Chapter 15

THE FORECASTING OCEAN ASSIMILATION MODEL (FOAM) SYSTEM

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Abstract: We present a detailed technical description of the present FOAM system and discuss some representative examples of the scientific investigations we undertake to track-down problems within the system and to understand the importance ("impact") of the various inputs to it. We also provide an historical perspective on the development of the system and the changing demands for it, and describe the way in which we are adapting to meet these demands.

Keywords: Operational ocean forecasting, data assimilation, assessments.

1. Introduction

The Forecasting Ocean Assimilation Model (FOAM) is a system for assimilating oceanographic measurements into a coupled dynamical model of the deep ocean and sea-ice. It is used on a routine daily basis to make forecasts out to five days ahead representing/resolving the ocean's mesoscale structure in selected regions. The system has been developed with funding from the Royal Navy and is used to support their operations. It also provides boundary conditions for a shelf-seas forecasting system operated by the Met Office. We aim to demonstrate in the near future that its analyses and forecasts of ocean currents are sufficiently skilful to be useful for search and rescue, oil spill drift prediction, and the deep-ocean oil and gas industry. We are also exploring the application of the system to monitoring of open ocean ecosystems and air-sea CO_2 fluxes and management of fisheries and are likely to explore its application to short-range, coupled, atmosphere-ocean forecasts.

The second section of this chapter provides an overview of the FOAM system and a technical summary of its inputs, dynamical model and assimilation methods as they stood in the operational suite in August 2004. The third section attempts to give some insight into the intellectual

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challenges inherent in developing these systems. It describes some representative examples of scientific trouble-shooting and some investigations of the impact of new observations and changes to assimilation methods on the performance of the system. The final section attempts to give an historical perspective. It summarises first the 20-year history of the FOAM project and then the changing world context in which it has been developing. Finally four major changes in the direction of the FOAM project are described and related to this changing context.

2. Description of the FOAM system

2.1 Overview and present configurations

The FOAM system produces 5-day forecasts of three-dimensional ocean temperatures, salinities and currents and sea-ice properties on a routine daily basis. It assimilates temperature profile data, surface height data from satellite-borne altimeters and satellite and in situ surface temperature data and is driven by 6-hourly surface fluxes from the Met Office's Numerical Weather Prediction (NWP) system. High resolution model configurations are nested inside the global configuration. Statistics on the differences between the model forecasts and observations are routinely produced and reanalyses can be generated from 1997 onwards.

The FOAM configurations that are presently run on a routine daily basis within the operational suite at the Met Office cover the globe with a 1° grid; the Atlantic and Arctic Oceans and the Indian Ocean with 35 km grids; and the North Atlantic, the Mediterranean Sea and the Arabian Sea with 12 km grids. An Antarctic configuration with a 27 km grid is also run on a daily basis and is to be transferred into the operational suite in the first half of 2005. All of these configurations have 20 vertical levels. The global, Atlantic and Arctic, and N Atlantic configurations are illustrated in figure 1.

2.2 Inputs

Six-hourly full-resolution **surface-flux** fields from the global forecasts by the Met Office's NWP system to 5-days ahead are currently used to drive all the FOAM configurations (in future fluxes from limited-area forecasts will drive some configurations). The flux fields used are the wind stress (vector with two components), wind mixing energy, penetrating heat flux, non-penetrating heat flux and precipitation minus evaporation. The NWP system calculates fluxes over sea-ice and open water ("leads") separately and combines them using sea-ice concentration analyses generated by NCEP. The surface temperature and salinity fields are also weakly relaxed towards the monthly Levitus et al. (1998) climatologies.

The global configuration is also driven by climatological monthly **river inflow** data from the Global Runoff Data Centre (GRDC) with the outflows from the largest 20 rivers adjusted to accord with Baumgartner & Reichel (1975).

Temperature and **salinity profile** data are assimilated at all depths (see section 3.1). In the operational system the data are obtained from BATHY, TESAC and BUOY messages distributed by the Global Telecommunications System (GTS). These message formats are used to report expendable bathythermograph (XBT) data reported by Voluntary Observing Ships (VOS), and data from the Argo profiling floats and TAO/Triton equatorial moorings respectively. Quality control checks on these data include track, stability, background and buddy checks (Ingleby & Huddleston 2004).

