**Ocean Science Discussions**

# Validation of the NEMO-ERSEM operational ecosystem model for the North West European Continental Shelf

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**Abstract**

This paper details updates to the Met Office's operational coupled hydrodynamic-ecosystem model from the Medium-Resolution Continental Shelf – POLCOMS-ERSEM (MRCS-PE) system (Siddorn et al., 2007) to the 7 km Atlantic Margin Model NEMO-ERSEM (AMM7-NE) system. We also provide a validation of the ecosystem component of the new operational system. Comparisons have been made between the model variables and available in situ, satellite and climatological data. The AMM7-NE system has also been benchmarked against the MRCS-PE system. The transition to the new AMM7-NE system was successful and it has been running operationally since March 2011 and has been providing products through MyOcean (http://www.myocean.eu.org) since July 2011. The results presented herein show the AMM7-NE system performs better than the MRCS-PE system with the most improvement in the model nutrient fields. The problem of nutrient accumulation in the MRCS-PE system appears to be solved in the new AMM7-NE system with nutrient dynamics improved throughout the domain. Improvements in model chlorophyll are also seen but are more modest.

# 1 Introduction

Continental shelf seas provide an important link between the land and the open ocean and mediate the transport of material such as nutrients, carbon, pollutants, and freshwater between them. The shelf seas are also the regions where most of the human interactions with the marine environment occur including leisure and recreation, aquaculture and fisheries, extraction of raw materials such as aggregates, oil and gas, and renewable energy (wind, wave, and tidal). These regions are highly productive with nutrient fluxes from both the open ocean and river runoff and are regions of generally rapid biogeochemical cycling (Gattuso et al., 1998). The shelf seas are a disproportionately important component of the marine environment: while they occupy less than

10 % of the area of the world's oceans, they account for up to 30 % of the ocean's primary production (Smith and Hollibaugh, 1993; Longhurst et al., 1995), include the major fisheries of the world (Pauly and Christensen, 1995), and may be important in global carbon budgets (Holt et al., 2009).

One important tool used to gain better understanding of the state of the shelf seas ecosystems is ecosystem modelling. Ecosystem models have been developed for a wide range of applications from process-oriented models designed to gain better understanding of shelf seas biogeochemical cycles, nutrient fluxes and pathways (e.g., Proctor et al., 2003) to application-based models designed to improve understanding of the effects of such things as eutrophication (Nobre et al., 2005 and references therein), fish farms (Wild-Allen et al., 2010) and aquaculture (Tsagaraki et al., 2011), hypoxia (Russo et al., 2009) and harmful algal blooms (HABS, see McGillicuddy, 2010 and the Special Issue on GEOHAB Modelling). Coupled 3-dimensional hydrodynamic-ecosystem models can simulate the biogeochemistry of coastal ecosystems and be used to explore a range of alternate situations or possible futures to provide a synthesis of how a particular ecosystem works (e.g., Moll and Radach, 2003; Popova et al., 2002) or to explore alternate states under a range of management scenarios (Petihakis et al., 2007; Wild-Allen et al., 2010).

Operational ecosystem models allow the near real time estimation of the state of the system and provide the only practical means of providing a snapshot of the complex 4-dimensional structure of the shelf and shelf-edge waters including the connection between the shelf seas and the open ocean. Operational systems, in this context, describe automated systems that run regularly in real-time or near-real-time such as that at the Met Office. These systems have been set up to provide support for scientific, coastal management and naval objectives, among others, in regional systems and use a variety of modelling tools and observations. Operational (or pre-operational) systems in the United States are being set up to provide regional forecasts of harmful algal blooms and water quality in the Great Lakes, coral bleaching in relation to ocean water temperatures, and pink salmon harvest in Southeast Alaska (Green et al.,

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2009). Also in the United States, the Naval Research Laboratory (NRL) has implemented a coupled hydrodynamic-biogeochemical model in the Gulf of Mexico (the Gulf of Mexico Modelling System, GOMMS) on an operational basis (de Rada et al., 2009). In the Mediterranean, an operational forecast system which includes ecosystem modelling at both the basin scale and sub-regional and shelf scales has been developed and provides algal biomass forecasts, estimates of coastal sediment transport and is being used in fish stock assessments (Lazzari et al., 2010; Pinardi and Coppini, 2010). Roiha et al. (2010) present an operational ensemble approach to forecasting HABs in the Baltic Sea while Glibert et al. (2010) provide a review of forecasting models of HABs in eutrophic systems. Coupled hydrodynamic-ecosystem models are also being used operationally to forecast hypoxic events in the Adriatic (Russo et al., 2009) and Gulf of Mexico (Justic et al., 2007).

