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Synthesis of new scientific challenges for GODAE OceanView

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The marine environment plays an increasingly important role in shaping economies and infrastructures, and touches upon many aspects of our lives, including food supplies, energy resources, national security and recreational activities. Global Ocean Data Assimilation Experiment (GODAE) and GODAE OceanView have provided platforms for international collaboration that significantly contribute to the scientific development and increasing uptake of ocean forecasting products by end users who address societal issues such as those listed above. Many scientific challenges and opportunities remain to be tackled in the ever-changing field of operational oceanography, from the observing system to modelling, data assimilation and product dissemination. This paper provides a brief overview of past achievements in GODAE OceanView, but subsequently concentrates on the future scientific foci of GODAE OceanView and its Task Teams, and provides a vision for the future of ocean forecasting.

Introduction

The world oceans offer new opportunities for sustainable economic growth. At the same time, the world oceans and their marginal seas are great environmental and recreational assets. To ensure a good environmental status[1] while simultaneously allowing for an expansion of economic activities in the ocean in an environmentally sustainable way, we 'need to know what the state of the sea is now, how it was in the past and how it might change in the future' (European Commission 2012). In this context, past information can inform decision-making for the future, which can be based on, a variety of past and extreme events, for example.

The GODAE OceanView Science Team ('GOV' and 'GOVST' hereafter) contributes to the science that underpins these societal needs. GOVST has been 'created, with the mission to define, monitor, and promote actions aimed at coordinating and integrating research associated with multi-scale and multi-disciplinary ocean analysis and forecasting systems' [GOVST (GODAE OceanView Science Team) 2014]. Building on the success of the GODAE, since its inception in 2008 the GOVST has addressed and provided international leadership in the four objectives identified in the GOV Strategic Plan [GOVST (GODAE OceanView Science Team) 2014]:

- the consolidation and improvement of global and regional analysis and forecasting systems;
- the progressive development and scientific testing of the next generation of ocean analysis and forecasting systems, covering biogeochemical and ecosystems as well as physical oceanography, and extending from the open ocean into the shelf sea and coastal waters;
- the exploitation of this capability in other applications (weather forecasting, seasonal and decadal prediction, climate change detection and its coastal impacts, etc); and
- the assessment of the contribution of the various components of the observing system and scientific guidance for improved design and implementation of the ocean observing system.

The target audience for this paper includes both the scientific oceanographic community and the broader user community. Hence, Table 1 provides definitions of the acronyms used, and the discussion of the specialist topics such as data assimilation seeks to minimize the use of scientific jargon. The objectives of this paper are to provide a brief overview of past achievements in

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Table 1. List of acronyms.

CLAM	Coupled Limited Area Model (Australian Bureau of Meteorology)
CLIVAR	Variability and Predictability of the Ocean–Atmosphere System (a core project of the World Climate Research Programme)
COAMPS	Coupled Ocean/Atmosphere Mesoscale Prediction System (US Navy)
CONCEPTS	Canadian Operational Network of Coupled Environmental Prediction Systems
COSS	Coastal Ocean and Shelf Seas
ECMWF	European Centre for Medium-Range Weather Forecasts
FOAM	Forecasting Ocean Assimilation Model (UK Met Office)
GODAE	Global Ocean Data Experiment (1998–2008)
GODAE OceanView (GOV)	Successor of GODAE (2008–present)
GOOS	Global Ocean Observing System
HF-radar	High-Frequency radar
IMBER	Integrated Marine Biogeochemistry and Ecosystem Research (a project of the Scientific Committee on Oceanic Research and the International Geosphere–Biosphere Programme)
IOOS	Integrated Ocean Observing System (USA)
NASA/GAO	National Aeronautics and Space Administration US Government Accountability Office
NRT	Near-Real Time (e.g. data processing)
NWP	Numerical Weather Prediction
OIS	Observation Impact Statement
OO	Operational Oceanography
OOFS	Operational Ocean Forecasting System (OOFS)
OSE	Observing System Experiment
OSSE	Observing System Simulation Experiment
SAR	Synthetic Aperture Radar
SEAPODYM	Spatial Ecosystem And Populations Dynamics Model
SMOS	Soil Moisture and Ocean Salinity (satellite)
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
SWOT	Surface Water and Ocean Topography (a joint USA/French satellite project)
THORPEX	The Observing System Research and Predictability Experiment (a long-term research programme organized under the World Meteorological Organization's World Weather Research Program)
WGNE	Working Group on Numerical Experimentation [jointly established by the World Climate Research Program Joint Scientific Committee and the World Meteorological Organisation/Commission for Atmospheric Sciences (CAS)]

GODAE OceanView, to discuss the future scientific foci of GODAE OceanView, and to provide a vision for the future of ocean forecasting. Its subsequent sections of this paper are structured as follows. The next section provides a synthesis of past achievements. This is followed by an integrated, system-wide perspective on future research activities in operational oceanography, which includes a précis of future research foci and activities to be pursued by the GOV Task Teams. The next section speculates about the shape of operational oceanography in 2030. The final section contains the conclusions.

