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GODAE APPLICATIONS USEFUL TO NAVIES THROUGHOUT THE WORLD

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ABSTRACT. The Global Ocean Data Assimilation Experiment (GODAE) brought together an international group of researchers to address the problem of predicting the ocean environment. GODAE addressed the necessary technological development for data assimilation, which is a critical choke point within the process of providing meaningful information. These efforts brought a significant step forward, and today these technologies are applied operationally in areas of historically strong need. One application is for navies throughout the globe. Navies are now making regular use of oceanographic information forecast by numerical models that are initialized by assimilation of global satellite and in situ data sets. Prior to GODAE, forecast properties were not available operationally, and the information provided to navy operators was typically either climatology or local observations. The ability to forecast the ocean environment has significantly changed how navies operate. Rather than going to a location at a predetermined time and determining whether the environment is suitable to safely conduct a mission, navies can now choose where and when they may operate safely and efficiently to either avoid adverse effects or take advantage of favorable conditions. Several example events over recent years highlight how navies around the world use GODAE forecast information.

INTRODUCTION: GODAE INTEGRATION WITHIN NAVIES

Nations worldwide have invested enormous portions of national wealth in nearshore and deep-water navies to provide national defense, ensure safe trade, enforce laws, assist in search and rescue, and provide relief and aid. The deployed platforms range from small boats carrying a few passengers to aircraft carriers with thousands of people aboard. Away from port, these investments are at the mercy of the ocean, and the effects of day-to-day changes in the ocean can range from decreased efficiency resulting in lost time and higher costs, to failed missions and damaged vessels, and even to loss of lives. Awareness of the environment in which navies will be operating allows commanders to make confident decisions to change deployment of assets or use of equipment to avoid these negative effects. This critical awareness of future environmental conditions has been significantly enhanced by the Global Ocean Data Assimilation Experiment (GODAE). Researchers developing an understanding of ocean physics, representing ocean physics within computer models, and constructing observing systems have made great strides in the past 20 years. GODAE efforts brought these fields together to provide a capability to predict ocean state and the environmental awareness necessary for safe operations of navies. Recognizing GODAE systems' potential to significantly impact their operations, navies have invested heavily in development of the systems. The challenge now is to ensure that this investment translates into real impacts on operations. The examples presented in this paper illustrate the great progress that has been made in the application of the systems; the next step will be to begin to quantify more comprehensively the benefits that the systems deliver.

Enabling operational forecasts requires substantial commitment of resources to ensure the availability of necessary personnel, communications, computational capability, and infrastructure. Examples are used here to demonstrate how forecast information provided by several different operational systems is being used. Implementation details are covered in many other manuscripts within this issue (e.g., Dombrowsky et al.), so only a short synopsis is provided here. Centered on Australia, the BLUElink> system uses the Ocean Forecasting Australia Model (OFAM) based on the Modular Ocean Model MOM4 numerical core (Brassington et al., 2007; Oke et al., 2008). Assimilating satellite observations and various in situ measurements, the system provides twice-weekly forecasts out to six days for applications such as passage planning and anti-submarine warfare (ASW) exercises. The system must contend with a diverse range of dynamics, from the tropics to the Antarctic Circumpolar Current. Civilian communities often request aid from navies in response to emergencies or simply to leverage resources. Defense centers are very eager to contribute to national capabilities. In particular, BLUElink> system results have been applied to areas ranging from leisure activities such as yacht racing to saving lives during search and rescue at sea.

The Naval Oceanographic Office (NAVOCEANO) at Stennis Space Center, Mississippi, provides products worldwide based on global and nested model predictions that run on a daily cycle with forecasts from 48 hours (i.e., the global Navy Coastal Ocean Model [NCOM]; Barron et al., 2007) to 30 days (i.e., the global Navy Ocean Layered Model [NLOM]; Shriver et al., 2007) along with the global Hybrid Coordinate Model (HYCOM; Hurlburt et al., 2009). These systems draw in data sets developed through GODAE, including satellite data streams and in situ profiling floats. Their results are used continually in regularly scheduled Navy exercises in addition to providing aid in emergency response and search and recovery, such as for the cockpit recorder of the Indonesian airline Adam Air flight 574 disaster (January 1, 2007).

