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Research priorities in support of ocean monitoring and forecasting at the Met Office

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Abstract

Ocean monitoring and forecasting services are increasingly being used by a diverse community of public and commercial organisations. The Met Office, as the body responsible for severe weather prediction, has for many years been involved in providing forecasts of aspects of the marine environment. This paper describes how these have evolved to include a range of wave, surge and ocean reanalysis, analysis and forecasts services. To support these services, and to ensure they evolve to meet the demands of users and are based on the best available science, a number of scientific challenges need to be addressed. The paper goes on to summarise the key challenges, and highlights some priorities for the ocean monitoring and forecasting research group at the Met Office. There is a need to both develop the underpinning science of the modelling and data assimilation systems and to maximise the benefits from observations and other inputs to the systems. Systematic evaluation underpins this science, and also needs to be the focus of research.

1 Introduction

Operational ocean monitoring and forecasting services provide information to marine users that primarily support safe operations in the marine environment, but have also evolved to cater for, amongst others, marine security, commercial operations, licensing, marine environmental monitoring and numerical weather prediction. Observations alone cannot, without enormous investment, provide the spatial or temporal coverage required for a marine monitoring capability, and are limited to a subset of the parameters that are required. It is therefore clear that modelling, with the appropriate assimilation of good quality observations, of the physical environment, the marine chemistry and the lower trophic level marine biology, is required to support these user needs.

Early operational forecasts were implemented in the UK to respond to catastrophic surge events, such as the 1953 storm that resulted in a surge event killing several hun-

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀▮ | ▶▮
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

dred people in the UK (Baxter, 2005). Surge forecasting services were subsequently implemented at the Met Office, and are a factor in ensuring that subsequent storms of comparable magnitude have not had the same catastrophic impact (Lewis, 2015). Wave models are used to forecast the sea state for mariners and commercial operators. They are also used in combination with surge modelling to forecast coastal flooding, to provide a well established part of the armoury for predicting and monitoring extreme weather events.

More recently ocean forecast and monitoring services have expanded from solving essentially two-dimensional wave equations to include the fully three-dimensional state (hydrodynamics) of the ocean. This was driven initially by the Royal Navy, with their requirement to understand the depth resolved currents (for diver operations, mine hunting and vessel operations) and the depth varying density and optical properties (for submarine operations and detection). A number of other users have since started using ocean analysis and forecast services, including seasonal forecasting, which relies on daily high quality ocean state analyses for initialisation of their forecasts. The need has also expanded to include reanalysis of the marine environment, to provide information about the mean state, variability and change for planning and monitoring purposes for a number of users.

Operational ocean services are still relatively immature and scientific innovation is required to improve their quality. Understanding the priorities for Ocean Forecasting Research is important at any time, but none more so than at the moment when fundamental changes in both the scientific capability and the user drive provide significant challenges and opportunities. The increasing emphasis on monitoring the marine environment under legislation such as the Marine Strategy Framework Directive (MSFD) is driving the need to monitor the marine environment at levels not presently achievable. MSFD requires that EU member states have a marine strategy in place by 2020 that defines how they intend to monitor their marine waters, and therefore ensure that they can maintain Good Environmental Status (GES). Alongside this statutory driver, other users of the marine environment also require good quality marine information, the most

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◂◂ ▸▸
◂ ▸
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

notable being the renewable and oil and gas industries which have huge infrastructure programmes in areas like the North Sea, and extending into deeper waters. To operate safely (and within the law) they require an understanding of the physical environment in which they are working, including the particularly challenging need to have accurate historical information about, and predictions of, currents.

This paper provides an overview of the operational ocean monitoring and forecasting services being provided by the Met Office that can, and do, provide underpinning information available to support maritime and marine sustainable growth. The critical investments in science to ensure that the services can improve and adapt to changing requirements are described.

2 Met office ocean monitoring and prediction systems

2.1 Surface waves

The Met Office wave models are based on NCEP's WAVEWATCH III™ (WWIII, Tolman, 2009, 2014). WWIII has recently adopted a community model status, enabling users to benefit from model developments implemented by numerous research groups worldwide. For example, in the present operational configurations run at the Met Office model options to use a flavour of WAM source terms physics (Saulter, 2015) and with a 2nd order propagation scheme (Li, 2008) have been selected.

Deterministic operational forecasts are based on a suite of three nested configurations. A global wave model at approximately 35 km resolution is run four times daily, alternating between forecasting two days and five days ahead. This provides boundary conditions for a European wave model at approximately 8 km resolution, running a similar cycle, and a UK waters model at 4 km resolution, which also runs four times daily but is limited to two day forecasts. At present, all configurations are forced by the Met Office global atmospheric model, which has a horizontal resolution of order 17 km. The Met Office has also built and run higher resolution wave models for coastal applications on an ad-hoc basis using the SWAN model. For example, an application was built and run for Weymouth Bay as part of the Met Office's support for the London 2012 Olympics (Golding et al., 2014).

In the next 12 months, the Met Office expects to make three enhancements to this system. The first is the implementation of a refined grid wave model, in which the wave model comprises cells of different resolutions so that high resolutions can be applied near the coast whilst retaining more computationally efficient larger cells in deeper open waters. The advantage of adopting this method is to reduce the need to maintain multiple nested model configurations. The grid refinement method developed at the Met Office uses the spherical multiple-cell (SMC) grid (Li, 2011) and will first be implemented as a global wave model (Li, 2012; Li and Saulter, 2014).

An SMC grid model for the Atlantic has already been implemented as a wave Ensemble Prediction System (wave-EPS; Bunney and Saulter, 2015). Forecasts from the system are being trialled with a number of users in order to establish requirements for probabilistic decision making data products. As a forced-dissipative system, spread in wave forecast errors can be primarily simulated using spread derived in wind data from an atmospheric ensemble. In this case, the Atlantic wave model is driven using members from the Met Office Global atmospheric ensemble MOGREPS-G (Bowler et al., 2008), with horizontal resolution of approximately 30 km.