Synthesis of achievements

Significant incremental progress has been made in ocean forecasting since the inception of GOV in 2008 (Bell et al. 2015; Tonani et al. 2015) and GOV has had a major impact on the development of the global operational[2] oceanography capability (Bell et al. 2015). Global modelling and data-assimilation systems have been progressively developed (Martin submitted) implemented (Tonani et al. 2015) and inter-compared (Ryan et al. 2015), taking advantage of increased computing power and enhanced model resolution. Improvements include:

- inclusion of tides, improved surface forcing/surface fields and waves/current interactions (Tonani et al. 2015; Chassignet and Sandery 2013);
- assimilation of new observations including sea-ice, salinity and biological/biogeochemical observations (Martin et al. 2015);
- broadening of the systems to include biogeochemistry and sea-ice predictions. Most systems are now working towards coupled physical–biogeochemical state estimation (both global and regional) and coupled ocean–wave–ice–atmosphere predictions (Gehlen et al. 2015; Brassington et al. 2015);
- improved forecast (Ryan et al. 2015) and reanalysis (Balmaseda et al. 2015) skill at all relevant scales for physical (e.g. temperature, salinity, three-dimensional velocity and sea surface height) and biogeochemical variables of interest (lower trophic level,

including nutrients and carbon) through, multi-model ensembles, for example;
- realization of observation impact studies (Balmaseda et al. 2015; Oke et al. 2015a,b), reanalyses, improved error covariances and bias correction schemes (Martin submitted), increased high-resolution regional predictions and ensemble forecasting.

In situ and remote sensing data are now routinely assimilated in global and regional ocean models to provide an integrated description of the ocean state, allowing for forecasts of the ocean's mesoscale of up to 10 days. However, despite this progress, some underlying problems remain to be solved with the specific nature of these depending on the individual forecasting system. An example is the assimilation of altimeter data, which works well with many systems when there is a strong thermocline, i.e. in low to mid latitudes, but which is often less effective in polar waters where the thermocline is weaker or non-existent or due to seasonal ice cover or shallow salinity stratification masking the thermocline signal. Another difficulty faced by many systems is the assimilation of physical data (e.g. temperature and salinity) near the equator, which induces spurious vertical circulations.

Progress in operational oceanography is accompanied by the use of new observations (e.g. high-frequency radar), including new technologies for platforms and sensors (e.g. wide-swathe altimetry), which are likely to bring more improvements to the fine-scale observation system (Legler et al. 2015; Le Traon et al. 2015). Many of the ocean forecasting centres involved in GOV take advantage of these new techniques and data sets.

One of the emerging user demands in operational oceanography is for a broader range of products and information such as multi-year (re-) analyses and forecasts for the open ocean and shelf seas. These products allow users to explore interannual variability in phenomena such as El Niño/Southern Oscillation (Balmaseda et al. 2015) and weather extremes like hurricanes/tropical cyclones (Brassington et al. 2015). Other applications support management of the shelf seas and coastal environment (physical, biogeochemical and potentially higher trophic levels of the ecosystem) and allow analysis of the coupling between the open ocean and coastal areas (Kourafalou et al. 2015).

Observation, analysis and forecast products are readily accessible by users through centralized data and product servers, which draw on distributed networks of data processing and forecasting centres. There has been increased attention to the development of products and services, and the demonstration of their utility for applications such as marine environmental monitoring, weather forecasting, seasonal and climate prediction, ocean research, maritime safety and pollution forecasting, national security, the oil and gas industry, fisheries management and search and rescue.

The multiple pathways to uptake by, for example, governments, private industry and research agencies, which have been established during GODAE and in the first 6 years of GOV, are summarized in Figure 1. By aligning itself with relevant international research and innovation frameworks, GOV ensures that it is underpinning science, and the research and development which is most relevant to the needs and opportunities related to ocean forecasting from global to regional/coastal scales. The next phase of R&D under GOV will strengthen these paths to ensure that the potential benefits of ocean forecasting can be translated to better economic, social and environmental outcomes.

Future research priorities and challenges

This section starts with a discussion of the priorities for and issues facing further development of the Operational Ocean Forecasting Systems (OOFS). The subsequent sub-sections provide high-level précis describing future scientific challenges within each of the five key research areas of GOV as discussed in detail in relevant preceding papers of the JOO Special Issue. These five key research areas are:

- development of global ocean forecast systems;
- intercomparison and validation of these systems;
- observing system evaluation;
- marine ecosystem assessment and prediction; and
- short- to medium-range coupled prediction.

Development of global forecast systems

The quality of the OOFS that are already established should be improved in the next few years. This sub-section describes improvements that can be expected from improved parameterizations of unresolved processes and increasing model resolution. It also discusses the limitations to predictability arising from the limitations of the observing system and the role of ensembles and the assimilation teams within GOV in assessing and addressing these limitations.

In the ocean models used by the forecast systems, there are still substantial uncertainties and deficiencies in the representation of frontal and instability processes such as Langmuir circulations (McWilliams et al. 1997) and shear spiking in the layers near the surface of the ocean (Crawford and Large 1996) and the downward propagation of energy into the ocean associated with inertial waves (Firing et al. 1997).

Improved representation of these processes could improve air–sea fluxes and weather forecasts, reduce

Figure 1. ‘Circle diagram’ (read from inside to out) illustrating how GOV links with the entire maritime sector, to generate scientific outputs that deliver benefits across all relevant sectors of global economy, society and environment. Abbreviations in parenthesis behend supporting institutions: Int’l = international, It = Italy, JA = Japan, No = Norway, Fr = France, In = India, Br = Brazil, Ca = Canada, Ch = China, Au= Australia.

biases in the forecasts of temperatures and improve the predictions of near-surface currents. Not surprisingly, this is an active area of research using field studies and large eddy simulations to develop improved parameterizations (McWilliams and Danabasoglu 2002; Molemaker et al. 2010). Coupled atmosphere–wave–ocean models will allow more complete representation of these processes, provided the models have sufficient spatial and temporal resolution to resolve them. Improved parameterization of other sub-grid scale processes such as the breaking of internal gravity waves could also be important (Liang and Thurnherr 2012). Improved treatment of the grid-scale closure in high-resolution models (e.g. the two-dimensional dissipation of enstrophy cascading to smaller grid-scales and the transfer of energy towards larger scales) may also be important; the original formulation of the Gent-McWilliams (Gent et al. 1995) scheme seems a less satisfactory solution to this issue in eddy-resolving models than coarse resolution ones.

