OceanPredict
Advancing the science of ocean prediction

National Report, 2020.

a. **UK – FOAM**

Background

Daily operational forecasts of open ocean variables have been produced using the Forecasting Ocean Assimilation Model (FOAM) system since 1997, which provides the main UK contribution to OceanPredict. Operational forecasts for the North-West European shelf seas are also produced. In addition, a high resolution (0.05˚ grid) global Operational Sea Surface Temperature and Ice Analysis (OSTIA) product has been developed to take full advantage of sea surface temperature (SST) products made available through the Group for High Resolution SST (GHRSST).

A partnership called the National Partnership for Ocean Prediction (NPOP; http://oceanprediction.org) was launched in 2016, to develop and promote marine products and services, with a focus on national and public benefit. This partnership includes inputs from the Met Office, Plymouth Marine Laboratory (PML), the National Oceanography Centre (NOC) and the Centre for Environment, Fisheries and Aquaculture Science (CEFAS), with Marine Scotland and the National Centre for Earth Observation in the process of signing up to the partnership. The work of the partnership is organized through various working groups including physical ocean modelling, data assimilation, biogeochemical modelling, ecosystem modelling, surface waves, and observational requirements. A joint Met Office/NERC supercomputing facility called MONSooN enables sharing of code systems as well as running of joint projects, and aims to improve the pull-through of research into operational systems.

A number of systems in the UK are contributing to the EU Copernicus Marine Environment Monitoring Service (CMEMS). The main responsibilities from the Met Office within CMEMS include:

- Developing and maintaining an operational global coupled forecasting system.
- Developing and maintaining operational European North-West Shelf-Seas model products
- Developing and maintaining observation derived global SST products from OSTIA and the GHRSST Multi-Product Ensemble (GMPE).

1. Input data

Sea Surface Temperature

In situ sea surface temperature (SST) data are obtained over the Global Telecommunications System (GTS) and include data from ships, drifting buoys and moored buoys. Satellite SST data are obtained from various sources through GHRSST. The satellite data currently assimilated into FOAM include infrared data from SLSTR on board Sentinel-3A and Sentinel-3B, VIIRS on board Suomi-NPP and NOAA-20, AVHRR on board MetOp, geostationary infrared data from SEVIRI on board MSG, and microwave data from AMSR2 on board GCOM-W1. Improvements to the bias correction of satellite SST data have been developed by While and Martin (2019), and were implemented operationally in FOAM in Sep 2018.

Sea level

Satellite altimeter sea level anomaly (SLA) data are obtained through CMEMS from CLS/Aviso. These currently include Sentinel-3A, Sentinel-3B and Jason-3 data with data from CryoSat-2 and Altika about to be reinstated after a gap. For the shelf-seas forecasting systems, a regional version of these products is used which includes the various corrections including those for tides and the dynamic atmosphere. We add back in these signals to the assimilated data in the shelf-seas systems, but only assimilate the data in the deep part of the model domain (see King et al., 2018). Recent work has tested the impact of SWOT in the shelf-seas forecasting system in idealised OSSEs.

Profiles

All temperature and salinity profile data available over the GTS are assimilated in FOAM and, for the North-West Shelf-Seas, data available from CMEMS. These include data from moored buoys, profiling floats (including Argo), eXpendable BathyThermographs (XBTs), gliders and marine mammals (only temperature data, as the real-time salinity data was shown to be biased in Carse *et al.* 2015).

Sea-ice

Sea-ice concentration data from SSMIS satellites, obtained through the EUMETSAT Ocean and Sea-Ice Satellite Application Facility (OSI-SAF), are assimilated into FOAM. A European project called SEDNA is underway in which our role is to develop assimilation of satellite sea-ice thickness data into FOAM. This has shown that assimilation of daily freeboard measurements from CryoSat-2 is able to adjust the thick sea-ice to improve the quality of short-range sea-ice forecasts. The work was motivated by the study of Blockley and Peterson (2018) who found considerable improvement to seasonal forecasts by including CryoSat-2 thickness within the initialisation. Recent work has included the assimilation of data of thin ice made by SMOS using daily data sets, with the data assimilated alongside Cryosat-2.