For waters around the UK, it is recognised that a high degree of variability in the oceanic conditions, particularly associated with the tides, will introduce variability in the wave field. A version of the UK waters wave model, which has been one-way coupled to currents from the Met Office's northwest European shelf seas model, is presently undergoing verification trials and will be made operational during 2016.

2.2 Storm surges

Tide-surge models are run in real-time as part of the forecast suite of models. Results are used by the joint Environment Agency/Met Office Flood Forecasting Centre, together with data from the National Tide Gauge Network, for coastal flood warning in England and Wales.

The first operational surge forecasts were run in 1978 using coarse grid surge and atmospheric models. The present system comprises a 12 km shelf model (CS3X), with refinements to 4 and 1 km in order to provide useful predictions in the complex regime of the Bristol Channel and Severn Estuary.

A deterministic surge model suite comprising CS3X, Bristol Channel and Severn Estuary models is run four times daily, forced by wind and surface pressure data from the Met Office's global atmospheric model. CS3X is also run as an ensemble prediction system forced by MOGREPS-G. Similar to waves, uncertainty in the surge forecast is primarily influenced by uncertainty in the atmospheric forecast, such that good probabilistic performance can be achieved through perturbing surge-EPS members purely by the forcing atmospheric-EPS data (Flowerdew et al., 2010).

2.3 OSTIA

The Operational Sea surface Temperature and sea Ice Analysis (OSTIA; Donlon et al., 2012b) system was developed at the Met Office for use in numerical weather prediction and ocean forecasting systems. It is run in near real-time on a daily basis. OSTIA produces a global field of sea surface temperature (SST) (free of diurnal variability) every day on a $1/20^{\circ}$ (~ 6 km) grid. The system uses SST input data from satellite measurements together with in-situ data and a sea ice concentration product. Data assimilation methods are used to combine the different SST input data, taking into account estimates of the observational uncertainty, to produce a gridded analysis. An uncertainty estimate is provided with each SST. OSTIA is widely used, particularly in numerical weather prediction centres (including the Met Office and ECMWF) where it is used as a lower boundary condition in weather forecast models. The OSTIA system is continually being developed and improved. For example, in November 2011, lake surface water temperatures were added for 248 lakes across the globe (Fiedler et al., 2014). The OSTIA analysis and analyses produced by various institutes around the world are used to create the Group for High Resolution (GHRSST) Multi-Product Ensemble (GMPE) product for the global ocean (Martin et al., 2012). The analyses are regridded onto a common 1/4° grid and the ensemble mean and standard deviation are calculated. This provides a mechanism to compare analyses and potentially faciliate their development.

The OSTIA processing system is also used to produce reanalyses of global SST over the satellite era (Roberts-Jones et al., 2012), Most recently, as part of the European Space Agency (ESA) SST Climate Change Initiative (CCI), the OSTIA system was developed and a reprocessing based on ESA SST CCI input satellite data was performed. Aimed at climate research users, this reprocessing covers late 1991–2010 (Merchant et al., 2014).

A new diurnal analysis has recently been developed which produces hourly skin SST fields on a 1/4° grid. It is generated by combining the OSTIA foundation SST analysis with models of the layer of water subjected to solar heating (the "warm layer") and the layer that loses heat through emission of long wave radiation (the "cool skin"). Satellite SSTs are assimilated into the warm layer model. This diurnal product, together with OSTIA foundation SSTs, the GMPE product and a reprocessing are made available through the Copernicus Marine Environment Monitoring Service (CMEMS), which are available from http://marine.copernicus.eu. The ESA SST CCI analyses are available from http://www.neodc.rl.ac.uk/.

2.4 Forecasting ocean assimilation model

The Met Office provides three-dimensional predictions of the ocean state using the Forecasting Ocean Assimilation Model (FOAM) suite of systems. These include global and shelf seas implementations, and as well as the physical environment the marine biogeochemistry and lower trophic level plankton are simulated for shelf seas.

The primary shelf seas region of focus is the European North-West Shelf, which include the continental shelf waters of the UK and neighbouring countries. A global capability is also required, with basin scale regions at higher resolutions in the North Atlantic, Mediterranean and Indian Ocean.

Since early this century the Met Office, in collaboration (in particular, but not exclusively) with the National Oceanography Centre (NOC) and Plymouth Marine Laboratory (PML), have developed and delivered operational services from ocean models coupled to marine biogeochemistry models. Siddorn et al. (2007) describes the first system, to our knowledge, to operationally produce analyses and forecasts of the hydrodynamics and biogeochemistry of shelf environments. It was implemented primarily for the use of the Royal Navy, but there is also significant interest in, and use of, this type of service from other agencies responsible for marine monitoring and response activities.

The shelf seas forecasting was transitioned to use NEMO (Madec, 2008), which is also used for the global and basin scale forecast systems. This allowed, amongst other things, a data assimilation capability already implemented for the deep water systems to be implemented efficiently in the shelf seas systems. At present only surface temperature data are assimilated in Met Office shelf seas systems. The short time and space scales in the shelf seas, with respect to the data availability, make assimilating data here a particular challenge. However, progress is being made and assimilation of subsurface temperature and salinity data and sea surface height data (King and Martin, 2013) will become operationally viable within the next couple of years. Research on ocean colour assimilation has also shown promise, although considerably more development is required before this is ready for operational implementation.

O'Dea et al. (2012) describes the operational implementation of the FOAM (Forecasting Ocean Assimilation Model) AMM7 (Atlantic Margin Model) at ∼ 7 km resolution, the successor to the forecasting system detailed in Siddorn et al. (2007). The model has now been consistently shown to be as good as or better than its predecessor, and was for example shown by O'Neill et al. (2012) to outperform a significantly higher resolution equivalent for the Liverpool Bay region. Within the Met Office the success of the NEMO based system led to a implementations in other regions, for example in the Persian Gulf region (Hyder et al., 2012). The development work done in the North-

West European Shelf region provided the science starting point for this work. The Gulf is an interesting region dynamically, with the Straits of Hormuz acting as the natural boundary between the shallow and tidal Persian Gulf waters and the Indian Ocean.