Short-to-medium-range predictions using global ocean models with (1/12)° grids are now affordable. Hurlburt et al. (2008) have argued that these models should be termed ‘eddy-resolving’ because they represent the interaction between the mesoscale and the bathymetry in a qualitatively different manner from coarser resolution models. Certainly the vertical velocities in these models have significantly greater variance than those in models using a (1/4)° grid. The experience in weather prediction is that improving the resolution of the grid steadily improves the representation of the evolution of the synoptic systems until a new set of atmospheric scales, the atmospheric mesoscale, introduces fresh errors. Improving the model resolution also involves improving the atmospheric forcing and bathymetry – a challenge over the next years.

Results also depend on the choice of the vertical coordinate as it impacts on the projection of surface boundary conditions onto the vertical ‘modes’, or structure. Most commonly among operational forecast models, the vertical grid resolution (which can be defined in density, depth or pressure coordinates or as a combination of these) is highest in the upper ocean and thermocline where the vertical modes are best resolved.

In ocean models, one might expect similar improvements in fidelity at least until the next scale of ocean processes (perhaps sub-mesoscale and internal waves) starts to fall within the model's scope, and new predictability challenges arise. The predictive capability of the forecast systems could, however, already be limited by our ability to initialize (constrain) errors with the observational coverage. Constellations of 3–4 satellite altimeters resolve a useful fraction of the variance of the sea surface height (Le Traon 2013), but it may be that swathe altimeters, or fine-resolution surface currents based on the matching of drifting patterns within images, could provide significantly more information on the near-surface mesoscale currents. Similar (horizontal) spatio-temporal resolution from *in situ* measurements does not appear to be achievable, but gliders and Acoustic Doppler Current Profiler ship observations have the potential to provide such information along their tracks, and fleets of gliders could be used in field studies to explore the factors currently limiting prediction of the ocean mesoscale.

GODAE [IGST (International GODAE Steering Team) 2000] was based on the hypothesis that data assimilation into high-resolution ocean models could succeed in constraining the evolution of the model's mesoscale fields. This hypothesis assumed the availability of information on the ocean's surface height (derived from satellite altimeters) and SST and broad-scale information on the vertical structure of water mass structure from an *in situ* observing system. Results from the forecasting systems suggest that these are able to track the larger mesoscale evolution and that, in this sense, the hypothesis has been confirmed.

Intuitively, one would expect that the above success would depend on using good estimates of the error covariances to project the sea surface height increments accurately onto the vertical thermohaline structure. The groups within GOV have implemented assimilation schemes that calculate their error covariances in quite different ways. It could be productive to compare how the three-dimensional increments generated from sea-surface height increments differ between the systems. This would inform the formulation of future hybrid assimilation schemes combining ensemble and 'climatological' error covariances.

In this context, it is noteworthy to mention the link between improvements to models and adjustments to data-assimilation processes. More specifically, as the models are improved both in resolution and through the addition of new processes, this will require the corresponding data-assimilation processes to account for this by adjustments to the use of representation errors in the background error covariances.

Because of the computational expense of resolving the ocean mesoscale, most of the GOV community has been slower to implement ensemble prediction systems than the weather prediction and seasonal forecasting communities (moreover, one needs to use an ensemble of forcing from boundary conditions). It is now computationally feasible to develop global and regional ensemble prediction systems, and these will offer valuable estimates of and insights into the spread of uncertainty and levels of predictability that can be achieved by these systems.

Intercomparison and validation of forecasting systems

OOFS are nowadays producing short term forecasts, hindcasts, reanalyses and associated products based on real-time monitoring. The new systems are extending the parameter space, by coupling with atmospheric, sea-ice and biogeochemical models. Time-scales cover several decades to hours; spatial scales include basin- to coastal mesoscale, and some systems also resolve sub-mesoscale variability. The validation and the intercomparison of such systems raise several new issues and scientific challenges (Ryan et al. 2015).

The first issue is the *observability* of ocean variability captured by model simulations. Changes in the technology of the observing network from the 1970s to today and the increase in the number of observations from satellite remote sensing and autonomous instruments raise questions about the homogeneity of validation results for reanalysis and ocean state monitoring. Assessments of heat-content variations and sea-level rise are sensitive to this inhomogeneity. Tide gauges are located around the boundaries of ocean basins and islands, and therefore, it is natural to ask how much information they convey about the sea-level variability in the ocean interior. With the advent of satellite altimeters, we now have a direct way of addressing this question. Furthermore, tide gauge networks prior to the satellite altimetry era have to be analysed carefully and compared with the most recent evaluations of sea level.

Conversely, very recent space observations from SMOS and Aquarius satellites, even if they provide useful SSS retrievals at scales of 100 km or more, represent a challenge for reporting on decadal changes in sea surface salinity (SSS) when compared with historical time series of SSS.

Ocean spatial patterns are also limited by observability. Sub-mesoscale filaments, tidal fronts, freshwater plumes generated by river runoff, etc. are produced by coastal OOFS with horizontal grids of 1 km or less. A future challenge will be how to use the fine-scale but spatially limited coastal observations, such as HF-radar, the temporally limited SAR or swathe altimetry observations as part of high-resolution, basin-scale OOFS.

