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Oceanographic Expert System: Potential for TESS(3) Applications

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Abstract

The Naval Research Laboratory (NRL-SSC) has developed an expert system with a rule base that "knows" about the evolution of mesoscale features in the Gulf Stream region of the North Atlantic. The expert system uses rules that describe the features' kinematics to evolve an earlier "state" to a later time. The NRL-SSC expert system has the potential to be useful in an operational environment. Hence, it is proposed as a candidate for implementation on the Tactical Environmental Support System, third generation (TESS(3)).

Continuing modifications to the expert system have improved its performance. Currently, work is centering on adding an explanation facility, increasing the accuracy of the ring-motion geometry, and replacing the Gulf Stream motion logic with an improved scheme. Those changes are combined with a transition from a VAX implementation to one running on a Sun workstation. The latter step, with associated changes in computer language, will facilitate subsequent transition to TESS(3). The current round of improvements will result in a system that performs better and is easier to use than the prototype system.

The TESS(3) implementation will be entirely in widely used computer languages. This, combined with the expert system's structure, will make it relatively simple for operational users to make incremental improvements (in many cases the changes will only be to the values of parameters in data files). The TESS(3) implementation of the NRL-SSC oceanographic expert system will be a straightforward extension of current work.

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Oceanographic Expert System: Potential for TESS(3) Applications

1.0 Introduction

The Naval Research Laboratory Detachment at Stennis Space Center (NRL-SSC) has sponsored the development of an oceanographic expert system for predicting mesoscale feature movement in the Gulf Stream region of the North Atlantic (Lybanon et al., 1986; Thomason and Blake, 1986; Thomason, 1989). While physics-based numerical ocean models show skill in predicting the Gulf Stream's path, they do not exhibit comparable skill in predicting the motion of associated warm- and cold-core rings (WCRs and CCRs), because small, intense mesoscale motions such as those associated with Gulf Stream rings are not easily handled by present model grids and numerical schemes. In contrast, the expert system has demonstrated a capability for accurately forecasting isolated WCR and CCR motion for up to 14 days in validation tests. Its performance on rings interacting with the Gulf Stream is almost as good (Lybanon and Romalewski, 1990; Lybanon and Thompson, 1991). The expert system has application to prediction when the features cannot be observed because of cloud cover, and in some other aspects of a semiautomated interpretation system (Lybanon et al., 1990).

Satellite sensors are a logical choice to fill the gaps left by conventional oceanographic measurements, due to their capability for synoptic coverage. An oceanographic analysis of satellite imagery may serve as input (along with other information) into a three-dimensional description of the ocean thermal structure, with the analysis used to initialize a forecast of the upper ocean thermal structure. The forecast may provide data for a subsequent analysis (Clancy et al., 1990). Infrared (IR) satellite imagery may provide useful information about sea surface temperature, which can be used to infer the thermal structure at depth with the aid of feature models (Hawkins et al., 1991).

Extraction of oceanographic information from satellite imagery can be a challenging problem for a number of reasons, among them the time-varying nature of ocean features, the presence of clouds and other interfering mechanisms, and the lack of general mathematical descriptions of features' surface signatures. Despite the difficulty of automated understanding of natural imagery, human analysts can frequently interpret oceanographic satellite imagery successfully. The provision of automated or semiautomated tools to aid interpreters has been an active area of research in NRL-SSC's Remote Sensing Branch for years (Lybanon et al., 1990; Krishnakumar et al., 1990).

The observation that human experts can surmount problems that thwart conventional computer techniques suggests that expert systems methodology may be useful. In meteorology, expert systems have been used for predicting severe weather on the meso- or smaller scales for several years (Moninger et al., 1991). In oceanography, the data base is so limited that the forecaster is usually forced to utilize a few one- or two-dimensional descriptors (frontal location, ring size and location) to build a three-dimensional field with feature models and model-based statistics.