Storkey et al. (2010) describes the first implementation of an operational forecasting system using NEMO at the Met Office. The primary configuration implemented was a global system based upon the configuration developed at Mercator-Océan, using an 1/4° ORCA grid (Drevillon et al., 2008), a tripolar, curvilinear discretisation that allows the poles to be placed over land and gives enhanced resolution at high latitudes. Three other basin scale configurations for regions of particular user interest (the Mediterranean, the North Atlantic and the Indian Ocean) were also implemented on regular lat-lon grids (rotated in the case of the North Atlantic model) at higher (1/12°) resolution, giving a suite of forecast systems that is eddy permitting over the globe and eddy resolving in key basins.

3 Science priorities

3.1 Observations

The importance of observations to operational ocean forecasting cannot be overstated. They provide the basis on which process understanding is acquired, and therefore underpin fundamental model and system development. They are also needed as the basis for understanding the skill of monitoring and prediction systems. Timeliness requirements for observations for model/system validation, which is done on simulations of the recent past and can therefore take advantage of research data and observations that have been through a rigorous quality control process, differs to verification which requires observations to be available within days if not hours of collection. Data assimilation also requires observations and, for forecast simulations, also needs them within a short period of the validity time. For both verification and assimilation it is therefore critical that the data are timely and have good metadata such as quality flags and well-described error characteristics.

The space and time sampling of the ocean is far from optimal, and one of the challenges for ocean services is to make the best use of the available observations. It is therefore a priority that best use is made of available datasets. Current verification is presently not done effectively, and more use could be made (for example) of global velocity observations from drifter displacements. ADCP data is still difficult to work with in operational settings, and more should be done to ensure they are used as effectively as possible. Gliders and other autonomous vehicles are becoming increasingly prevalent, and available in real-time. This has the potential to make a significant difference to the sub-surface data available, especially in marginal seas, if the data become readily available.

Satellite data are a key component of the observing system as they can provide relatively good spatial coverage and tend to be delivered to operational centres quickly after collection. The sensors and algorithms have generally relatively well-described error characteristics, and the missions are well-known in advance so can be planned for. The Sentinel-3 satellites due to be launched later this year and in future years will provide high quality sea-surface topography, sea surface temperature and ocean colour, and have been designed specifically for support of ocean forecasting systems. However, satellites can only provide measurements of the surface of the ocean, cover a relatively limited part of the desirable parameter space and can often be at lower accuracy than either in situ observations or at times the models themselves. Waves, for example, from Scatterometer have similar accuracy to the models they could be used to validate.

A well designed in-situ data network is therefore also critical for the success of operational oceanography. Collecting data at sea is a time consuming and costly business and there is never therefore likely to be the sort of observational coverage from traditional collection methods that we would like. However, there are a number of things that could be done to improve the current situation. The most likely to show impact in the short term is to ensure that data that are already collected are as widely (and quickly) available as possible. This is not a trivial task, given the difficulties in ensuring data are distributed with suitable quality control and metadata. It can also be complicated by intellectual property and commercial constraints. OceanObs'09 convened in Venice in 2009 to develop a "common vision for the provision of routine and sustained global information on the marine environment" and produced a conference statement (Conference Statement, 2010) that highlighted the need for systematic, sustained, real-time observations collection. The conference summary (Fischer et al., 2010) highlights the key investments needed to meet societal needs for an ocean observing system. The more the diverse communities involved in marine observation collection can work together to agree protocols for quality controlling and onwards distribution of their data the more benefit can be accrued from it, not least from improvements in the ocean forecasting and monitoring services.

Other datasets are becoming available that could, with effort, make a major difference. Satellite salinity data from SMOS and Aquarius have been demonstrated to provide some useful information (Martin, 2015), but improvements still need to be made to their biases for them to meet their potential. More widespread use of Voluntary Observers has significant potential. Sensors on fishing gear have shown significant potential, but are generally still at the trialling stage and do not as yet deliver significant quantities of data. HF Radar has the potential to provide a step change in the monitoring of sea level in coastal waters, but coverage is limited in many regions, notably in the North-West European Shelf.

Making optimal use of the present observing systems and technologies that are available or likely to become available in the near future will allow the ocean forecasting community to make good progress. However, that is not to say that the observing system is optimal for the purposes of ocean forecasting. A number of parameters are poorly observed, for example particularly salinity, currents and biogeochemical parameters. The evolving services will also put greater demands on the observation network, with for example more complete Earth Prediction Systems increasing the range of observations which will be required in real time. The drive to provide ocean forecasting services at eddy resolving scales globally and in shelf seas also means the requirements for the spatial and temporal frequency of the observational network to constrain the model systems is increasing. The ocean forecasting community must ensure that these needs are well-articulated through the use, for example, of Observing System Experiments (OSEs) to demonstrate the impact of existing observation types and Observing System Simulation Experiments (OSSEs) to ensure that the requirements for new observing networks are well-defined.

In summary, as a priority the ocean forecasting community must (a) make best use of available data, (b) support data collectors in making their data available in a timely and usable way and (c) support the investment in technologies already close to operational readiness and ensure they are pulled-through to demonstrate impacts, (d) demonstrate the impact of the present observing systems and (e) articulate the evolving needs for a new or updated observing system.

3.2 Ocean modelling

Progress is needed to ensure models used to provide ocean services are of sufficient quality to provide the information required. Producing operational simulations that have skill requires model developers to improve numerical schemes and parameterisations prescribe the inputs to the system.