Second, and strongly linked to observability, is the *independence* of observations for scientific assessments.

Most OOFS assimilate all available data to reduce errors and increase the realism of hindcasts and forecasts. Hence, most of the temperature, salinity and sea-level observations are used to produce an analysis. Independent validation usually relies on 'exotic' observations that are more difficult to assimilate. This is either because these observations are not available in real-time (e.g. deep moorings) or because they are more difficult to incorporate into the observation operator of a given OOFS, e.g. currents and waves. With increasingly more sophisticated OOFS that represent a wider range of ocean processes such as tides, the natural tendency is to assimilate all available observations. Consequently, most of the assessment is based on data-assimilation innovation and misfit statistics, which are clearly not independent. The purest validation of a forecast is the a posteriori validation of the forecast versus observations, but additional approaches might be developed in the future.

Third, additional mathematical tools and approaches for validation need to be applied to the outputs from the OOFS. At present, most of the results are based on first- and second-order statistical analyses such as mean and variances. Sea-ice error assessments, as well as biogeochemical parameter validations, have demonstrated that new approaches are needed. Forecasting skill based on contingency tables, pattern evaluation based on principal-component analysis, Lagrangian simulation and comparison are some examples of these approaches. The expansion of GOV systems to ensemble forecasting will also present new challenges to develop probabilistic verification techniques appropriate for the ocean and sea ice. Although these approaches are not new in other areas of research, they are relatively new to OOFS.

Fourth, the coupling of systems such as ocean and atmospheric models will re-orientate error analyses towards multi-parameter sensitivity. For instance, surface current and wind errors are linked and should be jointly evaluated with the associated wind stresses, which also depends on sea roughness (waves). Primary production depends on nutrient supply and thus on vertical and horizontal advection plus diffusion represented by the physical model. Consequently, there is a challenge to evaluate this cross-component sensitivity and to infer errors of some variables from a direct error evaluation of another one.

Another set of issues arises from the emergence of multiple estimate approaches, a challenge also well known to Numerical Weather Prediction (NWP). Through the expansion of GOV systems, there may be several estimates at the same location from different global and regional systems, from ensembles, as well as from observational estimates. It is thus important to be able to identify the different processes represented by each system and the specific benefits of regional and coastal systems. Multi-model ensembles have shown the potential to provide substantial gains over using single system products, but the limits and advantages of this approach need to be better understood. How can the strengths and weaknesses of each system be taken into account? As the resolution of the systems crosses the boundary between eddy-permitting and eddy-resolving, how can the representation of sub-grid scale parameterizations be included? The construction of a multi-parameter multi-model ensemble that can reflect the range of data assimilation and modelling approaches in the GOV systems is clearly a challenge for the years to come.

Observing system evaluation

The provision of ongoing demonstrations of the impacts of observations on global and regional ocean forecast and analysis systems is a key activity of GOV as it was for GODAE (Oke et al. 2009). This has involved a range of different activities – most of which have looked back in time, providing assessments of the Global Ocean Observing System (GOOS) for previous 'versions' of the observing system (e.g. different status of the Argo array, different types and constellations of altimeters, etc.). A description of the most recent of these activities is given in previous studies (Oke et al. 2015a,b). This has been achieved through a mix of traditional Observing System Experiments [OSEs; e.g. Oke and Schiller 2007)) and Observing System Simulation Experiments (OSSEs; e.g. Halliwell et al. 2014)]; through opportunistic scenarios, such as demonstrations of the degradation of operational forecast systems during data outages (see Figure 2); and through the development and dissemination of impact-related data-assimilation metrics (e.g. degrees of freedom of signal (Sakov et al. 2012) and observation footprints (Oke and Sakov 2012). More recently, adjoint-based techniques increasingly complement traditional OSE approaches (e.g. Heimbach and 28 other authors 2010).

The traditional approaches to observing system impact and assessment are very powerful. OSEs, for example, use real forecast systems with real observations to quantify the real impact of observations on the system employed, but the results are inevitably system-dependent. Other systems might make better (or worse) use of observations and/or have different systematic errors. Moreover, OSEs are almost always performed for the past (e.g. when there were four altimeters operating, or when the Argo array was at 75% of its target), and the near-real-time (NRT) availability of observations is not guaranteed (Figure 2). A comprehensive series of OSEs are also computationally expensive to perform, and require significant resources to analyse, interpret, and understand results.

The limitations mentioned above mean that results from a traditional series of OSEs can only provide general advice to decision-makers and tend to be performed sporadically. Suppose, for example, that an OSE study demonstrated that three altimeters were needed to constrain the mesoscale

