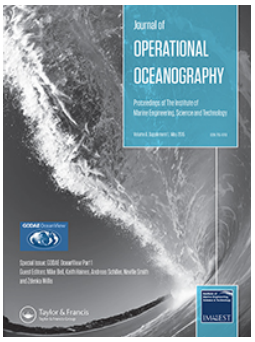

Journal of Operational Oceanography

ISSN: 1755-876X (Print) 1755-8778 (Online) Journal homepage: http://www.tandfonline.com/loi/tjoo20

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To cite this article: M.J. Bell, A. Schiller, P.-Y. Le Traon, N.R. Smith, E. Dombrowsky & K. Wilmer-Becker (2015) An introduction to GODAE OceanView, Journal of Operational Oceanography, 8:sup1, s2-s11, DOI: 10.1080/1755876X.2015.1022041

To link to this article: http://dx.doi.org/10.1080/1755876X.2015.1022041

Journal of Operational Oceanography, 2015
Vol. 8, No. S1, s2–s11, http://dx.doi.org/10.1080/1755876X.2015.1022041

An introduction to GODAE OceanView

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Real-time operational predictions of the major ocean basins which resolve the ocean mesoscale at mid-latitudes have become established in more than a dozen countries over the last 15 years. These predictions depend on the global ocean observing system (particularly satellite altimeters and the Argo profiling float system), high performance computers and sophisticated ocean models and data assimilation systems. They support an expanding range of information services for operations at sea, weather forecasts and protection of the environment. GODAE Oceanview (GOV) assists the groups developing these predictions. This paper provides an introduction to GOV and the papers in this special issue.

Introduction

Operational short-range forecasts of ocean surface waves and storm surges have been made by weather forecast centres since the late 1970s and early 1980s respectively. Predictions of the three-dimensional (3D) structure of the ocean temperatures, salinities and currents using dynamical ocean models only really started during the 1980s, with some groups developing systems for seasonal forecasting (Derber & Rosati 1989) and others (Thompson et al. 1986) focusing on the prediction of the ocean mesoscale for naval applications. By the mid-1990s, as anticipated in the mid-1980s (Hurlburt 1984), several technologies had progressed to the point where global prediction of the ocean mesoscale was becoming feasible and in 1998 a ten-year Global Ocean Data Assimilation Experiment (GODAE) was launched (Smith & Lefebvre 1997; IGST 2000) to provide support at an international level to the proof of concept and transition of these capabilities to operational status.

The progress made during GODAE was summarized in a special issue of Oceanography (Bell et al. 2009). Since then international coordination of activities has continued under GODAE OceanView (GOV) (GOVST 2012). An important new activity in the last five years has been the development of ocean prediction services with greater emphasis on the use of methodologies to identify and meet user needs in a wide range of application areas. The applications discussed below include the safety, efficiency and effectiveness of commercial and naval activities at sea; protection of the marine environment and coupled weather predictions from days to seasons ahead. Some of these services are provided for the open ocean but there is an increasing focus on providing services also for shelf-sea and coastal waters.

The progress achieved during this first five years of GOV are summarised in two special issues of this journal, this being the first. This introductory paper provides an introduction to the papers in this issue and a historical perspective on the development of 3D ocean prediction over the period 1997–2014. It starts with a summary of the developments to the technological capacities on which the predictions depend. It then outlines the user requirements and how they have evolved. The following sections describe highlights in the development of national capabilities and the value of international coordination. The final section discusses issues for the next phase of GOV based on this historical perspective.

Technological capabilities

Our ability to monitor and predict the evolution of the energetic motions in the ocean mesoscale (such as the meanders in the western boundary currents and the rings that break off from them) at mid-latitudes is based on four key technologies:

(1) satellite altimeters which measure the ocean's sea-level at the mesoscale,
(2) the Argo system of profiling floats which measure temperature and salinity profiles within the ocean (but do not resolve the ocean mesoscale)
(3) high resolution ocean models which resolve the ocean's mesoscale motions and
(4) data assimilation capabilities which combine the measurements from 1 and 2 with model predictions

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to provide accurate initial conditions for future predictions.

Each of these capabilities and some additional measurement capabilities of great importance to GOV are introduced in this section. More detailed descriptions of the status and future of the remote sensing observing system (Le Traon et al. 2015), and data assimilation (Martin et al. 2015) in operational oceanography are provided in this issue. The status of high resolution ocean modelling is described in various collections of papers (e.g. Griffies 2011) and introductory papers on many aspects of operational oceanography are contained in the book resulting from the 2010 GODAE summer school (Schiller & Brassington 2011).

Altimetry

Satellite altimetry provides global, real-time, all-weather measurements of sea surface heights (SSH) (sea level) at high space and time resolution. At mid-latitudes the sea level is to a good approximation an integral measure of the density variations in the upper ocean interior and provides a strong constraint for inferring the four dimensional (4D) ocean circulation through data assimilation. This explains the unique and fundamental role of satellite altimetry for data assimilation and operational oceanography. GODAE and GOV have thus right from the start maintained very strong links with the satellite altimetry community (e.g. the Ocean Surface Topography Science Team).

The quality of mesoscale predictions in ocean analysis and forecasting models is heavily reliant on the availability of altimeter data from multiple satellites. There is a common agreement that real-time analysis and forecasting of mesoscale circulation requires at least 3 or preferably 4 altimeters to be flown simultaneously in appropriately selected orbital configurations (Le Traon 2013). A very precise long-term altimeter system (Jason series) is also needed as a reference for the other missions (particularly for climate monitoring). During the last five years, there were, however, only 2–3 missions in flight. This was also a period of transition between two generations of altimeters: Jason-1, ENVISAT and GFO were replaced by Jason-2, CryoSat-2, HY-2A, and SARAL/AltiKa. SARAL/AltiKa had an immediate very positive impact on GOV systems as only Jason-2 and CryoSat-2 data were available before the SARAL launch. 2008–2013 was also a period of intense cooperation between the space agencies involved in the first altimetry missions (NASA, NOAA, ESA, CNES), EUMETSAT, and the space agencies from China (CNSA) and India (ISRO).