Ocean models (including biogeochemistry models) are still at a level of maturity where improvements to skill can be found from improving their process representation. Process improvements are important and will continue to improve the systems, but require significant investment of science expertise to have a significant impact. However, improving atmospheric, riverine or lateral boundary inputs is often overlooked as an important driver for improved skill, and can give substantial benefits for relatively minor investments of time and computing power. Unfortunately, there is a limit to the availability of good quality input data.

A key driver for the ocean forecasting community is the growing interest in coupled ocean–atmosphere forecasting, which has the potential to better represent some of the interface exchanges. Climate researchers have used coupled models for a long-time, but due to the latency in the ocean system it has not until recently been considered of interest to the numerical weather/ocean prediction community. However, as weather models increase in resolution, and the focus on hazards prediction increases, the potential for air–land–sea-ice-waves coupling systems is increasingly driving research activity. These systems are presently being developed at the Met Office, with a global coupled forecasting system already delivering forecasts operationally to the Copernicus Marine Environment Monitoring Service (CMEMS, http://marine.copernicus.eu). Regional systems are also being developed, one of the most advanced being the UK Environmental Prediction system, a joint NERC and Met Office activity led from the Ocean Forecasting group at the Met Office. Coupled systems are discussed in more detail below.

Changing the complexity can also provide benefits by replacing implicit or missing processes with well-posed algorithms or additional models/sub-models. Again, this can be time-consuming and also often comes with significant additional computation cost implications, especially when full coupling to additional components of the earth system. Increased complexity systems can often be helpful in informing the model development process even if not incorporated as part of the final production solution.

Errors in vertical mixing tend to be amongst the most significant for ocean forecasting problems, both because of the short time and space scales on which surface forcing and the dynamic processes in the mixed layer operate and because of the impact errors in exchange across the thermocline can have upon water masses. This is a particular problem for any coupled forecasting systems where the surface properties of the ocean are unconstrained by the atmospheric model forcing and errors can feedback to the atmosphere causing rapidly growing biases. Improving upon vertical mixing properties in ocean models is a priority for the ocean forecasting community. Present schemes are often dominated by pragmatic tuning options that dominate the mixing and result in mixing schemes that poorly represent the real processes. NEMO for example relies on both a constant background minimum viscosity and diffusivity and an additional wind related penetration of turbulent kinetic energy below the mixed layer due to internal and inertial waves to compensate for a lack of explicitly included processes like internal wave breaking or shear spiking at the base of the thermocline. The exchange of scalar properties from the surface to deep waters and vice versa is therefore dominated by a number of tunable parameters which have limited tracability to the true physical processes.

The OSMOSIS (Belcher et al., 2012) project is seeking to redress this problem by incorporating a more realistic set of processes into a mixed layer model that will couple to a more traditional two-equation model below the mixed layer. The project is still at the stage of developing schemes in idealised settings. There is still more to be done to move from the idealised to the real application, for example to address how the OSMOSIS mixed layer model will behave under ice and in shelf seas where the bottom and surface boundary layers can overlap. However, in the medium term this has the potential to redress some of the shortcomings in this area. As our understanding and parameterisation of mixing processes improves we will increasingly be adding new explicit terms for mixing into our models. This further highlights the issue of spurious numerical mixing, especially for relatively quiescent regions. Alignment of the vertical coordinate with isopycnals is important in reducing this spurious mixing, and a suitable choice of vertical coordinate (e.g. Siddorn and Furner, 2013) is key to this. However, short of working in an isopycnic framework which gives rise to other complications, a non-adaptive coordinate cannot eliminate the impact of undulating isopycnals. Leclair and Madec (2011) developed an Arbitrary Lagrangian–Eulerian (ALE) capability for the NEMO model (termed the $\tilde{z}$ coordinate) that applies the Lagrangian component (i.e. grid adaptation) in response to fast moving waves. This neatly allows the model to limit the amount of adaptation required whilst removing the primary source of spurious vertical mixing. Petersen et al. (2015) described the impact of a range of vertical coordinates, including fully ALE and the $\tilde{z}$ subset of ALE and concluded that the use these coordinates worked well at reducing spurious mixing under many scenarios. These formulations should be introduced into operational configurations once they are sufficiently mature

Improving the advection/diffusion schemes is very much business as usual for the ocean model development community and will undoubtedly continue. However, the numerical properties of any modelling framework are inextricably tied to the numerical framework within which they are coded. Work being done on grids for atmosphere modelling, where it is a pressing problem, is providing insight into the optimal approach to take. For example, there is the US MPAS project (Ringler et al., 2013) and the UK's GungHo project (Thuburn et al., 2015) both of which are, or have, developed new grid frameworks and appropriate numerical schemes that have improved properties for geophysical modelling (Cotter and Thuburn, 2014). There may be significant benefit for the ocean modelling community to follow the lead of these projects, but it should be noted one of the key drivers for these activities is the polar singularity issue which in ocean models can be hidden through placing poles over land. The present consensus is that the most promising numerical approach probably lies in C-grid finite volume methods like those implemented in MPAS rather than finite elements based discretizations (Danilov, 2013) which have been tried for the low aspect-ratio ocean problems but without great success to date. As most ocean models presently used are based upon C-grid finite-difference methods, the pressure for change is relatively low in the ocean community. However, as computing infrastructures change the benefits to move to unstructured, finite volume or element solutions may increase.

Shelf seas environments present a number challenges to modellers. Firstly, they are dynamic regions where a range of processes need to be represented if realistic simulations are to be achieved. The wind and buoyancy driven residual circulation is superimposed upon the tidal circulation that is a function of the local and far-field forcing, and has such a major impact upon these regions. The difficulty in representing the relatively poorly understood dynamics of shelf-slopes, where mesoscale and submesoscale processes can have a significant impact, means cross-shelf exchanges can be particularly difficult to model. This is compounded by enhanced numerical errors in regions where the model grid is not aligned well with isopycnals. Small scale (turbulent) processes are important in determining exchanges across interfaces, most notably vertically in seasonally and tidally stratified waters but also horizontally, for example in determining the horizontal extent of the influence of freshwater discharges as the freshwater is mixed with adjacent waters by baroclinic instabilities.