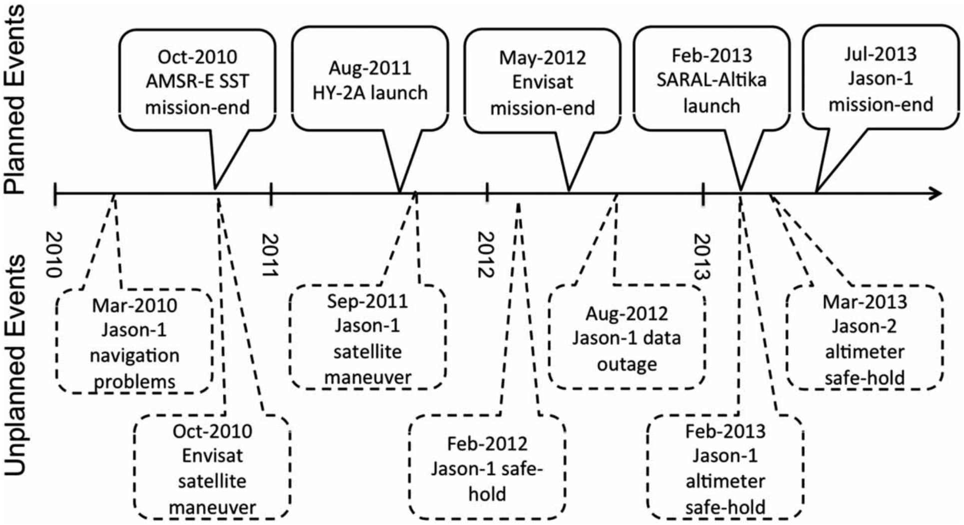

Figure 2. Schematic time series of ‘observing system events’ relating to satellite altimetry for the period 2010–2013, showing the planned (above the line) and unplanned (below the line) events. The schematic highlights the fact that the availability of observations in NRT is not guaranteed.

ocean circulation in 2004. This is statistically relevant in 2014 only if one assumes stationarity. The Argo array, for example, evolved between 2004 and 2014, with new floats deployed, old floats un-functional, and the spatial distribution of floats changed. These factors limit the relevance of the ‘historical OSEs’.

Observing system decision-makers now and in the future need quantitative feedback on the state of the system. To try to meet this need, the GOV proposed the idea of NRT OSEs. Several (ideally all) operational centres perform equivalent OSEs, withholding the same observations from their respective forecast systems, at the same time, using a set-up that is identical to their own operational system. By performing the OSEs in NRT, the results will be relevant to the present-day observing system and facilitate identification of potential ‘gaps’.

If multiple OOFS are used for the NRT OSEs, results can be inter-compared and the most robust findings identified and disseminated to interested parties. The hope is that community NRT OSEs become an integral and routine part of all operational centres’ activities – providing a regular, relevant and robust evaluation of the current state of the observing system. These NRT OSEs can also simulate data outages, providing a meaningful assessment of the impact and importance of each data type. The first examples of NRT OSEs were performed (Lea et al. 2013), using FOAM (Forecasting Ocean Assimilation Model) the Met Office’s open ocean assimilation and forecasting system. This study demonstrated the strength of this approach and took steps towards the development of Observation Impact Statements (OISs; see Lea 2012).

GOV is encouraging all operational centres to routinely perform the same NRT OSEs (Lea et al. 2013), with results synthesized into a small number of tables and figures to form community OISs (Lea 2012). Such an activity would inform decision-makers about the maintenance, enhancement, or modification of the observing system based on up-to-date evidence of observational impacts.

Coastal ocean and shelf seas forecasting

GOV aims to advance and promote science in support of coastal ocean and shelf sea (COSS) forecasting. The strategic goal is to achieve a seamless ocean forecasting framework, from the global to the coastal/near-shore scale. After three successful international coordination workshops, the current state of COSS forecasting has been reviewed, and a picture of future scientific challenges is emerging (Kourafalou et al. 2015).

First, despite efforts in integrated monitoring (e.g. IOOS,[3] JERICO[4]), there are still issues associated with routine observations in many coastal regions:

- The SWOT[5] wide-swathe altimeter mission is expected to provide high-resolution (HR) sea-surface height starting in 2020. This will facilitate a fundamental change in coastal-to-shelf scale modelling, parameterizations (previously unresolved processes now resolved) and data assimilation.
- Improving the use of existing observations is another challenge. Advanced data-assimilation methods will continue to be explored and compared in order to get the most out of existing observations.
- Observing System Experiments and Simulation Experiments (OSEs/OSSEs Balmaseda et al. 2015) are viewed as important activities for the optimization of existing and the design of future COSS observing systems (Oke et al. 2015b).

- While HR data assimilation is very important, there may not be enough observations to constrain the large number of degrees of freedom associated with COSS processes, even in densely observed areas. Therefore, ensemble and probabilistic approaches will probably be crucial for quantifying uncertainties and deriving new types of products [e.g. probabilistic forecasts (Rixen et al. 2008); Bayesian analysis (Abramsin et al. 1996)]. GOV will regularly review existing approaches, and foster research in COSS systems linked with applications (e.g. surface drift or coastal flooding).

Second, COSS models are sensitive to the various choices made by the providers of boundary conditions. GOV provides an ideal framework to test and validate boundary conditions for nested systems in the form of Pilot Projects and in close collaboration with centres that provide these boundary conditions. Techniques for optimal downscaling, as well as data assimilation within nested models, need to be further explored.

A third category of challenges in the coastal and shelf-seas domain concerns coupled modelling. More time and effort need to be invested in improving the coupled dynamics of ocean–wave models, ocean–atmosphere models, ocean–biogeochemical models and ocean–estuary–hydrology models. This includes the need for improved HR atmospheric forcing and bathymetry, even potentially the bathymetric changes from sediment transport in the near-shore zone. Data assimilation in coupled models is in its infancy and would benefit from a coordinated effort. Earth System Model approaches also provide a framework for integrating all components that influence air–sea, land-sea and coastal-offshore interactions that are fundamental for the advancement of COSS systems and forecasts.

Marine ecosystem assessment and prediction

The use of outputs from operational systems is progressively expanding to include biogeochemical applications. OO products are likely to have sufficient skill in the not-too-distant future to provide key information to many applications related to living marine resources, from regular monitoring to statutory advice on ecosystems. Despite the growing amount of information, the outputs are still not extensively used by potential end users, suggesting that more research is required to make them fit for purpose. End users may still be relying on the traditional uni-disciplinary approaches (see Berx et al. 2011). The capacity to deliver 'integrated products' based on syntheses between observations and model-derived information is likely to yield more systematic harvesting by users if the quality and reliability of the products is scientifically proven.