Système Opérationnel d'Analyse et de Prédiction (SOAP; Jourdan and Lucion, 2003) uses outputs from the various systems of the Mercator Océan consortium (Dombrowsky et al., 2009) to compute products and initialize higher-resolution nested models. It was primarily designed and developed to support ASW at the operative level, which requires description of the synoptic mesoscale. It provides products on a daily to weekly basis, ranging from classical isodepth maps of sound channel interfaces to high level added-value products, such as mesoscale activity analyses, with forecasts from 48 hours to 14 days, depending on the applications.

Each of these production centers has been instituted to provide insurance that the forecast information will be available, and the centers themselves represent a significant investment in resources. The wide range of uses to which navies apply the information provided by the production centers demonstrates the importance of the GODAE products. The areas of importance are broad and the impacts range from small efficiencies to the safety of lives. Here, it would not be possible to provide exhaustive examination of the ocean impact on navies' operations, but we do examine some of the major applications that are common among navies worldwide.

APPLICATION OF GODAE FORECAST PRODUCTS

The forecast ocean state includes thermohaline and velocity fields. In addition, model input includes ocean conditions that modulate exchanges with the atmosphere. We provide case examples in which navy products are used to support operational requests that require data in these areas. The first applications use velocity information, which provides currents for operations being conducted underwater at specific points as well as Lagrangian drift forecasts for either in-water drifting hazards or search and rescue operations. The second application involves ocean thermal and salinity structure forecasts, which are used regularly to select from the available sensors and determine optimum ensonified volumes for use during training exercises concerning acoustic systems. This area certainly has the most unique navy application, and a synopsis is provided on how the ability to provide acoustic information has progressed over time to the present GODAE capabilities. In one final application, models that show the ocean's effects on the atmosphere support search and rescue as well as drug interdiction efforts by indicating the range over which radar systems will reliably detect objects on the ocean surface.

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Forecast Velocity Fields

Velocity fields have important applications both from Eulerian and Lagrangian points of view. Operations often require predicted time series at specific places. A typical example (Figure 1) is a practice exercise for rescue of a submarine crew conducted off the West Australian Exercise Area (WAXA). The first step required grounding a submarine on the ocean floor, an operation that can only be safely conducted in areas where currents are sufficiently low; extreme currents could drag the submarine and cause extensive damage. Next, an escape pod had to be attached to the submarine to evacuate crew. This step required divers in the water for several hours, during which they were vulnerable to currents. The BLUElink> system provided predictions over the exercise area to allow scheduling of the work in nonhazardous conditions. Certainly, if forecast conditions were adverse, exercises would either be relocated or canceled. In either case, it is now possible to make such a decision using GODAE forecasts. Provided that the forecasts