Altimeter data from the Jason-1, Envisat and Geosat Follow-On (GFO) satellites are assimilated in all but the global configuration using products supplied twice a week by Collecte Localisation Spatiale (CLS) in Toulouse.

In situ **surface temperature** data from ships and drifting and moored buoys are assimilated. At present only advanced high resolution radiometer (AVHRR) data on a coarse grid (2.5^{o} spacing) are assimilated. All these data are distributed by the Global Telecommunications System (GTS). We will upgrade to using GODAE High Resolution SST (GHRSST) satellite data products when they become available.

Sea-ice concentration fields supplied by the Canadian Met Centre (CMC) on a daily basis are also assimilated. These fields are based on SSM/I (special sensor microwave imager) data processed using the York/AES algorithm (Ramseier et al. 1988).

2.3 Dynamical model

Storkey (2004) provides an excellent summary of the formulation of the physical ocean and sea-ice models used by FOAM in July 2004. The ocean model code, which originated from the Bryan-Cox code (Bryan 1969, Cox 1984), is developed jointly with groups in the Hadley Centre who use it for climate prediction. The FOAM formulation is quite close to that used by HadCM3 (Gordon et al. 2000).

Various bathymetries (Smith & Sandwell 1997, DBDB2 and GEBCO) have been used in building the present configurations. The bathymetry after interpolation to the model's grid is smoothed twice using a 1-4-1 filter. Grid-scale holes are filled to avoid an instability (Pacanowski & Griffies 1999) which appears to be associated witih the B-grid staggering of variables and the depth and width of important channels are adjusted using Thompson (1996) as a reference. At open boundaries of nested models the bathymetry in the relaxation zone (see below) is reset to be as similar as possible to the model providing its boundary data. Tests of the impact of code to achieve a smoother bathymetry using partial bottom cells (Pacanowski & Gnanadesikan 1998) are in progress.