For the next decade, future missions include Sentinel 3A&B, Jason-3 and Jason CS. Sentinel 3A&B and Jason CS will use an improved along-track SAR mode (higher along-track resolution, lower noise level). Although at the time of writing there are uncertainties about the launch dates of these missions and funding has not been confirmed for JasonCS, it is hoped that the altimeter constellation will be satisfactory (although not ideal) in the coming years. It is also hoped that by 2020 the new Surface Water Ocean Topography (SWOT) concept will have been demonstrated, giving new capabilities for very high resolution observations of the ocean mesoscale over a swath. SWOT should be seen as an essential contribution to operational oceanography helping observation capabilities to keep pace with our steadily increasing model resolutions.

Argo

A major challenge at the end of the 90s was to set up a real time global *in-situ* observing system to complement satellite observations. Based on technological progress made during the World Ocean Circulation Experiment (WOCE), proposals were made to develop a global array of profiling floats making temperature and salinity profile measurements down to 2000 m every 10 days throughout the deep global oceans. The resulting Argo international programme (Roemmich & the Argo Science Team 1999) was initially developed as a joint venture between GODAE and CLIVAR. Argo has been an outstanding achievement. In November 2007, it reached its initial target of 3000 profiling floats. Argo delivers data both in real-time for operational users and after careful scientific quality control for climate change research and monitoring. Argo has brought remarkable advances in ocean and climate change research (Freeland et al. 2009) and ocean forecasting capability (Oke et al. 2009; Dombrowsky et al. 2009). There are strong and unique complementarities between Argo and satellite altimetry, and Argo data are now systematically used together with altimeter data for ocean analysis and forecasting.

The main GOV requirements for Argo are to maintain Argo global coverage and sampling for the long term. As reanalysis is as important as real-time prediction, reprocessing of past data with improved quality has to be conducted in addition to the delivery of products in real-time. Finally, the need for an improved vertical sampling has been identified for both regional prediction systems and coupled ones; near surface sampling has to be improved to better reproduce interactions with the atmosphere. Operational oceanography should also benefit greatly from extending Argo capabilities towards deeper observations (below 2000 m) and towards the observation of biogeochemical variables. This should be quantified (e.g. through OSSEs) and tested as part of Argo extension pilot projects.

The main challenges for the next decade for Argo are first to maintain the global array and ensure its long term sustainability and second to prepare the next phase of Argo with an extension towards biogeochemistry, the polar oceans, the marginal seas and the deep ocean. Given the prominent role of Argo for constraining ocean models, meeting such challenges is essential for the long term sustainability and evolution of global operational oceanography.

Measurement systems for SST and other variables

GODAE recognized the inadequacy of the then (circa 1999) suite of SST products and launched a Pilot Project that would not only meet the requirements of GODAE, but also those of weather prediction and climate. The Group for High Resolution Sea Surface Temperature (GHRSST) (Donlon et al. 2009) was initiated in 2001 and has overseen the introduction of standardised and verified SST products for multiple uses, including ocean analysis and prediction. The basis for this success is the complementary polar orbiting and geostationary satellite radiometers which yield high-resolution infrared and microwave estimates of SST. Complementary data from a wide variety of *in-situ* sources are also used. Products are widely available from a number of sources and have both high-resolution and accuracy; documented bias and error characteristics; meet timeliness and temporal resolution demands; and are dependable and fit for purpose (Donlon et al. 2010).

Information on sea-ice concentration from satellites is also widely used by groups participating in GOV and information on sea-ice thickness, sea-ice drift and sea-ice temperature should be widely used in future.

A number of other systems contribute measurements of temperature, salinity, sea level and currents, among other variables. Argo is now the workhorse for broad-scale temperature and salinity measurements. The tropical moored buoy arrays (McPhaden et al. 2010) provide high-frequency sampling in the rapidly changing tropical waters (T, S and u); the Expendable Bathy-Thermograph (XBT) networks (Goni et al. 2010) provide high-resolution sections to complement the broad-scale Argo network (particularly important for ocean transport calculation); L-band microwave satellite-borne radiometers (Lagerloef et al. 2012; Font et al. 2013) are now, for the first time, providing measurements of surface salinity with of the order of 0.5 psu accuracy for 10 day averages in 50 km squares and are expected to have a positive impact on GOV systems (Le Traon 2015); and the Global Drifter Program (Dohan et al. 2010) provides important surface drift (and temperature) data for validation.

Modelling and computational capacities

Despite the increasing wealth of observations from satellites, floats, moorings and ships, observational coverage is still sparse for vast parts of the deeper ocean, especially on the ubiquitous mesoscale with horizontal scales of the order of 100 km. With the increasing exploitation of the seas, mesoscale prediction of ocean currents and, more recently, their biophysical variability have been key goals of GODAE and now GOV. Using numerical ocean models, national forecasting centres simulate the global and regional ocean circulation from the surface down to the abyss. Ocean models evolve according to physical and dynamical constraints. Using information on the atmospheric surface forcing, the ocean's bathymetry and the recent state of the ocean (obtained from the ocean observations discussed earlier and introduced into the model through data assimilation) they have the ability to produce forecasts. Ocean modelling is an active field and new knowledge from observations and theoretical studies produces a continuous stream of improvements to ocean models which enable more accurate ocean analyses and forecasts.

The first operational models applied to short-term ocean forecasting in the late 1990s and early 2000s had horizontal resolutions typically between 1° and ¼° in global configurations and higher resolutions in regional applications (Dombrowsky et al. 2009). This range of horizontal resolution is insufficient outside the equatorial domain to predict the mesoscale variability accurately. Such problems have been solved with the current generation of operational global ocean forecasting systems at model resolutions of about $1/10°$ or higher (and up to 80 vertical levels or layers). Work is progressing at some centres towards operational implementation of models with 1/25° grids in the next few years.

