THE OFFICIAL MAGAZINE OF THE OCEANOGRAPHY SOCIETY

Oceanography

CITATION

Burnett, W., S. Harper, R. Preller, G. Jacobs, and K. LaCroix. 2014. Overview of operational ocean forecasting in the US Navy: Past, present, and future. *Oceanography* 27(3):24–31, http://dx.doi.org/10.5670/oceanog.2014.65.

DOI

http://dx.doi.org/10.5670/oceanog.2014.65

Overview of Operational Ocean Forecasting in the US Navy

Past, Present, and Future

BY WILLIAM BURNETT, SCOTT HARPER, RUTH PRELLER, GREGG JACOBS, AND KEVIN LaCROIX

INTRODUCTION

A popular cigarette advertisement from the 1960s exclaimed, "You've come a long way, Baby!" That sentiment could be applied to Naval Oceanography. The US Navy has navigated the course of developing prediction technology over many fundamental shifts in global geopolitics while addressing the evolving challenges at the forefront of the oceanography mission to ensure the safety of the nation's armed forces. Originally motivated by Soviet-era submarine programs, accurate acoustic prediction necessitated forecasting the positions of ocean fronts and eddies. Since then, the scope of Naval Oceanography has expanded to encompass a littoral focus, including applications that assist Navy SEa Air and Land (SEAL) teams, amphibious vehicle landings, and mine warfare. The fundamental physics governing the universe remains unchanged and so has the Navy's need to understand ocean physics, build numerical representations, connect to data streams, and assimilate observations in order to provide forecasts addressing the challenges of today and tomorrow. A well-planned course is no accident, and the Navy's leading edge in ocean prediction is the result. This paper provides a description of the path to this leading edge, a synthesis of the current operational architecture that enables Naval Oceanography, an analysis of the triumphs of the last 10 years that are part of today's oceanography portfolio, and a prediction of what the next 10 years holds for Naval Oceanography.

CHARTING THE COURSE

As early as 1976, ocean forecasting was acknowledged as an important goal for the US Navy to provide ocean thermal structure to support accurate anti-submarine warfare (ASW) acoustic prediction performance. In June 1976, an "Ocean Forecasting" workshop was held in Monterey, CA, to assess Navy needs in prognostic and synoptic modeling and to define a preliminary long-term ocean forecasting plan (Anonymous, 1977). The workshop addressed two immediate goals to "dramatically improve" ocean prediction: (1) develop an improved sea surface temperature diagnostic model to upgrade the Navy's surface temperature maps to a 6- or 12-hour update using in situ data, and (2) use multilayer, open ocean boundary circulation and thermodynamic models to predict ocean state in a region where ocean fronts or temperature anomalies occur. Based on these recommendations, Navy efforts focused on the development of the Thermal Ocean Prediction System (TOPS), a grid of one-dimensional model vertical profiles of the thermodynamic structure of the upper mixed layer (Clancy and Pollak, 1983).

In 1981, the second "Ocean Forecasting" workshop was held in Monterey to discuss progress and future directions (Mooers et al., 1982). This group recommended improving ocean prediction by using real-time, in situ, and remotely sensed data; developing four-dimensional data assimilation methods; and developing advanced statistical and dynamical methods for open and closed boundary circulations and understanding deep ocean variability. High priority was given to designing an effective ocean observing system and providing high performance computing facilities with adequate scientific support for research and development (R&D). In 1986, the Oceanographer of the Navy and the Chief of Naval Research sponsored a third workshop to discuss a way forward

for ocean forecasting based on advancing technology and Navy requirements (Mooers et al., 1986). These goals included mesoscale ocean prediction using global ocean observing systems that employed multiple altimeters, multiple scatterometers, and ocean color sensing, as well as in situ measurements for surface and subsurface observations. To better address Navy requirements, especially those related to ASW, workshop participants recommended that higher resolution regional models be coupled to courser resolution global models to provide computationally feasible predictions at tactically relevant scales.

Coincident with the timing of this workshop, the Oceanographer of the Navy, RADM J.R. Seesholtz, delivered a mandate to the oceanographic community to develop a global ocean forecasting capability that would depict mesoscale features and to have it ready for operations by 1992. In addition, he initiated an effort to acquire supercomputing resources for the Naval Oceanographic Office (NAVOCEANO) and to upgrade the Fleet Numerical Oceanography Center (FNMOC) in order to operate these new forecast systems (Seesholtz, 1986).

Peloquin (1992) provided a status of Navy ocean modeling six years after the 1986 workshop and coincident with the Seesholtz target. Ten years later, Burnett et al. (2002) provided a further update on 10 years of progress (1992–2002) in bringing advanced weather and ocean models to production in support of Department of Defense operations. These papers revealed that many of the goals of the Ocean Prediction workshops had been met, including development of a global ocean prediction capability that resolved mesoscale features and successfully met the mandate given by the Oceanographer of the Navy.

ARCHITECTURAL EVOLUTION

Two key components enable ocean forecasting: technology and personnel. For this paper, technology applies to the hardware, software, and systems architecture required to process, deliver, and use information to make relevant decisions. The other key component is the availability of skilled and educated personnel able to interpret and advise decision makers based on available observations and forecasts. The Naval Oceanography Program (NOP) is the operational component that ensures technology and personnel are on hand to meet Navy and DoD requirements. The CNMOC (Commander, Naval Meteorology and Oceanography Command) manages the NOP and reports directly to the Commander, United States Fleet Forces Command (USFF). This ensures that the operational Naval Oceanography community is aligned toward operations and missions undertaken by the US Navy. Funding for the NOP is managed by the Oceanographer of the Navy.

Naval Oceanography's mission is to provide physical battlespace awareness, or environmental awareness, to operational forces. To support this mission, Navy R&D communities focus on improving knowledge and understanding of the maritime operating environment. These efforts provide the Navy with the information-based capabilities and capacities to maneuver freely at sea. The future for Naval Oceanography, and the information it provides, will be enabling our sailors and soldiers to operate safely and exploit environmental variability in an information-dominated world through the combination of real-time observations and numerical models.

There have been major, revolutionary infrastructure changes in Naval Oceanography since 2002. At that time, Naval Oceanography was still providing support from worldwide detachments and regional centers (see Figure 1 in Burnett et al., 2002). Detachments were aligned with fleet commands and backed up by major production centers located in Monterey, CA (FNMOC), and at Stennis Space Center, MS (NAVOCEANO). More recently, reachback cells have been established in key locations. These cells are well-manned concentrations of expertise aligned to support warfare areas such as ASW, Special Warfare, and Mine-Warfare communities. For example, the ASW reachback cell at NAVOCEANO provides on-demand analysis and information for submarine operations around the globe. Although Staff Oceanographers remain with the Fleet, leveraging reachback support provides greater capability by tapping into support from a concentrated group of oceanographic experts. Aviation support became similarly centralized in two Navy centers located in San Diego and Norfolk and two joint centers with the US Air Force (USAF) based in Germany and Hawaii.

Even with reachback support, there is still a need for on-scene expertise. Strike Group Oceanography Teams (SGOTs) were formed and deployed to big-deck aircraft carriers and amphibious ships to support the Operations Aerography (OA) division officer who is permanently assigned to the ship. In addition, the number of Mobile Environmental Teams (METS), small deployable forecast units, has increased to meet the demand of fleet forecasting requirements in supporting new missions such as unmanned aerial vehicle operations. The Fleet Weather Centers in Norfolk and San Diego were established in 2010 to support aviation and maritime communities. One of their tasks is to work with experienced enlisted chiefs and officers to train new aerographer's mates (AGs), military personnel responsible for providing battlespace environment forecasts, in order to achieve a quicker transition of the AGs to operations.

Today, the Naval Oceanography Operations Command (NOOC) is the major provider of direct meteorology and oceanography (METOC) support to operations. The NOOC is in charge of the Fleet Weather Centers, the SGOTs, and other warfare area commands such as the Naval Oceanography Mine-Warfare Center and the two Naval Oceanography Anti-Submarine Warfare Centers. The NOOC is a worldwide command that focuses on providing qualified AGs to war fighting units, thus ensuring the collection of oceanographic information and enabling decision support.

The two major production centers, FNMOC and NAVOCEANO, continue to provide specialized global weather and ocean prediction fields using up-to-date data services that allow Navy METOC users to pull only the data needed at their operational levels. NAVOCEANO has been a primary user of the Department of Defense Supercomputing Resource Center (DSRC), located at Stennis Space Center, MS, and has used the DSRC to further advance the quality and timeliness of model based oceanographic prediction (Figure 1). The next evolution in prediction architecture, Enterprise Operational Modeling (EOM), will allow both FNMOC and NAVOCEANO to control, execute, and monitor operational global models on the DSRC. This is a fundamental change from using in-house computational capability, motivated by the evolution toward coupled global and high-resolution systems.

TECHNOLOGICAL PROGRESS

The Navy understood in 1976 that they had a need for high-end computational capabilities to truly understand complex ocean physics and to properly simulate ocean dynamics. However, the understanding of physical processes and computational capabilities was not adequate at that time to allow realistic ocean prediction. This need led to an evolutionary implementation of systems that, while continually increasing skill and providing useful information, are recognized as not yet meeting the required level of forecasting skill. Refreshing operational capability with new technology is standard practice. In the Science and Technology (S&T) and R&D realms, the operational community has strong partnerships with the US Navy's Office of Naval Research (ONR), the Naval Research Laboratory (NRL), and the Battlespace Awareness and Information Operations Program Office (PMW-120) of the Space and Naval Warfare Systems Command

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(SPAWAR). ONR and NRL work closely to develop fundamental research, demonstrate new capability, and, through the Oceanographer of the Navy's SPAWAR PMW-120 programs, transition systems into operations, primarily at FNMOC and NAVOCEANO. This is accomplished through a coordinated process of determining the technology that is ready for operational use, ensuring that it is incorporated appropriately into the operational architecture, validating the results in the operational environment, and, finally, training operational personnel in the application. CNMOC prioritizes key operational requirements and, with an understanding of existing resources, provides guidance to the S&T and R&D communities regarding new and/or continuing research toward meeting operational goals. In addition to the regular development and transition process that can span several years, the NOP has instituted Rapid Transition to Production (RTP) projects that identify emerging issues and direct both S&T and R&D resources toward the goal of transitioning a new capability in three years. Recent RTP examples include a regional tropical cyclone model, a surge and inundation capability for storms, and four-dimensional variational data assimilation schemes for oceanographic models.

Table 1 shows the evolution in time of models and data assimilation techniques used in Navy operational prediction systems. Initial operational systems in the 1990s included the global Navy Layered Ocean Model (NLOM) that predicted mesoscale features, such as eddies, with high accuracy using 1/32° horizontal resolution and six vertical Lagrangian layers, and the regional Shallow Water Analysis and Forecast System (SWAFS) constructed around the Princeton Ocean Model (POM). Subsequently, a global application of the Navy Coastal Ocean Model (NCOM) was developed at a lower 1/8° horizontal resolution and with a higher vertical resolution of 41 sigma- and Z-layers to represent surface dynamical processes throughout the deep waters and extending onto the continental shelves. At this same time, the global atmospheric model Navy Operational Global Atmospheric Prediction System (NOGAPS) (Rosmond et al., 2002), the source of atmospheric forcing for many of the Navy's ocean prediction systems, was evolving to provide boundary conditions for the higher resolution atmospheric component of the nested Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®; Hodur, 1997). Global wave models including the WAVEWATCH III (WW3) system (Tolman et al., 2002) and the Wave Action Model (WAM) were implemented operationally and provided boundary condition information to nearshore predictive systems such as

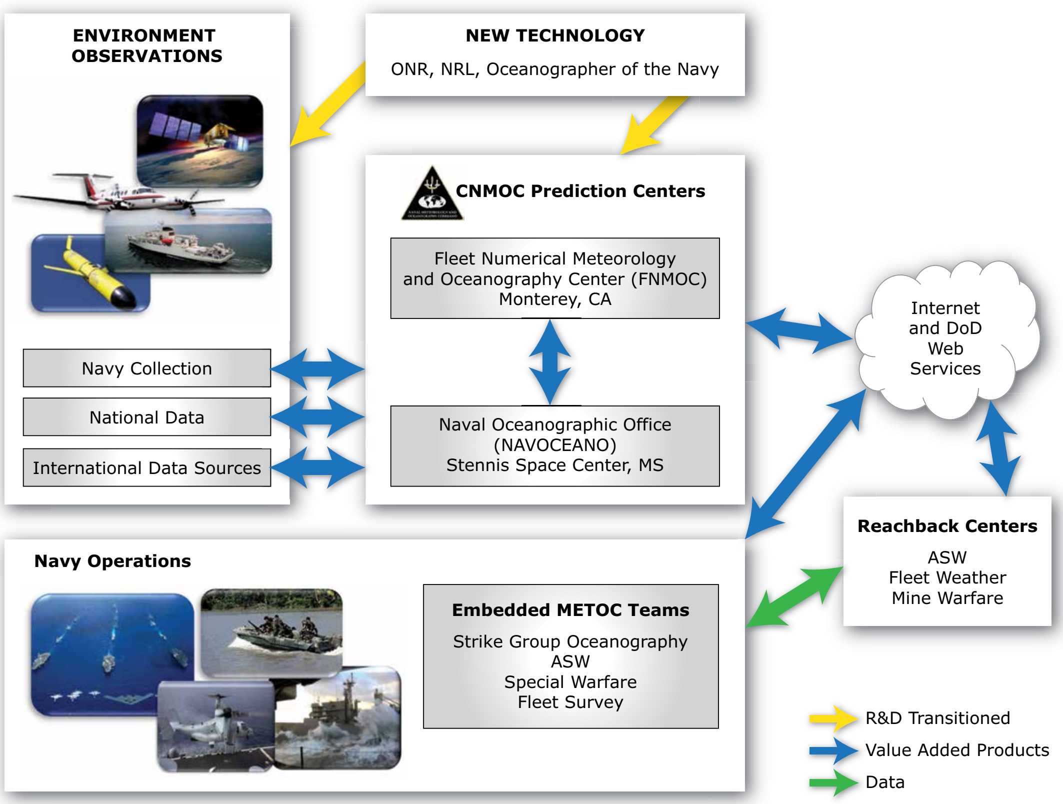

Figure 1. This schematic depicts the entire range of meteorological and oceanographic (METOC) operations for the US Navy, from scientific research and development (R&D) for new sensors and predictive models to data assimilation, model production, and support of the deployed fleet. New products from the R&D community enhance collection methods and predictive capabilities, providing a wealth of information to support the US Navy through production centers at the Fleet Numerical Oceanography Center and the Naval Oceanographic Office. The Department of Defense and community web-based services are used to distribute forecasts and observations to reachback centers where forecasters add value to observations and model output and then forward those products globally to the embedded METOC teams.

the Navy Standard Surf Model (NSSM; Mettlach et al., 2000).

In the first decade of this century, an operational higher resolution, rapidly relocatable nested capability for the ocean was developed around NCOM, and regional and coastal domains were rapidly implemented by NAVOCEANO to provide forecasts for key areas across the globe. In recent years, these nested ocean capabilities have been incorporated into COAMPS, along with the wave dynamical systems from the Simulating WAves Nearshore (SWAN) model (Rogers et al., 2003) and WW3, resulting in a fully coupled ocean/wave/atmospheric prediction system for high resolution at any location on the globe. Much of this development was enabled through collaboration with the Earth System Modeling Framework (ESMF), software for building and coupling weather, climate, and related models.

Currently, the operational global ocean system is based on the HYbrid Coordinate Ocean Model (HYCOM) running at 1/12° horizontal resolution and 32 hybrid vertical levels with work underway to replace it with 1/25° horizontal resolution and 41 hybrid vertical levels. The Los Alamos Community Ice CodE (CICE) is providing ice edge and thickness forecasts within the Arctic Cap Nowcast/Forecast System (ACNFS), which is a two-way coupled HYCOM/CICE system nested in the global HYCOM. The 1/25° global HYCOM incorporates the CICE model at the same resolution, includes advanced representation of tidal potential, and represents the generation of internal tides that propagate across ocean basins. At the same time, the global atmospheric forecasts have evolved from NOGAPS to the NAVy Global Environmental Model (NAVGEM). NAVGEM contains improved numerics that increase computational efficiency, making it feasible to increase the grid resolution and improve parameterizations of important physical processes. Work is underway to two-way couple the global WW3 system with HYCOM/CICE as well as couple these ocean models with NAVGEM to create the first implementation for the Navy of an Earth System Prediction Capability that will be part of a larger National Earth System Prediction Capability (N-ESPC; Curry et al., 2011).

New implementations of the nested system extend resolution and accuracy, including added physics such as that used to represent tropical cyclones in COAMPS-TC (Doyle et al., 2014, in this issue). COAMPS provides the flexibility to select the components—atmosphere, ocean, wave, or ice—that are needed for the problem at hand. The coupled NCOM/SWAN components have been applied in the operational centers to resolutions below 300 m, and resolutions down to 50 m have already been tested. Extensions to enable COAMPS to be applied to the nearshore regions will expand the application of

Table 1. Navy Environmental Prediction System, 2002 vs. 2014

	2002	2014
Data Assimilation	» Multivariate Optimal interpolation (MVOI) » Modular Ocean Data Assimilation System (MODAS)	» 3-Dimensional Variational Data Assimilation (3DVAR) » 4-Dimensional Variational Data Assimilation (4DVAR)
Circulation	» Thermodynamic Ocean Prediction System (TOPS) » Navy Layered Ocean Model (NLOM) » Navy Coastal Ocean Model (NCOM) » Princeton Ocean Model (POM) » Advanced Circulation Model (ADCIRC)	» HYbrid Coordinate Ocean Model (HYCOM) » Navy Coastal Ocean Model (NCOM)
Waves, Surf, Tides	» Wave Action Model (WAM) » WAVEWATCH III (WW3) » Steady State Wave (STWAVE) Model » Navy Standard Surf Model (NSSM) » HYDROMAP™ » PCTides	» WAVEWATCH III (WW3) » Navy Standard Surf Model (NSSM) » PCTides » DELFT3D
Ice	» Hibler Ice Model/Cox Ocean Model	» Community Ice CodE (CICE)/HYbrid Coordinate Ocean Model (HYCOM)
Atmosphere	» Navy Operational Global Atmospheric Prediction System (NOGAPS) » Coupled Ocean Atmosphere Prediction System (COAMPS) » Geophysical Fluid Dynamics Laboratory Navy Tropical Cyclone (GFDN TC)	» NAVy Global Environmental Model (NAVGEM) » Coupled Ocean Atmosphere Prediction System (COAMPS) » Coupled Ocean Atmosphere Prediction System – Tropical Cyclone (COAMPS-TC)

these operational tools.

The dynamical forecast components form the core of the operational forecast capability. However, necessary pieces of the entire forecast system include the data, data assimilation, and uncertainty forecasts enabled through ensembles. These components likewise have undergone great progress in the last 10 years. The assimilation methodology is advancing from a 3-Dimensional Variational Data Assimilation (3DVAR) scheme to a 4-Dimensional Variational Data Assimilation scheme (4DVAR) for both the atmosphere and the ocean within COAMPS. Both are scheduled to be operational in 2014. In addition, a 4DVAR transition is underway for SWAN within COAMPS, and the development of 4DVAR for the coupling between all components is ongoing. These data assimilation schemes allow a continuous flow of data from sensors to improve the models' initialization by using data throughout the day, as opposed to only those observations available to the model near its start time.

New satellite channels and sensor packages are continuously added to the assimilation systems. The NOP relies heavily on national satellite sensors for information on the atmosphere and ocean states and the fluxes between the two. In addition, areas of high interest require on-scene sensors. ONR pioneered the development of unmanned underwater vehicles (UUVs), and the Oceanographer of the Navy initiated the Littoral Battlespace Sensing Fusion and Integration (LBSFI) program that is delivering 150 ocean gliders to the operational forecast center NAVOCEANO for use in areas of high Navy interest. Likewise, development of unmanned aerial vehicles (UAVs) and sensors for characterizing the marine atmospheric boundary layer will provide additional important on-scene temperature and humidity data to determine surface radar ducting. The next decade will see improved ability for use of data from nontraditional sources such as transmission of shipboard radar, UUV, and UAV data to the production centers and the possible integration of these data into onboard short-term analyses, and rapidly updated short-term forecasts. The automated guidance and control of these sensors is a critical part of the entire system.

Knowing the level of confidence to ascribe to a forecast is a critical part of a Navy forecaster's job. The methodology to provide quantitative information has developed through the use of ensembles. Given the error probability distribution of initial conditions and forcing, ensembles provide probabilistic forecasts of environmental impact on operations. A national collaboration between the Navy, NOAA (National Oceanic and Atmospheric Administration), and the USAF leveraged earlier work between NOAA and Environment Canada to create a national atmospheric ensemble capability. This national ensemble capability is coordinated through the National Unified Operational Prediction Capability (NUOPC) program. NUOPC has enabled an operational, 60-member, multimodel global atmospheric ensemble product that brings the Navy, NOAA, and Environment Canada ensemble forecasts together with common resolution, timing, and forecast products. Initial operations of NUOPC began in 2011 for global atmospheric prediction systems, with increased resolution of the ensembles and more derived products operationalized since. NUOPC is similarly working to strengthen multi-agency partnerships in ocean modeling and regional ensembles.

The Navy has a unique and well-defined mechanism for the development and transition of METOC prediction systems to operations through the Administrative Modeling Oversight Panel (AMOP). The AMOP includes the sponsors who fund the basic and developmental research as well as the transition process for the generation of new operational capabilities. AMOP also includes members from the receiving operational command. The process includes procedures for validation and implementation of these systems as defined by a set of three milestones. It begins with a set of Navy requirements for a new capability. Programs to accomplish the needed basic and developmental research to meet these requirements are often funded through ONR or NRL, and solutions are vetted through peer-reviewed journal articles. Scientific developments that demonstrate the potential to address the requirement are then passed through AMOP Milestone 1. At this point, a research agency, such as NRL, is partnered with a production center (i.e., NAVOCEANO or FNMOC), and funding is provided to complete advanced development and thorough validation testing of the new system. The researchers and production center personnel cooperatively create a Transition Plan to ensure that there is agreement in defining the functional requirements, how they will be met, the timing of completion of tasks, and how the new system will fit into the operational environment. A science-based Validation Test Panel, consisting of the developer, production center scientists, and outside scientific experts, is convened to review and approve the new capability's applications and its skill to meet the Navy requirement, resulting in a comprehensive Validation Test Report (VTR). With the approval of the VTR by the panel, the system has now met Milestone II. The developers and the operational scientists jointly implement the systems into the operational infrastructure at the production center. The production team takes over the new system and performs an operational evaluation to provide a final review of the transition, to ensure that it fits into the operational system, to verify how well the original requirements are being met, and to set up delivery of operational products to Navy users. The result of these actions is documented in a report that is submitted to the AMOP. Upon approval, the system has met Milestone III and is declared operational. Through these governance procedures, R&D is focused on a viable solution to a Navy problem, all parties are aware of plans and progress, funding is intelligently prioritized and provided, production centers and Navy customers are familiarized with the new capability, and projects are focused and completed in a timely manner. This unique AMOP process ensures a close relationship among the research and operational scientists, sponsors, managers, and customers and results in new operational systems that meet Navy requirements.

THE FUTURE

Future thrusts in Navy ocean prediction include increasing use of coupled models along with greater reliance on ensembles to quantify uncertainty. The CNMOC modeling "roadmap" or future plan aims to increase the amount of two-way/multiway coupling of regional METOC models in the next 10 years. Some of the coupled modeling technologies expected to transition in the next 10 years include ocean-wave, ocean-ice, air-wave, and air-ocean-ice-wave (Figure 2). Coupling models is a small overhead on the efficiency of the model runs, as the most substantial computational cost is the forward integration of the equations of motion.

Whereas the long-term goal defined by the Oceanographer of the Navy in 1986 focused on the development of a global ocean prediction capability that resolves mesoscale features, the current Oceanographer's long-term goal addresses the development and operational implementation of an N-ESPC. This N-ESPC will require global coupling of models (air-ocean-wave-ice-land) to ensure information feedback between components because there are important physical interplays between these different dynamical environmental systems (Figure 2). The motivation lies in the recognition of coupled processes such as the Madden-Julien Oscillation in which feedbacks between the ocean, the atmosphere, and the intervening wave field result in a process that propagates across the Indian Ocean and maritime nations. The fundamental observation is that the speed at which this process propagates is not a natural response speed for any of the separate dynamical systems. Only through the coupling can such events be predicted (Waliser, 2006). The Navy goal for the N-ESPC is to provide longer forecasts (out to seasonal prediction) of key environmental parameters such as ocean currents, thermal structure, waves,

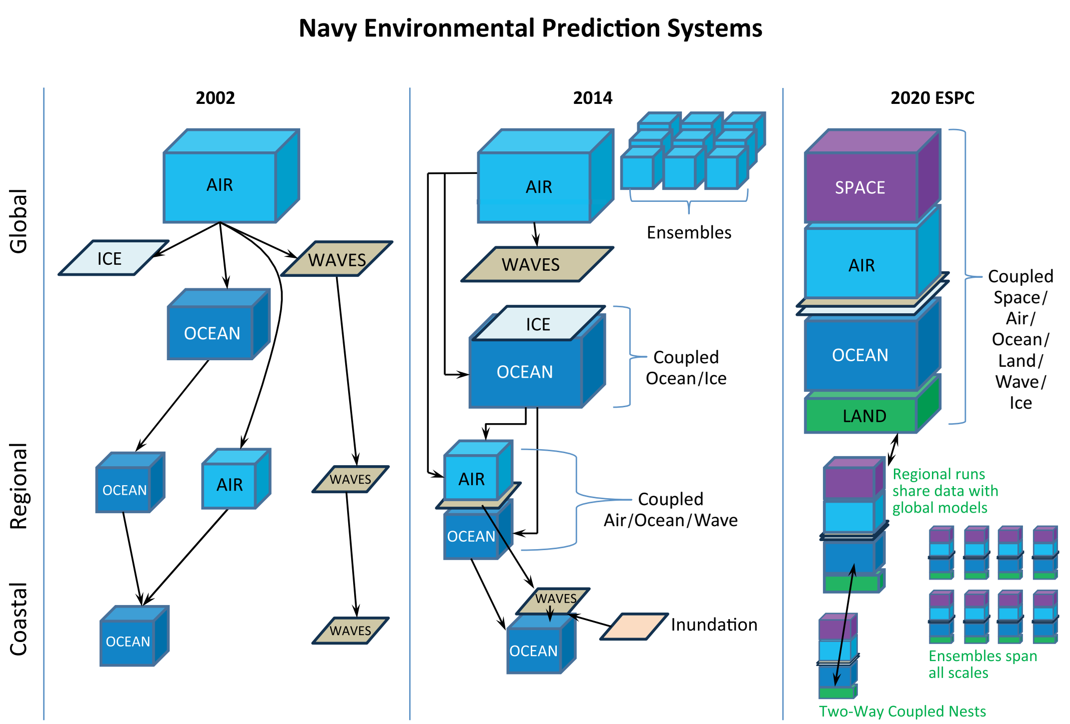

Figure 2. The structure of Navy environmental prediction systems past, present, and future. US Navy METOC models are evolving from loosely or one-way coupled models to tightly or two-way coupled models. Today, US Navy modeling supports limited ensemble-based probabilistic forecasts for the atmosphere and regional ocean models. In the future, the National Earth Systems Prediction Capability will be supported by the Navy's use of tightly coupled models across an increasing list of mediums and more and improved ensemble-based predictions. Two-way coupling of regional and coastal models with global models will improve the overall systems' predictive capability.

ice cover, and atmospheric conditions. N-ESPC is also a project that encompasses prediction systems on a national scale. This larger national project is a multi-agency partnership with NOAA, the Department of Defense, National Aeronautics and Space Administration, National Science Foundation, and Department of Energy. By coupling the individual components (see Figure 2), the N-ESPC aims to develop a seamless seasonal and high-impact forecast modeling system for use nationwide by the initial operational target date in 2018.

In the next 10 years, the N-ESPC capability will introduce a national multimodel ensemble prediction system that will enhance and expand the NUOPC multimodel capability available today. This new national system will introduce longer-term prediction capability from climatological models into the forecast as well as increasing the number of ensemble members involved in the system. The advantages of this include having coupled ocean and atmospheric models improving the feedback and transfer of energy through flux interactions between the different coupled model mediums.

The knowledge and skills of aerographer's mates will be challenged in the future as they make use of the probabilistic predictive capabilities and associated product uncertainty generated by ensemble coupled models. Critical tools and techniques are being introduced earlier in their career training so they can recognize and take full advantage of the coming probabilistic forecasts. This additional information will allow trained forecasters to make improved decisions based on forecast guidance over longer periods of time.

Five to 10 years from now, the capabilities discussed here should be available as resources for the operational Naval Oceanography community. As geopolitical changes and technological advances present new challenges, the Navy will be ready to address them across the globe. A key part of this future will be the ability to accurately forecast the environment with long lead times. It is an exciting time to be involved with Naval Oceanography as new technologies transition into operations allowing fleet forecasters the best possible opportunity to influence decisions in a timely manner.

ACKNOWLEDGEMENTS

The authors wish to thank John Harding and George Heburn for their insightful comments. Gregg Jacobs's contribution was funded under Program Element (PE) 62435 by the Office of Naval Research. This paper, NRL contribution NRL/JA/7300—14-2033, is approved for public release, distribution unlimited.

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REFERENCES

Anonymous. 1977. Ocean forecasting. *Eos Transactions, American Geophysical Union* 58(5):279–281, http://dx.doi.org/10.1029/EO058i005p00279-02.

Burnett, W., J. Harding, and G. Heburn. 2002. Overview of operational ocean forecasting in the US Navy: Past, present, future. *Oceanography* 15(1):4–12, http://dx.doi.org/10.5670/oceanog.2002.31.

Clancy, R.M., and K.D. Pollak. 1983. A real-time synoptic ocean thermal analysis/forecast system. *Progress in Oceanography* 12:383–424, http://dx.doi.org/10.1016/0079-6611(83)90001-0.

Curry, W., S. Sandgathe, S. Lord, F. Toepfer, and M. Peng. 2011. The Earth System Prediction Capability: A multiagency partnership to advance US environmental prediction. Paper presented at the 24th Conference on Weather and Forecasting/20th Conference on Numerical Weather Prediction, Seattle, WA, January 25, 2011. Available online at: https://ams.confex.com/ams/91Annual/webprogram/meeting2011-01-25.html.

Doyle, J.D., R.M. Hodur, S. Chen, Y. Jin, J.R. Moskaitis, S. Wang, E.A. Hendricks, H. Jin, and T.A. Smith. 2014. Tropical cyclone prediction using COAMPS-TC. *Oceanography* 27(3):104–115, http://dx.doi.org/10.5670/oceanog.2014.72.

Hodur, R.M. 1997. The Naval Research Laboratory's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS). *Monthly Weather Review* 125:1,414–1,430, http://dx.doi.org/10.1175/1520-0493(1997)125<1414:TNRLSC>2.0.CO;2.

Mettlach, T.R., Y.L. Hsu, M.D. Marchall, and E.D. Osiecki. 2000. Applications of the Navy standard surf model: SURF 3.1. Pp. 380–391 in *Proceedings of the 6th International Workshop on Wave Hindcasting and Forecasting, Environment Canada, November 6–10, 2000,* Monterey, CA.

Mooers, C.N.K, S.A. Piacsek, and A.R. Robinson. 1982. Ocean prediction: The scientific basis and the Navy's need. A status and prospectus report. *Proceedings of the Ocean Prediction Workshop, April 29–May 2, 1981,* Monterey, CA.

Mooers, C.N.K., A. R. Robinson, and J.D. Thompson. 1986. Ocean Prediction Workshop, 1986. A status and prospectus report on the scientific basis and the Navy's need. *Proceedings of the Ocean Prediction Workshop, April 17–19, 1986, and November 5–7, 1986.* Long Beach, MS.

Peloquin, R.A. 1992. The Navy Ocean Modeling and Prediction Program—From research to operations: An overview. *Oceanography* 5(1):4–8, http://dx.doi.org/10.5670/oceanog.1992.25.

Rogers, W.E., P.A. Hwang, and D.W. Wang. 2003. Investigation of wave growth and decay in the SWAN model: Three regional-scale applications. *Journal of Physical Oceanography* 33:366–389, http://dx.doi.org/10.1175/1520-0485(2003)033<0366:IOWGAD>2.0.CO;2.

Rosmond, T.E., J. Teixera, M. Peng, T.F. Hogan, and R. Pauley. 2002. Navy Operational Global Atmospheric Prediction System (NOGAPS): Forcing for ocean models. *Oceanography* 15(1):99–108, http://dx.doi.org/10.5670/oceanog.2002.40.

Seesholtz, J.R. 1986. Oceanographer of the Navy, CNO ltr Ser. 0060/6U449045, 14 Oct. 1986.

Tolman, H.L., B. Balasubramaniyan, L. Burroughs, D.V. Chalikov, Y.Y. Chao, H.S. Chen, and V.M. Gerald. 2002. Development and implementation of wind-generated ocean surface wave models at NCEP. *Weather and Forecasting* 17:311–333, http://dx.doi.org/10.1175/1520-0434(2002)017<0311:DAIOWG>2.0.CO;2.

Waliser, D., K. Weickmann, R. Dole, S. Schubert, O. Alves, C. Jones, M. Newman, H. Pan, A. Roubicek, S. Saha, and others. 2006. The experimental MJO prediction project. *Bulletin of the American Meteorological Society* 87:425–431, http://dx.doi.org/10.1175/BAMS-87-4-425.