Sea surface salinity

The assimilation and bias correction of daily satellite SSS data from SMOS, Aquarius and SMAP was developed and tested in the tropics during the 2015/16 El Nino through a set of coordinated observing system experiments with Mercator/CLS. A small positive impact was found from assimilating the satellite SSS data and is reported in Martin et al. (2019a). An inter-comparison of the impact of assimilating satellite SSS in FOAM and Mercator-Ocean systems has been reported by Martin et al. (2020). We hope to continue this work to bring it up to the standard for operational implementation.

Ocean colour

In the North-West European shelf-seas forecasting system, assimilation of ocean colour data is now operational. This uses data from OLCI on Sentinel-3, Aqua-Modis and SNPP-VIIRS. This data is assimilated into a coupled physical-biogeochemical model which also assimilates physical data.

2. Data serving

See section 5.

3. Models

The NEMO system is used within the UK as the primary tool for open ocean modelling and for use in the shelf seas forecasting systems. A global ¼º configuration has been run operationally for about 10 years with nested 1/12º resolution configurations in the North Atlantic, Indian Ocean and Mediterranean. The global model has 75 vertical levels and the regional configurations have 50 vertical levels, all with high resolution (1m) near the surface. The latest operational version of FOAM uses a configuration of NEMO 3.6 called GO6, described in Storkey et al. (2018). This is coupled to the GSI8 configuration of the CICE sea-ice model as described in Ridley et al. (2018). GO and GSI configurations are developed through a joint NERC-Met Office activity called the Joint Marine Modelling Programme. GO6 has a non-linear free surface, with time-varying vertical coordinates, and includes changes to the parameterization of near-surface vertical mixing. The grid of the model has also been extended to the south to improve modelling of Antarctic shelf-ocean exchanges, and to allow future implementation of ice cavities. Icebergs are also now explicitly modeled, with the aim of improving the input of fresh water. GSI8 includes multi-layer thermodynamics, with 4 layers of ice and 1 of snow, with temporally and spatially varying conduction that means the sea ice has heat capacity and thermal inertia. Also included within GSI8 is the addition of a prognostic model to describe the evolution of surface melt-ponds.

We are now in the final stages of parallel operational testing of a global 1/12° configuration, also based on the GO6/GSI8 ocean/sea-ice model. This will become fully operational before the end of 2020 and will replace the existing 1/4° global configuration as well as the regional systems at 1/12° resolution. Data from this system is primarily aimed at serving the UK Royal Navy.

Work is underway to move to using a new NEMO-based sea-ice model called SI^3. This combines aspects of the LIM3, CICE and GELATO sea ice models, and will be used in future versions of FOAM. Updating our ocean and coupled forecasting systems to a new version of the ocean and sea-ice models, both based on NEMO version 4, will begin in 2021.

The existing operational coupled model used for the coupled data assimilation work described later is at roughly 40km atmosphere resolution and 1/4° ocean resolution. The GC2 version of the HadGEM3 coupled climate model, the ocean/sea-ice component of which was used in the previous v13 FOAM system is running operationally for coupled short-range forecasting. A new coupled NWP system is under development in which the coupled model is the newer GC3 version (and will soon be moved to GC4), with the ocean configuration the same as the GO6 model used in operational FOAM. The resolution of this system is ¼ degree in the ocean, and about 10km in the atmosphere in its initial implementation. An upgrade of the ocean resolution to 1/12 degree is planned in future years. As well as this deterministic system, a coupled ensemble system is being planned for operational implementation. The ocean component of the ensemble will be the same as in the deterministic system with 1/4° resolution. The coupled deterministic and ensemble system (both at 1/4° resolution) is planned for operational implementation in 2021.

Regional models around the North-West European Shelf-Seas (NWS), also based on NEMO, have been running operationally for a number of years, coupled with the biogeochemical model ERSEM. The coupled physical-biogeochemical model is run at about 6km resolution. A physics-only configuration, based on the CO7 NEMO model described by Graham et al. (2018) with 1.5km resolution is also run operationally with assimilation of SST, SLA and profile data. A coupled ocean-wave version of the 1.5km resolution system, with the wave component using WaveWatchIII, has been developed and is now running operationally.

4. Assimilation method

A variational data assimilation scheme called NEMOVAR (developed by CERFACS, ECMWF, the Met Office and INRIA/LJK) is used to assimilate data in the operational FOAM systems. The scheme is based on the multivariate incremental formulation and is implemented in 3DVar first-guess-at-appropriate-time (FGAT) mode. The implementation of NEMOVAR in the global system at the Met Office, described in Waters et al. (2015), includes developments to the parameterization of error covariances, a variational bias correction scheme for altimeter data (Lea et al. 2008), a satellite SST bias correction scheme (While and Martin 2019), and sea-ice concentration assimilation. The scheme run operationally in the v14 FOAM system has two background error correlation length-scales. The longer length-scale of about 4 degrees, on top of the existing Rossby radius-dependent one, helps to constrain larger-scale errors in the sub-surface temperature and salinity fields, and is described in Mirouze et al. (2016).

The NEMOVAR scheme has been implemented in the new 1/12º global configuration described earlier. The resolution of the inner loop of the data assimilation is ¼º in the operational implementation in order for the data assimilation to be computationally feasible. Work to allow the data assimilation to be run at the same resolution as the model is underway which will make use of developments at INRIA to allow the diffusion operator (which models the background error correlations in NEMOVAR) to be run on lower resolution grids for certain error components. We can therefore model the long length-scale error covariances on a lower resolution grid within the inner loop in a multi-grid data assimilation capability, which will significantly reduce the cost of the data assimilation.

A major focus over the past year or so has been the development of an ensemble ocean capability and the use of the ensemble in a hybrid ensemble/variational data assimilation scheme. The global ocean ensemble uses an ensemble of data assimilation (EDA) approach with perturbed observation values and locations to generate an initial condition ensemble. Stochastic model perturbations are applied in NEMO using three schemes: stochastic parameter perturbations (SPP), stochastic perturbed parameterization tendencies (SPPT), and stochastic kinetic energy backscatter (SKEB). For testing in ocean/sea-ice only mode, we have been testing with an ensemble of atmospheric forcing coming from the Met Office ensemble prediction system (MOGREPS-G). The operational implementation of these ocean ensemble developments will be in the coupled version of MOGREPS-G. Recent work to assess the impact of using the ensemble in a hybrid ensemble/variational scheme has shown some significant improvements to the accuracy of the ensemble mean. Work is now underway to carry out some tuning experiments to set the hybrid weights and inflation factors.

Work has continued on the development of a weakly coupled data assimilation system as part of the coupled NWP implementation planned for 2021. A lower resolution system has been run operationally for a few years to deliver ocean products to CMEMS using the existing atmosphere data assimilation (hybrid 4DVar), land assimilation, ocean and sea-ice data assimilation (3DVar-FGAT), and coupled model

(HadGEM3) systems which are combined in Rose, the Met Office's wrapper for the Cylc workflow engine. The full atmospheric resolution (10km) version of this system, with updated model configurations and including the latest developments in ocean and atmospheric DA systems is now being trialled. At the same time, research is underway in collaboration with the University of Reading to better understand aspects of the coupled DA system, including the ensemble generation and its use in coupled DA, as well as investigating methods for dealing with the different timescales of the ocean and atmosphere.

Improving the assimilation of data into the regional shelf-seas forecasting system has been a focus over the last few years. Previously only SST data were assimilated in the NWS model operationally using NEMOVAR, but recent developments include the assimilation of temperature and salinity profile data throughout the domain, as well as altimeter sea level anomaly data in the deep part of the domain. The data assimilation has to deal with the temporally and spatially varying vertical coordinates, as well as dealing with the sparse sampling compared to the dominant physical processes on the shelf (including tides). Assessment of these developments showed significant reduction in short-range forecast bias and root-mean-square (RMS) errors compared with SST-only assimilation of up to about 30% for temperature profile innovations (King et al. 2018). This capability was implemented operationally in Spring 2017. More recently, assimilation of SST, SLA and T/S profiles has been implemented into the 1.5km resolution configuration (AMM15) shelf-seas forecasting system, and this is now running operationally. The latest update includes assimilation within the coupled ocean-wave 1.5km resolution forecasting system.

We have also recently been preparing for the launch of SWOT by running some OSSEs in the AMM15 system. This has shown promise, particularly in the deep part of the domain, but has highlighted known issues with SWOT data which will need to be dealt with over the coming year or so, namely the large, correlated observation errors. It has also highlighted issues with our attempts to assimilate the data in the shallower waters of the domain which are also being investigated.

A test of the assimilation of data into the WaveWatchIII system has also been carried out using NEMOVAR, with the results described in Saulter et al. (2020).

The ability to assimilate ocean colour chlorophyll data has been developed and is implemented in the next shelf-seas reanalysis for CMEMS, due to be released soon. This capability has also been implemented operationally in the North West European Shelf operational system.

5. Assimilation products and dissemination

Global ocean forecasts from the Weakly Coupled Data Assimilation system are delivered to users through CMEMS (http://marine.copernicus.eu). Forecasts from the European NWS system and analyses from OSTIA and GMPE are also disseminated through CMEMS.

Analyses and 6-day forecasts from the global and North Atlantic FOAM systems are available from the Met Office data wholesale service under licence (https://www.metoffice.gov.uk/services/data). FOAM data is also sent to the Royal Navy using secure communications links to deliver data directly. For research purposes, most FOAM data can be made available free of charge directly from the Met Office under licence.

6. Systems

As described above, the operational FOAM system includes a global ¼º configuration with nested 1/12º resolution configurations in the North Atlantic, Indian Ocean and Mediterranean, and shelf-seas systems at ~6km (coupled physical-biogeochemical) and at 1.5km (physics-only). The global configuration has 75 vertical levels, the regional configurations have 50 vertical levels, all with high resolution (1m) near the surface, and the shelf-seas configurations have 50 sigma-coordinate levels. FOAM configurations all run on a daily basis in the operational suite at the Met Office, starting at 05:00UTC and completing before 07:30UTC. Within this time the observations are extracted and quality controlled, the NWP fluxes are processed, a two day hindcast is run for each configuration assimilating all the data available for the previous two days, and a 6-day forecast is run. The outputs are post-processed in the operational suite and sent directly to the various dissemination routes described above.

A 1/12º global configuration is in the final stages of parallel testing and will be made operational before the end of 2020. This will deliver products to the Royal Navy. We plan to switch off the ¼º global ocean/sea-ice system and the regional 1/12º configurations in 2021.

The weakly coupled DA system has an atmospheric resolution of about 40km and the ¼º ocean. This system is run with a 6-hour data assimilation time window, and multiple assimilation windows are performed each day (going back 24 hours) to allow the system to use ocean observations which have a more significant delay in our receipt of them than atmospheric observations. This system has been assessed in an operational environment in terms of forecast skill compared to coupled forecasts initialised from uncoupled DA systems and is shown to provide better forecasts of SST than coupled forecasts produced from uncoupled DA. The ocean and sea-ice forecasts are now delivered from this system through CMEMS. In 2021 we plan to implement a coupled NWP system with increased atmospheric resolution (to 10km) and an updated version of the coupled model.

7. Observations - Links to (Argo, GHRSST, etc.)

GHRSST

The Operational Sea Surface Temperature and Sea-Ice Analysis (OSTIA) system (Good et al. 2020), developed and run at the Met Office, provides a major UK contribution to GHRSST. The GHRSST Multi-Product Ensemble (GMPE), which takes inputs from a number of objective analysis systems around the world and produces ensemble median and standard deviation fields, is also run at the Met Office (Martin et al. 2012, Dash et al. 2012). A number of UK SST scientists contribute to the GHRSST science team and its various working groups.

Argo

The UK contribution to Argo is managed by the Met Office and deploys a number of floats each year. Temperature and salinity observations from Argo profiling floats are assimilated operationally into FOAM. The Met Office has also been involved in the AtlantOS project to design improved observing systems in the Atlantic. A paper describing the coordinated AtlantOS OSSEs has been published by Gasparin et al. (2019) and a paper describing more detail with regard to the Met Office results has been published by Mao et al. (2020). A paper describing the impact of Argo data within the Met Office weakly coupled data assimilation system has also been submitted by King et al. (2019).

8. Internal metrics and intercomparison plans

Operational systems to provide verification of the ocean analyses and forecasts have been running for many years. Developments have been made to define file formats and systems to produce class 4 diagnostics, comparing forecasts against observations. These diagnostics are made available to OceanPredict partners as part of a routine OceanPredict inter-comparison initiative. Quarterly reports on product quality are made available as part of CMEMS at http://marine.copernicus.eu/services-portfolio/validation-statistics.

9. Targeted Users and envisioned external metrics

A major user of FOAM data is the UK Royal Navy that makes use of ocean data for a number of applications. Of particular interest are the impact of model dynamics on sound speed diagnostics, the development of biogeochemical and sediment systems in coupled physical-biogeochemical models, and the assessment and improvement of diurnal SST analyses and forecasts. A number of groups also make use of the North-West European Shelf-Seas model outputs. These include various users through the CMEMS programme.

Another application which is directly related to FOAM is the GloSea5 seasonal forecasting system at the Met Office which uses FOAM analyses to initialise its forecasts, and uses the same global ocean model as FOAM (but in a coupled configuration) to produce the forecasts. Development of the coupled ocean-atmosphere forecasting system described earlier will also provide the basis for potential future coupled NWP use, and products from the existing coupled forecasting system are provided to users through CMEMS.

10. Reanalysis activities

A new reanalysis covering the period from 1993-present is being carried out at the Met Office using the latest v14.1 global FOAM system described above (NEMO/CICE/NEMOVAR at 1/4° resolution with 75 levels).

A reanalysis of the European North-West Shelf has been produced and is disseminated via CMEMS. This covers the period 1990-2016 and is based on the NEMO model with assimilation of SST data and profiles of temperature and salinity, using the NEMOVAR scheme. This reanalysis also includes a coupled biogeochemical model (ERSEM). A new version is currently in production which also assimilates altimeter SLA data and satellite ocean colour data.

Reanalyses of SST using the OSTIA system have been carried out. The first version, covering the period 1985-2007 was reported in Robert-Jones et al. (2012). Reanalyses for climate users have also been developed as part of the European Space Agency Climate Change Initiative, most recently for the period late-1981 to 2016 (Merchant et al., 2019).

11. Computing resources

The Met Office's HPC facilities consist of a Cray XC40 system with 460,672 cores. The part of the HPC used for operational running is split between two computer halls to ensure operational levels of resilience and is used to run the operational ocean forecasting systems as well as reanalysis and research experiments. Ocean forecasting (research and operations) uses only a small fraction (a few percent) of these machines. A collaboration HPC (also a Cray XC40) is used for collaborative research integrations.

12. Consolidation phase and transition to operational system (activities)

All FOAM configurations are operational with full operational support including 24/7 operator cover, on-call arrangements for response to problems by scientific staff, backup procedures, and use of resilient systems. Developments to the operational systems are made through the development of parallel operational suites. These parallel suites are implemented during prescribed periods, with usually two planned upgrades each year.

13. OceanPredict related achievements and measures of success

Class 4 files, containing comparisons of forecasts with observations, are produced on a daily basis from the global FOAM system for temperature and salinity profile data, in situ SST data, altimeter SLA data and sea-ice concentration data. Other groups are contributing to this inter-comparison exercise.

System information overview

System name	**FOAM**
Ocean Models	
OGCM	NEMO
Domain	Global; regional in N. Atlantic, Indian Ocean, Mediterranean; shelf-seas in the NW European Shelf Seas (NWS)

Horizontal resolution	1/4º globally, 1/12º regionally and 1.5km shelf-seas. A 1/12º global system will be implemented operationally before the end of 2020.
Vertical sampling	75 levels in the global and 50 levels in the regional configurations, all with 1m resolution in the top 10m of the ocean. 50 sigma-coordinate levels in the shelf-seas.
Atmospheric Forcing	3 hourly surface heat and freshwater forcing, with 1 hourly winds, from Met Office NWP system A global coupled atmosphere/land/ocean/sea-ice forecasting system with the same ocean resolution is also run operationally, with atmosphere resolution of ~40km. A global coupled NWP system with coupled data assimilation, 10km atmospheric/land resolution and ¼º ocean/sea-ice resolution will be implemented operationally during 2021.
Assimilation characteristics	
Assimilation Scheme	NEMOVAR (3DVar-FGAT).
SST data	GHRSST data including SLSTR, VIIRS, AVHRR and AMSR2. Also in situ surface data from ships, moored buoys and drifting buoys.
SSH data	Along-track satellite altimeter data from Aviso, including Sentinel-3, Jason-3, and CryoSat-2 data.
In situ profiles	All available in situ temperature and salinity data including XBTs, Argo, CTDs, moored buoys, gliders, marine mammals.
Sea-ice data	SSMIS sea-ice concentration data from EUMETSAT OSI-SAF.
System Set-ups	
Forecast range	6-days
Update frequency	Daily
Hindcast length	2-day hindcast every day. Reanalysis back to early 1990s.
System website links	
General information	https://www.metoffice.gov.uk/research/modelling-systems/ocean-models
Technical description	https://www.metoffice.gov.uk/research/modelling-systems/ocean-models https://marine.copernicus.eu/
Viewing service	https://marine.copernicus.eu/

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