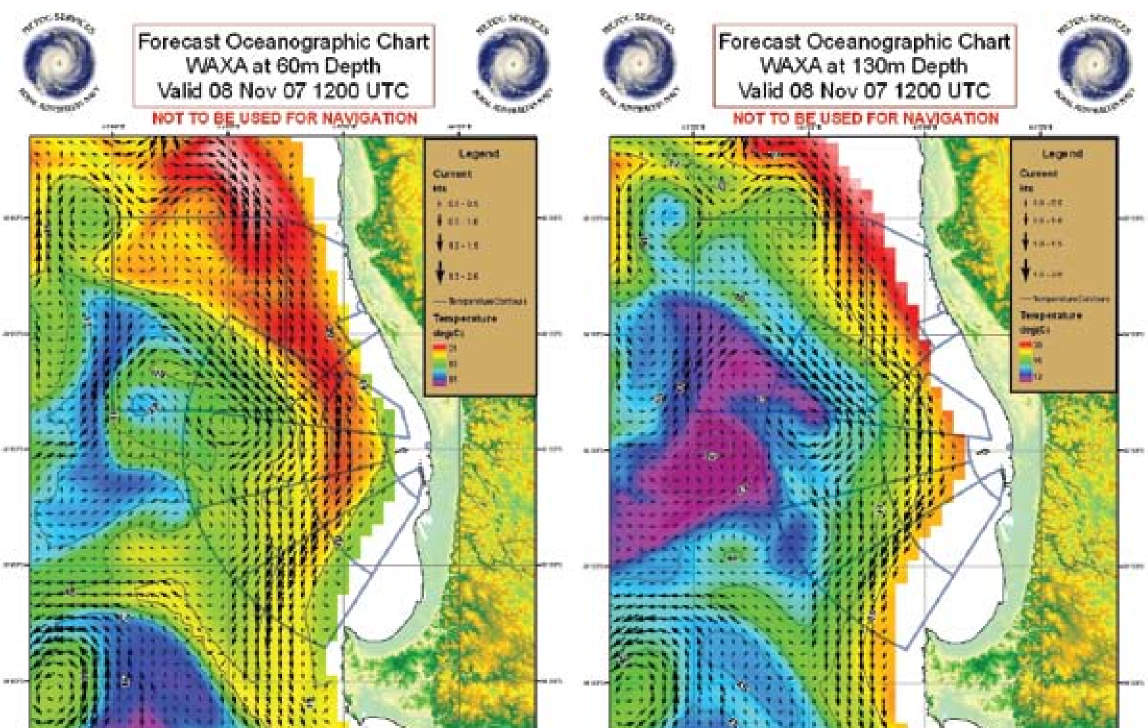

Figure 1. BLUElink> forecasts of ocean state at 60-m depth (left) and 130-m depth (right) in the West Australian Exercise Area (WAXA) show velocities (vectors) and temperatures (color) used to determine whether underwater training exercises could be conducted safely. Such forecasts that allow determination of where and when exercises may be conducted safely increase naval efficiency. In real rescue situations, such information is crucial.

are sufficiently accurate, such informed decisions significantly increase efficiency as opposed to moving forward without forecast information, only to find that exercises are not possible once vessels and personnel are on scene.

In applications involving drifting objects or hazardous material, a Lagrangian prediction can provide trajectory information. Navies are required to contend with oil spills continually, and there are navy organizations whose goal is to mitigate any navy spill. The oil tanker *Prestige*'s oil spill in the Bay of Biscay during 2002 extended over a very large area, and shifting ocean currents changed the spill path continuously. The large scope of the spill pressed response teams to seek out information from navy as well as civilian organizations. Crews cleaning up along the shoreline were limited, and inaccurate estimates of spill pathway would result in misplacement of assets, inefficient application of effort, additional environmental damage, and subsequent increase in cost of mitigation. The GODAE development proved very timely in this situation, with capabilities ready to provide forecast information. The Service Hydrographique et Oceanographic de la Marine (SHOM) assisted the crisis headquarters coordinating the *Prestige* pollution monitoring and cleanup effort, and also examined the problem in retrospect (Figure 2). In this case, drifting particles were injected into a HYCOM reanalysis to determine the accuracy of the prediction system. The *Prestige* oil spill represented a significant event to which the GODAE development could be applied. Continued examination of the problem in retrospect could lead to better understanding of forecast accuracy and impact on such emergency operations.

The 2007 Adam Air flight 574 disaster in Indonesia presented an unfortunate loss of life. The airline industry uses information returned from the onboard flight recorders in aircraft to prevent reoccurrences of any aircraft or human malfunction that leads to such tragedies. Unfortunately, Adam Air Flight 574 was lost from radar, and the position at which it impacted the water surface was unknown. Due to international communications difficulties, the point at which radar contact was lost was also unknown. The NAVOCEANO survey vessel *Mary Sears* was sent to assist with the search, though the area that required searching was so large that finding the flight recorder boxes, whose acoustic transmitters have limited battery life, seemed impossible. Within two days, material from the crash was found washed ashore, and the currents from numerical ocean models at NAVOCEANO were integrated backward in time to estimate the source position (Figure 3). The search was concentrated within this area, and the information on the last radar contact was provided shortly after. Note that the trajectories indicate the general vicinity of the last radar contact from the National Transportation Safety Board (NTSB). Using both drift trajectories that provided the general area and the last radar contact localization, *Mary Sears* personnel were able to locate the flight recorders shortly before the batteries were exhausted. Without such information, ship search planning would have been required to cover a much larger area, and the recorders would not have continued to transmit.