Shelf seas environments also present particular challenges in that they are significantly influenced by the deep ocean, land, sea-bed and air boundaries. Not only, therefore, do the relevant dynamical processes need to be well represented but the inputs to the system also need to be well specified. Poor river sources of freshwater can have a dramatic effect upon the model solution. Good quality bathymetry and coastlines still remains a limitation, exacerbated by the difficulty in defining a roughness length in an environment that not only has highly spatially variable bottom types that are poorly monitored, but may also have rapidly evolving changes to the bed morphology. Air–sea exchange parameterisations tend to be based upon empirical formulations derived in regimes far removed from those being modelled. The atmospheric models used to provide atmospheric boundary information are imperfect and primarily tuned to give the best solutions over land where the dominant societal impact is to be found.

There are fundamental scales in the ocean that need to be considered when deciding at which resolution to develop model configurations. At the smallest scales turbulent motions are clearly not resolvable and so these are parameterised, in the vertical using turbulence closure models and in the horizontal through diffusion operators. In the recent past mesoscale processes have not been resolved, and so methods for parameterising the impacts of mesoscale motions upon vertical restratification have been included in global models (e.g. Gent and McWilliams, 1990). We are now entering a period when computing power is such that operational modelling systems are under development at resolutions that can in the main resolve the mesoscale (of the order $1/15^{\circ}$ globally and 1 km in mid-latitude shelf regions). At these resolutions the challenge is to parameterise turbulent motions at the (smaller) grid scales, including sub-mesoscale eddies and filaments.

Increasingly there is a drive for forecasting and monitoring of the whole earth system, including the marine biogeochemistry. Presently the skill of biogeochemistry models is limited for forecasting bloom events. Allen et al. (2010) gives an interesting oversight of the challenges confronting the developers of biogeochemistry systems. The biogeochemistry model accentuates physical model errors, and therefore particular attention needs to be paid to the hydrodynamic modelling framework (including assimilation) errors in the context of their implications for biological function. These seem to particularly pressing in the vertical. We are still at the stage in the biological modelling community of trying to understand what modelling tools give the best trade off between complexity (costly, but potentially overfitted) and simplicity (inexpensive, but missing key processes). Even in any given model structure, the parameterisations are not necessarily well described given a lack of understanding of the processes and data to constrain them. Developing well-posed biogeochemistry models is therefore still an area that needs active research.

3.3 Waves and surge

Although wave forecasting services have a longer track record of operational use than their ocean counterparts, continuing enhancements in the parameterizations and numerical methods underpinning spectral wave models (as summarized by the WISE group 2007, Tolman et al., 2013; and in proceedings of the ECMWF Workshop on Ocean Waves, 2012) present numerous opportunities to improve both skill and utilisation of wave forecasts. Recent years have seen a number of refinements to the source term physics schemes used to represent the growth and dissipation of wind-sea energy. In particular, work by Ardhuin et al. (2010) and Babanin (2011), amongst others, has begun the process of explicitly parameterizing wave energy dissipation in wave models, rather than treating this term as a method to achieve energy closure. An improved representation of wave dissipation will be crucial to more accurately representing the transfer of momentum from the atmosphere-wave boundary layer into the ocean within coupled models. Increased computational resources and numerical scheme developments (e.g. Tolman, 2012) indicate a longer term potential to improve on the nonlinear wave-wave interaction parameterization source term which, for reasons of computational efficiency, has long used the Discrete Interaction Approximation of Hasselman et al. (1985). For any change to the source terms, moving to an operational model that better represents one source term generally requires review and re-tuning of the other terms, in order to derive the best overall representation of day to day wave spectrum evolution by the forecast model. The challenge for an operational wave forecasting group, such as the one at the Met Office, is in identifying the value of these improvements in the background science and when they can be practically applied within an operational computing framework that has finite resources and strict release timing deadlines.

Whilst source terms improve, it remains the case that the key determinant for wave forecast skill is the quality of the wind forcing applied to the model (Cavaleri and Bertotti, 2006; Janssen, 2008) and, where appropriate, inclusion of variations in the current and depth regimes affecting wave energy propagation and wave steepness. Regarding the latter processes, UK waters are subject to strong tidal regimes and depth variations, such that wave observations in the coastal zone often exhibit a significant tidal signature. Improving the wave model's representation of tidal processes is presently a priority area for research. In principle, incorporating (at least) ocean current fields in global wave models in order to properly represent wave field evolution in known strong current regions, such as the Gulf Stream, Agulhas and Kuroshio, should be a next stage in development, although generic concerns over the quality of ocean model forecast fields and challenges in demonstrating the value of this coupling (due to sparseness in wave observations) suggests that near-future developments may remain restricted to regional systems. The development of increasingly high resolution atmospheric models, which explicitly represent convective processes, may also lead to challenges in future. In such models a high level of detail can be developed in the wind field, but not

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

necessarily placed correctly in time and space, presenting a particular problem for site specific forecasts due to “double penalty” effects. How these effects play out over the ocean needs to be assessed, since wave and ocean models generally smooth wind field effects and coastal zone wind representation may well be improved.