High-seas fisheries are catching annually ~6 million tonnes of tuna and tuna-like species that represent ~20% of the economic value of all marine capture fisheries (Food and Agriculture Organization of Nations 2012), making them an ideal first candidate for demonstrating the utility of basin-scale operational oceanography for improving monitoring and management of marine resources. A proof-of-concept of the operational management of pelagic ecosystems has been provided for pelagic tuna fisheries. The application relied on operational model data providing forcing to a spatial population dynamics model (SEAPODYM) simulating intermediate trophic levels (Lehodey et al. 2008) and their predator dynamics, here tuna (Lehodey et al. 2010). This quantitative estimation approach (Senina et al. 2008) allowed management scenarios to be tested (Sibert et al. 2012).

There is an increasing demand for operational systems to be deployed at the regional to local scale in coastal environments. Potential applications include the monitoring and prediction of oxygen and pH for early warning and detection of hypoxia and of ocean acidification events for the forecasting of harmful algal blooms or jellyfish proliferation. Information could also assist natural marine resource management, and prevention of the spreading of fish diseases among aquaculture facilities. Associated applications require OOFS with high spatial resolution and are tightly linked to the provision of high-quality physical/biogeochemical state estimates.

As a first step towards coupled physical–biogeochemical data assimilation, physical data-assimilation products were used to drive biogeochemical models (Brasseur et al. 2009; El Moussaoui et al. 2011). The analysis of biogeochemical tracer distributions revealed, however, the risk of a degradation of modelled biogeochemical distributions (e.g. chlorophyll-a, nutrients, sea-to-air CO_2 fluxes) by physical data assimilation most notably in the equatorial Pacific (e.g. Fontana et al. 2013; Barciela et al. 2012; El Moussaoui et al. 2011). Understanding the causes of spurious vertical fluxes and identifying a solution are critical to the development of biogeochemical applications of physical data assimilation and remains a priority for GOV.

The advent of biological data assimilation could bring a step change in the potential capabilities of GOV systems, ultimately promoting the development of applications integrating biological and ecosystem monitoring and prediction. The capability of generating biogeochemical reanalyses could be used to differentiate natural variability and long-term trends. Assimilation of biological data proved to be efficient in reducing model biases not only of the assimilated variables, such as chlorophyll (Fontana et al. 2013), but also of the unobserved simulated variables or biological process parameterizations (Doron et al. 2013). The use of multivariate assimilation schemes, integrating physical and biological observations, remains a high priority for GOV, and the expansion of these techniques to simultaneous state and parameter estimation should be considered.

The ocean is still critically undersampled for biological and biogeochemical properties. The lack of data is the main obstacle to the implementation of operational systems suitable for the routine and accurate monitoring of ocean biogeochemical state. GOV research should contribute to the specification of essential physical and biological/biogeochemical observations; to identify the best sampling strategies; and to formulate recommendations to improve the observing capacity needed to sustain full-fledged integration of biogeochemistry into operational systems.

There is a clear need for a roadmap regarding future ocean colour missions needed to consolidate the space component in the next 20 years, combining conventional low-earth orbit and geostationary orbit missions. New *in situ* observing programmes such as Bio-Argo offer opportunities to improve synergies with present and, hopefully, future ocean colour satellite missions. A first solid set of recommendations was provided by the OceanObs09 conference (Claustre and co-authors 2010), though a number of questions remain.

Short- to medium-range coupled prediction

The availability of GOV-type forecast systems of the ocean state provides the opportunity to develop HR coupled prediction systems for the short- to medium-range. Making progress in this field is a grand challenge owing to the complexity of coupled infrastructure, coupled modelling, observational requirements (including experimental campaigns) and the resulting need for more diverse teams of scientific experts.

Progress is being driven at the institutional level with a number of systems developed or under development including (Chassignet and Sandery 2013): US Navy (COAMPS), NOAA (including but not limited to the coupled hurricane prediction system), ECMWF (coupled atmosphere–wave), UK Met Office (coupled and UK-scale modelling), Bureau of Meteorology (CLAM), Canadian Meteorological Centre (CMC; CONCEPTS), Mercator (coupled atmosphere–ocean tropical cyclone), NASA/GAO (coupled atmosphere–ocean) and others. There have been several workshops relevant to this area driven predominantly by the needs of NWP. A joint GOV-WGNE workshop was held March 2013, Washington, DC, to draw expertise across the GOV and NWP communities (Chassignet and Sandery 2013).

The groups active in coupled prediction research are pursuing a wide range of applications including global weather forecast systems and predictions of hurricanes, tropical cyclones and typhoons, extra-tropical storms, high-latitude weather and sea-ice, as well as coastal upwelling, sea breezes and sea fog. Research has moved beyond case studies and sensitivity studies to controlled experiments to obtain statistically significant measures of impact. First systems run in coupled prediction mode (Brassington et al. 2015).

The modelling systems being employed include regional and global coupled models of atmosphere–wave, atmosphere–ocean, atmosphere–wave–ocean and atmosphere–sea-ice–ocean. All published systems thus far have made use of uncoupled data assimilation with a coupled initialization procedure. Despite the relatively unsophisticated configurations, the results obtained thus far are generally positive and have encouraged more research and development in this area.

In many cases, progress is being accelerated through the developments already made in the seasonal and climate forecasting community. Nonetheless, there are several research challenges that have been identified at the national level and a community-based approach to share advances in coupled science and coordinate international experiments and observation campaigns is being pursued.