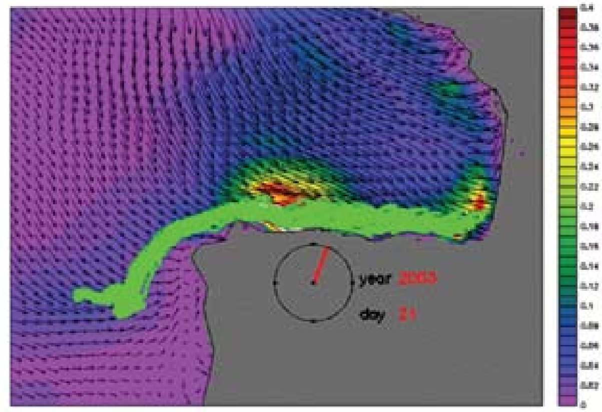

Figure 2. A reanalysis by Service Hydrographique et Oceanographic de la Marine (SHOM) of the *Prestige* oil spill that occurred on November 19, 2002, is used to determine the ability of ocean forecast systems to help focus efforts in areas where they are needed most. Here, the vectors show surface velocities, with color indicating magnitude (m s^{-1}). The green area is the position of drifters injected into the model system to show the dispersion of the oil spill. When personnel available to address such a large spill are limited, forecasting the areas in which they will have the most impact is important.

Forecast Acoustic Propagation

Acoustic energy propagation is extremely important for navy operations because acoustic methods are used for communications as well as for detection. Continual training is necessary to maintain operator proficiency. Prior knowledge of the ocean volume ensonified by an acoustic signal is used to determine what sensors may be employed, what frequencies may be used, how the sensors may be used, and, ultimately, how ships carrying the systems are placed. Ocean properties affect the horizontal and vertical gradients of sound speed, which refract acoustic energy. A hot road in summer generates a warm air layer at the surface that refracts light to create a mirage. Analogous effects are commonplace in the ocean due to changes in the mixed layer, upper ocean heat content, small gradients in thermal properties within the thermocline, variations in thermal structure due to ocean mesoscale eddies, and even internal waves.

The advancements provided by GODAE are reflected in the accuracy with which acoustic energy propagates through the ocean state estimate. In Figure 4, an observed sound speed structure serves as ground truth, and an acoustic source is placed at 25 m. The ratio of energy at any point in the water column at any range to the energy of the source, measured in dB, is the transmission loss, which is computed by an acoustic propagation model. In the Figure 4 case, one observed sound speed profile shows a large horizontal extension of low transmission loss at the source's depth (25 m), where the sound speed structure forms a surface duct that causes sound speed to increase with depth, resulting in upward refraction of the sound energy (Figure 4a).

Originally, climatology was the best source of information as there was no prediction capability available. To form climatologies, historical observations were averaged, and several disadvantages soon became apparent. First, no synoptic effects were taken into account. Second, the averaging process smooths out sharp features in the profile. In particular, the mixed-layer depth, which is a key controller of the surface duct, is too smooth and shallow. Transmission loss results using climatology led to no surface trapping of energy (Figure 4B).

When satellite information first became available, only sea surface temperature (SST) was accessible operationally. There is some correlation of the ocean structure at depth to SST. Using this correlation to construct the sound speed profile still results in the lack of a surface duct (Figure 4C). Altimeter-observed sea surface height (SSH) is affected by thermal expansion due to temperature structure beneath the surface. A temperature profile is computed using temperature at depth correlated to SSH and SST, and the transmission loss begins to show a surface duct (Figure 4D). When an understanding of the physical processes controlling ocean development is used to estimate mixed-layer depth, and this mixed-layer depth is used in the process of constructing the temperature profile, a much stronger surface duct appears (Figure 4E).

Through the efforts of GODAE, when satellite observations are used in conjunction with numerical forecast models, a good representation of the surface duct is seen in the transmission loss prediction (Figure 4F). Finally, it is only possible to predict the ocean's influence on acoustics through numerical model forecasts, and the ocean structure changes spatially. In addition to advancement of ocean state estimation, GODAE provides a critical new capability to predict the full time-varying, three-dimensional field.

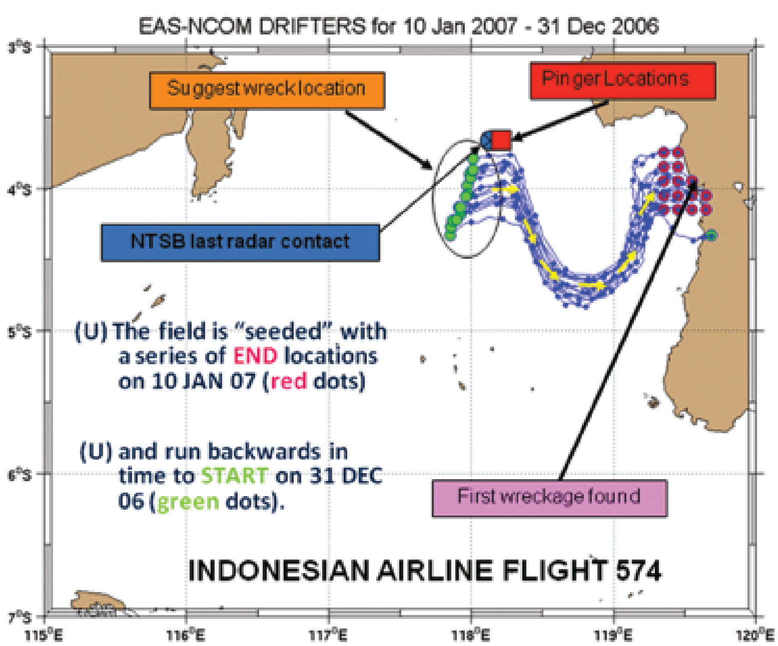

Figure 3. After Adam Air flight 574 crashed in January 2007, debris was found off the west coast of Sulawesi. NAVOCEANO used numerical model velocity fields to determine the path the wreckage followed to determine the probable location of the crash site. The black boxes were located through their acoustic pingers soon after. Provision of the NTSB last radar contact information was delayed until after the model trajectories were computed. Without such information, the searchers would have been required to cover a much larger area, and the recorder batteries may have been depleted before they were found.

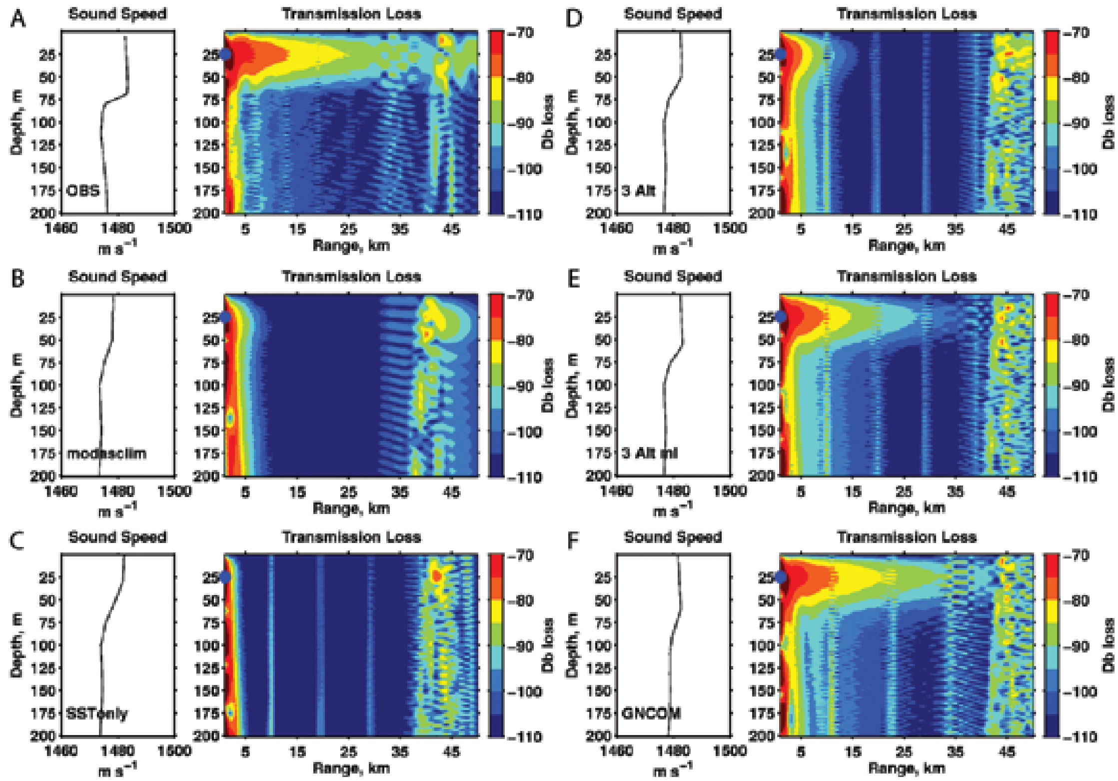

Figure 4. (A) An observed sound speed profile is combined with an acoustic propagation model to plot the transmission loss for a source of sound at 25-m depth. The extension of low transmission loss to the right at 25-m depth is due to an upward refracting sound speed profile that creates a duct. The transmission loss in the other estimates is based on (B) climatology, (C) SST only, (D) SST and SSH from three altimeter satellites, (E) the same satellite data with the addition of information on mixed layer depth, (F) a global numerical model assimilating the satellite data. The GODAE effort to assimilate observations into numerical models has led to advancement in acoustic propagation prediction. These results are based on historical products from NAVOCEANO.

The past capability used in situ data, which only observes the present at one point. Prior climatologies and data-only analyses (such as Figure 4E) have been discontinued at operational centers and replaced by numerical forecast systems that have demonstrated additional skill.

Each acoustic sensor uses a different frequency range and different methodology for detection, and the ocean sound speed structure affects each frequency differently. Performance in the local environment is a key issue in determining what level of performance operations may achieve. In order to apply GODAE capabilities directly for use in decision making related to acoustic sensors on board ships, navies must consider and apply suitable processing of numerical model forecasts. This is a common purpose of navy production centers. The temperature or sound speed fields themselves are not of significant use to acoustics operators. An example from the SHOM center shows the steps required to move from the GODAE ocean model state to actionable information (Figure 5). First, derived information is constructed to indicate the existence of certain acoustically important features. The sonic layer depth (SLD) is the near-surface depth at which sound speed is maximum. Above this depth, sound will propagate long distances by refracting upward. The derived information provides an indication of how different acoustic signals may propagate. From this information, system performance may be determined. Will a particular acoustic system be able to provide the necessary performance for a specific application? Stoplight maps are typically constructed to show where a particular system will perform as expected and where it will not. These tools are valuable, particularly when based on forecast GODAE fields. The positioning of ships, sensors, and exercises in advance is greatly aided. Finally, knowledgeable guidance is based on derived information, system performance, and human interpretation

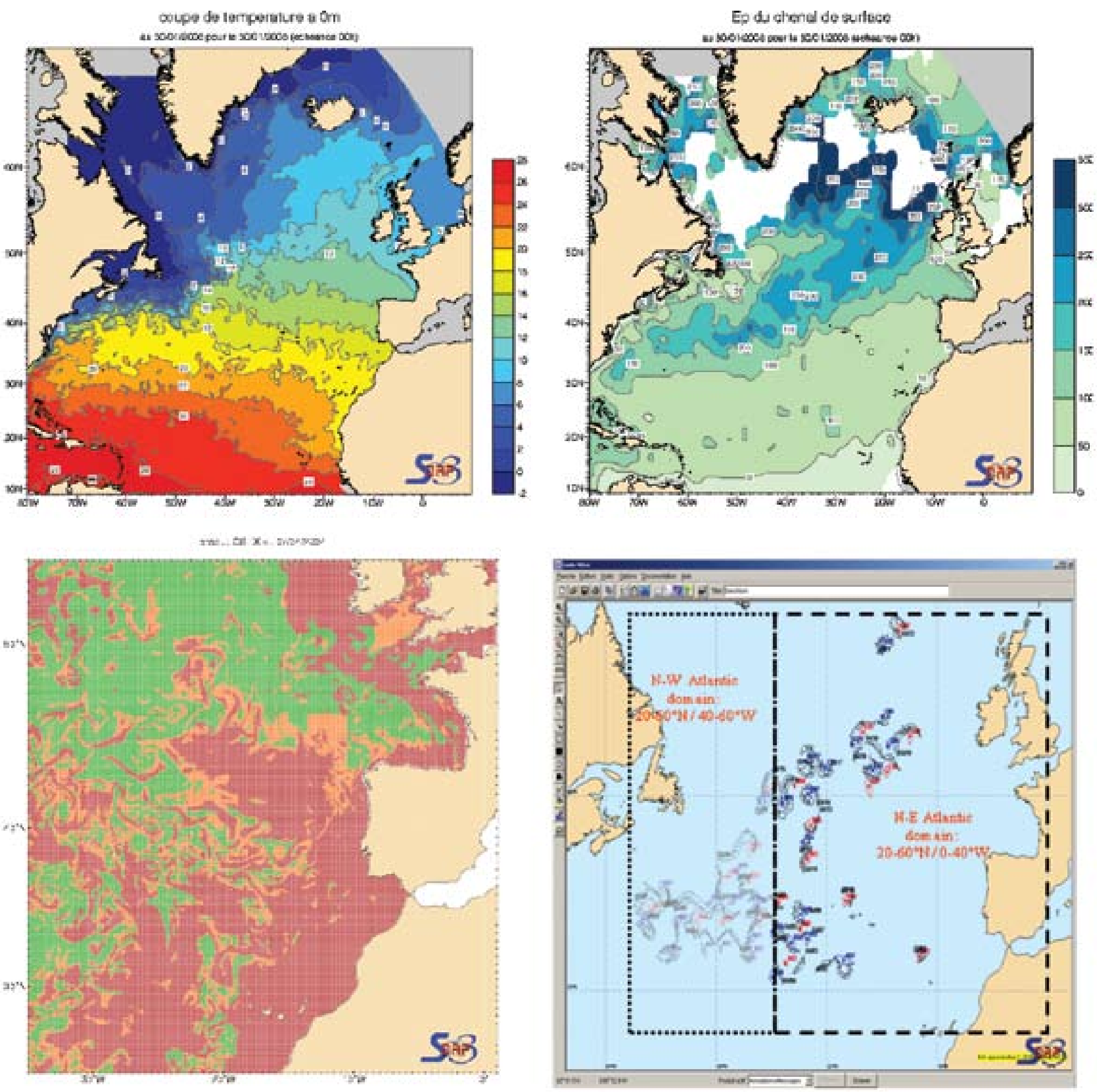

Figure 5. Operational centers convert GODAE ocean predictions (top left, SST) into derived information (top right, sonic layer depth) to apply sensor performance specifications that indicate where a certain sensor will or will not work (bottom left) and to actionable information (bottom right) that indicates in what areas ships should or should not operate. The example here is from the SOAP (Système Opérationnel d'Analyse et de Prédiction) system.

of the local situation that takes into context the end goals of a mission as well positioning and availability of resources. This last step is the most critical and requires well-trained and capable staff at the production centers. Without these people, GODAE products would not have the impact that they presently do within navies.

Coupled Atmospheric Effects

The ocean and atmosphere exchange heat and material at the ocean/atmosphere interface, and evolution of the ocean environment strongly affects the atmosphere due to the ocean's much greater heat capacity. Evaporation of moisture from the ocean creates a duct in the atmosphere that controls radar propagation. Knowledge of the distance a radar signal will propagate is important when searching for objects on the ocean's surface. These operations usually involve search and rescue as well as drug interdiction. To predict atmospheric properties, it is necessary to include interactions with the ocean. The BLUElink> system contains a high-resolution nested ocean and atmosphere prediction system that exchanges information between the two to provide a forecast of the environment. From the forecasts, derived information on sensor performance is obtained (Figure 6). Such maps of sensor performance help to determine where radar search assets can best be concentrated to ensure that the entire area is properly searched. In the same manner, other areas will require less-dense coverage for a proper search. Such forecast information is needed to plot flight tracks that will not leave gaps in the search area.

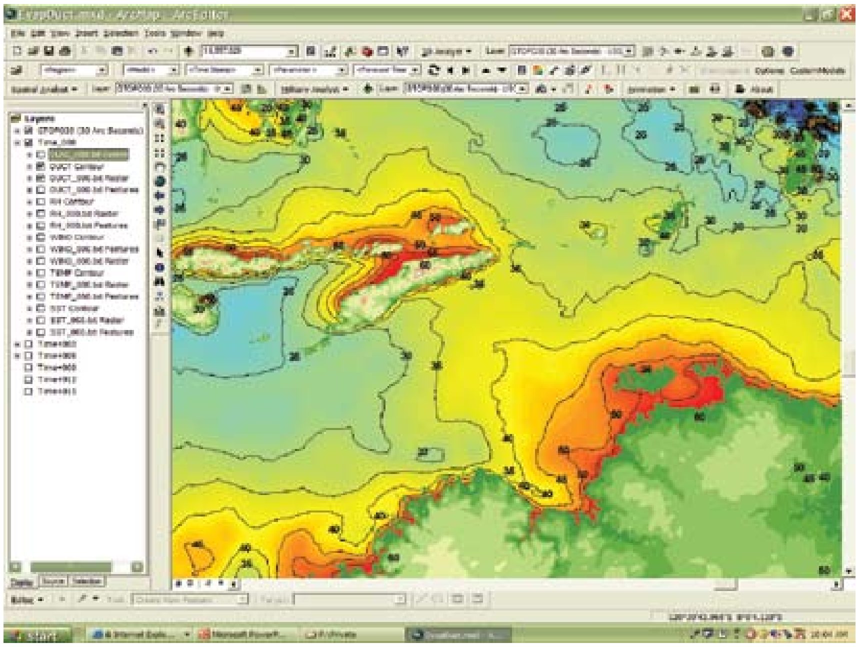

Figure 6. Evaporative duct height in meters forecast by the BLUElink> coupled ocean/atmosphere model system.

CONCLUSIONS FOR THE FUTURE

GODAE has enabled forecasts of the ocean environment where none had existed previously, and navy operators around the globe use these forecasts. The examples given in this paper demonstrate a few of the real day-to-day applications of the products. GODAE results have enabled a first-generation ocean prediction capability that is of potential value to navies worldwide. The scientific community strives to understand the underlying physics of problems and to prove this knowledge through demonstration, culminating in the systems in place today. With this first taste of the possibilities, great interest has risen within navies. In particular, the accuracy of the systems in terms of the impact on operations is of high interest. Operators are only beginning to become experienced in system accuracies and applications. Development of end application performance is underway in many areas. Some simple examples from meteorology are tropical cyclone track prediction and the impact of inaccurate forecasts on resources if people are evacuated unnecessarily or on lives lost if people are not evacuated. Operational navies do not yet have the answers as to how accurately the mesoscale field or the vertical temperature structure must be predicted. The GODAE demonstration has certainly piqued interest, and with the realization that ocean prediction is feasible, efforts to quantify accuracy requirements are under way.

New possibilities have come to light in the operational centers, which had previously worked under the assumption that the only information available would be in situ observations. These observations were typically out of date by the time they reached the operational centers (anywhere from 12 to 48 hours), and by the time the center provided information to end users the value had further degraded. Having realistic ocean forecasts makes every ocean observation crucial as it provides increased fidelity in forecasts. With these forecasts, sensor system performance prediction and new actionable information is being provided. Entire new lines of products have opened up with the successful conclusion of GODAE, and there is no end in sight for continued construction of new and useful products.

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