The MRCS-PE shelf seas hydrodynamic-ecosystem system has been run daily since 2007 at the UK Met Office. It is described and validated in Siddorn et al. (2007) and is based on the POLCOMS hydrodynamic model (described further below) and the ERSEM model for the marine ecosystem component. It was used with Ferrybox data to evaluate the leak of phosphoric acid from the wreck of the MV Ece in the English Channel in 2006 (Kelly-Gerreyn et al., 2007). One important application of the shelf-seas coupled system is to provide support for the UK agencies responsible for ecosystem health, water quality monitoring and nuisance algal bloom prediction. The Met Office, Plymouth Marine Laboratory (PML) and the Environment Agency (EA) have been working on a joint project, AlgaRisk, designed to develop a forecasting tool as a demonstration service for forecasting water quality and nuisance algal blooms (Mahdon et al., 2010). The system has also been used as part of the European COastal-shelf sea Operational observing and Forecasting system (ECOOP; http://www.ecoop.eu) to provide ecosystem boundary conditions on an operational basis to European partners for regional models within the MRCS domain. Most recently, daily analysis and forecasts from the ERSEM biological variables for the North West European Shelf (NWS) are being delivered via the MyOcean project (http://www.myocean.eu.org) as part of the

prototype for the GMES (Global Monitoring for Environment and Security) programme.

This paper details updates to the Met Office's operational coupled hydrodynamic-ecosystem model for the NWS from the system described in Siddorn et al. (2007) along with a validation of the ecosystem component of the operational system. O'Dea et al. (2012) describes the transition to the NEMO system for the hydrodynamics while this paper concentrates on the relevant changes to the biogeochemical component, ERSEM. Comparisons have been made between the model variables and available in situ, satellite and climatological data.

This paper is structured as follows. Section 2 provides a description of the new coupled AMM7-NE system highlighting differences from the MRCS-PE system described in Siddorn et al. (2007) along with the setup of the model hindcast runs, the data used for comparison and the metrics applied for skill assessment. Section 3 presents the results which are discussed in Sect. 4 and concluding remarks are provided in Sect. 5.

## 2 Materials and methods

### 2.1 System description

For the UK shelf-seas operational modelling at the UK Met Office, the underlying physical model has recently been transitioned to the NEMO (Madec, 2008; Storkey et al., 2010) framework adapted for use on the 7 km Atlantic Margin Model (AMM7) domain. This model has been coupled to the ERSEM (Baretta et al., 1995; Blackford et al., 2004) biogeochemical model. The AMM7-NE configuration includes the assimilation of sea surface temperature (SST) using an adaptation of the existing Forecasting Ocean Assimilation Model (FOAM; Martin et al., 2007) system suitable for use in the shelf seas.

Both the MRCS-PE and the AMM7-NE models are part of a system of one-way nested hydrodynamic operational models as shown in Fig. 1. This series of nested domains provides 3-D boundary conditions for the regional models (sea surface height,

temperature, salinity and current fields). The model (in both the MRCS-PE and AMM7-NE) is forced at the surface by fluxes (three-hourly means of heat and moisture and hourly fluxes of winds and pressure) from the global Met Office Numerical Weather Prediction (NWP) model. The NWP model has a horizontal resolution of approximately

5   25 km. River flow is specified for 320 European rivers (Young and Holt, 2007).

However, both the domain and the hydrodynamic component have been changed for the new AMM7-NE. Previously, the coupled system was run on the MRCS domain covering the NWS from 12° W to 13° E and 48° N to 62° N, as shown in Fig. 1 (bottom) in which the open boundary follows the 200 m depth contour around most of

10   domain. The hydrodynamic component was the Proudman Oceanographic Laboratory (now National Oceanography Centre) Coastal-Ocean Model System (POLCOMS, Holt et al., 2001, 2005). The model resolution was approximately 6 km in the horizontal with 18 S-coordinate levels in the vertical.

In the new AMM7-NE system, the domain covers the NWS and part of the North-

15   East Atlantic Ocean (from approximately 40° N to 65° N and 20° W to 13° E) as shown in Fig. 1 (top). The horizontal resolution of the coupled system has remained at approximately 7 km while the vertical levels have increased from 18 to 32. The boundary conditions for the ecosystem model nutrients in AMM7-NE are provided by monthly World Ocean Atlas values (Garcia et al., 2010) with zero-flux boundary conditions used for the

20   other variables. A comparison of the POLCOMS and NEMO shelf physics is provided in O'Dea et al. (2012) and O'Neill et al. (2012).

### 2.1.1   Hydrodynamic model description

NEMO was originally developed as an open ocean model and was missing many of the features needed to accurately model shelf-seas such as tides. The shelf adaptations to

25   the NEMO system are described fully in O'Dea et al. (2012) and only a brief summary of those differences is presented herein. First, the shelf seas version of NEMO includes a fully non-linear free surface using a variable volume (Levier et al., 2007) which is important for modelling tides and surges. The second main departure of the NEMO

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shelf system from the open ocean is the use of terrain-following vertical coordinates in place of regular $z$ coordinates. Benefits from terrain following coordinates include maintaining high vertical resolution in the shelf, both in the surface and the bottom boundary layers. This is particularly useful when trying to capture both off shelf and on shelf dynamics, which would require a very high resolution $z$-level model. Such coordinates do have drawbacks, including dealing with horizontal pressure gradients errors, and vertical diffusion which needs special treatment not required in an open ocean model. In the NEMO system for the shelf seas, use is made of a hybrid $z$-$\sigma$ model where the number of levels is decreased near particularly steep topography to prevent very steeply inclined model levels (see O'Dea et al., 2012 and references therein). The third major difference in the NEMO configuration on the shelf is the use of a more sophisticated turbulence scheme, necessary for the modelling of complex interactions such as seasonal stratification, tidal fronts and haline stratification from river plumes. A Generic Length Scale (Umlauf and Burchard, 2003) framework is used. This uses a $k$-$\varepsilon$ turbulence closure scheme and the Craig and Banner (1994) surface wave mixing parameterization.

The river scheme in NEMO has been updated so temperature, salinity, nutrients and sediment boundary conditions at river inflow points can be specified flexibly to better represent the vertical structure of different river outflows. The rivers have been modified to allow for a depth at which to mix the incoming flow rather than mixing the river flow through the entire water column. Currently, the river input data represents climatological values. In the current configuration, the temperature of the river water is not included (i.e. a zero flux gradient condition is applied) and the river flow only is specified (i.e. the river input is assumed to be of water of zero salinity). The Baltic flows through the Belt region are treated as additional rivers with specification of fluxes including temperature, salinity and sediments.

Finally, the light attenuation formulation, affecting both the hydrodynamics and ecosystem variables, in NEMO has been modified. The light attenuation is a very simple scheme following POLCOMS, which is also used in ERSEM, that attempts to

account for reduced near coast visibility by decreasing the depth to which light penetrates as a function of the bathymetry (Baretta et al., 1988).

## 2.1.2 Ecosystem model description

The ecosystem component of the coupled operational system is ERSEM (Baretta et al.,
1995; Blackford et al., 2004) which is one of the most complex lower trophic-level marine ecosystem models. ERSEM is a generic model that parameterises physiological processes and population dynamics through changes in biomass in both the pelagic and benthic ecosystems and the coupling between them in terms of the significant biogeochemical processes affecting the stochiometrically variable flow of the main con-
stituents of the system: carbon, nitrogen, phosphorus and silicon. It uses a functional group approach to divide the ecosystem into aggregated groups representing basic functional roles (production, consumption and decomposition) and sub-divided according to size and feeding method. The pelagic module in ERSEM includes one bacterial group, four phytoplankton and three zooplankton functional groups, a fully resolved
diurnal cycle, and variable carbon to chlorophyll ratios. In the benthos, ERSEM includes both aerobic and anaerobic bacteria, suspension feeders, bottom feeders and the meio-benthos. The parameter set used in this study is from Blackford et al. (2004) with modifications as described in Butenschön et al. (2012). The main difference is the choice of values for the maximum and minimum chlorophyll to carbon cell ratios ($\phi_{max}$
and $\phi_{min}$). ERSEM now allows the flexibility for these parameters to vary by phytoplankton type, although they have not been set to do so in this setup. The new value for $\phi_{max}$ is 0.035 with 0.025 for $\phi_{min}$.

Light attenuation within ERSEM is calculated using the attenuation contributions from seawater, various biological components and suspended (inorganic) sediment.
The sediment contribution is provided through a coupled 3-D sediment model. The sediment model has successfully been coupled to POLCOMS (Souza et al., 2007) and, more recently, to NEMO. It consists of two user-defined sediment size classes described by characteristic settling velocities. Recently, the sediment size classes,

settling velocities and critical erosion/deposition rates have been updated and equations to represent the sedimentary process of aggregation and disaggregation have been added (Sykes and Barciela, 2012).

As discussed by O'Dea et al. (2012) in terms of the hydrodynamic model, the 7 km resolution of the AMM7 domain is not sufficient to resolve the internal Rossby radius on the shelf, which is on the order of 4 km, and is therefore insufficient to resolve the fine-scale physics on the shelf. This will also influence the sediment and biogeochemical fields in the coupled system including the chlorophyll a concentration and distribution. The spreading and mixing of the river-based freshwater might also be insufficiently simulated in the 7 km model.

## 2.2 Model hindcasts

Hindcasts for calendar years 2007 and 2008 were run for both the MRCS-PE and the NEMO-ERSEM. For the hindcasts, the NEMO physical fields were spun up for a total of 2 yr while the ERSEM and SPM fields were spun up for one year with the NEMO physics. The NEMO model was initialized with temperature and salinity fields which were interpolated from the operational North Atlantic FOAM system onto the AMM7 grid. The currents were allowed to spin-up from rest. Due to the long spin-up time required for the ERSEM fields (both benthic and pelagic), the ERSEM restart used at the beginning of the NEMO-ERSEM one year spin-up period was the final state from a POLCOMS-ERSEM simulation for the years 1960–2004 on the 12 km AMM domain (Butenschön et al., 2012). The sediment fields, at the start of the NEMO-ERSM one year spin-up, were initialized with a completely sediment-free water column and a uniform initial bed supply of 150 gm m$^{-2}$ per active model grid point for each of the two size classes of sediment.