The most challenging area identified to date is the development of coupled data assimilation, which must correctly handle the different temporal and spatial scales across the ocean, wave, sea-ice and atmospheric environments. There is a need to explore new approaches to address coupled model biases and to optimize the weighting of coupled covariances. Further progress will require community-established benchmarks, test cases, targeted observation campaigns and coordination across the existing international teams.

A vision for ocean forecasting in 2030

When we look back over the early days of ocean forecasting, it is astonishing to see the immense progress that has been achieved in the science and practice of operational ocean forecasting, and in the extensions such as ocean re-analyses. In the mid 1990s, global ocean forecasting was in its infancy, and oceanographers were looking with some envy at the progress in NWP. Indeed, many lessons have been and continue to be taken from NWP. A key driver for establishing GODAE in the mid 1990s was to enable global ocean forecasting to advance more rapidly by creating an international collective effort taking advantage of the parallel revolution in observing the oceans. The vision of the GODAE Strategic Plan [IGST (International GODAE Steering Team) 2000] has been realized, and today we expect mesoscale ocean forecasts to have useful skill up to a couple of weeks ahead. Scientific developments, an enhanced ocean observing system and increased computational capability have all played a critical role.

What does the future hold, and what could we expect ocean forecasting systems to be like in, say, 2030? Based on the recent past, it is difficult to foresee all of the scientific and technological advances. However, some of the scientific trends are more straightforward to extrapolate. For example, the gestation period for mainstreaming new observation techniques is 10–15 years, so we probably already have the prototypes for what will be deployed through the next decade, such as SWOT. Similarly, the future growth in computing power is difficult to predict, but we can probably make a reasonable estimate, certainly within an order of magnitude, of what will be available operationally in 2030.

Another increasing trend is to deliver a diverse range of three-dimensional past and present (re-)analyses and future forecasts of the ocean state at global to regional to local (coastal) scales. Horizontal grid resolution of global forecast systems (and of their embedded regional systems) has been increasing at a steady rate for the last two decades concomitant with an increase in forecast skill. Within the next 3–5 years, typical horizontal grid resolutions will be of the order of 5–10 km for global models and are likely to approach the sub-mesoscale (in the order of 1 km) in the next decade. The latter will depend on continued growth in computer power and will increasingly be based on unstructured grids (with highest resolution in regions of highest interest), perhaps coupled to adaptable ‘relocatable’ models.

A fundamental issue and looming major question for operational ocean forecasting is about controllability, which includes predictability, observability and the ability of observations to constrain initial conditions for forecasts. The increase in computing power has enabled the development of higher-resolution models, but this was not accompanied by a simultaneous growth of the global and regional ocean observing networks at the same rate. We have to ask ourselves if future *in situ* and remotely sensed observations will have sufficient spatio-temporal resolution to constrain sub-mesoscale models, or, if not, do these models have sufficient skill to interpolate dynamics between the relatively coarse observation networks? Perhaps we have made progress in understanding predictability of the ocean but we still do not understand the predictability of mesoscale fronts, of currents across the shelf break, of errors propagated in through the surface from NWP or of error in biophysical systems, etc.

A question to ask is what the global ocean models of the future will be able to predict (a similar question is relevant to climate/earth system models) and how to communicate the increasingly complex information to users. We have to remind ourselves that the physical aspects of the ocean such as temperature, salinity and currents form only part of the information societies want to know about their oceans. Near the surface, accurate wave forecasting is of major societal concern when we think about tsunamis, coastal tides and storm surges (the latter two also vary in the context of climate change, coastal erosion, etc.). Moreover, users are increasingly demanding probabilistic information to provide measures of confidence to decision makers. As scientific and operational priorities are ever more ‘user-driven’, we can expect an expansion of GOV products to meet tailored user needs.

Another related aspect of knowledge about the marine environment is our growing capability of accurately simulating and predicting key components of the marine biogeochemical cycle, including carbon and nutrient cycles. The combined physical–biogeochemical systems will increasingly resemble ‘environmental prediction systems’. These developments are happening because of growing demand by users for multi-disciplinary information and the progress in relevant science areas but also because new observations of environmental properties are available from satellite remote sensing and elsewhere. By 2030 or sooner, we can expect to have

> access to timely observations and information on the present and past physical, chemical and biological state […], […] associated data on human activities, […] their impact on the sea and […] oceanographic forecasts. All this should be easily accessible, interoperable and free of restrictions on use (European Commission 2012).

Simultaneously, there will be demand for interoperable access by users to a large variety of observational and modelling products to produce their own ‘scenarios’ of the marine environment by, for example, running online model simulations with different forcing scenarios, especially in the coastal domain to inform management decisions. We can expect this area to grow significantly as future communication technologies will open up new opportunities for societies to use ocean information in a much more interactive way than experienced hitherto.

The above advances will require an increasingly multidisciplinary effort in physics, chemistry, biology, geomorphology, IT/visualization expertise and eventually ecology, progressing the science and leading to applications in unison. GOV has already embarked on this route by creating Task Teams for biogeochemical and coupled ocean–atmosphere–wave analysis and forecasting. 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 many unknowns and uncertainties about the future, but there are ample opportunities for GOV and partners to advance the science of ocean forecasting and to improve its skill to yet unknown levels.