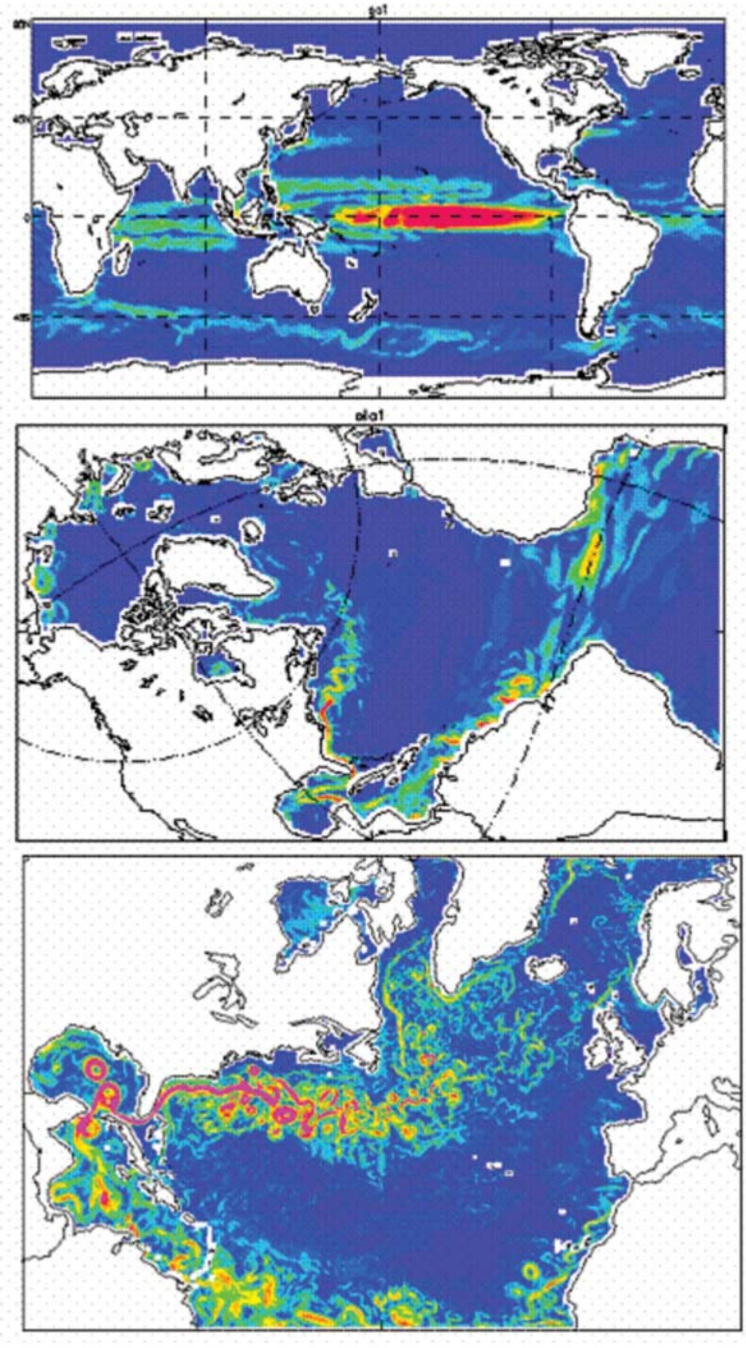

Figure 1. Surface current speeds in the FOAM global, Atlantic and Arctic, and North Atlantic configurations.

The limited area models use the Flow Relaxation Scheme (FRS) (Davies 1983, McDonald 1997) as boundary conditions for all prognostic variables (including temperature, salinity and horizontal velocity components). This relaxes the model fields in the inner model towards those in the outer model over a relaxation zone typically 4-8 gridpoints wide, the strength of the relaxation increasing as the outer edge of the inner model is approached. (When FOAM transitions to a free-surface we will transition to Flather conditions for the external modes.) Most of the limited area models use a rotated latitude-longitude grid to achieve for given resolution the largest minimum grid-spacing Δx. This allows a longer time-step to be used. At present resolutions it has been found that the maximum model timestep Δt is limited by the CFL criterion $2(c+u)\Delta t < \Delta x$ in which c is the speed of fastest internal waves (about 3 m/s), u is the fastest advecting velocity in the model and the factor of 2 arises from the use of the leapfrog scheme.

The prognostic equation for horizontal momentum is similar to that in the Bryan-Cox code except that the advection of momentum uses the Webb (1995) scheme and a simple quadratic bottom friction with $C_D = 0.00125$ is used to crudely parametrise tidal mixing. To increase the timestep that can be used the Coriolis term is calculated semi-implicitly in coarser resolution configurations, and the pressure gradient is averaged across timesteps in higher resolution configurations (Brown & Campana 1978). A combination of harmonic and biharmonic viscosities is used to damp gridscale noise and westward migrating eddies. The choice of parameters has a significant impact on the model simulation (Chassignet & Garraffo 2001). The barotropic flow is represented by a streamfunction using the rigid-lid approximation (see Storkey 2004 for details).

The prognostic equation for tracers presently uses a form of third-order upwind advection similar to Holland et al. (1998). A combination of a less diffusive advection scheme and the thickness diffusion scheme of Gent & McWilliams (1990) is being trialled as an alternative. The Griffies et al. (1998) formulation of isopycnal diffusion is employed.

The formulation of vertical mixing is explained by Gordon et al. (2000) and Storkey (2004). Momentum and tracers are mixed using the Pacanowski & Philander (1981) scheme and a simplified form of the Large et al. (1994) scheme. In addition tracers are mixed using a mixed-layer energetics scheme based on Kraus & Turner (1967) and Davis et al. (1981). Convective adjustment of tracers is performed by applying the Roussenov scheme (Roether et al.1994) followed by the Rahmstorf (1993) scheme.

The thermodynamic component of the **sea-ice** model uses the zero-layer model of Semtner (1976) and Hibler's (1979) formulation for leads processes. The dynamic component is based on Bryan et al. (1975): the ice concentration is advected using the top-level ocean currents and smoothed using Laplacian diffusion. The EVP formulation of Hunke & Dukowicz

(1997) and ice thickness distribution scheme of Lipscomb et al. (2001) are being trialled.