In many cases, improvements to wave model science lead to small incremental benefits in terms of the most commonly used wave model data, i.e. forecasts of significant wave height derived from the overall wave spectrum. However, the bigger picture is that many recent science and model resolution changes ought to lead to a significant expansion in the geographic scope and range of wave forecast services that can be provided to users. For example, the development of the SMC grid models run by the Met Office is aimed at providing wave forecasts that correctly represent the near coastal zone without the requirement to run and maintain multiple high-resolution nested coastal wave models. This development is important in terms of service “reach”, as the coastal zone has a far higher number of marine users than the open seas. As well as improving the bulk wave energy prediction represented by significant wave height, recent source term improvements have led to a verifiable improvement in representation of the wave spectrum (e.g. Bidlot et al., 2005; Ardhuin et al., 2010). This means that forecasters should be able to offer a wider range of wave forecasts describing characteristics of the sea-state additional to significant wave height; for example wave steepness (Savina and Lefevre, 2004; Niclasen et al., 2010), whether seas are confused or regular due to the presence or otherwise of multiple wave components comprising wind-sea and swells (Savina and Lefevre, 2004; Kohno, 2013) and, potentially, the risk of occurrence of so-called rogue or freak waves (Janssen and Bidlot, 2009), Development of ensemble prediction systems also expands the list of potential products that can be developed dependant on a users preference to receive deterministic or more risk based information. A significant proportion of the operational model development team’s task is, therefore, to demonstrate and advise marine forecasters on the value of, and methods to, exploit an increasingly rich dataset of good quality wave parameters.

In a similar vein, a key challenge for improvement of both modelling and utilisation of parameters associated with storm surges is to better combine the effects of both surge and wave when issuing flood forecast advice. In terms of background science, two-way feedbacks exist between surface waves and tide plus surge in shallow waters. Brown and Wolf (2009) demonstrated that these effects modify both the wave field and the surge, indicating the need both for coupling wave and surge models and applying wind stress to the surge model via the waves. Generally, UK storm surge modelling has concentrated on large (basin) scale surges, which are driven by synoptic scale meteorology. However, resolution improvements enabling an understanding of variability introduced on the convective scale may lead to the addition of useful detail to the forecast surge and wave forecast, for example in indicating smaller scale surges sometimes referred to as “meteotsunamis” (e.g. Tappin et al., 2013). From the forecasting point of view, understanding details of the wave field alongside high tide plus surge conditions should enable forecasts to add extra detail when identifying areas of coastline at particular risk. This is since the degree of wave energy reaching the coast will be highly dependent on the difference in angles between waves offshore and the alignment of the coast, plus the likelihood of waves shoaling and refracting in the nearshore. Both of these processes are influenced by wave period, leading to a problem with many degrees of freedom. Ongoing work at the Met Office includes a dialogue between flood forecasters and the modelling team on how best to work with a combination of both surge and wave information within a probabilistic forecasting framework.

3.4 Quantifying uncertainty

Ensemble predictions are increasingly being seen as a priority for future generations of ocean forecasting systems. Ensembles are already routinely, and widely, being produced for surface wave and storm surge systems, with the spread in the ensemble generated by fluxes from an atmospheric ensemble prediction system (e.g. Bowler et al., 2008). This provides reasonable spread for surface wave and storm surge systems, where the solution is tightly coupled to the forcing. However, this is not likely to be sufficient in full ocean simulations, where the initial state and internal ocean dynamics are also important components of the uncertainty. Forcing perturbations (e.g. from a coupled atmosphere) may induce some spread in the near surface ocean variables (e.g. Sakov et al., 2012; Pinardi et al., 2011) but are unlikely to be enough to produce the correct spread for the deeper ocean. In order for the ensemble to be useful for ocean forecasting, perturbations to the ocean initial conditions and internal dynamics are therefore required.

3.5 Coupled prediction

The importance of air–sea interaction in both the modelling of the ocean and atmosphere has been recognised for many years. The timescales on which these interactions have traditionally been considered important has limited the use of coupled models to studies or prediction systems for monthly and longer timescales and while the need to represent feedbacks between different components of the environment is well understood and mature for climate prediction, the use of coupled approaches is not as well developed on shorter timescales. However there have been several vision papers (e.g. Brunet et al., 2010) and workshops relevant to this area, in which the importance of coupling is becoming increasingly recognised for weather timescales. The need to accelerate progress in Earth System prediction across all scales (climate and weather, global and local) was discussed by Shapiro et al. (2010), and this message was strongly reinforced during the 2014 WMO WWRP World Open Science Conference in Montreal.

The GODAE OceanView (GOV) Science Team, recognizing the need to explore the potential benefit to both oceanic and atmospheric forecasting, formed the Short- to Medium-Range Coupled Prediction Task Team. Given the obvious need to join up efforts with other communities, a link with the Working Group for Numerical Experimentation was formed and a Joint GOV-WGNE workshop was held in March 2013 to discuss the status, plans and challenges of coupled forecasting. The progress made by the communities involved in the SMRCP-TT since its inception on understanding coupled modelling, its challenges and benefits, and in building coupled systems, is detailed in Brassington et al. (2015).

One of the key regions where coupled ocean/air interactions are of importance is in the tropics, and recent work has demonstrated that, in addition to improved verification against various tropical ocean and atmospheric metrics, Madden–Julian Oscillation (MJO) predictions are in some instances superior in coupled hindcasts (Shelly et al., 2014). Also important for the Met Office, in its role as the UK's weather service, is the formation and/or evolution of extra-tropical storms, the ability to simulate land–sea-breeze circulation and the formation of coastal fog, all of which can be expected to be improved by coupled modelling.

The Met Office strategy for weather and ocean forecasting is to focus upon a two system approach, one global and one for the UK. The coupling activities follow the same approach, and this paper outlines the rationale and benefits for, and recent progress in developing, each system separately. Given the scientific and technical expertise on coupled modelling in the Met Office, and the strategy for seamless prediction that is increasingly bringing the weather and climate systems in closer alignment, we are well placed to make (and are already making) significant progress in coupled modelling on weather timescales. Nonetheless the move to coupled forecasting presents significant technical, scientific and resourcing challenges which are discussed below. Presently the use of coupled systems in weather forecasting is in its research phase (although it should be noted ocean forecasts are already being produced from coupled systems), but planning for the operational phase for our global systems has begun.

