CHAPTER 1

An Overview of Operational Oceanography

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Operational oceanography is like weather forecasting for the ocean, it provides estimates of ocean variables (temperature, currents, surface height, etc.) for the past, present, and future. There is a systematic focus on sustained operational ocean observing systems, estimates of the current state, short-range predictions and ocean reanalyses. Operational oceanography systems provide routine and fully supported production and delivery of oceanographic information at pre-determined and agreed upon service levels. Nowadays, many operational oceanography systems cover global-to-coastal marine environments, and physical and biogeochemical properties, with active research underway to eventually include ecosystems. Operational oceanography involves and benefits marine industries, service providers, government agencies, and research and development (R&D) providers.

Introduction

This chapter provides a high-level overview of the key elements of state-of-the-art operational oceanography systems, including observing systems, modelling, data assimilation, service delivery, applications and benefits derived from operational oceanography. The efforts of the international GODAE OceanView team are being described, which targets consolidation and improvement of global and regional ocean analysis and forecasting systems as well as assessment of contributions to the global ocean observing systems and scientific guidance for its improvement. The chapter concludes with a discussion of current and future research challenges in operational oceanography that aim to increase forecast skill and support Earth system modelling efforts.

What Is Operational Oceanography?

There is no widely accepted, unambiguous definition of “operational oceanography.” The European component of the Global Ocean Observing System provides the following working definition: *Operational oceanography* can be defined as the activity of systematic and long-term routine measurements of the seas and oceans and atmosphere, and their rapid interpretation and dissemination. Ocean forecasting as part of operational oceanography is based on the near real-time

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collection of ocean observations and proceeds by the rapid transmission of observational data to data processing centres, which conduct quality controls and provide the data to forecasting centres. There, powerful computers using numerical ocean forecasting models assimilate the observations into the models to improve and create initial conditions for ocean forecasts, with forecasts typically up to 10 days in advance. Data analysis and ocean forecasting centres are operating at a routine, fully supported production and delivery level of services to user-defined levels. At present, ocean forecasting centres cover global-to-coastal marine environments, and physical and biogeochemical properties. Ecosystems analysis and forecasting are active areas of research.

Outputs from the models are used to generate data products, often through intermediary, value-adding service providers. Examples of final products include optimised shipping routes, coastal flood warnings, and forecasts of harmful algae blooms. Because ocean conditions are constantly changing over time, the final forecasts and products must be distributed rapidly to marine industry, governments, regulatory authorities and the public.

A Brief History of Operational Oceanography

This subsection provides a brief introduction to the history of operational oceanography with a focus on elements that laid the scientific foundation of ocean forecasting, i.e., ocean observations, ocean general circulation models, and data assimilation tools. It then describes the scientific achievements of the first phase of internationally coordinated efforts in the development of global- and basin-scale operational ocean forecasting systems during the Global Ocean Data Assimilation Experiment (GODAE) from 1997–2008.

Three key developments took place in the 1980s and 1990s that had a profound impact on the development of operational oceanography. First, there was the launch of Earth observation satellites designed to observe the oceans and its mesoscale structures. Second, "supercomputers" surpassed a threshold of availability and capability in providing simulations of the ocean general circulation at basin and global scales. Third, adopting advances being made in meteorology enabled oceanographers to leapfrog developments in ocean data assimilation. All three of these (observations, modelling, and data assimilation) are key elements of today's ocean forecasting systems.

Before satellites became more commonly available in the 1980s, oceanographers were "data poor." However, since then, significant technological and scientific advances in satellite remote sensing have made it possible to obtain near real-time measurements of sea surface height anomalies, sea surface temperature (SST), and ocean colour. These key observations have, for the first time, enabled ocean forecasting applications (Fu and Cazenave, 2001). The realisation of a network of 3,000 Argo profiling floats freely reporting temperature and salinity profiles to 2,000 m depth in a timely fashion has transformed the in situ ocean measurement network in the new millennium. This enables oceanographers to continuously monitor the temperature, salinity, and velocity of the upper ocean, with all data being relayed and made publicly available within hours after collection.

The advent of "supercomputers" in the 1970s and 1980s provided researchers with a new capability to describe the ocean within a mathematical framework and allowed the development of the first basin- and global-scale numerical ocean circulation models. Since that time, there has been increased emphasis on the application of computers in oceanography to allow numerical simulations and predictions of the state of the ocean. Based on significant advances in supercomputing technologies, the 1990s saw the emergence of the first large-scale, eddy-resolving models (Semtner and Chervin, 1992) and the first ocean-atmosphere coupled climate change projections (see e.g., IPCC First Assessment Report, 1990).

Over the last 20 years, the global ocean observing system (in situ and remote sensing) has been progressively implemented and led to a revolution in the amount of data available for research and forecasting applications. The ocean observing system, primarily designed to serve climate research, is the backbone for most operational oceanography applications. Although significant progress has been made, sustaining the global ocean observing system remains a challenging task (Clark et al., 2009). This recent progress in the global ocean observing system was complemented by advances in supercomputing technology, allowing for the development and operational implementation of eddy-resolving (~10 km), basin-scale ocean circulation models.

GODAE was established in 1997 with the two primary goals: (i) to demonstrate the feasibility and utility of global ocean monitoring and forecasting on the daily-to-weekly timescale and on eddy-resolving spatial scales, and (ii) to assist in building the infrastructure for global operational oceanography (Smith and Lefebvre, 1997; GODAE Strategic Plan, 2000; Bell et al., 2009). GODAE has had a major impact on the development of global operational oceanography capability. Global modelling and data assimilation systems have been progressively developed, implemented, and inter-compared (Dombrowsky et al., 2009; Cummings et al., 2009; Hernandez et al., 2009). There has been increased attention to the development of products and services and the demonstration of their utility for applications such as marine environment monitoring, weather forecasting, seasonal and climate prediction, ocean research, maritime safety and pollution forecasting, coastal and shelf-sea forecasting, national security, as well as forecasting for the oil and gas industry and fisheries management (Davidson et al., 2009; Hackett et al., 2009; Jacobs et al., 2009). GODAE as an experiment ended in 2008 having achieved most of its goals. It has been demonstrated that global ocean data assimilation is feasible and GODAE made important contributions to the establishment of an effective and efficient infrastructure for global operational oceanography that includes the required observing systems, data assembly and processing centres, modelling and data assimilation centres, and data and product servers.