The NRL-SSC expert system concentrates on mesoscale feature motion. In effect, it provides forecasts of feature positions and sizes at times later than the initial conditions. Thus, it could be useful to an analyst in an operational setting who must "fill in" information when adverse conditions, such as extensive cloud cover or missed "passes," prevent the addition of new observations since a previous analysis. It has also proven its value in connection with other components of the semiautomated mesoscale analysis system developed by NRL-SSC. It must be emphasized that this expert system was not designed as a "stand-alone" simulation to give accurate, long-term predictions; rather, it should be regarded as forming hypotheses about mesoscale feature evolution that must then be validated as much as possible by evidence from satellite and in situ data. It is an intermediate step between a synoptic analysis scheme and a fully prognostic dynamical system.

The oceanographic expert system was originally implemented on a VAX computer. Test and evaluation of the prototype system has led to several improvements. Currently, several additional improvements are being made in conjunction with a move of the software to a Sun workstation. The optimized Sun version will be available for implementation on TESS(3) in the near future.

TESS(3) is a computer workstation to provide environmental information for the Navy's tactical decision makers. It is the third generation in a sequence of systems intended to provide a workstation environment, to help assimilate the tremendous amount of available data, and run a large library of environmental software. The first two phases of TESS were funded by the Oceanographer of the Navy and developed by the Naval Oceanographic Office. The first phase, operational in 1985, had no electronic interfaces and served as a platform for running Geophysics Fleet Mission Program Library software. The second phase added additional applications as well as electronic interfaces to observation and warning data via radioteletype and an older satellite receiver, designated SMQ-6. TESS(3) was acquired by contract with Lockheed Missiles and Space Company, with program management provided by the Space and Naval Warfare Systems Command. It employs a Concurrent (formerly Massachusetts Computer Corporation) 6605 computer that uses three Motorola 68030 central processors. The software is menu-driven, with most of the operator interaction via a trackball. TESS(3) is designed to be interfaced with the new AN/SMQ-11 satellite receiver/recorder, as well as other command and control, communication, and display facilities. TESS(3) is designed to provide tailored environmental information to users in an automated fashion (Phegley and Crosiar, 1991).

The suggested "destination" for the oceanographic expert system is the Three-dimensional Ocean Thermal Structure (TOTS) software module developed for TESS(3) by NRL-SSC (Hawkins et al., 1991). The TOTS system is intended to give ship- or shore-based units the capability to map the sparsely sampled subsurface temperature field provided by expendable bathythermograph reports. The present TOTS system uses surface front and eddy maps ("bogus" maps) to supplement the subsurface measurements. The surface information is converted into synthetic temperature profiles, from the surface to the bottom, by means of "feature models" (Glenn, et al., 1990). Feature models reproduce the subsurface temperature structure of well-defined ocean features based on extensive hydrographic data and climatological data bases. TOTS also permits the shipboard user to tailor the product for a specific region and time using the latest onsite information. This scheme will allow the expert system to fit in as an additional data source.

2.0 Expert System Software

The NRL-SSC expert system incorporates a rule base of information about mesoscale features' kinematical aspects, and uses the rules to evolve an initial "state" to a later time. The new, hypothesized state can then be used as a new initial condition and the process repeated, possibly for several steps. Rules about expected ring movement and decay were extracted from a larger base of oceanographic information. Also included is a simplified model of Gulf Stream motion as wavelike downstream propagation of meanders. Work is currently in progress to change the implementation in several ways that will both improve the system's accuracy and provide additional, helpful information to the user.

In a run of the system through a sequence of registered IR images, the "working memory" (the data base that stores current, changing information) stores the current status of all mesoscale events known to the system. In the present implementation, the working memory is initialized with information obtained interactively by the user from the first image. At any time during the run, the working memory has entries for each WCR and CCR known to the system. Information about the Gulf Stream is handled separately. Each entry includes some historical information about the ring as well as its current status (its location, size, speed and direction of motion, and similar physical characteristics).

A complete cycle of the system causes rule-based estimates of changes to be generated for all rings. Selection and firing (a rule is said to have "fired" when its premise is satisfied and its conclusion drawn) of rules follows a conventional sequence for rule-based computation: *matching* with elements in the working memory determines which rule(s) can fire, *conflict resolution* selects one rule to fire next, and *action* fires that rule to execute the associated procedures. Based on the current data about a ring in the working memory, these procedures compute the system's estimates of changes in the ring's location, size, and direction and speed of motion. The estimates are generated for each ring in a sweep from west to east, WCRs first, then CCRs.

The expected characteristics of a ring's actions vary according to its position in the ocean as well as its proximity to the Gulf Stream (Thomason et al., 1986, and references cited therein). For purposes of rule-based computation, the northwest Atlantic Ocean is partitioned into nine disjoint sections, with the details of ring evolution different in each. Each section has its own set of rules for WCRs and for CCRs that describe expected characteristics such as speed of drift, direction of drift, rate of decay when not near the Gulf Stream and when interacting with the Gulf Stream. These rules determine the expected changes in a ring during a specified period of time.

Previous work has led to some "global" changes in ring velocity vectors (i.e., the same change was applied to the velocity vectors in all regions) that improved the system's performance with respect to ring motion (Lybanon and Thompson, 1991). Work is currently under way that will produce further improvements. The newer changes are of three types: addition of an explanation facility, increasing the accuracy of the ring motion geometry implemented in the rules, and replacing the Gulf Stream motion logic.

An explanation facility will allow the user to ensure that the system's reasoning is appropriate and the conclusions are believable. It can also make it easier to detect and trouble-shoot problems. Although one of the trademarks of knowledge-based systems is their ability to explain their own reasoning, it is often not easy to add explanation capability to existing expert systems. The difficulty usually arises because the knowledge needed for explanation is not explicitly represented in the system's knowledge base. In the case of the NRL-SSC expert system, the changes needed in the rule base structure to facilitate explanation will both simplify the rules and make them more general.

Each of the present ring motion rules is large and complex. However, the rules for different regions have similar forms. The changes will divide the existing rules into several smaller rules, more general in the sense that they can be applied to specific cases by specification of the appropriate parameters. Thus there will be one set of rules for CCRs and one set for WCRs, rather than different rules for each region, so the changes will not result in an explosive increase in the number of rules. Replacement of the long, complex rules with several simpler ones will provide several benefits. First, an explanation component can be added by capturing the chain of rule firings and the associated changes to working memory. The simpler rule structure will also make the information governing the details of ring motion more easily accessible for inspection, change, and maintenance by scientists who are interested in modifying the program.

Since the expert system deals with motion on the Earth's curved surface, the mathematical description is more complicated than that for motion in a plane. In some cases approximations are necessary, to remove the need for time-consuming numerical solutions of transcendental equations. Approximations of the same level of accuracy as the data used by the system are perfectly legitimate, but suitable care must be used to ensure that the accumulation of error during a run of the system is not excessive. The planned changes are expected to improve the accuracy of the motion equations used, both for ring motion and Gulf Stream motion.

NRL-SSC research has shown that the Gulf Stream's shape can be represented accurately by an empirical orthogonal function (EOF) expansion involving 20 coefficients. An extension of that work indicates that sufficient time coherency between consecutive coefficient sets exists to allow prediction 1 week into the future. Further, a neural network can generate the predicted EOF coefficients. Forecast skill for the neural network is found to be comparable to other methods, while computational requirements are only a fraction of those required by the others. A neural network module to handle Gulf Stream motion is being incorporated into the expert system.