2.4 Assimilation methods

Data assimilation is based on a new version of the analysis correction (a/c) scheme. The a/c scheme was originally devised by Lorenc et al. (1991) and implemented for FOAM by Bell et al. (2000a). The new version (Bell et al. 2003) provides a sub-optimal approximation to a variant of 4D variational assimilation. Analysis steps are performed once per day. Each observation makes its full impact on the model on the day it arrives and on subsequent days is taken into account by giving additional weight to the model at the observation's location. Each analysis step consists of a number of iterations. On each iteration the observations are separated into groups which are easily related (thermal profiles, saline profiles, surface temperature, surface height). For each group of observations (e.g. the temperature profile data), increments are calculated first for the directly related model variables (e.g. the temperature fields). These increment fields are then used to calculate increments for less directly related model variables (e.g. the velocity fields) using hydrostatic and geostrophic balance relationships, water property conservation or statistical relationships. These balancing increments make the analysis multivariate. Increments are also made to the observations (Bratseth 1986) so that the iterations converge towards the statistically optimal analysis. The univariate components of the model error covariance are specified as the sum of two 3D error covariances, one describing the ocean mesoscale, the other large scales including atmospheric synoptic scales (Martin et al. 2002). These and the observation error covariances are estimated from statistics of observation minus model values obtained from hindcast assimilations. Altimeter data are assimilated by displacement of isopycnal surfaces (an extension of the Cooper & Haines 1996 scheme). A pressure correction technique (Bell et al. 2004) is employed to improve the dynamical balance near the equator (see section 3.1) and analyses performed with large correlation scales are used to attempt to remove large-scale biases in the AVHRR surface temperature data.

3. Trouble-shooting, assessments of impact and developments

3.1 Trouble-shooting

Bell et al. (2004) report a serious problem encountered assimilating thermal profile data into the global FOAM configuration in the equatorial Pacific region where the TAO moorings provide good observational coverage. Figure 2 shows the annual mean temperature increments applied by the assimilation scheme along the equator. The units are ^{o}C per month. Just below 100 m depth, between 150^{o}W and 120^{o}W, over the course of a year the assimilation scheme is decreasing the temperature by as much as 30 ^{o}C! Since the change in temperature over the course of a year is a small fraction of this, it is clear that in this integration the ocean model must be increasing the temperature at this location by a similar amount. Since internal sources and sinks of heat are relatively small, the change in temperature is due to advection. Diagnostics of the vertical velocities confirm that they are much stronger at and below 100 m depth when the model is assimilating data than when it is not assimilating data. Bell et al. (2004) propose a dynamical explanation for these spurious over-turning circulations and suggest that the problem arises from inaccurate parametrisation of the downward mixing of momentum input by the wind stresses acting on the ocean surface. Assuming that these inaccuracies result in a slowly varying bias in the momentum equation they propose a scheme to estimate the bias using the observational data. Huddleston et al. (2004) show that the scheme is quite effective in reducing the vertical circulations and the net heat input by the assimilation scheme and improves the zonal currents along the equator in integrations using a number of wind stress products.

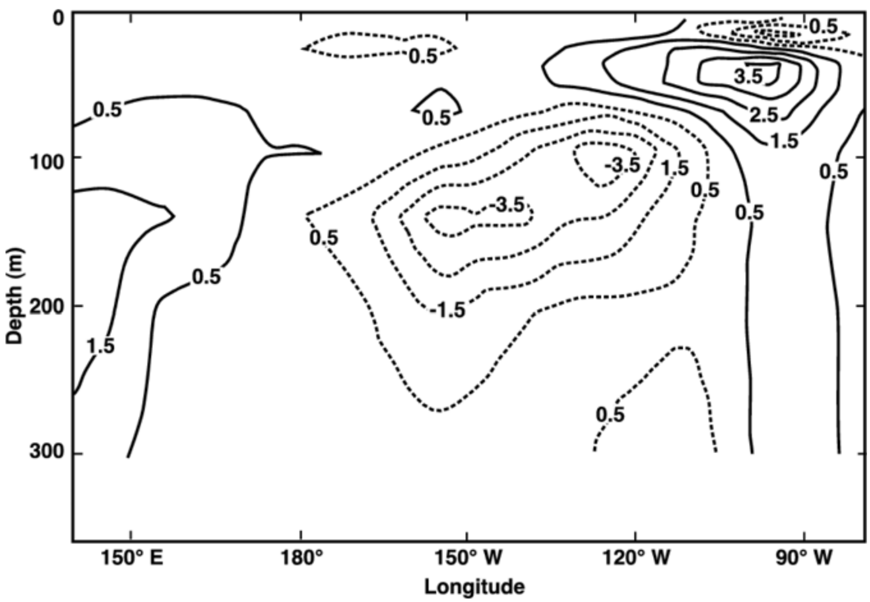

Figure 2. Annual mean potential temperature increments (^{o}C per month) for a cross-section along the equator between 140^{o}E and 90^{o}W. Negative contours are dashed.

