prevailing winds are shown by the red arrows. Off the coast of Korea during northerly summer winds (left), warm water is advected onto the coast from deep water. After the onset of southerly winds (right), surface water is advected off the coast, resulting in cooler water being upwelled from deeper depths (shown by the shaded area). The upwelling phenomenon represents a complex interaction between the prevailing (large-scale) winds and the smaller-scale coastal geometry. Upwelling is common in many coastal areas and must be represented in the coastal scene description process. (Adapted from Ref. 18, p. 92.)

potentially relevant to the coastal ocean, but not yet associated with processes in the specific local region of interest. Should evidence be provided that such processes exist, the information would be added to the Climatologies Knowledge Base for future use. In this way the benefits of the extensive research literature on coastal processes and characteristics can be represented and exploited.

### The Reasoning Process

The OES is structured to support emulation of the human analyst's reasoning. It will produce three classes of analytical products: a significant events summary derived from local data, an environmental context based on off-board data extending beyond the local scene, and an estimate of the local scene representing the fusion of all available information. The system will develop and revise the environmental scene description as information becomes available. Without any on-scene or forecast data, the coastal scene description will substantially represent the data and knowledge in the climatologies and process-oriented knowledge bases. As on-scene information and regional forecast data become available, the scene description will be revised. Consequently, the OES will be able to provide an estimated scene description on demand as well as the basis for that estimate.

An object-oriented approach in knowledge representation and system implementation will allow the rapid association of different types of relevant, previously disjointed data sets. A drop in measured sea-surface temperature will be evaluated, for example, in the context of the ship's location and orientation with respect to the nearest coast, the likelihood of ocean frontal activity in the area, the local water depth, the atmospheric wind fields, and the time-history of previous sea-surface temperatures in the area. The interpretation could be that the ship had entered a coastal upwelling zone that probably extends along the coast, or a local anomaly. The process of interpretation previously required a human analyst, who did not necessarily have all the relevant information conveniently at hand. The OES will allow such a process to be automated and will facilitate application of that interpretation to the tactical problem.

## RISKS AND CHALLENGES

The need for forward-deployed naval units to access and interpret local oceanographic information during littoral operations, as well as the likely reduced availability of trained analysts on platforms other than major combatants, suggests that the application of autonomous information-processing technologies may be valuable. Preliminary investigations into the approaches currently followed by human analysts further suggest that a knowledge-based systems approach may be particularly appropriate. The road is not without challenges; the process of knowledge acquisition, the nature of the knowledge used in formulating an environmental scene description for tactical oceanography, and the need to refine that description over time must be managed.

### Knowledge Acquisition

Knowledge acquisition, commonly identified as the major bottleneck in the construction of a knowledge-based system, can be defined as the process of extracting, structuring, and organizing knowledge from some source (usually human experts) so that it can be used in a computer-based system. The central problem of knowledge acquisition is putting the knowledge into a form that can be processed by a computer. The selection of a knowledge representation scheme that closely matches the expert's reasoning process will greatly facilitate not only the knowledge acquisition process, but the construction of a viable explanation facility as well. Initial interviews have been conducted with experienced Navy operational environmental forecasters and have resulted in the reasoning process defined previously. We intend to continue in an interview-based approach to knowledge acquisition in which operational forecasting experts will work through a broad range of specific problem situations with a knowledge engineer for the purpose of knowledge capture.

### Nature of the Knowledge Used for Oceanographic Scene Description

The nature of the knowledge used in formulating and refining a coastal ocean environmental scene description poses numerous challenges. Multiple types of expertise are required, including knowledge of coastal oceanographic processes, knowledge of regionally specific climatologies, and knowledge relating to the reconciliation and integration of data at multiple resolutions, as described previously. To obtain such knowledge, many human experts will probably be required. The integration of their knowledge into a single system will be a complex task. Further, the amount of oceanographic process knowledge potentially of interest to the system is quite large.[20] The regionally specific nature of the climatological knowledge presents another challenge. We intend to focus initially on a specific geographic region as a test case while designing the system, but we will also ensure that the reasoning framework will be adaptable to different coastal regimes.

Initial knowledge acquisition interviews with experienced naval forecasters have raised other questions. In particular, human analysts have historically been stationed on (and had primary support responsibility for) major command ships at sea such as aircraft carriers. The OES, on the other hand, is targeted for forward-deployed platforms such as submarines and antiair defense frigates where TESS and human analysts are unlikely to be available. Consequently, we are forced to mine knowledge from experts and apply the knowledge in areas other than where it has been developed and traditionally used. A final challenge is presented by the nature of the task knowledge. Initial interviews of expert analysts suggested that elements of both commonsense and creative reasoning in the human analyst's approach combine to refine the environmental scene description over time. These types of domain knowledge must be separated to help define the scope of the system's functionality.

## Refining the Environmental Scene Description

The location of future military operations cannot necessarily be predicted in advance. Interviews with Desert Storm environmental forecasters highlighted the need for the OES to be able to refine its understanding of the coastal ocean environmental scene over time. Specifically, we must have a mechanism for accumulating evidence and refining analyses, estimates, and conclusions, as shown in Figure 3. Two theories of evidence and reasoning in the presence of uncertainty that are now used in artificial intelligence research seem promising: casual (or Bayesian belief) networks[21] and Dempster-Shafer theory.[22]

A Bayesian belief or causal network is a directed acyclic graph in which each node represents a discretely valued propositional variable, and in which the direction of the arcs usually represents the direction of causality (i.e., each arc points from its cause to its effect). An advantage of such a network is that it supports the propagation of the effects of new evidence on the beliefs about the values of the individual variables. The physical mechanisms influencing environmental modeling often involve causal chains that can be reasonably mapped to a causal network. The historical data for an area would be the source of the initial values (prior probabilities) of the nodes in the network. Real-time incoming data would then be used as evidence and propagated through the network in a manner consistent with the axioms of probability theory, resulting in a refined scene description based on the available data/evidence.

Dempster-Shafer theory, which can be viewed as a generalization of probability theory, is another method for evaluating the weight of evidence in support of multiple hypotheses. A belief interval can be computed for any hypothesis where the lower bound is a measure of how much belief we have committed to the hypothesis. The upper bound is a measure of how much belief we have committed to the negation of the hypothesis. The width of the interval is a measure of the uncertainty in our beliefs. Both Bayesian belief networks and Dempster-Shafer theory are being investigated as potential formalisms for supporting the refinement of the environmental scene description over time in view of accumulating evidence.

## SUMMARY

The accurate forecasting of oceanographic conditions for the coastal region (the coastal scene description) is inherently complex and demanding. The large-scale atmospheric and oceanic fields impose a background set of environmental conditions that are subsequently modified by a local region's smaller-scale characteristics. Reconciling the relative influences between the differently scaled forcing processes historically required expert human forecasters who became increasingly proficient with time spent in a particular area as they "learned" vagaries of the local region. Unfortunately, human forecasters will increasingly be in short supply as the Navy faces the prospect of conducting operations in remote, nontraditional coastal areas of the world. A careful examination of the role that automation can play in facilitating the coastal ocean scene description process is appropriate.

The Laboratory is well positioned to contribute to the development of improved tools based on information technology to support the coastal ocean scene description process. The feasibility of using knowledge-based computer decision aids in a complex decision-making environment has already been reported.[23] The Ocean Expert System represents a transition of that enabling technology to the oceanographic environment. Work is rapidly progressing toward the demonstration of an initial prototype OES capability for a few selected coastal areas within the Mediterranean Sea by the end of 1993, as part of the Navy's Exploratory Development Tactical Oceanography Program. Upon successful completion of that effort, the prototype system will be extended to a more general coastal environment and tested to determine its capabilities in the autonomous environmental scene description process for different large-scale forcing areas. Should this technology transition prove successful, a more automated process for generating the local, coastal time-dependent scene description can be provided to the operator at sea.

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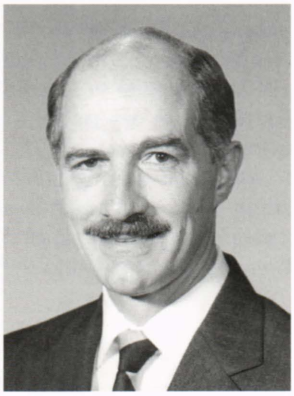

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