3.0 Computer Languages

The NRL-SSC oceanographic expert system was coded in a combination of OPS83, C, and FORTRAN. It should be noted that programming an expert system differs from conventional (procedural) programming in that rule-based processing is performed. In rule-based programming for expert systems, the concept variously called a production, an if-then rule, or a logical implication generically has the form LHS —> RHS and has the meaning that "if the left-hand-side LHS is TRUE, then the rule is satisfied and may be executed or fired to yield a right-hand-side RHS also TRUE." Different programming languages use entirely different syntax for defining rules and different strategies for firing them. In the case of the expert system described here, the rule-based component is one part of the total programming of a system in which substantial requirements for conventional procedural computations also exist.

OPS83 is an expert system language that offers facilities for rule-based programming and for procedural programming as well. Thus, rule-based computation (as in OPS5, a predecessor to OPS83, and PROLOG) and procedural computation (as in FORTRAN and C) are possible in the same language. Linking to external procedures written in other languages is also straightforward.

The "standard" artificial intelligence language for TESS(3) is PROLOG. The name is an acronym for programming in logic. Roughly speaking, as a PROLOG program runs there is at any time a current data base of TRUE statements (the knowledge base) in which each statement is taken to be a predicate (a function whose value is either TRUE or FALSE) in which unbound variables may appear. Some of these predicates are implications, as, e.g., P(x) —> Q(x) in which the TRUTH of P(x) implies the truth of Q(x). Unless constrained otherwise by explicit program structure, PROLOG carries out an exhaustive search in the knowledge base. During the search it is constantly seeking to establish the TRUTH of various (chains of) propositions by binding variables in predicates to values for which TRUE entries can be found in the knowledge base. The knowledge base may be modified by propositions in the program that either ASSERT new entries or RETRACT existing ones.

PROLOG's "inference engine" is different from OPS83's, so conversion of the oceanographic expert system to PROLOG would require significant programming. (OPS83 is not currently available for the Concurrent computer, so conversion may be required for reasons other than a desire to conform to an official standard.) There is an alternative without this drawback, however. CLIPS, which has become widely used by a variety of government (military and civilian), university, and industry organizations, is an expert system tool developed for NASA's Johnson Space Center. CLIPS is written in C and can be ported to any system that has an ANSI compliant C compiler. It supports rule-based, object-based, and procedural programming paradigms, and can be embedded within procedural code, called as a subroutine, and integrated with languages such as C, FORTRAN, and ADA. In addition, CLIPS is available without charge to U.S. Government agencies and their contractors. The current effort to add an explanation capability to the expert system will involve some conversion to CLIPS.

4.0 Implementation Issues and Documentation

The TESS(3) implementation of the NRL-SSC oceanographic expert system is envisioned as a straightforward extension of current work aimed at converting the system to run on a Sun workstation while simultaneously introducing some improvements. Current work also includes documentation of the system. That documentation will serve as a starting point for the TESS(3) documentation.

The Sun workstation implementation currently under development will result in a version of the expert system that incorporates the latest improvements to the ring motion rules available (both the structure of the rules and the details of the motion), improved logic for Gulf Stream motion, and an explanation capability. Further incremental improvements will be relatively simple for operational users to make, by changing the values of parameters stored in data files. The rule-based portion will be largely in CLIPS, and the procedural portion will be in C.

Changes to the code necessary for a TESS(3) implementation will be primarily in two areas:

1. Any remaining OPS83 modules will need to be converted into CLIPS and C, and
2. The appropriate interface to the TESS(3) graphics must be developed (graphical output on the Sun will make use of a proprietary package, PV-WAVE).

Several approaches to the second of these are possible. Graphical output is desirable but not necessary, so the simplest option would be to eliminate the feature. Next in complexity would be to produce graphical output offline after a run of the system, making use of position and size information written to standard output files. Real-time, online graphical displays would need to make use of routines specific to the TESS(3) system. The difficulty of this option must be investigated, but it does not seem likely that the last option will involve serious difficulty. Because of the utility that real-time graphical output would provide to an interactive user, that option is the preferred one.

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