It has been found that the assimilation of temperature and salinity data below 1000 metres depth can have major impacts on the barotropic flow and the meridional overturning in the FOAM system. The version of the FOAM system implemented in 1997 deliberately excluded observational data below 1000 metres depth because of the deleterious impact of occasional deep observations in the Gulf Stream region (Bell 1994). With the advent of the Argo system it is highly desirable to assimilate both temperature and salinity data at all depths (see next sub-section). It is important for the quality control of the Argo data to detect suspect observations, particularly those with depth independent offsets.

Small-scale noise in ocean forecasts is undesirable for several reasons. Storkey (2004) describes how biases in model integrations can develop from small-scale noise when upwind vertical advection schemes are employed. He found that for these advection schemes reducing the horizontal viscosity below a certain limit led to significant biases within the thermocline.

3.2 Assessments of impact

In order to prioritise developments one would like to be able to predict what the impact of a given development is likely to be. Should one give highest priority to the use of additional observational data, to improvements to the assimilation scheme or to the dynamical model?

Figure 3 shows the impact on verification statistics of assimilating Argo profile data into the FOAM 1° model. The statistics are root mean square differences between profile observations and model fields valid the day before the observations (i.e. fields in which the observations have not been assimilated). All the model integrations covered the period January to May 2003, were forced by 6-hourly NWP fluxes and were started from the operational analysis for 1st January 2003. A "control" integration assimilated no data; a second integration assimilated only salinity profile data from Argo; a third assimilated only temperature profile data from Argo and the final integration assimilated both temperature and salinity profile data. No other data were assimilated and an early version of the new assimilation scheme was used.

It is clear that the Argo data have a major beneficial impact on the model fields but several points of detail are worth noting. First much of the impact in the deeper temperature and salinity fields arises from corrections to biases in the model fields which had accumulated in the operational model since 1995 when the integrations were initialised. Second the assimilation scheme does not attempt to conserve T/S properties (Troccoli & Haines 1999). It is likely that assimilation of temperature data only using T/S conservation ideas could produce better salinity analyses. Third, assimilation of salinity data only degrades the temperature fields compared to the control and similarly assimilation of temperature data only degrades the salinity fields.

Assimilation of temperature and salinity data produces markedly better salinity statistics than assimilation of just salinity data and slightly better temperature statistics than assimilation of just temperature data. These results may be explained by the impact of the assimilation on the advecting velocity field but this hypothesis has not been verified in detail.

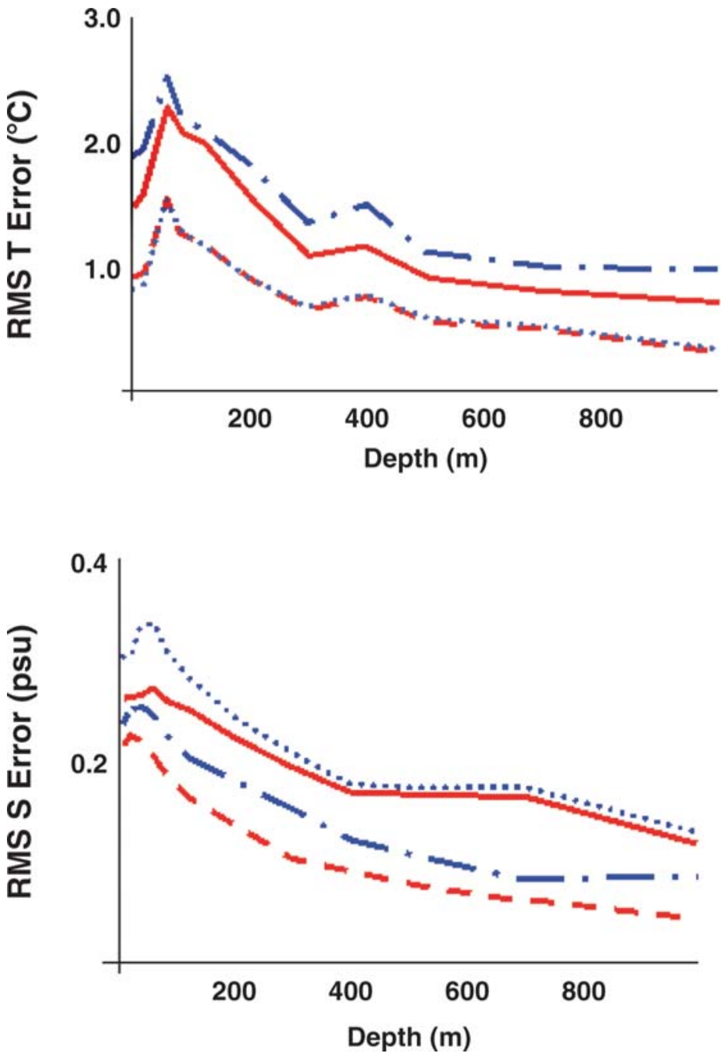

Figure 3. Impact of assimilating Argo data on FOAM global model: no assimilation - full line; temperature data only – dotted; salinity data only - dot dash; temperature and salinity data – dashed.

The impact of the representation of the background error covariance on the effectiveness of the data assimilation is also of considerable interest as differences between most assimilation schemes can be interpreted as differences in the representation of the background error covariance. Figure

4 gives a simple indication of the importance of the background error covariance for assimilation of SST data into the global FOAM configuration.

The r.m.s. difference between the model and AVHRR satellite observations just before they are assimilated is again taken as an indication of the effectiveness of the assimilation. The original FOAM scheme with a 300 km correlation scale produced the rms scores indicated by triangles and a version of the scheme using two iterations, one with a 500 km correlation scale and one with a 100 km correlation scale produced the scores indicated by crosses. A number of other tests (including ones in which biases in the satellite data are estimated) indicate that it is important to cover a range of scales in analysis of SST data but that the results are not particularly sensitive to the details of how this is done.

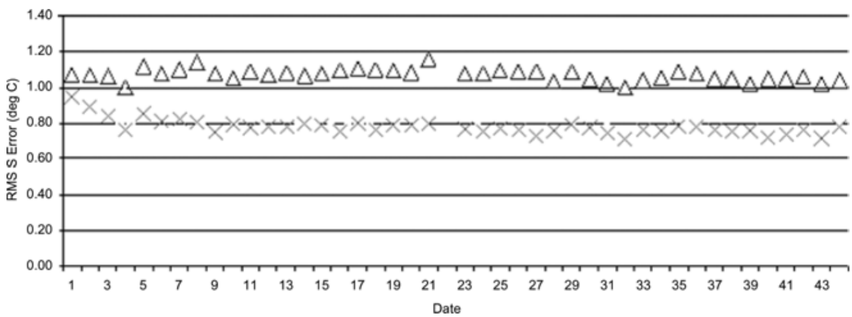

Figure 4. Time-series of global average root mean square differences between model fields and satellite SST observations prior to their assimilation. Assimilation used one scale of 300 km for triangles and two scales of 500 km and 100 km for crosses. The ordinate is the day number. Day 1 is 22 January 2001. See text for more details.

4. Historical perspective

4.1 A history of the development of the FOAM system

The first proposals for the development of a FOAM system to make daily forecasts of the three-dimensional temperature, salinity and current structure of the ocean and of sea-ice were written in 1985 by Howard Cattle & Adrian Gill. Developments started in 1988 and by the end of 1994 a global configuration of FOAM on a 1^o grid with 20 vertical levels, driven by six-hourly surface fluxes and assimilating temperature profile data, was being run on a daily basis (Alves et al. 1995). This system was adapted for introduction into the operational suite used for numerical weather prediction in November 1996. Its assimilation scheme was described in some detail by Bell et al. (2000a). A simple sea-ice assimilation scheme and improvements to the representation of atmospheric surface fluxes over water partially covered by sea-ice were introduced in July 1999 (Bell et al. 2000b). Significant amendments to the advection and diffusion within the ocean model were introduced in September 2000. A configuration of FOAM covering the North Atlantic and Arctic oceans with a 1/3° grid, nested inside the global model, was introduced into the operational suite in January 2001 and assimilation of altimeter data based on the Cooper-Haines scheme (Cooper & Haines 1996 and Forbes 1996) was introduced in November 2001. The capability to implement quickly high resolution configurations for new areas was also demonstrated in 2001. Daily pre-operational running of a North Atlantic configuration with a 1/9° grid and distribution of the output via a Live Access Server first for GODAE and then for the MERSEA intercomparison project started in April 2002. The major changes to the assimilation scheme described in section 2.3 were introduced into the operational suite in November 2003 and July 2004.

4.2 Changing priorities

The FOAM project was devised towards the end of the Cold War and the development of FOAM has been supported largely by Navy funding. By 1995 the Navy's requirement for high-resolution open ocean forecasts had weakened and the main value of deep ocean forecasts was seen to be in the provision of boundary conditions for forecasts of shelf-seas and coastal waters. The Met Office started to collaborate with Proudman Oceanography Laboratory (POL) to implement a shelf-seas system for the North-West European continental shelf. Configurations of POLCOMS (POL Coastal Ocean Model System) have been run in the operational suite at the Met Office since June 2000.

Proposals for a Global Ocean Data Assimilation Experiment (GODAE) and an Argo system of autonomous profiling floats emerged during 1997. Since then the Argo system has revolutionised the sub-surface in situ observing system. GODAE is motivated by the need to demonstrate the value of the oceanographic observational networks; both space-based (e.g. altimeter, scatterometer and surface temperature) and in situ. This is essential to justify their transition from research to operational funding and urgent in view of the extended planning periods and expense of satellite programs. In order to accelerate this demonstration, the International GODAE Steering Team (IGST) has championed open scientific collaboration. This includes open access to the inputs to the systems (e.g. surface fluxes) and forecasts from them, shared documentation of the input and output data sets, development of shared tools for serving of data and products, and detailed intercomparisons of methods and results.

During 2001, the European Commission (EC) and European Space Agency (ESA) started to implement the GMES (Global Monitoring for Environment and Security) program which aims to supply the environmental information needed to formulate and monitor policies for sustainable management of the environment. In the oceans there is a particular emphasis on coastal regions, management of pollution and the health of biological ecosystems.

Freely distributed “community” ocean models (such as MOM, HYCOM and ROMS) have been developed in the USA for two decades. In the last 5 years, flexible software tools (such as PRISM) for generating complex earth system models from component models (e.g. of the atmosphere, ocean and sea-ice) have started to gain maturity. Within Europe collaborative projects (e.g. EnAct) have started to compare data assimilation methods for ocean models.

4.3 Response to Changing Priorities

The Met Office is adapting its program for ocean forecasting in response to these changing priorities and the improved climate for collaboration and coordination.

First, it is starting to transition all of its ocean modelling activities (including seasonal forecasting and climate prediction) to use the NEMO (Nucleus for European Modelling of the Ocean) code. NEMO will be jointly owned by a consortium (including CNRS, Mercator-Ocean and the Met Office) who undertake to maintain and develop it. It will be freeware, the aim being to encourage a wide range of ocean modellers to use it and to contribute to its development. NEMO will be based on the OPA code and developed for use in shelf and coastal waters in addition to the deep ocean. It will be coupled to other models at the Met Office through a Flexible Unified Model Environment (FLUME) which will build on experience gained within PRISM.

Second, the Met Office is actively engaged in the Mersea (Marine Environment and Security in the European Area) project, which is building the open ocean component of the monitoring and forecasting system required for GMES. Mersea aims to improve the collaboration and coordination between European ocean forecasting systems and the Met Office is actively supporting this aim.

Third, a National Centre for Ocean Forecasting is being established at the Met Office in association with four of the NERC (Natural Environment Research Council) institutes (namely Proudman Oceanography Laboratory (POL), Plymouth Marine Laboratory (POL), Southampton Oceanography Centre (SOC) and Environmental Systems Science Centre (ESSC)).

The fourth initiative aims to strengthen the awareness within relevant UK government departments and the offshore industry of our growing capabilities in ocean forecasting and to work together to assess their needs and to develop the capabilities to meet them. The Ocean Customer Group formed to do this includes government departments with responsibilities for marine pollution and search and rescue (Maritime Coastguard Agency), water quality, fisheries and coastal flooding (Environment Agency and Dept for Environment, Food and Rural Affairs), environmental impact assessments and offshore wind farms (Dept for Trade and Industry), and representatives of the oil industry.

Together it is hoped that these initiatives will consolidate the UK contribution to operational oceanography, strengthening the scientific input into it, the coordination and collaboration with European colleagues, and enabling it to evolve to meet the UK needs for environmental management.

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