3.5.1 Regional systems

For regional high resolution prediction, there is already evidence of the benefit of coupled prediction for improving weather forecast skill. For example, coupled atmosphere-ice–ocean forecasts are now operational at the Canadian Meteorological Centre for the Gulf of St Lawrence region in Canada, with evaluation demonstrating significant improvement in the skill of both atmospheric and ice forecasts (Smith et al., 2013 and others). A key component of this activity was the design and development of a flexible and collaborative modelling framework for coupled land-surface and hydrological models (Pietroniro et al., 2007; Deacu et al., 2012). This enabled better understanding of the behaviour of different land-surface models and objective testing of different schemes for producing ensemble streamflow forecasts to improve the representation and accuracy of the regional water budget.

Coupled regional prediction systems have also been applied in research mode to improve the representation of air–sea interactions on Bora winds over the Adriatic (e.g. Pullen et al., 2006), on the evolution of Mediterranean storms (e.g. Renault et al., 2012) on hurricane formation and development (e.g. Warner et al., 2010) and on suppressing the urban heat island effect in New York (e.g. Pullen et al., 2007). The challenge now is to realise the potential of integrated regional coupled prediction in the UK context, and a robust flexible coupling strategy over the short-medium term is a key requirement to underpin this research activity.

The Met Office, the Centre for Ecology and Hydrology, the National Oceanography Centre and Plymouth Marine Laboratory are now working with others to accelerate research progress in developing the foundations of a coupled high resolution UK forecast system that links together predictions of the atmosphere, coastal ocean, land surface processes and hydrology. A prototype project is now in progress to develop and evaluate a first look system. This work has needed to develop and test new ocean and atmosphere (and land surface) configurations on a new domain – extending the atmosphere model domain relative to the operational configuration to provide sufficient coverage across the North-West Shelf and increasing the horizontal resolution of the ocean component relative to the AMM7 operational configuration to be comparable with the atmospheric resolution. Initial evaluation of the first coupled atmosphere–ocean system is currently under way. The immediate development priority is to add a wave model component to begin to represent and evaluate three-way interactions acting on a variety of timescales between ocean, atmosphere and the surface wave field.

3.5.2 Global systems

The leading order impact of including an interactive ocean model as part of a coupled operational NWP system is that the atmosphere will see a more realistic evolving sea surface temperature (SST) during the forecast period. It is therefore expected that the main benefits will be in regions where there is a large diurnal SST range (particularly the tropics) or where ocean surface temperatures can change rapidly due to large heat fluxes or strong ocean mixing processes. Previous work (e.g. Kim et al., 2010) has shown that permitting high frequency SST variability (by coupling atmosphere and ocean components at least every few hours) has significant benefits in the tropics by allowing a better phase relationship between SSTs and convection, and increasing the ability of models to forecast the spatial and temporal evolution of the Madden–Julian Oscillation (MJO). As mentioned above indications of improved MJO predictions have already been seen in Met Office coupled systems (Shelly et al., 2014). There is also evidence that mid-latitude storm generation and evolution can be better predicted in a forecast model with an interactive ocean and atmosphere. Such benefits are expected to be more fully realised once the ocean model resolution is high enough to provide a detailed representation of the sharp SST gradients (associated with, for example, eddies) which can then strongly influence the atmospheric boundary layer. A number of studies (e.g. Janssen et al., 2013) have shown that using a coupled system has an impact on the evolution of slow moving tropical cyclones due to cooling of SSTs as heat is removed from the surface ocean. This is expected to correctly reduce the tendency of atmosphere-only models to otherwise over-develop such systems, particularly as the resolution increases.

Development towards using global coupled atmosphere/land/ocean/sea-ice prediction, including coupled data assimilation, for operational short-range forecasts at the Met Office continues. The coupled system is based upon the Global Coupled system (GC2) being developed for applications across all timescales (Williams et al., 2014) and therefore benefits from the significant development across the Met Office over the last decade for monthly, seasonal and climate coupled applications. A consistent atmosphere configuration is used for operational NWP. The ocean configuration (and ocean data assimilation) relies heavily on the existing ocean-only global Forecasting Ocean Assimilation Model (FOAM).

Modest improvements in coupled forecast skill (particularly in the tropics) compared to uncoupled atmospheric and ocean control experiments have been demonstrated and validation of coupled forecasts for provision of the Copernicus Marine Service forecasts showed improvements in some regions over FOAM (which benefits from higher resolution atmosphere forcing), although differences are relatively small. Given the FOAM and Numerical Weather Prediction systems are well-tuned and have been shown to perform extremely well when compared with international partners (e.g. Ryan et al., 2015) this is encouraging and one would expect significant benefits to be realised as the system matures.

In the configurations currently used, the SST field coupled to the atmosphere is from the top ocean model depth level which has thickness of $\sim 1\,\mathrm{m}$ and is coupled hourly. However it is known that net surface heat fluxes calculated from a 1 m layer instead of a skin SST can differ by $\sim 10\,\mathrm{W\,m^{-2}}$ (Brunke et al., 2008). A skin SST scheme is being developed to implicitly calculate skin SST and non-solar fluxes within the coupled model. Research is ongoing but the diurnal range in SST in the tropics is significantly improved when validated against satellite data.

Work is also ongoing to include a wave model component within the global coupled model system. There are a number of potentially important wave-atmosphere and wave-ocean interactions but the initial focus is on the wave-dependent surface roughness seen by the atmosphere model.

3.6 Ocean data assimilation

There are a number of different methodologies for data assimilation of varying levels of complexity and computational cost. The ocean forecasting systems at the Met Office use an incremental, first guess at appropriate time (FGAT) three-dimensional variational (3DVAR) data assimilation scheme, NEMOVAR (Waters et al., 2015a). This has a number of properties that make it suitable for operational use, not least the computational cost, and it produces good quality analyses and forecasts (Ryan et al., 2015). Improvements to this methodology are currently being considered. Ensembles are a useful tool for producing uncertainty estimates in forecasts at various lead times, and can therefore provide useful information about the short-range forecast errors required by data assimilation schemes. Pure ensemble-based data assimilation methods can suffer from sampling issues when small numbers of ensemble members are available. As this is likely to be the case for initial implementations of ocean ensemble forecasting systems at the Met Office, we intend to make use of the ensemble information using hybrid 3DVAR-ensemble data assimilation schemes. Initial work to implement the capability for using such a scheme in NEMOVAR has been completed (Weaver et al., 2015). Much work remains to be done though to develop an operational system based on this methodology.