Components of Operational Oceanography

Overview of Components of Operational Oceanography Systems

Operational Oceanography is comprised of five key components. Fig. 1.1 captures the main functional components required by any state-of-the-art ocean forecasting system. It also illustrates many of the interactions required to ensure or enhance the quality of the ocean forecasting systems and their outputs. These are: the observation networks, data management and monitoring, prediction and assessment, service delivery and dissemination, and uptake of products by end users/clients (and their feedback about fit-for-purpose products to the operational centres). The rest of this chapter is structured in line with these components.

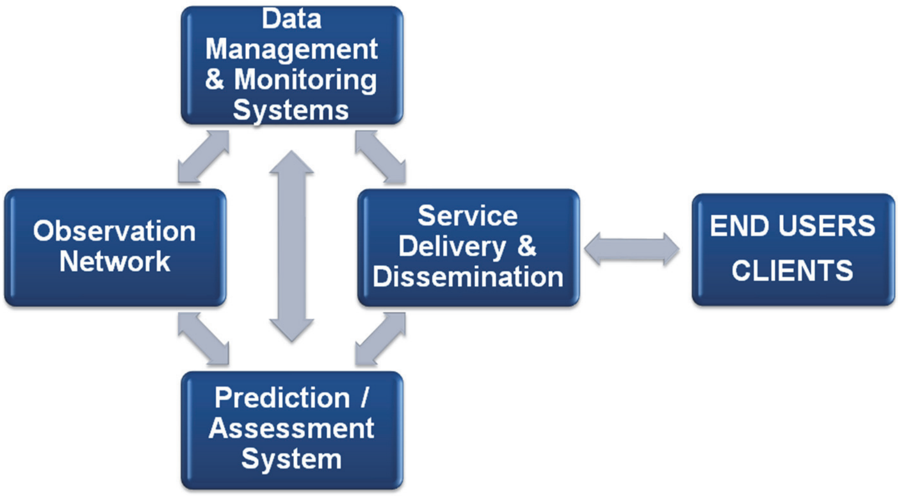

Figure 1.1. Operational oceanography components.

Our ability to monitor and predict the evolution of 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 five key technologies:

1) satellite altimeters, which measure the ocean's sea level at the mesoscale;
2) surface forcing fields such as heat and freshwater fluxes plus remotely sensed and in situ SST;
3) the Argo system of profiling floats, which measures temperature and salinity profiles within the ocean (but does not resolve the ocean mesoscale); and
4) high-resolution ocean models that resolve the ocean's mesoscale motions and data assimilation capabilities that combine the measurements from the above three technologies plus other ocean monitoring platforms with model predictions to provide accurate initial conditions for future predictions.

Observations

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. Consequently, sea level provides a strong constraint for inferring the four-dimensional (4-D) ocean circulation through data assimilation. This explains the unique and fundamental role of satellite altimetry in data assimilation and operational oceanography. The quality of mesoscale predictions in ocean analysis and forecasting models is heavily reliant on the availability of altimeter data from multiple satellites. It is commonly agreed that real-time analysis and forecasting of mesoscale circulation requires at least three or preferably four altimeters to be flown simultaneously in appropriately selected orbital configurations (Le Traon, 2013). A very precise long-term altimeter system (e.g., Jason series) is also needed as a reference for the other missions (particularly for climate monitoring). Jason-2, CryoSat-2, HY-2A, and SARAL/AltiKa altimetry missions are the result of a period of intense cooperation between the space agencies (NASA, NOAA, ESA, CNES, EUMETSAT, CNSA, and 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 this writing, there are uncertainties about the launch dates and funding of some of these missions, it is hoped that the altimeter constellation will be satisfactory (although not ideal) in the coming years. For example, the Sentinel 3A mission was launched in 2016 and sea level anomaly observations are already available and assimilated in several operational forecasting systems. It is also hoped that by 2020 the new Surface Water Ocean Topography (SWOT) concept will have been demonstrated, providing 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 1990s 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, 1990-2002), proposals were made to develop a global array of profiling floats taking 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 (Climate and Ocean: Variability, Predictability and Change). Argo has been an outstanding achievement, and in November 2007 it reached its initial target of 3,000 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 ocean forecasting 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 must 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 needs 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 could be quantified through Observing System Simulation Experiments (OSSEs) and tested as part of Argo extension pilot projects. The main challenges for Argo over the next decade will be 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 in constraining ocean models, meeting such challenges is essential for the long-term sustainability and evolution of global operational oceanography.

Measurements of SST and other variables

GODAE recognized the inadequacy of the suite of SST products in the late 1990s and launched a pilot project that would not only meet the requirements of GODAE, but also those of weather prediction and climate centres. 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 GODAE-sponsored project has resulted in a coordinated network of centres disseminating SST data in real time in a common format to agreed standards from a wide range of microwave and infrared instruments on polar orbiting and geostationary satellites. 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). There is also a wide usage of information on sea-ice concentration from satellites by groups participating in GODAE OceanView (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 (temperature, salinity, velocity); 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 ocean forecasting systems (Le Traon et al., 2015). Although the current accuracy of remotely sensed salinity limits its impact on the skill of ocean forecasting systems, it is expected to increase in the coming years with the launch of new sensors. The Global Drifter Program (Dohan et al., 2010) provides important surface drift (and temperature) data for validation. Further information about future plans regarding SST remote sensing can be found in Le Traon et al. (2015); future developments of all components of the global observing system are described elsewhere in this book.