The practical impact of weather, ocean and climate prediction on the world's population and economy drives the use of high performance computing (HPC), which includes supercomputing and data management, for earth system modelling. The computational and operational requirements for ocean simulations of appropriate spatial and temporal scales are immense and require HPC to provide forecasts and services in practical time frames. Supercomputers have enabled the weather, ocean and climate research and operational communities to produce results in the shortest amount of time possible while investigating and predicting increasingly complex and detailed phenomena like eddies. Nowadays, the world's most powerful supercomputers (many of them are being used in earth system modelling and forecasting) have peak performances of tens of petaflops (10^{15} calculations per second) [http://www.top500.org/lists/].

Data assimilation

GODAE was predicated on the expectation that profiles of temperature and salinity data and altimeter data would provide complementary information and that their assimilation would control the evolution of ocean models, the altimeter data controlling the ocean mesoscale and the profile data controlling the vertical water mass structure on larger horizontal scales. Initial evidence that the altimeter data could be effectively assimilated into models came mainly from idealised experiments using simple models (Hurlburt 1986) statistics on vertical structure (De Mey & Robinson 1987) and ideas on conservation of water mass properties (Cooper & Haines 1996).

The groups within GODAE chose to adopt quite widely differing approaches to data assimilation (Cummings et al. 2009; Martin et al. 2015) (this paragraph only gives references not available in those papers). For example, the core algorithms for estimating the covariances of the errors in the model fields differ widely. The Norwegians pioneered the Ensemble Kalman filter approach, the French pioneered and use a SEEK filter (Pham et al. 1998), the Australians use a static error covariance estimated from an ensemble of integrations and the Italians (Dobricic & Pinardi 2008), Japanese, US Navy and Met Office use 3D variational assimilation schemes with geographically varying covariances calculated from observation minus model (and other) statistics using balance operators. 4D variational methods have also been explored by some of the GOV groups (Stammer et al. 2003; Sugiura et al. 2008). There have also been large differences between the centres in the priorities for assimilation of different observation types, the pre-processing and quality control of the observations, the specification of the time window for the observations, the methods for adding increments into the models, and the methods for assimilation into models with significant biases (whose drifts can be exacerbated by data assimilation particularly near the equator). Whilst each of these systems has had some success in constraining their ocean models, a better understanding of their relative effectiveness is highly desirable as it would greatly assist the improvement of the systems.

User requirements

The main sectors which the teams collaborating in GOV aim to serve are outlined in Table 1. These sectors are not exhaustive. One of the GOV task teams (Kourafolou et al. 2015a,b) is dedicated to the improvement of shelf-sea and coastal prediction systems using the GOV open ocean prediction systems. So a wide range of coastal services such as warnings of coastal flooding and threats to human health could in future benefit from the open ocean predictions. But the sectors in Table 1 are sufficiently broad and distinct for the purposes of this paper and the open ocean predictions are directly relevant to them. Of course in many sectors the ocean predictions are used together with meteorological predictions (e.g. surface winds and waves) to provide services to users but the focus here is on the ocean predictions. Some examples of the use of predictions in these sectors are provided in the next four paragraphs.

The first three sectors in Table 1, marine transport, search and rescue (Davidson et al. 2009), and oil spill prediction (Hackett et al. 2009), all rely on predictions of near surface conditions, in particular the surface currents. Predictions of transit times and advice on route choice support the efficiency of the shipping industry. Information on ocean surface temperatures can also be valuable as they affect the efficiency of the ship engines and the durability of some cargoes. Most search and rescue operations are confined to coastal waters but some operations occur in deeper waters and in these cases information on currents and temperatures is required very rapidly to optimize the search radius. Responses to spills of oil, chemicals, hazardous substances and other ship cargo also require rapid initial predictions of the expected drift and dispersion and more detailed longer period simulations later in the response cycle. Some nations also use surface currents to trace spills resulting from illegal discharges back to individual ships. Again the surface temperatures are relevant and in the case of sub-surface releases (e.g. from well-heads) the sub-surface temperatures and currents are critical.

Table 1. Sectors in which ocean analyses and predictions are used. Columns (a) – (c) show responses from 14 operational systems in 10 countries. (a) The number of systems for which this sector rates as one of their top 3; and the number of systems for which (b) the real-time and (c) the hindcast products are used by each sector.

Sectors	(a) In top 3	(b) Real-time use	(c) Hindcasts used
Marine transport	2	6	3
Search & rescue	3	7	7
Oil spill response	3	8	8
Oil & gas	2	7	6
Naval operations	8	9	8
Environmental protection	1	6	8
Fisheries	2	6	5
Short-range weather prediction	4	7	5
Seasonal prediction	5	7	7

In addition to its impact on the environment the oil and gas industry require information to predict the impact of the environment on their operations so they can adapt them to optimize their safety and efficiency. For example, subsurface current shears can generate severe stresses on risers (the pipes conveying oil from the well to the surface) which affect operations. Naval defence operations have a diverse range of requirements for information (Jacobs et al. 2009) the most well-known being that the temperature variations in ocean mesoscale phenomena have a major impact on sonar propagation.

Ocean prediction systems are now used to generate predictions for the shelf-seas as well as the open ocean. They are also used to produce hindcasts and re-analyses for the last 20–50 years as well as real-time predictions. The re-analyses for the shelf seas have great potential to support important widely held aspirations for a more holistic ecosystem-based approach to the management of the marine environment (European Parliament 2008) and fisheries. Adapting the ocean prediction systems to meet these demands and to exploit the potential of biogeochemical models provides a number of important challenges for the future (Berx et al. 2011). Real-time ocean prediction systems can also help to improve the efficiency of fisheries by giving guidance on the best areas for fisheries (e.g. regions of frontal upwelling).

The final two sectors listed in Table 1 (weather and seasonal prediction) are closely related, the difference between them being the timescale. Short-range weather prediction which covers forecasts a few days ahead, requires good surface temperature fields not least because the development of mid-latitude cyclones is strongly influenced by them. As mentioned earlier, coupled atmosphere-ocean models have been developed for seasonal predictions for many years. There is growing evidence that relatively high ocean model resolution is valuable to improve the skill of the seasonal forecasts (Scaife et al. 2011) and that short-range weather forecasts can also be improved using atmosphere models coupled to sea-ice, wave and ocean models (Goni et al. 2009).

The numbers shown in columns (a)–(c) of Table 1 are based on the results of an informal 'survey' of 14 of the operational centres involved in GOV from 10 countries. Column (a) shows how many of the centres rated each of the services as being one of the 'top three' in importance for them. Services for defence is clearly the top sector as it has been since the start of GODAE. Seasonal forecasting and weather forecasting rank second and third in column (a). This probably reflects the strong involvement of weather agencies in GOV and hence the relative ease with which these applications can be developed. Interest is spread quite broadly across the remaining 6 sectors.

The other columns of Table 1 indicate the number of systems whose real-time forecasts (column b) and long period hindcasts (column c) are used in each sector. On this measure the hindcasts are used as widely as the real-time forecasts and both are used across a wide range of sectors. This does not indicate however that exploitation of the products is mature. Each of the sectors contains a number of segments with different types of users. For example in the oil and gas sector there are a number of key players (such as government regulators and agencies, major oil companies, commercial operators and environmental service suppliers) and environmental support is required throughout the life cycle of production including exploration, production and decommissioning. In most countries surveyed there are 3–4 government departments and 3 government agencies active within each sector and considerable effort is required to make the internal links within government to fully exploit the predictions.

Exploitation of products is also heavily dependent on their fitness for purpose, the information that is provided with them on their expected accuracy, and the robustness and reliability of the service. The data policy for the service and access conditions to the products are also believed to have a significant impact on their take-up in downstream services by small to medium enterprises (SMEs) and by the research sector. Open access to freely available products, free of charge at point of use, with minimal restrictions on their use, has been promoted strongly both by GEO (Group on Earth Observation) and by the European Copernicus programme. From its inception GODAE also strongly supported open exchange of information.

Some sectors, such as the oil and gas industry, have extremely demanding requirements for the accuracy of currents at small spatial scales which continue to challenge the ocean predictions. The nature of the decisions based on weather forecasts has changed dramatically in the last 10 years as the forecasts and confidence in them have improved. A similar revolution in the exploitation of ocean predictions should be one of the aims of GOV for the next decade. Systems to provide ocean environmental services such as the Integrated Marine Observing System (IMOS) in Australia, the Integrated Ocean Observing System (IOOS®) in the United States and the Copernicus marine service in Europe are now being developed to address these challenges.

National and regional capabilities

The aim of this section is to give a broad-brush perspective on the development of ocean prediction capabilities across the continents of the world.

Americas (USA, Canada, Brazil)

The US Navy has been a strong supporter of GODAE and GOV. It led the development of high resolution global models and made the outputs from these models and the observations assimilated into them openly available through web portals, in particular the GODAE server at Monterey, California. It has also forged active collaborations with academia and is supporting the rapidly growing ocean prediction capabilities within NOAA's National Center for Environmental Predictions (NCEP). A number of other groups within the USA, particularly the ECHO consortium and GSFC have also contributed strongly to GODAE and GOV. The IOOS is leading the development of regional prediction systems and active within GOV's Coastal Ocean and Shelf Seas Task Team (COSS-TT).

The CONCEPT consortium of Canadian institutes has developed and implemented a very successful coupled atmosphere-ice-ocean prediction system for the Gulf of St Lawrence and the Great Lakes. Canada has also developed global and regional ocean prediction capabilities in collaboration with Mercator-Ocean. The links with the downstream government agencies such as the Coastguard and the department for fisheries are also very strong.

A specific Brazilian effort on operational oceanography called REMO with focus on short-range ocean forecasting over the tropical Atlantic and the South Atlantic Ocean for the Navy and the oil and gas sector started in 2008 under the Oceanographic Modelling and Observation Network (Marta-Almeida et al. 2011). The first phase of REMO focused on the implementation of a nested operational forecasting system over the Atlantic Ocean. REMO's operational system combines global analysis fields of sea level anomalies (SLA) and sea surface temperature (SST) produced using HYCOM and the Navy Coupled Ocean Data Assimilation system (NCODA) with an Ensemble OI approach to constrain its initial conditions (Lima et al. 2013). Data from Jason-1, Jason-2, Argo, XBTs, CTDs and PIRATA are all used in the data assimilation system currently being developed and for validation.

Europe: (France, UK, Norway and Italy)

Several European nations developed their initial contributions to GODAE in the late 90s (Mercator Ocean in France, FOAM and NCOF in UK, TOPAZ in Norway, MFS in Italy). The MERSEA (Marine EnviRonment and Security for the European Area) project allowed initial steps to be made in the integration of these contributions (Johannessen et al. 2006). This led to the development of the GMES/Copernicus Marine Service which is a major initiative to set up a sustained capability to observe and forecast the global ocean and European regional seas. The Copernicus Marine Service has been implemented through the MyOcean-1&2 projects (Bahurel et al. 2010). *In-situ* and satellite observations are now routinely assimilated in global and regional ocean models to provide in real time or in delayed mode (re-analyses) integrated descriptions and short-term forecasts of the ocean physical and biogeochemical state. These core products serve a wide range of applications and users. Strong links are also developed with EuroGOOS, in particular, to develop the upstream *in-situ* observing system infrastructure and national downstream capabilities (e.g. coastal). The past 5 years have thus seen the development of a well-structured community at European level (covering science, observations, modelling and applications) at global, regional and coastal scales. The successful development and integration of the MyOcean infrastructure, operational service and user base is a major achievement for GOV in Europe.

Eastern Asia (Japan, China and India)

The Meteorological Research Institute (MRI) has led the development of global, regional (western North Pacific) and shelf sea/coast ocean assimilation and forecast systems for Japan (see, for example, Kamachi et al. 2004; Fuji et al. 2008; Usui et al. 2006b; Toyoda et al. 2013). The Japan Meteorological Agency (JMA) provides the operational systems. MRI has been particularly active in the use of 4DVAR systems, including within coupled models (Fujii et al. 2009), and has completed a number of studies looking at the predictability of the Kuroshio (Usui et al. 2006a; Tsujino et al. 2013). The global models typically have horizontal resolution of ½–1° while the regional models are fully eddy resolving (typically 1/10°). The assimilation systems typically use 3DVAR and include sea-ice and there are plans to use 4DVAR in the near future.

Ocean forecasting capability in China and India is expanding rapidly thanks to increased recognition by their governments of the benefits of ocean forecasting. Since 2011, the National Marine Environmental Forecasting Center (NMEFC) [http://english.nmefc.gov.cn/] has developed regional state-of-art ocean forecasting systems and upgraded its global operational forecasting systems. New-generation regional systems, based on ROMS [https://www.myroms.org/] are currently under development for the Northwest Pacific and China coastal seas, respectively. Based on assimilation of altimetry, SST, *in-situ* temperature and salinity, the NMEFC systems provide temperature, salinity and currents as forecast products.

The Indian Ocean Forecast System (INDOFOS [http://www.incois.gov.in/Incois/indofos_main.jsp]) is currently based on ROMS and GODAS (Ravichandran et al. 2013) and uses atmospheric forcing data from the operational atmospheric prediction system of the National Centre for Medium Range Weather Forecast (NCMRWF) in New Delhi. An integrated Indian Ocean forecast system, which consists of a very high resolution configuration of ROMS (1/32°) for coastal waters, a high resolution configuration of HYCOM (1/12°) [http://hycom.org/] for the Indian Ocean region and a coarse resolution configuration of MOM4 [http://www.gfdl.noaa. gov/mom-ocean-model] is under development. In addition to web-based dissemination of forecasts, these are also provided to the targeted users by using electronic display boards installed in the fishing harbours and village information centres. Some users, such as maritime boards, port and harbour authorities and shipping agencies, receive tailored forecast products by emails.

Australasia

Established in 2002, Bluelink is a partnership between the Bureau of Meteorology, CSIRO, and the Royal Australian Navy. The key developments of Bluelink have been the development of the Bluelink ocean model called the Ocean Forecasting Australia Model (OFAM) (Oke et al. 2013a) and the Bluelink Ocean Data Assimilation System

(BODAS) (Oke et al. 2013b), a system based on Ensemble Optimal Interpolation. Operational eddy-permitting ocean forecasts of the three-dimensional ocean circulation have been produced using an operational system called Ocean-MAPS (Ocean Model, Analysis and Prediction System) (Brassington et al. 2007) since 2007. Bluelink has also delivered a series of multi-year ocean reanalyses – called Bluelink ReANalyses (BRAN) – that has provided a test-bed for OceanMAPS and data sets for research and commercial applications (Schiller et al. 2008). Other activities under Bluelink include the development of the Australian Coupled Ocean Model (AusCOM), and several regional modeling systems including the Relocatable Ocean Atmosphere Model (ROAM) and the Coupled Limited Area Model (CLAM) [http://wp.csiro.au/bluelink/].

International coordination

The aim of GOV is to accelerate the development of operational ocean forecasting. Most of the development is of course done within individual institutions so one of the challenges for GOV is to identify the activities where international coordination is required or can add significant value. This section describes activities where GODAE and GOV have provided tangible added value.

Intercomparisons of the accuracies of predictions of core variables (e.g. surface temperatures) are routinely carried out within the weather and surface wave forecasting communities. Clearly these intercomparisons have to be coordinated at the international level. The GOV task team for intercomparison and validation (ICV-TT) has developed protocols for controlled comparison of model predictions against carefully selected sets of observations which enable statistics of the differences between observations and predictions from a number of operational centres to be regularly calculated and rigorously intercompared. Two papers in this edition describe recently obtained results (Ryan et al. 2015; Divakaran et al. 2015). Results from similarly careful intercomparisons of long period hindcasts (assimilating data) carried out by the observing system experiment task team (OSE-TT) jointly with the CLIVAR Global Synthesis and Observations Panel (GSOP) are presented in a third paper (Balmaseda et al. 2015).

Experiments to assess the impact of various components of the observing system on analyses and predictions similarly have the potential to be vitally important but the results from studies using individual prediction systems depend on the system used and their interpretation can be controversial. Successful international coordination of experiments and consensus on interpretation would transform the value that can be extracted from such experiments. The aim of the OSE-TT is to produce coordinated and timely assessments of the impact of observing systems on the GOV forecasting systems and to communicate the results so that they are used to inform the maintenance and adaptation of the observing system. Very good progress has been made in this direction using global (Oke et al. 2015a) and regional (Oke et al. 2015b) prediction systems in the last five years and there is great potential for further progress.

GODAE and GOV have also sought to bring together new international communities where they have significant potential to improve ocean predictions. The GHRSST group started as a pilot project within GODAE and has had great success in coordinating the processing of satellite SST data (Donlon et al. 2009). The COSS-TT (Kourafolou et al. 2015a; Kourafolou et al. 2015b) is similarly forming a vibrant new community of teams developing prediction systems for shallow water. Coupled atmosphere-ice-wave-ocean prediction systems are now being developed in several countries. Jointly with the World Meteorological Organisation (WMO) Working Group on Numerical Experimentation (WGNE) GOV has formed a Short-Range Coupled Prediction task team (SRCP-TT) to provide a forum for exchange of information on new results and to coordinate planning of activities and comparison of results.

GODAE and GOV have also worked closely with and complemented other international programmes for ocean monitoring and prediction. As mentioned previously the Argo project was started as a pilot project of GODAE and CLIVAR. GOV also works closely with and seeks to complement the Expert Team for Operational Ocean Prediction Systems (ET-OOFS) within JCOMM (the Joint WMO and IOC Technical Commission for Oceanography and Marine Meteorology). GOV coordinates leading edge ocean predictions whilst ET-OOFS translates the research progress into standards and practices for ocean prediction services. GOV also coordinates with and seeks to complement the activities within the Global Ocean Observing System (GOOS) Regional Alliances, the Committee on Earth Observation Satellites (CEOS) and the Blue Planet initiative within GEO.

GODAE and GOV have also helped to develop the next generation of R&D professionals in operational oceanography by organizing summer schools for students accompanied by books containing the lectures (Chassignet & Verron 2006; Schiller & Brassington 2011). Three GODAE and GOV symposia have also been converted into conference proceedings (Smith & Le Traon 2002) or journal special issues (Bell et al. 2009) which provide a legacy of reviews of progress and the state of the art in operational oceanography.

GODAE and GOV have not attempted to coordinate funding for large-scale projects. GODAE did however act as a catalyst for developing consortia and funding within continents. GODAE helped to generate the confidence in the future of operational oceanography that led to the Blue-Link project in Australia and the National Ocean

Partnership Program (NOPP) funding for long-term collaboration between the US Navy, NOAA and academia within the USA. Within Europe teams collaborating in GODAE provided the foundation of the MERSEA and MyOcean consortia which have used European Commission funding to develop a marine monitoring and prediction service for Europe.

Finally, perhaps less tangible but certainly important, the GOV and GODAE Science Team and Task Team meetings have given the experts in their field excellent opportunities to share expertise and plans. Friendly competition between teams has spurred invention and ambition.

Preparing for the next phase

Fifteen years after the start of GODAE and five years after the start of GOV, a formal review of GOV was held in November 2013, immediately following the first GOV symposium. The purpose of the review was to assess the effectiveness of GOV and to make recommendations on how to improve its performance. The review team found that 'GOV has demonstrated great success in continuing the direction defined by GODAE, and in meeting critical objectives'. Its main recommendation is 'the formal development and confirmation of a strategic plan (with 5 and 10 year horizons) defining, with clear priorities, the expected outcomes, the expected investments and 'returns' as reflected in robust metrics.' It also recommended that 'the principles for prioritization in the strategic plan should include:

- Actions and efforts that must be done collectively, or
- Actions and efforts that can be done more effectively on a collective basis
- Clear implications for major practical applications
- Representative of the intersection of community scientific interest and patrons' expectations or requirements
- Aligned with patrons' core interests and priorities.'

These recommendations have been accepted and a Strategic Plan is being written with a short central section (around 10 pages) describing the vision and primary priorities of GOV drawing on recent discussions of future scientific priorities. This section will be complemented by specific short-term plans describing proposed activities with expected outcomes and the resources they will require which will be agreed on an annual basis by the GOVST and endorsed by the Patrons group. Clearly the activities in these plans should focus on activities such as those described in the previous section which align well with the principles for prioritization articulated by the review team.

References

Bahurel P, Adragna F, Bell MJ, Jacq F, Johannessen JA, Le Traon P-Y, Pinardi N, She J. 2010. Ocean Monitoring and Forecasting Core Services, the European MyOcean Example. In Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society (Vol. 1), Venice, Italy, 21–25 September 2009, Eds Hall J, Harrison DE, Stammer D. ESA Publication WPP-306, doi:10.5270/OceanObs09.pp.0.

Balmaseda M, Storto A, Palmer M, Valdivieso M, Haines K, Smith G, Shi L, Hernandez F, Toyoda T. 2015. Intercomparing ocean estimates during the last decades: New approaches & results in the framework of the joint CLIVAR/ GSOP - GOV effort. J Oper Oceanogr. forthcoming.

Bell MJ, Lefebvre M, le Traon P-Y, Smith N, Wilmer-Becker K. 2009. GODAE: The Global Ocean Data Assimilation Experiment. Oceanography 22: 14–21.

Berx B, Dickey-Collas M, Skogen MD, de Roeck YH, Klein H, Barciela R, Forster RM, Dombrowsky E, Huret M, Payne M, et al. 2011. Does Operational Oceanography Address the Needs of Fisheries and Applied Environmental Scientists? Oceanography 24 (1): 166–171.

Brassington GB, Pugh TF, Spillman C, Schulz E, Beggs H, Schiller A, Oke PR. 2007. BLUElink development of operational oceanography and servicing in Australia. J Res Pract Inf Technol. 39: 151–164.

Chassignet EP, Verron J. 2006. Ocean Weather Forecasting: An Integrated View of Oceanography, New York, Springer, 577 pp.

Cooper M, Haines K. 1996. Altimetric assimilation with water property conservation. J Geophy Res. 101, C1: 1059–1077.

Cummings J, Bertino L, Brasseur P, Fukumori I, Kamachi M, Martin MJ, Mogensen K, Oke P, Testut CE, Verron J, Weaver A. 2009. Ocean data assimilation systems for GODAE. Oceanography 22: 96–109.

Davidson FJM, Allen A, Brassington G, Breivik, Breivik Ø, Daniel P, Kamachi M, Sato S, King B, Lefevre F, Sutton M, Kaneko H. 2009. Applications of GODAE ocean current forecasts to search and rescue and ship routing. Oceanography 22: 176–181.

De Mey P, Robinson AR. 1987. Assimilation of altimeter eddy fields in a limited-area quasi-geostrophic model. J Phys Oceanogr. 17: 2280–2293.

Derber J, Rosati A. 1989. A Global Oceanic Data Assimilation System. J Phys Oceanogr. 19: 1333–1347.

Divakaran P, Brassignton GB, Ryan AG, Regnier C, Spindler T, Mehra A, Hernandez F, Smith CG, Liu Y, Davidson F. 2015. GODAE OceanView Inter-comparison for the Australian Region. J Oper Oceanogr. doi:10.1080/1755876X.2015.1022333.

Dobricic S, Pinardi N. 2008. An oceanographic three dimensional variational data assimilation scheme. Ocean Model. 22: 89–105.

Dohan K, and co-authors. 2010. Measuring the Global Ocean Surface Circulation with Satellite and In Situ Observations. In Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society (Vol. 2), Venice, Italy, 21-25 September 2009, Hall J, Harrison DE, Stammer D, Eds., ESA Publication WPP-306, doi:10.5270/OceanObs09.cwp.23.

Dombrowsky E, Bertino L, Brassington GB, Chassignet EP, Davidson F, Hurlburt HE, Kamachi M, Lee T, Martin MJ, Mei S, Tonani M. 2009. GODAE systems in operation. Oceanography 22: 80–95.

Donlon CJ, Casey KS, Gentemann C, LeBorgne P, Robinson IS, Reynolds RW, Merchant C, Llewellyn-Jones D, Minnett PJ, Piolle JF, et al. 2010. Successes and challenges for the modern sea surface temperature observing system: The Group for High Resolution Sea Surface Temperature (GHRSST) Development and Implementation Plan (GDIP). Community white paper for OceanObs09, Venice, Italy, 21-25 September, 2009.

Donlon CJ, Casey KS, Robinson IS, Gentemann CL, Reynolds RW, Barton I, Arino O, Stark J, Rayner N, LeBorgne P, et al. 2009. The GODAE high-resolution sea surface temperature pilot project. Oceanography 22: 34–45.

European Parliament. 2008. Directive 2008/56/EC and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive). [http://eur-lex. europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0056].

Font J, Boutin J, Reul N, Spurgeon P, Ballabrera-Poy J, Chuprin A, Gabarro C, Gourrion J, Guimbard S, Henocq C, et al. 2013. SMOS first data analysis for sea surface salinity determination. Inte J. Remote Sens. 34 (9–10): 3654–3670.

Freeland HJ, Roemmich D, Garzoli SL, Le Traon P-Y, Ravichandran M, Riser S, Thierry V, Wijffels S, Belbeoch M, Gould J, et al. 2009. Argo - A Decade of Progress, Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society (Vol. 2), Venice, Italy, 21-25 September 2009, Hall J, Harrison DE, Stammer D (Eds.,), ESA Publication WPP-306, 2010.

Fujii Y, Nakaegawa T, Matsumoto S, Yasuda T, Yamanaka G, Kamachi M. 2009. Coupled climate simulation by constraining ocean fields in a coupled model with ocean data. J Clim. 22(20): 5541–5557.

Fujii Y, Tsujino H, Usui N, Nakano H, Kamachi M. 2008. Application of singular vector analysis to the Kuroshio large meander. J Geophys Res. 113: C07026. doi:10.1029/2007JC004476.

Goni G, and co-authors. 2010. The Ship of Opportunity Program in Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society (Vol. 2), Venice, Italy, 21-25 September 2009, Hall J, Harrison DE, Stammer D. Eds., ESA Publication WPP-306, doi:10.5270/OceanObs09.cwp.35.

Goni G, DeMaria M, Knaff J, Sampson C, Ginis I, Bringas F, Mavume A, Lauer C, Lin I-I, Ali MM, et al. 2009. Applications of satellite-derived ocean measurements to tropical cyclone intensity forecasting. Oceanography 22: 190–197.

GOVST (GODAE OceanView Science Team). 2012. The GODAE OceanView Work Plan version 8, Met Office, Exeter, 120 pp. [https://www.godae-oceanview.org/documents/q/category/general-documents/].

Griffies S. 2011. Preface to the Ocean Modelling special issue on ocean eddies. Ocean Model. 39: 1.

Hackett B, Comerma E, Daniel P, Ichikawa H. 2009. Marine oil pollution prediction. Oceanography 22: 168–175.

Hurlburt HE. 1984. The potential for ocean prediction and the role of altimeter data. Mar Geod. 8: 17–66.

Hurlburt HE. 1986. Dynamic transfer of simulated altimeter data into subsurface information by a numerical ocean model. J Geophys Res. 91(C2): 2372–2400.

IGST (International GODAE Steering Team). 2000. The Global Ocean Data Assimilation Experiment Strategic Plan. Bureau of Meteorology, Melbourne 26 pp.

Jacobs GA, Woodham R, Jourdain D, Braithwaite J. 2009. GODAE applications useful to Naves throughout the world. Oceanography 22: 182–189.

Johannessen JA, Le Traon P-Y, Robinson I, Nittis K, Bell MJ, Pinardi N, Bahurel P. 2006. Marine Environment and Security for the European Area. Bull. Am. Meteorol Soc. 1081–1090.

Kamachi M, Kuragano T, Sugimoto S, Yoshita K, Sakurai T, Nakano T, Usui N, Uboldi F. 2004. Short-range prediction experiments with operational data assimilation system for the Kuroshio south of Japan. J Oceanogr. 60: 269–282.

Kourafolou VK, De Mey P, Charria G, He R, Herzfeld M, Le Hénaff M, Pasqual A, Stanev E, Tintore J, Usui N, et al. 2015a. Coastal Ocean Forecasting: System integration and evaluation. J Oper Oceanogr. doi:10.1080/1755876X.2015.1022336.

Kourafolou VK, De Mey P, Staneva J, Ayoub N, Barth A, Chao Y, Cirano M, Edwards J, Herzfeld M, Kurapov A, et al. 2015b. Coastal Ocean Forecasting: Science drivers and user benefits. J Oper Oceanogr. forthcoming.

Lagerloef G, Wentz F, Yueh S, Kao H-Y, Johnson GC, Lyman JM. 2012. Aquarius satellite mission provides new, detailed view of sea surface salinity. State of the Climate in 2011. Bull Am Meteroro Soc. 93(7): S70–71.

Le Traon P-Y, Bonekamp H, Santoleri R, DiGiacomo P, Corlett G, Maturi E, Miller L, Mingsen L, Lindstrom E, Faugère Y, et al. 2015. Status & future of the remote sensing ocean observing system. J Oper Oceanogr. forthcoming.

Le Traon P-Y. 2013. From satellite altimetry to Argo and operational oceanography: Three revolutions in oceanography. Ocean Sci. 9(5): 901–915. http://dx.doi.org/10.5194/os-9-901-2013.

Lima JA, Martins RP, Tanajura CAS, Paiva AM, Cirano M, Campos EJD, Soares ID, França GB, Obino RS, Alvarenga JBR. 2013. Design and implementation of the Oceanographic Modeling and Observation Network (REMO) for operational oceanography and ocean forecasting. Rev. Bras. Geofis. 31: 209–228.

Marta-Almeida M, Pereira J, Cirano M. 2011. Development of a pilot Brazilian regional operational ocean forecast system, REMO-OOF. J Oper Oceanogr. 4: 3–15.

Martin MJ, Balmaseda M, Bertino L, Brasseur P, Brassington G, Cummings J, Fujii Y, Lea DJ, Lellouche J-M, Mogensen K, et al. 2015. Status and future of data assimilation in operational oceanography. J Oper Oceanogr. doi:10.1080/1755876X.2015.1022055.

McPhaden MJ, Ando K, Bourlès B, Freitag HP, Lumpkin R, Masumoto Y, Murty VSN, Nobre P, Ravichandran M, Vialard J, et al. 2010. The Global Tropical Moored Buoy Array. In Proceedings of the OceanObs'09: Sustained Ocean Observations and Information for Society Conference (Annex), Venice, Italy, 21-25 September 2009, Hall J, Harrison DE, Stammer D, Eds., ESA Publication WPP-306, 2010.

Oke P, Larnicol G, Fujii Y, Smith GC, Lea DJ, Mourre B, Guinehut S, Remy E, Balmaseda MA, Martin MJ, et al. 2015a. Assessing the impact of observations on ocean forecasts and reanalyses: Part 1: Global studies. J Oper Oceanogr. doi:10.1080/1755876X.2015.1022067.

Oke P, Larnicol G, Jones EM, Kourafalou V, Sperrevik AK, Carse F, Tanajura CAS, Halliwell GR, Le Hénaff M, Atlas R, et al. 2015b. Assessing the impact of observations on ocean forecasts and reanalyses: Part 2: Regional applications. J Oper Oceanogr. doi:10.1080/1755876X.2015.1022080.

Oke PR, Balmaseda MA, Benkiran M, Cummings JA, Dombrowsky E, Fujii Y, Guinehut S, Larnicol G, le Traon P-Y, Martin MJ. 2009. Observing system evaluations using GODAE systems. Oceanography 22: 144–153.

Oke PR, Sakov P, Cahill ML, Dunn JR, Fiedler R, Griffin DA, Mansbridge JV, Ridgway KR, Schiller A. 2013b. Towards a dynamically balanced eddy-resolving ocean reanalysis: BRAN3. Ocean Model. 67: 52–70.

Oke PR, Griffin DA, Schiller A, Matear RJ, Fiedler R, Mansbridge JV, Lenton A, Cahill M, Chamberlain MA, Ridgway K. 2013a. Evaluation of a near-global eddy resolving ocean model. Geosci Model Dev. 6: 591–615.

Pham DT, Verron J, Roubaud MC. 1998. A singular evolutive extended Kalman filter for data assimilation in oceanography. J Mar Syst. 16: 323–340.

Ravichandran M, Behringer D, Sivareddy S, Girishkumar MS, Chacko N, Harikumar R. 2013. Evaluation of the Global Ocean Data Assimilation System at INCOIS: The Tropical Indian Ocean. Ocean Model. 69: 123–135.

Roemmich D, and the Argo Science Team. 1999. On the design and implementation of Argo: An initial plan for a global array of profiling floats. International CLIVAR Project Office Report, 21, GODAE Report 5, GODAE International Project Office, Melbourne, Australia, 32 pp.

Ryan A, Regnier C, Divakaran P, Spindler T, Mehra A, Smith GC, Davidson F, Liu Y, Hernandez F. 2015. GODAE OceanView Class 4 forecast verification framework: Global ocean intercomparison. J Oper Oceanogr. doi:10.1080/1755876X.2015.1022330.

Scaife AA, Copsey D, Gordon C, Harris C, Hinton TJ, Keeley SPE, O'Neill A, Roberts MJ, Williams KD. 2011. Improved Atlantic Winter Blocking in a Climate Model. Geophys Res Lett. 38. doi:10.1029/2011GL049573.

Schiller A, Brassington GB. 2011. Operational Oceanography in the 21st century. Springer, Dordrecht, 745 pp.

Schiller A, Oke PR, Brassington GB, Entel M, Fiedler R, Griffin DA, Mansbridge JV. 2008. Eddy-resolving ocean circulation in the Asian-Australian region inferred from an ocean reanalysis effort. Prog Oceanogr. 76: 334–365.

Smith N, Lefebvre M. 1997. The Global Ocean Data Assimilation Experiment (GODAE)Monitoring the Ocean in the 2000s: An Integrated Approach, October 15–17, 1997; Biarritz, France.

Smith NR, Le Traon P-Y. 2002. En route to GODAE. International Symposium Proceedings. CNES, Paris 372 pp.

Stammer D, Wunsch C, Giering R, Eckert C, Heimbach P, Marotzke J, Adcroft A, Hill CN, Marshall J. 2003. Volume, heat and freshwater transports of the global ocean circulation 1993–2000, estimated from a general circulation model constrained by World Ocean Circulation Experiment (WOCE) data. J Geophys Res. 108(C1): 3007, doi:10.1029/2001JC001115.

Sugiura N, Awaji T, Masuda S, Mochizuki T, Toyoda T, Miyama T, Igarashi H, Ishikawa Y. 2008. Development of a four-dimensional variational coupled data assimilation system for enhanced analysis and prediction of seasonal to interannual climate variations. J Geophys Res. 113: C10017. doi:10.1029/2008JC004741.

Thompson JD, Hurlburt HE, Kindle JC. 1986. Numerical modelling and assimilation of altimeter data in the Gulf Stream system. NORDA Technical Reviews (1976-1986), 99–111.

Toyoda T, Fujii Y, Yasuda T, Usui N, Iwao T, Kuragano T, Kamachi M. 2013. Improved Analysis of the Seasonal- Interannual Fields by a Global Ocean Data Assimilation System. Theoretical and Applied Mechanics Japan 61: 31–48.

Tsujino H, Nishikawa S, Sakamoto K, Usui N, Nakano H, Yamanaka G. 2013. Effects of large scale wind on Kuroshio path south of Japan in a 60-year historical OGCM simulation. Clim Dyn. 41: 2287–2318. doi:10.1007/s00382-012-1641-4.

Usui N, Ishizaki S, Fujii Y, Tsujino H, Yasuda T, Kamachi M. 2006a. Meteorological Research Institute multivariate ocean variational estimation (MOVE) system: Some early results. Adv Space Res. 37: 806–822. doi:10.1016/j.asr.2005.09.022.

Usui N, Tsujino H, Fujii Y, Kamachi M. 2006b. Short-range prediction experiments of the Kuroshio path variabilities south of Japan. Ocean Dyn. 56: 607–623.