As well as the planned improvements to the underlying data assimilation methodology, other aspects of the data assimilation are also being developed. For instance, data assimilation near the equator has been shown to induce spurious vertical motions which can adversely affect the biogeochemistry in coupled physical-biogeochemical models. Schemes to reduce the impact of physical data assimilation on vertical motions have been developed and implemented over the years (Bell et al., 2004; Balmaseda et al., 2007), but these schemes do not completely resolve the problem. Waters et al. (2015b) describes a new scheme (based on the ideas of Bell et al., 2004), which is shown to further reduce the variability in the spurious vertical velocities induced by physical data assimilation near the equator. Further work on this scheme, and implementation in the operational forecasting systems, is expected over the next year or two.

New data types often become available and are assessed for their suitability to be assimilated in the forecasting systems. Satellite Sea Surface Salinity (SSS) data from the SMOS and Aquarius satellites were assessed by Martin (2015) by comparing them to outputs of the FOAM system and showed some potential for future assimilation. The impact of assimilating data from animal-borne temperature and salinity sensors was assessed by Carse et al. (2015) and the temperature data from these platforms are now assimilated operationally, with the near real-time salinity data shown to degrade results. Data from the Sentinel-3 satellite (Donlon et al., 2012a) are expected to become available soon, and preparations for their ingestion into the operational ocean forecasting systems at the Met Office are underway.

Asides from the general desire to improve the data assimilation capability a number of new activities and challenges need to be addressed in the coming years. Data assimilation has (in the ocean forecasting community) been primarily developed for global or basin scale applications in forced mode (i.e. the ocean model is not coupled to an atmosphere). The development of coupled ocean/atmosphere systems for short-range forecasting means that assimilation schemes need to adapt to this change. A significant recent step forward has been in the setting up of a prototype "weakly coupled" atmosphere/land/ocean/sea-ice data assimilation system described by Lea et al. (2015). The system is termed weakly coupled as the data assimilation schemes for the ocean and atmosphere both take as their initial background state the output from a coupled model and add increments to the coupled model, but do not include any information from the ocean when calculating the increments in the atmosphere, and vice versa. Initial results from a weakly coupled data assimilation system are promising, for example giving reduced SST increments as a result of a better balanced system. The impacts on the forecast skill are presently modest though, and further work is required to tune the system. On-going work to assess the future direction of coupled data assimilation includes the calculation of coupled ocean/atmosphere error covariances. This work will inform the decision of whether a fully coupled data assimilation system will be developed, and if so, the design of such a system.

The Met Office shelf-seas configurations have assimilated only SST data up to now. Work is underway to develop the assimilation of altimeter sea level anomaly data and temperature and salinity profile data in these configurations. This requires research into how best to make use of these data types in the presence of tides and a changing vertical coordinate, and how to deal with the sparseness of the data compared to the dominant time and space scales.

3.7 Quantifying skill

It is critical for the future utility of ocean forecasting services that there is a focus on quantifying and understanding the skill and uncertainty in ocean forecasting systems. Quantifying skill must include an evaluation of systems and components of systems prior to inclusion in a service (validation) and a continuous evaluation of the outputs of a service in operations (verification). Additionally, the quantification of uncertainty can be included as part of the validation or verification process, and is most robustly done using ensemble methods.

Historically, verification has been approached as a secondary activity, and has often been undertaken with a brief and often basic representation through summary statistics. Increasingly, there is a demand from users for clear information on accuracy which is relevant to the users' application, as well as a more considered approach as to which statistics are applied and reported. There is also the obvious scientific benefit from the insight that verification provides, and a good understanding of the system skill will drive priorities for model and system development. Focussing on the user aspect of verification will help to ensure that existing users make best use of the data, and give them an understanding of the confidence which can be placed in the forecasts. Model development priorities should be informed by knowledge of the errors which have greatest impact on users. Presently this is generally driven by a largely subjective attempt to understand user needs, but with improved user driven verification this can become increasingly objective.

Compared to Numerical Weather Prediction (NWP) and wave forecasting, the routine verification for ocean forecasts uses a very limited set of metrics, primarily mean and RMS error and in some cases Pearson correlation coefficient. Whilst providing a useful measure of the overall skill of the forecasts, these statistics can also give a misleading picture in more dynamic situations, especially as model resolutions increase. There is a danger of driving model development inappropriately unless these simpler statistical measures are augmented by more sophisticated and well-posed metrics. The development of these metrics is happening in various guises (see e.g. Divakaran et al., 2015 and Ryan et al., 2015). Lessons can be learnt from the science already done in other communities, particularly atmospheric science, but a significant research effort is needed to apply techniques to the specific nature of the ocean and the needs of the ocean users.

3.8 Summary

Ocean services in support of blue and green growth are available, and have evolved to meet a growing range of users needs. The Met Office has a wide range of applications that are increasingly supporting public and commercial organisations that operate in the marine environment. These services can and will be improved. This paper summarises the science priorities for driving these improvements. Science based services need to be supported by a balanced research programme. In this case, that means developing not only the underpinning science of the modelling systems and data assimilation but also the inputs to them, including observations and boundary conditions. Coupled modelling provides one means (albeit a costly one) to do this. Methods to initialise analysis and prediction systems will continue to improve, and increasingly probabilistic information will become available to users, improving the utility of the services. Systematic and appropriate evaluation of product skill, in a user focused way, is still in need of considerable research, but must underpin all of the aforementioned activities to ensure that the research activities both lead to scientifically justifiable, and known, quantifiable, changes to the products.

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Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

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Title Page
Abstract Introduction
Conclusions References
Tables Figures
I◀ ▶I
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion