Better Informed Marine Operations and Management

Multidisciplinary Efforts in Ocean Forecasting Research for Socioeconomic Benefit

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In Numerical Weather Prediction (NWP), forecast systems are used to transform meteorological observations into forecasts that provide the basis for information services to the general public and many other users. In oceanography, in order to best exploit the observations, it is similarly necessary to transform them into coherent analyses and predictions that can be the basis for information services about the marine environment, its ecosystem, and the cryosphere that can be used in many applications and that can provide boundary data for weather predictions. Marine industries (e.g., commercial fishing, aquaculture, shipping, oil and gas, renewable energy, tourism), government agencies (e.g., those responsible for search and rescue, defense, coastal management, environmental protection), and other stakeholders (e.g., recreation, water sports, artisanal and sport fishing) depend on timely and accurate information about the marine environment. This includes ocean physical and biological states, the weather, and for some areas, ice cover from hours to weeks in advance as well as in the past. Supported by progress in numerical ocean modeling and data assimilation methods; increased supercomputing capacity; and most importantly, enhanced, routine, and sustained in situ and remotely sensed ocean observations, the last decade saw the development and operational implementation of mesoscale (eddy-resolving) short- and medium-range (days to weeks) ocean forecasting and reanalysis capabilities at many operational[1] weather and ocean forecasting centers. The building and maintaining of operational ocean forecasting systems require a wide range of expertise. Most global ocean forecasting systems transition from research and demonstration modes to sustained, permanent operational capabilities with attendant infrastructure (European Commission 2015). Beyond the traditional short-term forecasting of physical ocean properties (temperature, salinity, surface height, currents, waves), marine activities such as water quality and habitat management as well as climate research increasingly rely on operational oceanographic data and products. To satisfy existing and new requirements for end-use applications, such as coastal protection, ecosystem monitoring and forecasting, and climate monitoring, these operational ocean forecasting systems must be sustained, as well as evolve and improve, to remain relevant with broad utility.

There has been significant progress in ocean forecasting in recent years, which can be summarized as follows (Bell et al. 2015):

- Improvements of forecasting systems included increased resolution (horizontal and vertical), tides, sea ice drift and thickness, ecosystem

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[1] Following Smith and Lefebvre (1997), "operational" is used here "whenever the processing is done in a routine predetermined systematic approach with embedded accuracy and constant monitoring. With this terminology, regular re-analyses may be considered as operational systems, as well as organized analyses and assessment of climate data."

approaches, improvement to mixing biases, and extending regional mode areas [e.g., polar regions and progress of coupled modeling (wave coupling, sea ice, hurricane models, etc.)].

- Data assimilation schemes vary among ocean forecasting groups, ranging from Ensemble Optimum Interpolation (EnOI) and Ensemble Kalman Filter (EnKF) to three- and four-dimensional variational methods (3DVar and 4DVar). Observations assimilated in ocean forecast systems now include ocean color, surface velocities, sea ice, and gliders. Many systems now employ multimodel approaches or ensemble modeling techniques.
- As the demand on forecasting products from ocean predictions is growing, the communication and dissemination of information to downstream users has been improved. Nowadays, dissemination of outputs from forecasting systems is akin to the approaches taken in NWP.
- Most ocean forecasting systems are now investing in verification and validation efforts to be able to show the value of their products to their users.

With the maturing of oceanographic forecast systems and research, the core ocean forecasting disciplines of ocean modeling, data assimilation, forecast verification, and observing system evaluation are now enabling new research and operational areas to flourish. This includes

- short-to-medium-term (three days to two weeks) coupled ice–ocean–wave–atmosphere prediction to improve weather forecasts that will enable safer at-sea and coastal operations through, for example, improved severe environmental event prediction (i.e., tropical cyclones);
- coastal operational oceanography with its increasing demand to provide accurate information to decision-makers looking after increasingly populated and urbanized coastal areas (including coastal river plumes from sediments and nutrients);
- biogeochemical, biological, and ecological forecasting, noting that the maturity and reliability, at this stage, of physical ocean forecasts are greater than those of biogeochemical, biological, and ecological forecasts;
- high-latitude (Arctic and Antarctica) operational ice and ocean prediction;
- three-dimensional analyses of the past as well as the present ocean state at global-to-coastal scales based on the same modeling and assimilation infrastructure used for ocean forecasting; and
- use of boundary or forcing conditions from global ocean–atmosphere climate projections in physical–biogeochemical–ecological modeling, and based on ocean forecasting infrastructure to downscale projections at regional and local scales.

Founded by an international group of experts in ocean forecasting as an experiment in the late 1990s, GODAE OceanView (GOV) currently coordinates multiagency efforts to optimally support the research, development, and operational implementation of physical

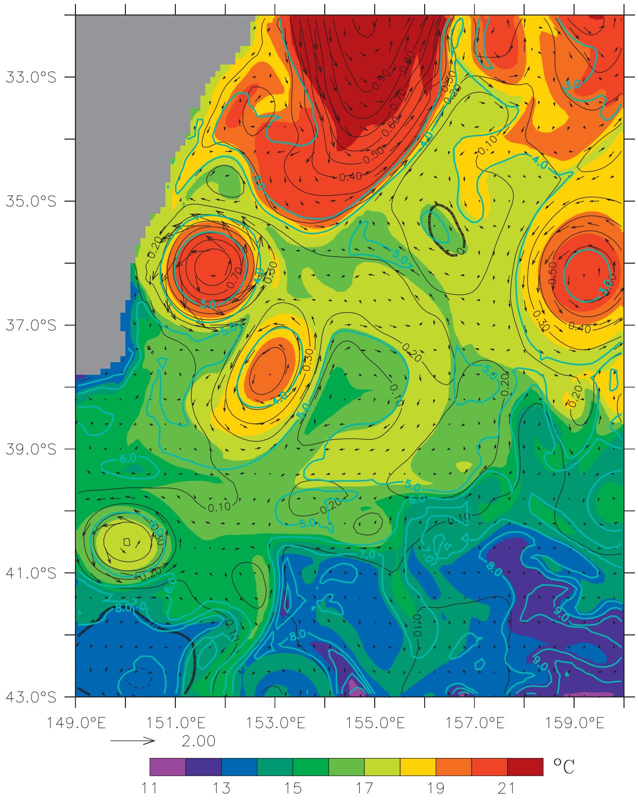

Fig. 1. Snapshot of daily-mean output of four variables from the coupled OFAM3 biophysical ocean model (Oke et al. 2013) showing mesoscale features in the top 50-m layer of the Tasman Sea. The color map represents sea surface temperature (°C). Black contour lines represent sea surface height anomaly in 0.1-m (m) intervals. Turquoise contour lines represent nitrate concentration in 1-mmol/m^3 increments. The vector arrows represent the top 50-m layer velocity with the reference arrow of 2 m s^{-1} plotted on the lower left.

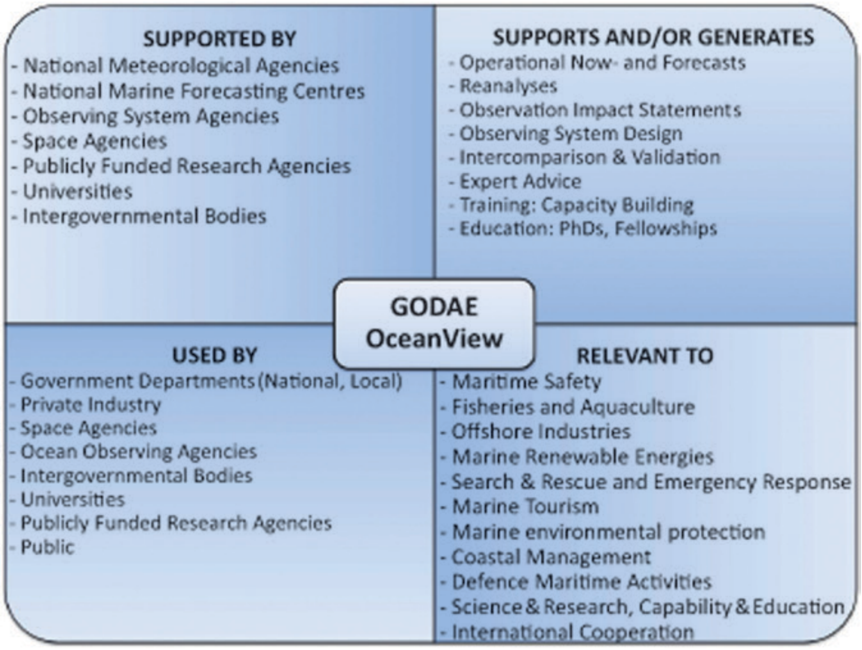

Fig. 2. The diagram summarizes the GODAE OceanView collaborative network role in enhancing the output, impact, and relevance of participating agencies/groups in operational oceanography. The objective is to harness national and international innovation systems, operational infrastructure, and maritime sectors to generate science-based outputs that deliver benefits to the global economy, society, and the environment [adapted from Schiller et al. (2015)].

and biogeochemical ocean forecasting systems through its science team (www.godae-oceanview.org). For example, GOV coordinates international activities in support of ecosystem assessments (coral reef and other habitats), forecasts (harmful algal blooms, spills), and the development of associated prediction applications (climate impacts, living marine resource management). GOV continues the legacy of GODAE[2] with collaborators from more than 50 academic and national agencies worldwide. The research focus is on improving short- to medium-range operational ocean forecasting systems, and on enhancing and sustaining their development and routine operations. Figure 1 shows a typical forecasting result of such systems. It is a snapshot of daily mean output of four variables from the coupled Australian OFAM3 biophysical ocean model (Oke et al. 2013) showing mesoscale features in the top 50-m layer of the Tasman Sea. The relationship between the modeled variables is evident with low (high) nitrate concentrations in the centers of the warm anticyclonic (cold cyclonic) eddies. Furthermore, high nitrate concentrations are found along the coastal upwelling west of 151°E as well as in the cool blue region south of the sub-Antarctic front in the lower part of the figure.

A recent formal expert review of GOV (www.godae-oceanview.org/files/download.php?m=documents&f=150107120408-GOVStrategicPlan20152020.pdf) recognized the enormous benefits reaped by this globally coordinated operational oceanography effort over the last decade. The review identified areas of research where improvement of interinstitutional scientific coordination could deliver greater societal benefits. The recommendations have informed the GODAE OceanView Strategic Plan 2015–2020 (GODAE OceanView Science Team 2014), which will guide internationally coordinated research in short-term ocean prediction, data assimilation, application development, and service delivery for years to come. The development of and operational support for end-to-end capabilities (i.e., from research through to service delivery) is important to GOV and its sponsoring agencies and includes routine and sustained ocean observing, data management, and the prediction system, as well as operational production and dissemination. Figure 2 illustrates the links between research funders, outputs, beneficiaries, and application areas relevant to and supported by GOV.

The core objectives of the GOV Science Team (GODAE OceanView Science Team 2014) are

- assessments of forecast system and component performance combined with component improvements;
- initiatives aiming to exploit the forecasting systems for greater societal benefit; and
- evaluations of the dependence of the forecasting systems and societal benefits on the components of the observation system.

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[2] GODAE—Global Ocean Data Assimilation Experiment, predecessor of GOV from 1997 to 2008 (www.godae.org)

These overarching objectives are aligned with those of the World Weather Research Program (WWRP), the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC) Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM), the Committee on Earth Observation Satellites (CEOS), and the Blue Planet initiative of the intergovernmental Group on Earth Observations (GEO). In this context, GOV contributes to the prioritization, advocacy, implementation, and exploitation of the Global Ocean Observing System (GOOS) and the Global Climate Observing System (GCOS).

Horizontal ocean model grid resolution has been steadily increasing over the last two decades, accompanied by increases in forecast skill (Tonani et al. 2015). By 2020, typical horizontal grid resolutions will be of the order of 5–10 km for global ocean prediction systems and will approach 1 km or less for systems that resolve submesoscale processes by 2025 (with local/regional implementation much earlier). This will depend on continued growth in supercomputer power and evolution of ocean modeling techniques to make best use of computing power. For instance, the use of unstructured grids or grid nesting will allow models to increase their grid resolution specifically where needed by applications. Because of the computational expense of resolving the highly energetic ocean mesoscale, most of the ocean forecasting community has been slower to implement state-of-the-art ensemble prediction systems than their NWP and seasonal atmospheric counterparts. However, it is now computationally feasible to develop global and regional ocean ensemble prediction systems that will provide uncertainty and event predictability estimates.

Ensemble prediction also offers an opportunity for multimodel ensembles from participating centers, similar to the approach used in climate projections by the Intergovernmental Panel on Climate Change (IPCC) and in short-term operational weather prediction. However, this approach has yet to be explored by the GOV community in terms of efficiency and possible gains in forecast accuracy.

As the ocean forecast models progress in the future, it will become increasingly important to the end user that GOV defines and projects what type of events will be predictable by its systems with useful accuracy and confidence intervals. With the implementation of ensemble forecasts at high resolution, a question of how to deliver and present the forecast and accuracy information to the end user/decision-maker is an important challenge.

The ensemble methods allow research on prediction controllability, which includes predictability, observability, and the ability of observations to constrain initial conditions of ocean models. Regular increases in computing power have enabled the development of higher resolution and ensemble models. However, while computing power versus cost ratio increases rapidly every year, the observing network capacity versus cost ratio is relatively fixed, particularly for in situ data. An important question is what level of future observation density is needed in future ensemble prediction systems to accurately initialize features like fronts with typical scales of 1–10 km, of currents across the shelf break, and of errors propagated in the ocean through air–sea fluxes. Submesoscale filaments and coastal eddies with horizontal scales of less than 10 km, tidal fronts, and freshwater plumes generated by river run-off are generally well simulated by coastal ocean forecasting systems with horizontal grids of 1 km or less. A challenge is how to use the finescale but spatially limited coastal observations, like high-frequency (HF)-radar observations as part of high-resolution, shelf- and basin-scale ocean forecasting systems. The advent and deployment of new observing systems (e.g., HF-radars, gliders and low-cost buoys) will provide the necessary in situ observations density, at least on a regional scale. The Surface Water Ocean Topography (SWOT) wide-swath altimeter mission scheduled to launch in 2020 is expected to provide high-resolution sea surface height (Fu and Ferrari 2008). This dataset will resolve the submesoscale and improve parameterizations in and forecasts with global, basin, and shelf-scale models. SWOT should also help to better understand and monitor estuaries, and link properties and fluxes from continent to coastal ocean (and vice versa). The impact of these planned future satellite missions (such as SWOT) on ocean forecasting systems can be tested beforehand through Observing System Simulation Experiments, and is currently the subject of research. For ocean biology and biogeochemistry, significant benefits will be realized by incorporating a constellation of geostationary ocean color radiometry missions into predictions systems.

Operational ocean prediction systems transform data from satellite and sparse in situ measurement systems into value-added comprehensive and vetted oceanographic data and information products with "uniform-gridded" coverage (e.g., mitigating cloud cover and other data dropout issues), but also enable Lagrangian applications for, for example, oil spill forecasting and search-and-rescue activities. The increased international focus on developing shelf-scale analysis and prediction capabilities brings with it the additional challenge of developing cost-effective in situ coastal observing systems that enhance prediction system performance. Work currently undertaken by GOV and its partners is paving the way for fully automated multimodel ensemble Observing System Evaluations (OSEs) assessing all components of the Global Ocean Observing System (GOOS) from global to shelf scales. Through associated Observation Impact Statements (OIS), GOV will contribute to coherent, effective, and scientifically robust advocacy for the GOOS. This effort will allow observing system agencies to assess the impact of past, present, and future observations on forecast and (re-)analysis skills. Consequently, this will enable future observation strategy and scenario evaluation at a fraction of the cost of implementing a new observing system. Furthermore, this activity maximizes the return on investment for the GOOS, a crucial need given limited funds.

To further increase observation network capability, encouraging end users of prediction information to collect and contribute ocean observations from their marine (e.g., fishing vessels, sailboats) as well as shore-based (e.g., piers, docks) platforms on a best-effort but consistent and quality-controlled basis will complement prediction systems in two ways. First, these "citizen science" observations would provide a prediction validation mechanism at the end-user location of interest and, second, they would also enhance ocean forecast initial conditions. These efforts will be facilitated by the rapid growth in wireless communication capabilities and mobile computing platforms, such as smartphones.

A key point is the evolution of low-cost, efficient observing systems with minimal operating costs similar to the already operating "ship of opportunity" network. As with all volunteer observing systems (e.g., commercial ships deploying observing instruments), it will be imperative for the members of GOV to develop feedback to these observation-contributing end users. This is achieved by producing standard GOV observation-based validation metrics (Ryan et al. 2015) from all available prediction system output at the end user's observation location and time. Furthermore, this approach also addresses the need for intercomparisons of different forecast systems and their respective forecast skill to allow for steady improvements to the systems.

Another important benefit of operational ocean forecasting systems is our growing capability to accurately simulate and predict key components of the marine biogeochemical cycle, including carbon and nutrient cycles. Combined physical–biogeochemical systems will increasingly resemble "environmental prediction systems" for end use in stock assessment, fisheries and habitat management, marine pollution, carbon cycle monitoring, and functional ecosystem understanding. These developments are happening because of growing demand by users for multidisciplinary information, supported by progress in relevant science areas including new observations (satellite and in situ) of environmental properties. Simultaneously, user demand for interoperable prediction systems accessing a large variety of observational and modeling products to produce their own "scenarios" of the marine environment is increasing. We can expect this area to grow significantly as new communication technologies will open new opportunities for society to use ocean information in a much more accessible and interactive way than experienced previously. Despite some prototype biogeochemical ocean forecasting systems currently operating as part of integrated biogeophysical systems, unresolved challenges to increasing skill remain. This includes appropriate representation of ecosystem complexity and limited observations compared to physical ocean models and observations (Gehlen et al. 2015).

International groups active in coupled prediction research are pursuing a wide range of applications, including global weather forecasting systems and predictions of tropical cyclones, hurricanes and typhoons, extratropical storms, high-latitude weather, and sea ice, as well as coastal upwelling, sea breezes, and sea fog. In many cases, progress is being accelerated through the developments already made in the seasonal prediction and climate projection communities. Research has moved beyond case studies and sensitivity studies to controlled experiments to obtain statistically significant measures of impact. Some first systems are already run in prototype coupled prediction mode (Brassington et al. 2015). The modeling systems being employed include regional and global coupled models of atmosphere–wave, atmosphere–ocean, atmosphere–wave–ocean, and atmosphere–sea ice–ocean. Despite relatively unsophisticated configurations, the results obtained thus far are generally positive and have encouraged more research and development in this area, including coupled initialization and error propagation. Another related area of increasing interest is that of interactions across the dynamic land–sea interface, including coupled watershed and hydrodynamic modeling efforts for heavily populated coastal zones impacted by both natural as well as anthropogenic phenomena.

The above advances require an increasingly multidisciplinary effort in physics, chemistry, biology, geomorphology (especially in the littoral zone), IT/visualization, and exploitation of "big data" expertise, which furthers the science, engineering, and infrastructure leading to sustained and integrated applications. GOV has already embarked on this route through specific task teams for biogeochemical/ecological and coupled ocean–atmosphere–wave analysis and forecasting (GODAE OceanView Science Team 2014). Associated data assimilation tools are being extended to other branches of marine environmental prediction but require new approaches (e.g., ensemble and parameter estimation techniques, coupled initialization) to capitalize on an increasingly diverse ocean observing system. There are ample opportunities for GOV and partners to advance the science of ocean forecasting and to improve its skill. Although speculative at this point in time, scientific developments and prioritization will evolve over time, which might eventually lead to reorganization of the forecasting community itself to better respond to new challenges and societal needs. This could involve increased collaboration with international and intergovernmental organizations, providing recommendations and advice on questions related to the GOOS, and developing operational ocean forecasting capabilities and systems in developing countries (through summer schools, training, and communication).

Apart from the scientific challenges, there are a wide range of additional factors that will influence the progress of ocean forecasting. GOV ocean forecasting systems are critically dependent on both the satellite and in situ components of the physical GOOS, and the sustainability and expansion of the biological and biogeochemical GOOS (Legler et al. 2015). New opportunities arise in regional seas with the advent of "intelligent" new in situ sensors, sensor networks/webs, and new and improved remote sensing technologies.

Based on the recently released GODAE OceanView Strategic Plan 2015–2020 (GODAE OceanView Science Team 2014), the analysis and forecasting systems developed by GOV partners are open to further input from the research community, and contribute back to the research community by providing vetted ocean information products of past, present, and near-future states of the ocean. The facilitation of cooperation between research teams, operational groups, and the wider science and user community will remain a key element of the future GOV Science Team. These collective activities will result in improved research, applications, and services for both developed and developing regions, and significant socioeconomic benefits for a world that increasingly depends on and cares for the health of its oceans.

FOR FURTHER READING

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