The increased focus on developing coastal/shelf-scale analysis and prediction capabilities brings with it the additional challenge of developing cost-effective *in situ* coastal observing systems. In this context, work currently undertaken by GOV and its partners is paving the way for fully automated multi-system OSEs about all components of the GOOS. Through associated OIS, GOV contributes to coherent, effective and scientifically robust advocacy of the case for, and prioritization of, the components of the GOOS (in addition to the 'user pull' in deciding what quantities should be measured by the GOOS). An increasing future effort will allow system agencies to be observed to assess the impact of past, present and future observations on forecast and (re-)analysis skills 'offline' at a fraction of the cost of implementing the new observing system and will contribute to maximizing the return on investment of the GOOS. A complementary future trend is to integrate 'citizen science' into observing networks. These significant contributions to the observing system by the public will happen by developing small systems that can be housed in fishing or sailing boats at comparatively low investment and operating costs.

Finally, the uptake of ocean analyses and forecasting products by public and commercial users is steadily increasing, leading to more demand but also new science challenges and opportunities. For example, the number of registered users of MyOcean2 services (http://www.copernicus.eu/library) has doubled during the first 12 months of MyOcean2 in 2013, with about 100 new users every month. Our vision is for a truly integrated ocean system and associated services from the global ocean to shelf/coastal-scales to eventually include estuaries and the littoral zone with multi-disciplinary components and users. In 2030, we can expect to see communication media to provide (near-coastal) ocean forecasts similar to what we are accustomed to today about daily weather prediction. First steps in this direction have already been taken by various national initiatives [e.g. the Chesapeake Bay Forecasting Project (cbfs.umd.edu/) and Northern Gulf of Mexico Operational Forecast System (tidesandcurrents.noaa.gov/ofs/ngofs/ngofs.html), the US IOOS Coastal and Ocean Modeling Testbed (www.ioos.noaa.gov/modeling/testbed.html), the French Previmer activity (www.previmer.org/), the eReefs project in Australia,: www.ereefs.org.au, and the Canadian Gulf of St Lawrence (weather.gc.ca/marine/index_e.html)].

Conclusions

This paper provides an overview of the future scientific challenges and opportunities to be faced by ocean forecasting. Apart from the scientific challenges, a wide range of additional factors will influence the progress of ocean forecasting. Among these challenges and factors are:

- the sustainability and expansion of the biophysical GOOS (Task Team for an Integrated Framework for Sustained Ocean Observing 2012); new opportunities arise in regional seas and the advent of 'intelligent' new sensors and new remote sensing technologies both from space and *in situ*;
- the future growth of the public profile and visibility of ocean forecasting and analysis (public awareness creates interest, which creates user pull, which, ideally, is aligned with science push);
- the associated need for and evolution of service delivery, including between R&D providers, intermediate and end users of oceanographic information [this particularly relates to offshore petroleum industry where advances in underwater observation, remote handling and construction technology now allow for safe operations in deeper waters under a wider range of oceanographic and meteorological conditions (European Commission 2012)];
- the need for increasingly close research collaboration and cooperation with other major research domains such as the weather and climate communities (Brunet et al. 2010), and international programmes such as CLIVAR, THORPEX and IMBER in research areas of mutual interest and benefit; for example, developing 'seamless' prediction (spatially and temporally) and towards Earth System Modelling, environmental prediction and forecasting (http://www.icsu.org/future-earth).

Operational oceanography continues to face many scientific challenges with time-scales ranging from weather to climate. It is inherently an international issue, requiring broad collaboration to span the coastal to global oceans; it is beyond the capability of any one country. As a consequence and in the foreseeable future, GOV [GOVST (GODAE OceanView Science Team) 2014] will continue to:

- promote the development of ocean modelling and assimilation in a consistent framework to optimize mutual progress and benefit;
- promote the associated exploitation of improved ocean analyses and forecasts (also in the context of climate monitoring and societal impacts); and
- provide a means to assess the relative contributions of and requirements for observing systems, and their respective priorities.

The societal benefits from OOFS systems will only be fully realized through joint networks with other global teams of experts and linking global with national expertise. Potential benefits derived from OOFS include improvements in the day-to-day management of coastal waters, emergency environment response, search and rescue, management of marine ecosystems, weather prediction from hours to decades ahead, and advice on the expected impacts of climate change on the oceans and coastal waters. These benefits and the OOFS collaborating under GOV are critically dependent on both the satellite and *in situ* components of the GOOS. The reanalysis, hindcast and forecast systems developed by GOV both require inputs from, and should be valuable resources for, the oceanographic research community as a whole. The facilitation of cooperation between research teams, operational groups and the wider science community will remain a key element of the future GOV.

There is an emergence of an increasing number of countries with forecasting capacities at various levels of maturity. Although many of these efforts have a more regional or coastal focus rather than global, they seek advice from GOV partners about establishing a capacity to develop their own operational oceanography activities and to gain access to knowledge and suitable global forecasting data to provide boundary conditions for their regional or coastal systems.

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Notes

1. The Marine Directive of the European Commission defines Good Environmental Status as: **'**The environmental status of marine waters where these provide ecologically diverse and dynamic oceans and seas which are clean, healthy and productive'. (http://ec.europa.eu/environment/marine/good-environmental-status/index_en.htm).
2. Following (29), 'operational' is used here 'whenever the processing is done in a routine and regular way, with a pre-determined systematic approach and constant monitoring of performance. With this terminology, regular re-analyses may be considered as operational systems, as may be organized analyses and assessment of climate data'.
3. IOOS: Integrated Ocean Observing System (http://www.ioos.noaa.gov).
4. JERICO: Towards a Joint European Research Infrastructure Network for Coastal Observatories (http://www.jerico-fp7.eu).
5. SWOT: Surface Water and Ocean Topography, a joint US/French satellite project (http://smsc.cnes.fr/SWOT).

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