Data Management and Monitoring Systems

Measurement network and data assembly and processing centres provide the main inputs to assimilation centres. This includes the in situ and satellite components of the current global observing system.

Near real-time quality control of observational data and the joint use of in situ and satellite data are key elements of any operational ocean forecasting system, as indicated by the product servers. Product servers also provide the underpinning concepts and technologies that enable the observed data to be discovered, visualised, downloaded, intercompared, and analysed all over the world.

Prediction and Assessment Systems

Models

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 growing exploitation of the seas, mesoscale prediction of ocean currents and, more recently, their biophysical variability have been key goals of the ocean forecasting community. 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. They have the ability to produce forecasts using information on the atmospheric surface forcing, the ocean's bathymetry, and the recent state of the ocean obtained from ocean observations and introduced into the model through data assimilation. Ocean modelling is an active field and new knowledge stemming from observations and theoretical studies produces a continuous stream of improvements to ocean models, which leads to more accurate ocean analyses and forecasts.

The first operational models applied to short-term ocean forecasting in the late 1990s and early 2000s typically had horizontal resolutions 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 global models with at least 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 timeframes. 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, such as 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/].

In general, nearly all basin- and global-scale ocean models use forms of the primitive equations, whereas the first systems developed in the 1990s were based on quasi-geostrophic approach. These equations relate the variables of velocity, temperature, and salinity, and their evolution over space and time. The primitive equations are a set of nonlinear differential equations that are used to approximate the ocean circulation (and atmospheric flow in atmospheric models). They consist of three main sets of balance equations:

- A *continuity equation*: Representing the conservation of mass.
- *Conservation of momentum*: Consisting of a form of the Navier–Stokes equations that describe hydrodynamical flow on the surface of a sphere under the assumption that vertical acceleration is much smaller than horizontal acceleration (hydrostatic) and that the fluid layer depth is small compared to the radius of the sphere.
- A *thermal energy equation*: Relating the overall temperature of the system to heat sources and sinks. As similar equation applies to salt in the ocean (absolute salinity).

Further details about ocean circulation modelling can be found in, e.g., Haidvogel and Beckmann (1999) and Griffies (2004).

Data assimilation

GODAE was predicated on the expectation that profiles of temperature and salinity data, as well as 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 widely differing approaches to data assimilation (Cummings et al., 2009; Martin et al., 2015). For example, the core algorithms for estimating the covariances of the errors in the model fields differ a great deal, including the Ensemble Kalman filter approach, the SEEK filter (Pham et al., 1998), the static error covariance estimated from an ensemble of integrations, and the use of 3-D variational assimilation schemes with geographically varying covariances calculated from observation minus model (and other) statistics using balance operators (Dobricic and Pinardi, 2008). Four-dimensional variational methods have also been explored (Stammer et al., 2003; Sugiura et al., 2008). There have also been large differences between the centres in terms of prioritizing 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). While each of these systems has had some success in constraining their ocean models, a better understanding of their relative effectiveness is very desirable as it would assist in the improvement of the systems.

Examples of prediction and assessment of forecasting systems

Forecasting centres comprise modelling and assimilation components and cover coastal and/or basin-scale ocean forecasting. Most centres now operate systems with 1/10° or finer horizontal grid spacing in global models; make use of community ocean models like HYCOM (Bleck, 2002, Chassignet et al., 2003); MOM4 (Griffies et al., 2004) or NEMO (Madec, 2008) and assimilate in situ profile data, altimeter data, some form of surface temperature data, and sea ice observations. Product assessments and interactions with research users have been key activities since the inception of operational ocean forecasting systems. An important component of product assessment is procedures developed to intercompare forecasts produced by different centres. The intercomparisons of results from the systems are being used to assess the consistency and uncertainty of the state estimates.

Today, there are numerous ocean forecasting consortia covering the coastal-to-basin/global scales. Many of these initiatives provide forecasts based on multiply nested models, with finer resolution in shelf-scale and coastal models. Here, we describe two initiatives: one with a regional focus (SOCIB) and one with a quasi-global to regional focus (Bluelink).

SOCIB, the Balearic Islands Coastal Observing and Forecasting Initiative (Tintoré et al., 2013), started its activities in 2009 in Mallorca Island, Spain, in order to implement and operate a multi-platform observing and forecasting research infrastructure providing streams of oceanographic data and modelling services that could support operational oceanography at a national, European, and international level. As part of its mission, driven by science, technology, and society needs, SOCIB acquires, processes, analyzes, and disseminates multi-disciplinary information about the sea in a systematic way, participates in the development and testing of new technologies, and provides science-based tools and products for society and coastal management.

SOCIB operates a variety of observing platforms, including a coastal research vessel, two high-frequency radar antennas, gliders, Argo floats, surface drifters, fixed moorings, weather stations, and beach monitoring systems. Additionally, SOCIB's modelling and forecasting facility develops and implements operational ocean prediction systems to complement and integrate these observations in line with the initiative's objectives. These modelling systems aim to represent: (i) the ocean circulation in the Western Mediterranean Sea (WMOP system), (ii) hazardous sea level oscillations in Ciutadella (locally known as "rissaga" phenomenon, Menorca, Spain; BRIFS system), and (iii) waves around the Balearic Islands (system operated in collaboration with Puertos del Estado). The first two prediction systems are briefly described next.

The 2 km-resolution ocean circulation model WMOP (Western Mediterranean OPerational System, Juza et al., 2016) is used to investigate processes and to provide short-term numerical predictions, which are then integrated in SOCIB products and services. WMOP is a regional configuration of the ROMS over the Western Mediterranean Sea, extending from the Strait of Gibraltar to the Sardinia Channel. It is initialized from and nested in the larger scale Mediterranean Model distributed through the European Copernicus Marine Environment Monitoring Service

(CMEMS-MED). High-resolution atmospheric model outputs are used to force the system (Spanish National Meteorological Agency HIRLAM model), with a 0.05° spatial resolution and a 1h temporal resolution. Due to the lack of data assimilation in the present operational WMOP system and to avoid a drift from realistic conditions, the model restarts every week from the outputs of a three-week spin-up simulation initialized from CMEMS-MED model fields, which include assimilation of sea level anomalies and temperature and salinity profiles. Data assimilation algorithms based on a local Ensemble Optimal Interpolation approach have recently been developed and tested in the model. They will soon be implemented in the operational chain, allowing models to ingest observations from satellites and in situ platforms, including altimeter sea level anomaly (gridded or along-track), SST, temperature and salinity profiles from Argo, CTDs and gliders, as well as high-frequency (HF) radar sea surface currents.

The operational system is run once a day, starting at 07:30 local time and delivering model outputs (72-hour forecasts) in the morning. In recent years, WMOP model outputs have been used to support efforts to deal with emergencies at sea related to oil spills, search-and-rescue, or for forensic purposes. Moreover, WMOP hindcast simulations over the period 2009-2015 have also been used to investigate ocean variability, regional connectivity, larval and plastics drifts, and to simulate future SWOT altimeter measurements and virtual observations to study innovative high-resolution multi-tracer analysis methods.

SOCIB has developed a second ocean forecasting system (BRIFS; Renault et al., 2013, Licer et al. 2017) aimed at representing the occurrence and magnitude of meteotsunamis (Monserrat et al. 2006; locally also known as “rissagues”) in Ciutadella harbour, Menorca, Spain. A meteotsunami or meteorological tsunami is a tsunami-like wave of meteorological origin. Meteotsunamis are generated when rapid changes in barometric pressure cause the displacement of a body of water, which is amplified under specific resonant conditions. The representation of such phenomena requires high-resolution ocean simulations forced by very high temporal resolution atmospheric forcing. As a consequence, BRIFS is an atmosphere-ocean modelling system using a very fine horizontal grid resolution (10 m) around the Menorcan harbour of Ciutadella, and a two-minute temporal resolution of atmospheric pressure forcing. WMOP and BRIFS outputs are illustrated in Fig. 1.2.

The atmospheric part is based on the WRF model with a 4 km resolution in the inner grid. The atmospheric pressure outputs of the WRF model are used to force two nested configurations of the ROMS model.

The Australian ocean forecasting initiative Bluelink operates two systems: a global system called OceanMAPS and a relocatable regional system called ROAM. OceanMAPSv3 represents a major upgrade in operational ocean forecasting for Australia over the previous version, with near-global (75°S-75°N) 0.1° horizontal resolution and improved vertical resolution. OceanMAPSv3 was declared operational in April 2016. The model is an implementation of the Modular Ocean Model version 4p1 (MOM4; Griffies et al., 2004). The data assimilation system is based on an Ensemble Optimal Interpolation (EnOI) implementation of an Ensemble Kalman Filter (EnKF-C; Sakov, 2014). The analysis assimilates all available altimetry, satellite SST, and in situ profiles of temperature and salinity. The forecast cycle is a three-day cycle with an analysis window for all observations of three days. A behind real-time analysis is performed -6 days behind real-time with a near real-time analysis performed at -3 days behind real-time. The surface is forced by the Bureau of Meteorology's global numerical weather prediction system (ACCESS-G) based on the UMv8.2 (UKMetOffice). Boundary conditions are based on GAMSSA and NCEP 1/12° sea ice analysis. The ocean model is forced by the atmospheric fluxes for wind stress and total heat flux (solar radiation, longwave radiation, sensible heat and latent heat). A climatological river discharge is applied based on Dai and Trenberth (2002).

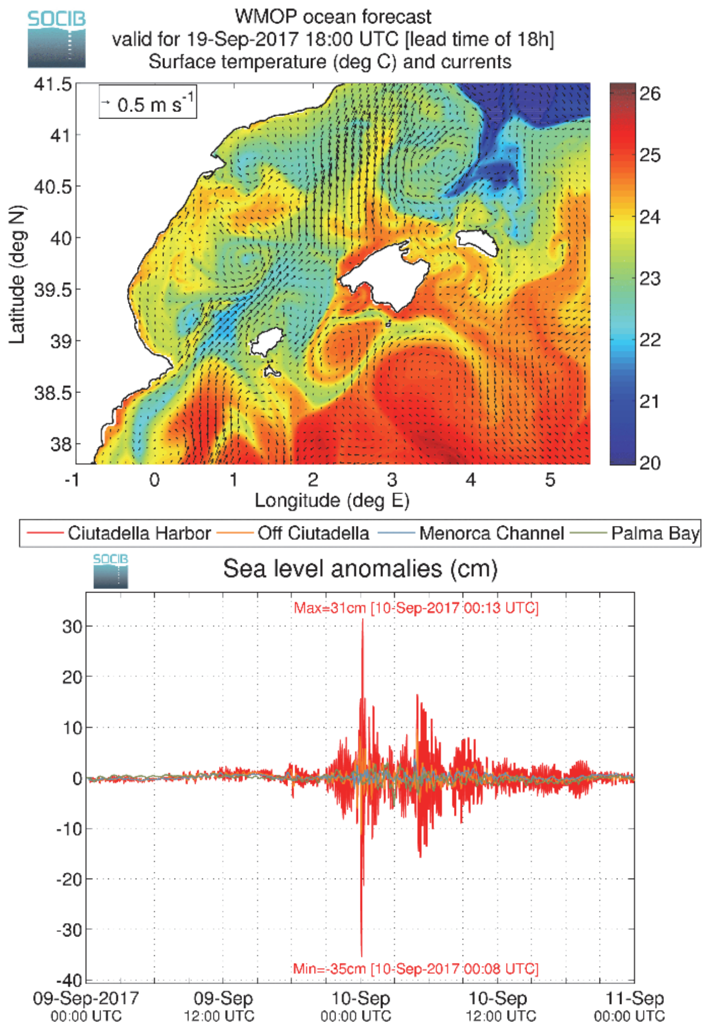

Figure 1.2. Top: WMOP prediction of SST and currents around the Balearic Islands, valid for 19 September 2017. Bottom: BRIFS prediction of sea level anomalies associated with a meteotsunami event in Ciutadella on 9-10 September 2017.

The Relocatable Ocean Atmosphere Model (ROAM) can be configured to have a high grid resolution (variable, resolution as high as one km horizontally, resolving tides and other high-frequency events) and output to file multiple times per day. This high spatial and temporal resolution allows in the ocean component for complex topography, tidal dynamics, and short-lived sub-mesoscale features to be modelled. The ROAM system is presently nested within OceanMPAS (data-assimilating) near-global models run on a 0.1° grid (≈ 10 km). ROAM-SHOC is initialized from fields derived from OceanMAPS and is subsequently forced with boundary conditions from the same model. OceanMAPS does not have tides, it has a coarse bathymetry due to the near-global grid resolution, and it is primarily designed for use in the deep ocean. ROAM is primarily designed for use over the continental shelf and slope, including areas with complex bathymetries or if a high temporal resolution is needed.

Service Delivery and Dissemination

Ocean forecasting systems deliver a broad range of products and services. Here we provide an overview of one of the most advanced systems, the European Copernicus Marine Environment Monitoring Service (CMEMS) (http://marine.copernicus.eu). CMEMS provides regular and systematic reference information on the physical state, variability, and dynamics of the ocean and marine ecosystems for the global ocean and the European regional seas. Some variables extracted from the global high-resolution forecasting system are shown as an example in Fig. 1.3. Other products, such as wave parameters and biogeochemistry variables, are also available at a global scale and for the European seas based on dedicated regional forecasting systems. Reanalyses, which are long time series produced based on homogeneous analysis systems, are available from the 1990s when altimetry observations first became available.

The CMEMS service is based on a network of production centres (Le Traon et al., 2017) with a cross-cutting coordination and strong links to scientific research to ensure a continuous evolution of the service (Fig. 1.3). The observations and forecasts produced by the service support all marine applications (Fig. 1.4). For instance, the provision of data on currents, waves, winds, and sea ice helps to improve ship routing services, offshore operations, or search and rescue operations, thus contributing to marine safety.

The products delivered by the CMEMS are provided free of charge to registered users through an interactive catalogue available on a web portal and with a strong support for all user needs through a dedicated service desk. These products encompass a description of the current situation (analysis), the variability at different spatial and temporal scales, the prediction of the situation a few days ahead (forecast), and the provision of consistent retrospective data records for recent years (reanalysis). The web portal allows for global and regional searches and includes over 40 variables, including physical variables (e.g., temperature, sea ice, waves) and biological variables (e.g., plankton, nutrients, turbidity).

CMEMS also contributes to the protection and the sustainable management of living marine resources, especially aquaculture, fishery research, and regional fishery organisations. Physical and marine biogeochemical components are useful for water quality monitoring and pollution control. Sea level rise helps to assess coastal erosion. SST is one of the primary physical impacts of climate change and has direct consequences on marine ecosystems. As a result, the service supports a wide range of coastal and marine environment applications. Many of the data delivered by the service (e.g., temperature, salinity, sea level, currents, wind, and sea ice) also play a crucial role in the domain of weather, climate, and seasonal forecasting.

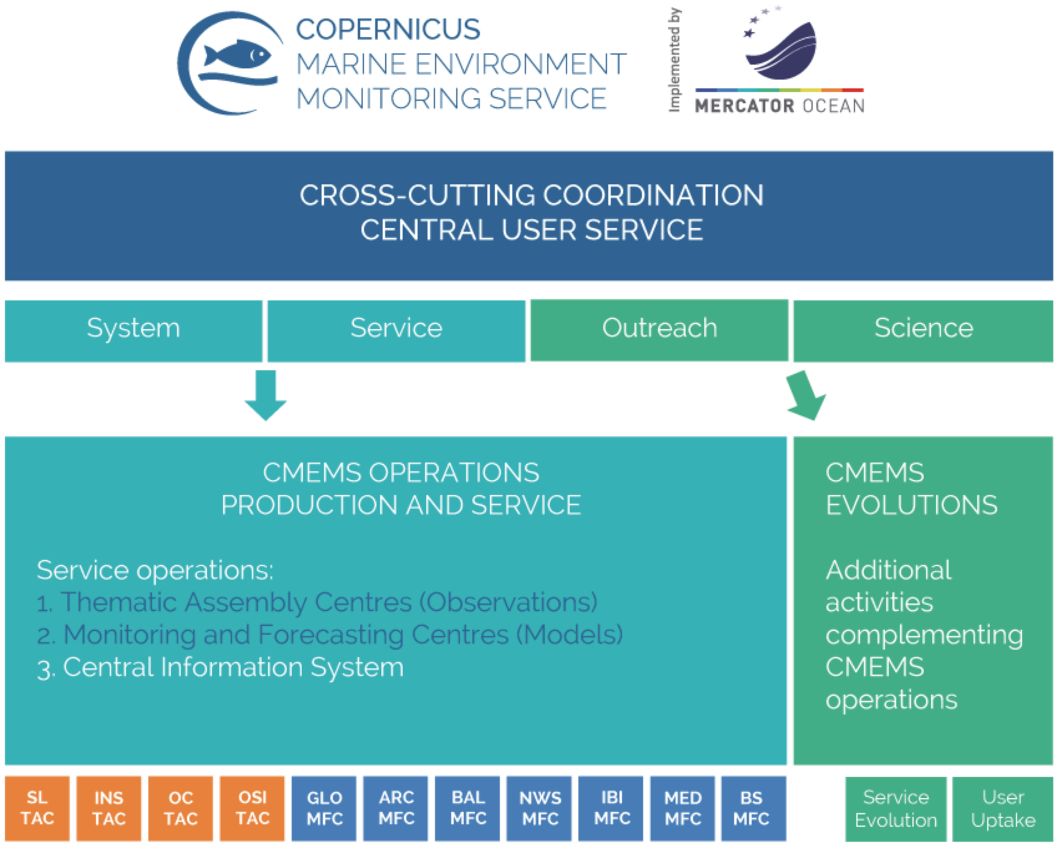

Figure 1.3. Organization of the CMEMS service with the four Thematic Assembly Centres (TACs for the Sea Level, In Situ, Ocean Colour, Ocean and Sea Ice observations) in charge of the observations and the seven Monitoring and Forecasting Centres (MFCs for the global ocean, the Arctic Ocean, the Baltic Sea, the North West Shelf area, the Iberian Biscay and Irish Seas, the Mediterranean Sea and the Black Sea) in charge of the models reanalysis, real-time analysis and forecast.

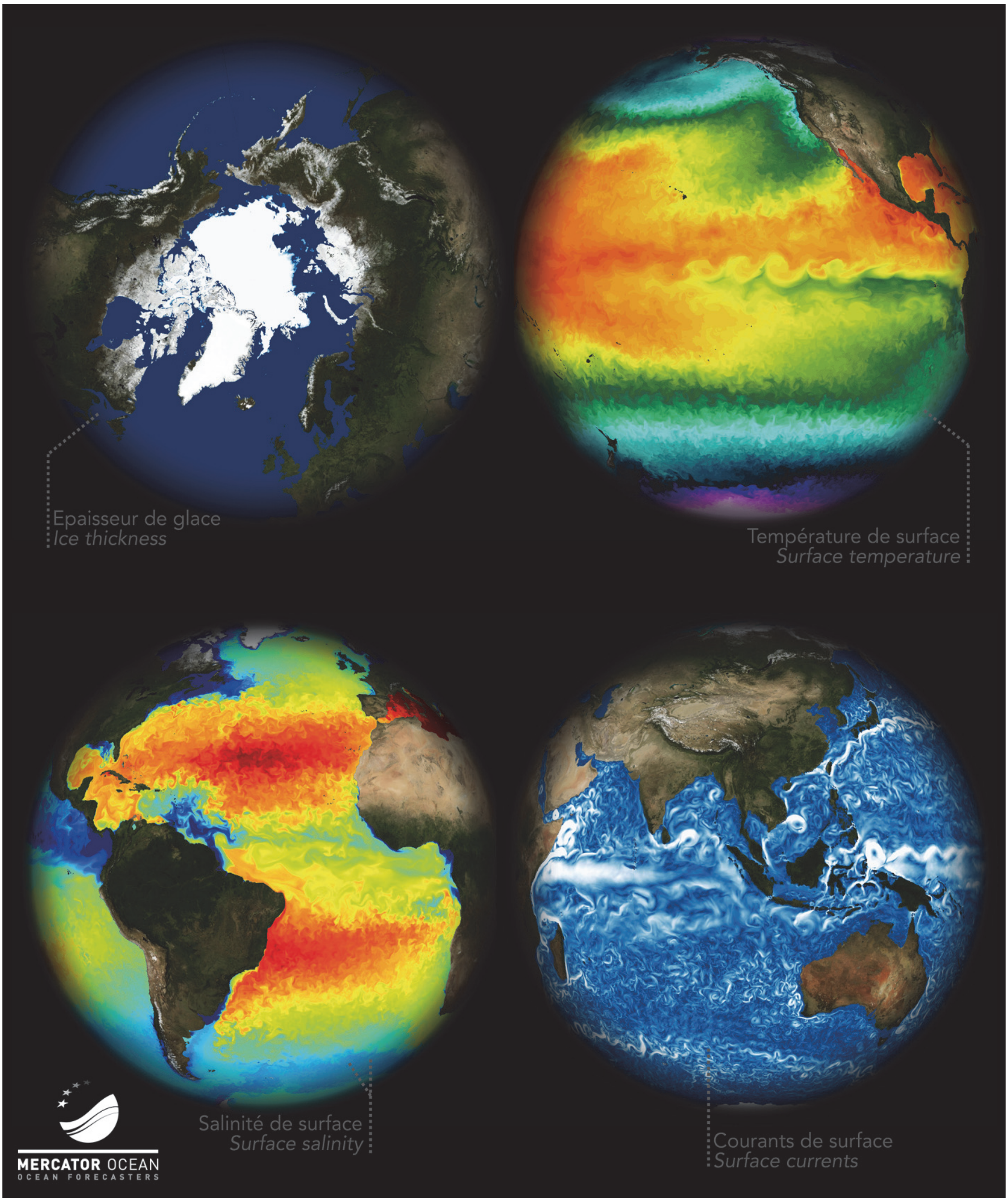

Figure 1.4. Example of variables from the global high-resolution forecasting system available in CMEMS. Ice thickness (top left), temperature (top right), salinity (bottom left), and current (bottom right) are available at 1/12° of resolution from the surface to the bottom, in the past (from 2007) and in the future (10-day forecast are provided daily).

Client Applications and Benefits

Broadly speaking, the primary sectors supported by ocean forecasting and reanalysis products are marine operations and activities with a focus to make these safer and more efficient. 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. Data policies for service and access conditions to the products are also believed to have a significant impact on their uptake in downstream services by small-to-medium enterprises 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 by the GEO (Group on Earth Observation) and by the European Copernicus programme. From its inception, GODAE also strongly supported open exchange of information.

Data access and visualisation

State-of-the-art information technology and visualisation techniques are being developed and updated by forecasting centres and intermediary service providers to facilitate uptake of products by end users.

For example, the 3-hourly WMOP forecasts (temperature, salinity, currents, and sea level) produced by the SOCIB system are made available through the SOCIB Thredds server. The SOCIB website (www.socib.es) also provides access to plots and animations of oceanic surface conditions, as well as interactive visualizations allowing users to superpose model results with other datasets such as the present platform deployments. Operational model validation based on observations from satellite SST, surface geostrophic currents, Argo, moorings, glider, and HF radar is also performed operationally and provided on the SOCIB website. Regarding the local meteotsunami phenomenon, BRIFS predictions are available on the SOCIB website as pictures of sea level time series in four points of interest, including Ciutadella harbour. Moreover, figures and videos are provided, illustrating the evolution of atmospheric pressure over the whole domain of the WRF model so as to visualize the occurrence of small-scale instabilities responsible for the generation of meteotsunamis. BRIFS outputs are used to complement the official warning system from the Spanish Meteorological Agency based on the analysis of synoptic atmospheric conditions.

The European Commission has launched an initiative to develop Copernicus Data and Information Access Services (DIAS) that facilitate access to Copernicus data and information from the Copernicus services (http://copernicus.eu/news/upcoming-copernicus-data-and-information-access-services-dias). By providing data and information access alongside processing resources, tools, and other relevant data, this initiative is expected to boost user uptake and stimulate innovation based on Earth observation data and information.

Marine transport, search and rescue, oil and gas industry

All of these industries 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.

In the oil and gas sector, there are a number of key players who require products from ocean forecasting centres (such as government regulators and agencies, major oil companies, commercial operators, and environmental service suppliers). Generally speaking, environmental support is required throughout the life cycle of oil and gas production including exploration, production, and decommissioning. 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 affects operations.

Naval defence 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 sonar 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.

Environmental protection and fisheries

The reanalyses for shelf seas has 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).

Short-range weather and seasonal prediction

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 in part because the development of mid-latitude cyclones is strongly influenced by them. Coupled atmosphere-ocean models have been developed for seasonal predictions of many years. There is growing evidence that relatively high ocean model resolution is needed 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).

Some sectors, such as the oil and gas industry, have extremely demanding requirements for the accuracy of currents at small spatial scales, which continues to challenge the ocean predictions. The nature of the decisions based on weather forecasts has changed dramatically in the last ten years as the forecasts and confidence in them have improved. 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.

International Coordination

International coordination facilitates progress in all functional components of operational oceanography systems shown in Fig. 1.1 (observations, data management/provision, prediction systems, and service delivery/products). GOV currently coordinates multiagency efforts to optimally support the research, development, and operational implementation of physical and biogeochemical ocean forecasting systems through its science team (www.godae-oceanview.org; Bell et al., 2015). For example, GOV coordinates international activities in support of ecosystem assessments (coral reef and other habitats), forecasts (harmful algal blooms, spills), and the development of associated prediction applications (climate impacts, living marine resource management). GOV continues the legacy of GODAE[2] with collaborators from more than 50 academic and national agencies worldwide. The research focus is on improving short- to medium-range operational ocean forecasting systems, and on enhancing and sustaining their development and routine operations. A formal expert review of GOV in 2013 (www.godae-oceanview.org/files/download.php?m=documents&f=150107120408-GOVStrategicPlan20152020.pdf) recognized the enormous benefits reaped by this globally coordinated operational oceanography effort over the last decade. The review identified areas of research where improvement of interinstitutional scientific coordination could deliver greater societal benefits. The recommendations have informed the GODAE OceanView Strategic Plan 2015–2020 (GODAE OceanView Science Team, 2014), which guides internationally coordinated research in short-term ocean prediction, data assimilation, application development, and service delivery for years to come. The development of an operational support for end-to-end capabilities (i.e., from research through to service delivery) is important to GOV and its sponsoring agencies, and includes routine and sustained ocean observing, data management, and the prediction system, as well as operational production and dissemination. The core objectives of the GOV Science Team (GODAE OceanView Science Team, 2014) are to:

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

- assess forecast system and component performance combined with component improvements;
- establish initiatives aimed at exploiting the forecasting systems for greater societal benefit; and
- evaluate the dependence of the forecasting systems and societal benefits on the components of the observation system.

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

Trends and Future Developments

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

- Improvements of forecasting systems included increased resolution (horizontal and vertical) tides, sea ice drift and thickness, ecosystem approaches, improvement to mixing biases, and extending regional mode areas (e.g., polar regions and progress of coupled modelling [wave coupling, sea ice, hurricane models, etc.]).
- Data assimilation schemes vary among ocean forecasting groups, ranging from Ensemble Optimum Interpolation (EnOI) and Ensemble Kalman Filter (EnKF) to three- and four-dimensional variational methods (3DVar and 4DVar). Observations assimilated in ocean forecast systems now include ocean colour, surface velocities, sea ice, and data from gliders. Many systems now employ multi-model approaches or ensemble modelling techniques.
- All major numerical weather prediction systems have now transitioned to ensemble forecast systems. Taking advantage of an ensemble in air-sea forcing within an equivalent ocean ensemble forecast system will provide crucial uncertainty information in the upper ocean properties.
- As the demand on forecasting products from ocean predictions is growing, the communication and dissemination of information to downstream users has been improved. Today, dissemination of outputs from forecasting systems is akin to the approaches taken in numerical weather prediction.
- Most ocean forecasting systems are now investing in verification and validation efforts to be able to show the value of their products to their users.

- Research in high-latitude (Arctic and Antarctica) operational ice and ocean prediction has increased significantly, driven by increased demand for accurate forecasts by industry and in support of sovereignty.
- Ocean reanalyses (three-dimensional analyses of the past) as well as the present ocean state at global-to-coastal scales based on the same modelling and assimilation infrastructure used for ocean forecasting are increasingly being used in, e.g., climate research and industry applications (extreme events).
- Boundary and forcing conditions from global ocean-atmosphere climate projections are being used in physical-biogeochemical-ecological modelling to downscale projections at regional and local scales, based on ocean forecasting infrastructure.

With the maturing of oceanographic forecast systems and research, the core ocean forecasting disciplines of ocean modelling, data assimilation, forecast verification, and observing system evaluation are now enabling new research and operational areas to flourish. Some of these focus areas for research and development are described in the subsequent subsections.

Model Development

Model grid resolution

Horizontal ocean model grid resolution has been steadily increasing over the last two decades, accompanied by increases in forecast skill (Tonani et al., 2015). By 2020, typical horizontal grid resolutions will be of the order of 5–10 km for global ocean prediction systems and will approach 1 km or less for systems that resolve sub-mesoscale processes by 2025 (with local/regional implementation much earlier). This will depend on continued growth in supercomputer power and evolution of ocean modelling techniques to make best use of computing power. For instance, the use of unstructured grids or grid nesting will allow models to increase their grid resolution specifically where needed by applications. These are particularly attractive options for coastal and regional forecasting models where there is a growing demand to provide accurate information to decision-makers looking after increasingly populated and urbanized coastal areas (including coastal river plumes from sediments and nutrients).

Because of the computational expense of resolving the highly energetic ocean mesoscale, most of the ocean forecasting community has been slower to implement state-of-the-art ensemble prediction systems than their numerical weather prediction and seasonal atmospheric counterparts. However, it is now computationally feasible to develop global and regional ocean ensemble prediction systems that will provide uncertainty and event predictability estimates.

Coupled prediction

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

Biogeochemical ocean forecasting

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

Data Assimilation and Observing System Requirements

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

As the ocean forecast models progress in the future, it will become increasingly important to end users that ocean forecasting centres define and project what type of events will be predictable by their systems with useful accuracy and confidence intervals. With the implementation of ensemble forecasts at high resolution, determining how to deliver and present the forecast and accuracy information to the end user/decision-maker is an important challenge.

The ensemble methods allow research on prediction controllability, which includes predictability, observability, and the ability of observations to constrain initial conditions of ocean models. Regular increases in computing power have enabled the development of higher resolution and ensemble models. However, while computing power versus cost ratio increases rapidly every year, the observing network capacity versus cost ratio is relatively fixed, particularly for in situ data. An important question to ask is what level of observation density is needed in future ensemble prediction systems to accurately initialize features like fronts with typical scales of 1–10 km, of currents across the shelf break, and of errors propagated in the ocean through air–sea fluxes? Sub-mesoscale filaments and coastal eddies with horizontal scales of less than 10 km, tidal fronts, and freshwater plumes generated by river run-off are generally well-simulated by coastal ocean forecasting systems with horizontal grids of 1 km or less. A challenge is how to use the fine-scale but spatially limited coastal observations, such as HF radar observations, as part of high-resolution, shelf- and basin-scale ocean forecasting systems. The advent and deployment of new observing systems (e.g., HF radars, gliders, and low-cost buoys) will provide the necessary in situ observations density, at least on a regional scale. The SWOT wide-swath altimeter mission scheduled to launch in 2021 is expected to provide high-resolution sea surface height (Fu and Ferrari, 2008). This dataset will resolve the sub-mesoscale and improve parameterizations in and forecasts with global-, basin-, and shelf-scale models. SWOT should also help us better understand and monitor estuaries, and link properties and fluxes from continent to coastal ocean (and vice versa). The impact of these planned future satellite missions (such as SWOT) on ocean forecasting systems can be tested beforehand through Observing System Simulation Experiments (OSSEs), and is currently the subject of research. For ocean biology and biogeochemistry, significant benefits will be realized by incorporating a constellation of geostationary ocean colour radiometry missions into predictions systems.

Operational ocean prediction systems transform data from satellite and sparse in situ measurement systems into value-added comprehensive and vetted oceanographic data and information products with "uniform-gridded" coverage (e.g., mitigating cloud cover and other data dropout issues). They also enable Lagrangian applications, e.g., oil spill forecasting and search and rescue activities. The increased international focus on developing shelf-scale analysis and prediction capabilities brings with it the additional challenge of developing cost-effective in situ coastal observing systems that enhance prediction system performance. Work currently undertaken by GOV scientists and collaborators is paving the way for fully automated multi-model ensemble Observing System Evaluations assessing all components of the Global Ocean Observing System (GOOS) from global-to-shelf scales. By issuing associated Observation Impact Statements, ocean forecasting centres will contribute to coherent, effective, and scientifically robust advocacy for the

GOOS. This effort will allow observing system agencies to assess the impact of past, present, and future observations on forecast and (re-)analysis skills. Consequently, this will enable future observation strategy and scenario evaluation at a fraction of the cost of implementing a new observing system. Furthermore, this activity maximizes the return on investment for the GOOS, a crucial need given limited funds.

New Observing System Requirements

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

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

Conclusion

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

Apart from the scientific challenges, there are a wide range of additional factors that will influence the progress of ocean forecasting. For operational oceanography to excel, there needs to be mutualistic benefit across all its components (observations, data management, prediction system, production/service delivery, and the clients). For example, prediction systems become stronger with better observing systems and vice versa. More specifically, ocean forecasting systems are critically dependent on both the satellite and in situ components of the physical GOOS, and the sustainability and expansion of the biological and biogeochemical GOOS (Legler et al., 2015). New opportunities arise in regional seas with the advent of "intelligent" new in situ sensors, sensor networks/webs, and new and improved remote sensing technologies.

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

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