## 2.3 Data sets

The MRCS-PE system provides a baseline target for the new system, so model results were compared with each other and with available data in the region and the World Ocean Atlas monthly nutrient climatology (Garcia et al., 2010).

Time series of in situ fluorescence (as a proxy for chlorophyll), nitrate and silicate data from four of the UK's Centre for the Environment, Fisheries and Aquaculture Science (Cefas) monitoring buoys (SmartBuoy) were also used for comparison with model values. The SmartBuoy locations are: Liverpool Bay (53°32′.0 N–003°21′.8 W), Oyster Ground (54°25′.0 N–004°02′.0 E), Warp Anchorage (51°31′.5 N–001°01′.9 E) and West Gabbard (51°59′.0 N–002°05′.0 E). The Liverpool Bay, Warp Anchorage and West Gabbard sites are all relatively near-shore in water depths of 22 m, 15 m and 32 m, respectively. The Warp Anchorage and West Gabbard buoys are situated in the Thames outflow region. The Oyster Ground buoy is further offshore in the southern North Sea and is part of a UK-Netherlands collaborative monitoring programme.

Time-series data from the Western Channel Observatory station L4 have also been used (Smyth et al., 2010). The L4 station (50°15′N–04°13′ W) is approximately 10 km off Plymouth in the English Channel in around 50 m of water. The L4 site is situated in the river Tamar outflow region. Weekly chlorophyll and nutrient (nitrate, phosphate, and silicate) data was used in this study. Details of the data and sampling protocols are available at the observatory's website (http://www.westernchannelobservatory.org.uk).

Comparisons were made between satellite-derived and model surface chlorophyll (and log chlorophyll) for the AMM7-NE and MRCS-PE systems with averages over different time periods (daily, monthly, and seasonal). The satellite-derived chlorophyll data was calculated using the OC5 algorithm for Case II coastal waters (Gohin et al., 2002; Gohin et al., 2005) by IFREMER and delivered through MyOcean (http://www.myocean.eu). The daily comparison between the model and satellite chlorophyll fields was made online for the total domain and a series of sub-domains on the shelf (Fig. 2). These sub-domains also include the on-shelf region or Actual

North West Shelf (as labelled in the Taylor plots below). The on-shelf region was defined to fit the MRCS model grid and includes the following regions: Norwegian Trench, Northern North Sea, Southern North Sea, English Channel, Irish Sea, South Western Approaches and North Western Approaches. For the monthly and seasonal comparisons, the daily satellite-derived chlorophyll data was first (bilinear) interpolated onto the model grid and then averaged as appropriate.

## 2.4 Skill assessment

The main statistics used to assess the results in this paper are mean error (or bias = observations minus model), root mean square error (RMSE), and Pearson's correlation coefficient ($r$). The bias and RMSE measure the discrepancy between modelled and observed values where values closer to zero indicate a closer match. The correlation provides a measure of linear correspondence between two variables and values can range from $-1$ to $+1$. A value of $+1$ implies that a linear equation defines the relationship between the two variables while a value of $-1$ still indicates that the data points also fit a linear equation but with negative slope. A value of zero indicates no linear relationship. The square of the correlation coefficient ($r^2$) is an estimate of the fraction of the variance accounted for.

The RMSE, correlation and normalised standard deviation (model standard deviation divided by observation standard deviation) can be summarised on a single diagram, a Taylor plot (Taylor, 2001). The use of Taylor plots for coupled hydrodynamic-ecosystem models is well described in Joliff et al. (2009). A perfect match between model and observations would plot at the reference point labelled 1.0 on the $x$-axis.

## 3 Results

### 3.1 Nutrient assessment

Comparisons were made between the World Ocean Atlas 2009 nutrient climatology (Garcia et al., 2010) and the AMM7-NE and MRCS-PE results for monthly and seasonal averages. Seasonal averages of 2008 nitrate values for MRCS-PE (top) and AMM7-NE (bottom) are provided in Fig. 3 along with the WOA09 climatological values (centre) while the combined 2007–2008 statistics (created from the averaged fields) are provided in Table 1. For comparison to the MRCS-PE, the statistics for AMM7-NE are provided for both the entire domain and just the MRCS domain. The improvement in the nitrate field in the AMM7-NE model is evident on the MRCS domain with much lower RMSE (3.455 mmol $NO_3$ m$^{-3}$ versus 9.124 mmol $NO_3$ m$^{-3}$ based on monthly averages) and bias estimates (0.153 mmol $NO_3$ m$^{-3}$ versus $-5.251$ mmol $NO_3$ m$^{-3}$) as compared to MRCS-PE. The AMM7-NE bias, which is approximately $-1.1$ mmol $NO_3$ m$^{-3}$, is small in comparison to the wide range of nitrate values, which can be as high as 30 mmol m$^{-3}$. The AMM7-NE statistics over the entire AMM7 domain are also quite good with lower RMSE values and higher correlations which are above 0.600 for both the monthly and seasonal averages.

A similar analysis has been completed for the phosphate and silicate fields in ERSEM as compared with WOA09 with the results shown in Table 2 and Figs. 4 (phosphate) and 5 (silicate). As in Table 1, the phosphate and silicate statistics for the AMM7-NE system are provided both for the entire domain and the MRCS region only in Table 2. The phosphate results show marked improvement over the MRCS-PE values with lower RMSE values (0.303 mmol m$^{-3}$ versus 0.616 mmol m$^{-3}$) and biases ($-0.125$ mmol m$^{-3}$ versus $-0.434$ mmol m$^{-3}$) on the MRCS domain. While the AMM7-NE correlation on the MRCS domain is lower than the MRCS-PE system, the correlation over the entire AMM7 domain is similar while the RMSE values and biases show improvement.

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The statistics for the AMM7-NE silicate field (on both the full domain and the MRCS sub-domain) are not as good as for the nitrate and phosphate, with lower correlations (0.244 and 0.280 for silicate versus 0.476 and 0.534 for phosphate on the AMM7 domain) for both the monthly and seasonal averages along with relatively higher RMS errors (2.776 mmol m$^{-3}$ and 2.391 mmol m$^{-3}$ for silicate and 0.261 mmol m$^{-3}$ and 0.228 mmol m$^{-3}$ for phosphate), the improvement in silicate from the MRCS-PE system is evident. As compared to the MRCS-PE, the bias on the MRCS domain for the AMM7-NE system is significantly reduced (−0.207 mmol m$^{-3}$ versus −0.753 mmol m$^{-3}$). From Fig. 5, it is also apparent that the main source of excess silicate in the AMM7-NE system is in the Bay of Biscay and northward along the shelf-break to the west of Ireland. This may be partially caused by excess upwelling in the NEMO model along the steep slopes in these regions (John Siddorn, personal communication) and is also evident, but to a lesser extent, in the other ERSEM variables (see Figs. 2, 3 and 9).

Figure 6 provides a time series comparison between the model results and in situ data at the L4 buoy. The AMM7-NE model nutrient values follow the in situ observations very well and generally match the observed seasonal pattern, although the silicate draw-down in the model occurs earlier in each calendar year than in the observations. The nutrient correlation values are quite high: with nitrate equal to 0.835, phosphate equal to 0.678 and silicate equal to 0.665. The AMM7-NE model log$_{10}$ (chlorophyll) also matches the observations well with a bias of approximately zero but a correlation of only 0.254. From Fig. 6, the MRCS-PE model nutrients are too high resulting in high chlorophyll values throughout most of the year (a bias of −0.257 log$_{10}$ (mg m$^{-3}$)).

Finally, although the in situ data are very sparse for 2007 and 2008, a comparison (not shown) has been made between the model results and the Cefas SmartBuoy nitrate and silicate data. The best overall fit between the AMM7-NE model results and SmartBuoy data is at the Oyster Grounds with correlations of around 0.57 for both nitrate and silicate. The AMM7-NE RMSE (1.37 mmol m$^{-3}$ for nitrate; 2.41 mmol m$^{-3}$ for silicate) and bias (0.49 mmol m$^{-3}$ for nitrate; −1.96 mmol m$^{-3}$ for silicate) statistics are also very good. The negative bias values indicate that the AMM7-NE model

underestimates the nutrient values at this location. Although the AMM7-NE nitrate correlation is quite high at Warp Anchorage (0.818) indicating that the pattern of nitrate concentration is good, the remaining statistics at Warp Anchorage are poor (with an RMSE of approximately $50 \, \mathrm{mmol \, m^{-3}}$ for both nitrate and silicate) and the model nutrients are very high (almost double the in situ observations in the winter). This is probably due to the fact that the Warp Anchorage SmartBuoy is located at the first water point adjacent to the land in the AMM7-NE domain; the model does not resolve very small, fine scale processes in the estuary. This is also one of the river input points for the model so nutrients and sediment are constantly being added into the domain at this point. In fact, it is probably the effect of the high sediment input on the ERSEM light field that results in chlorophyll statistics with relatively low bias (between 0.08 and $0.4 \, \mathrm{mg \, m^{-3}}$) as described in the next section (see Tables 4 and 5). At all locations, it is appears that the silicate in the model is drawn-down too early in the spring with respect to the observations in a similar pattern to that seen at L4 (Fig. 6).

## 3.2 Chlorophyll assessment

A summary of the on-shelf statistics for the entire 2-yr hindcast period is presented in Table 3. In general, the statistics for the AMM7-NE system are improved relative to the MRCS-PE system with slightly higher correlations (0.294 versus 0.255) and similar RMS errors ($0.645 \log_{10} (\mathrm{mg \, m^{-3}})$ versus $0.613 \log_{10} (\mathrm{mg \, m^{-3}})$). Of note is the reduction in mean error (or bias) for the two-year hindcast period. The AMM7-NE mean error is $0.009 \log_{10} (\mathrm{mg \, m^{-3}})$ – indicating that the total chlorophyll in the MRCS region is approximately of the correct magnitude on average; while the negative bias for the MRCS-PE system indicates that the model has too much chlorophyll relative to observations. However, the relatively high RMS errors indicate that the timing and pattern of the model chlorophyll is not entirely correct.

A time series of the daily mean and RMS errors of surface $\log_{10}$ (chlorophyll) for the on-shelf region of the MRCS-PE and AMM7-NE systems is provided in Fig. 7. In the winter, when the bias is positive for both model systems, the model chlorophyll

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is too low relative to the observations. This is reversed in the spring and summer, when the bias is negative indicating that the model chlorophyll is higher than the observations. From this figure, it is also apparent that at certain times of year (most obviously April through October), the AMM7-NE system has a lower RMS error (solid line) and bias (dotted line) than the MRCS-PE system but during the first two winter periods, the AMM7-NE errors are much more variable and higher than the MRCS-PE. However, by the end of the hindcast period and the third winter season of the run, the AMM7-NE model errors on the shelf are comparable to MRCS-PE (Fig. 7). This may indicate that the AMM7-NE model needed more time to synchronise from the initial conditions interpolated from the AMM12 POLCOMS-ERSEM model to AMM7-NE or that the sediment model needed more than one year to spin-up. Calculating the statistics separately for 2007 and 2008 for the AMM7-NE on-shelf region results in correlations which are essentially the same (0.303 for 2008 versus 0.301 for 2007) but reduced RMSE ($0.637 \log_{10}$ (mg m$^{-3}$) versus $0.654 \log_{10}$ (mg m$^{-3}$)). In the on-shelf region for AMM7-NE, the bias in chlorophyll is close to zero for both years, but reverses sign from $+0.082 \log_{10}$ (mg m$^{-3}$) in 2007, indicating slightly too little chlorophyll, to $-0.060 \log_{10}$ (mg m$^{-3}$), indicating slightly too much chlorophyll in 2008.

Taylor plots are used in Fig. 8 to compare the two model systems over the entire domain as well as the pre-defined sub-domains and show some specific areas where the AMM7-NE system clearly outperforms MRCS-PE with respect to surface $\log_{10}$ (chlorophyll) concentrations. The areas with the most improvement include the Irish Sea, English Channel, Norwegian Trench and Southern North Sea as defined in Fig. 2. In this plot, the Norwegian Trench and Southern North Sea data for AMM7-NE sit very close to the curved dashed line running between 1.0 on both the $x$- and $y$-axes. This line represents a perfect match of the model and observation standard deviations (for the Taylor plot only, a minimum model value of 0.1 mg chlorophyll m$^{-3}$ was used to match the minimum value provided by the satellite data). The Irish Sea area also had a negative correlation in the MRCS-PE model which has been improved in AMM7-NE. The correlation, obtained by drawing a line from the origin through a plotted point to

the curved right-axis, is generally low for most regions with the English Channel having the highest correlation of 0.366. This region also has a relatively low mean error of $-0.001\log_{10}$ (mg m$^{-3}$) and RMS error of $0.293\log_{10}$ (mg m$^{-3}$).

The statistics presented in Table 3 and Fig. 7, are based on a daily comparison of the model versus satellite values which may be overly strict as the errors in both can be high. Averaging over weeks, months or seasons before comparing the model results to the satellite data improves the correlations in AMM7-NE $\log_{10}$ (chlorophyll) to 0.383, 0.455 and 0.415, respectively with relatively small changes to the RMS error or bias. A similar pattern in these statistics is seen with higher, positive biases in the winter months (October through March) and lower, slightly negative biases in the remainder of the year. Figure 9 shows the seasonal averages of the satellite observations compared to the AMM7-NE model results for chlorophyll on a log scale. The spatial and temporal differences become readily apparent in this figure: the spatial pattern of chlorophyll in winter looks quite reasonable although the model values are generally lower than the satellite observations while in spring and summer, the model has too much chlorophyll relative to the observations which is widely distributed through the domain (except very near the coast).

The final comparison for the model chlorophyll is provided at four of the Cefas SmartBuoy sites. Figure 10 provides a comparison of model, satellite and Smart-Buoy $\log_{10}$ (chlorophyll) data at the West Gabbard location. At this location, the correlation between satellite and SmartBuoy in situ data is 0.600, while the correlation between the model and satellite is 0.190 and the model and in situ data is 0.310. In the time series plot provided by Fig. 10d, it is apparent that while several of the peaks in $\log_{10}$ (chlorophyll) values match in both the satellite and SmartBuoy time series, the SmartBuoy data has several other peaks which may or may not be realistic, but also, the satellite data does not have correspondingly low values where both the in situ and model values are low. Tables 4 and 5 present the statistics for all of the SmartBuoy locations. Table 4 includes both the model and satellite statistics versus the SmartBuoy in situ data while Table 5 has the model versus satellite statistics at the SmartBuoy

location. The Oyster Banks SmartBuoy is located much further from the coast than the other three, so it is surprising that the statistics at this location are worse (from Table 4, lowest and negative correlations, highest RMSE and bias) than at the coastal locations for both the AMM7-NE model and satellite data as compared to the in situ data. However, it is not surprising that the AMM7-NE model does not do very well at the coastal locations when compared with observations. One of the limitations in our current system is the use of climatological values as input for the rivers; this will naturally mean that the model misses large freshwater inputs as they will be smoothed in the climatological input.

## 4   Discussion

This paper describes updates made to the Met Office's operational coupled hydrodynamic-ecosystem model for the European NWS to the AMM7-NE system. It also provides validation of some of the ecosystem variables including chlorophyll and the main nutrients: nitrate, phosphate, and silicate. This new system has been part of the daily operational suite at the Met Office since March 2011 and provides 5-day forecasts with products delivered through MyOcean (http://www.myocean.eu.org) since July 2011.

The results show that the AMM7-NE system shows significant skill and performs better compared to the previous MRCS-PE system especially for the nutrient fields. It would have been desirable to validate the ecosystem behaviour against a wider range of in situ observations including sub-surface observations throughout the domain. Further efforts are being made to validate the model fields against in situ data from other sources including zooplankton and phytoplankton biomass data from the Sir Alister Hardy Foundation for Ocean Science (SAHFOS) and cruise data for nutrients and chlorophyll from the Institute of Marine Research (IMR) in Norway. Additional collaboration with Cefas and the Agri-Food and Biosciences Institute (AFBI) in Northern Ireland will result in further validation efforts within the NWS region.

The AMM7-NE system seems to have solved the main problems with the nutrient dynamics in the MRCS-PE system as discussed in Siddorn et al. (2007). As can be seen in Figs. 3 through 6 and the statistics provided, the annual cycle of nutrient levels is much improved throughout the domain. This is apparent in both the winter nutrient levels and the draw-down of the nutrients in spring and summer. The MRCS-PE system had a problem with the accumulation of nutrients throughout the domain over time. This problem also appears to be solved and was possibly due to the size of the domain itself which extended only to the 200 m isobath along with the zero flux boundary conditions that were applied. As mentioned in Sect. 2.1, with the AMM7 domain the boundaries are further from the shelf in the new system, WOA09 values are used to force the nutrients at the model edge.

The distinct feature seen in the Figs. 3, 4, 5 and 9 shows the spatial distribution of nutrients and chlorophyll, which characteristically follow the Shelf Edge Current (SEC) that flows around the continental margins. The Eastern North Atlantic Water (ENAW), which forms in the Bay of Biscay (Pollard et al., 1996), is advected northwards, around the Porcupine Bank into the southern Rockall Trough (Ellett and Martin, 1973; New et al., 2001) by the poleward SEC. The irregular shape of the European shelf, with capes, canyons, and varying shelf width, can cause locally enahanced up/downwelling and cross-slope flow (Throwbridge et al., 1998). Hence as mentioned above, we believe the excess of nutrients depicted in the above figures is partially caused by excess upwelling in the NEMO model along the steep slopes in these regions.

To understand the differences in the effects of moving to a larger domain versus the change in boundary conditions for the nutrient fields, an additional experiment was performed which used the old boundary conditions (zero-flux) on the new AMM7-NE domain. This experiment included the same one year spin-up and two year hindcast as the other model runs. The only difference was the application of zero-flux boundary conditions for the nutrients instead of WOA09 values. The effect of the WOA09 boundary conditions can be seen in Fig. 11 which compares the monthly average AMM7-NE model for December 2008 with (Fig. 11, left) and without (Fig. 11, right)

WOA09 nitrate values applied at the boundaries with the WOA09 December climatological field (Fig. 11, centre). In the northeastern part of the domain, the improvement through the use of the boundary conditions is most apparent. A comparison of the statistics calculated using seasonal averages for the AMM7-NE model shows an improvement with the WOA09 boundary conditions (correlations: 0.643 versus 0.416; RMSE of 2.72 mmol m$^{-3}$ versus 3.23 mmol m$^{-3}$). The bias switches signs between the two runs with a positive bias (indicating higher nutrient values in the model relative to the climatology) of 1.08 mmol m$^{-3}$ in the run with WOA09 boundary conditions to a negative bias (indicating lower nutrient values in the model relative to climatology) of $-0.74$ mmol m$^{-3}$ without boundary conditions. The AMM7 domain appears to rely on nutrient influx from the North East Atlantic Ocean, especially during the winter months, and in fact, the negative bias in the model run without WOA09 boundary conditions increases from a value of $-0.34$ mmol m$^{-3}$ in 2007 to $-1.11$ mmol m$^{-3}$ in 2008.

While the new AMM7-NE system now has approximately the correct amount of chlorophyll in total over the MRCS domain and the two-year hindcast period (represented by the bias of 0.009 in Table 3), the spatial distribution and timing of that chlorophyll warrants additional investigation. There are also marked differences in the performance of the sub-regions within the model domain with the best correspondence in the English Channel region, as shown in Fig. 2, which includes the L4 site. The Norwegian Trench and Southern North Sea also provide a good approximation to the satellite chlorophyll while the offshelf region, in general, has too much chlorophyll throughout the spring and summer. Further investigation into the timing and succession of the phytoplankton functional groups is necessary and is being planned.

Improvements to both the NEMO and ERSEM models are being investigated which should have an impact on the biogeochemical cycles within ERSEM. Due to the challenges of acquiring river data in NRT for use in the operational model, the use of a hydrological model to replace the current climatological river outflows, temperature and nutrient values is being investigated. Additionally, the replacement of the current specification of a climatological Baltic boundary with real time data from a Baltic

model is under consideration. Improvements to the light attenuation scheme are also being investigated including the use of a three-band scheme and spatial variation of the light attenuation coefficient based on satellite observations. The non-operational POLCOMS-ERSEM system in development at PML and the National Oceanography Centre in Liverpool (NOCL) uses satellite inherent optical properties within ERSEM which has been shown to have a positive impact on the model chlorophyll fields (Wakelin et al., 2012). In the long-term, work is being done to improve the ecosystem model further by including data assimilation of the chlorophyll field from satellite data (Ciavatta et al., 2011) and to include the satellite optical information as used in the POLCOMS-ERSEM system in either NRT or as climatological input for the AMM7-NE system.

## 5 Conclusions

The AMM7-NE system has been shown to be an effective modelling tool which demonstrates increasing amount of skill in the European NWS domain. O'Dea et al. (2012) provide a domain-wide validation of the AMM7-NE tides, SST and salinity fields. They find that, in general, the AMM7-NE is better than or equal to POLCOMS-AMM for SSH amplitude and phase, while the annual RMSE in SST in AMM7-NE without data assimilation is similar to POLCOMS-AMM, but with areas and seasons of weakness and strengths in each. The addition of SST data assimilation in AMM7-NE markedly reduces these errors. Additionally, O'Neill et al. (2012) provide a validation of the AMM7-NE temperature and salinity fields in Liverpool Bay and the Irish Sea in comparison with two POLCOMS systems: the 12 km AMM model and a 1.8 km Irish Sea model. While the 1.8 km Irish Sea model is the only one of the three that is capable of representing the small-scale coastal physics, they found that the AMM7-NE system performed as well as the 1.8 km POLCOMS model when using the same forcing data set and that the AMM7-NE system better captured the Liverpool Bay tidal variability.

In the AMM7-NE system, the nutrient dynamics throughout the domain are much improved, while there is potential for further improvements in the chlorophyll field. The

system can be used to extend the products and projects already developed using the MRCS-PE system, such as the nuisance bloom prediction tool for the Environment Agency (Mahdon et al., 2010; Barciela et al., 2012), and to provide derived products such as annual or seasonal mean primary productivity and OSPAR-like eutrophication indices. As part of the operational system at the Met Office, the AMM7-NE is regularly delivering products through MyOcean and to other users such as the UK Royal Navy. The need for operational ecosystem models for fisheries and environmental scientists has been highlighted recently by Berx et al. (2010) along with the further potential for using these types of models for spatial management decisions in the marine environment (Janssen et al., 2011) and the use of the AMM7-NE system in such management context is being explored. With further improvements and validation against available observations, this system could become a component of an integrated model and observation-based monitoring system for the coastal regions around the UK and could potentially be used to provide input to a climate status assessment of the NWS region.

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**Table 1.** Statistics for monthly-mean and seasonal-mean values of nitrate for AMM7-NE and MRCS-PE versus WOA09 climatology values on the model domains. The first two columns include the entire AMM7 domain, while the two middle columns provide the statistics from the AMM7-NE model on the MRCS sub-domain only. The units for the RMSE and Bias are $mmol\,m^{-3}$.

| | AMM7-NE | | AMM7-NE–MRCS | | MRCS-PE | |
|---|---|---|---|---|---|---|
| | Monthly | Seasonal | Monthly | Seasonal | Monthly | Seasonal |
| Correlation | 0.604 | 0.642 | 0.420 | 0.440 | 0.521 | 0.553 |
| RMSE | 3.012 | 2.722 | 3.455 | 3.246 | 9.124 | 8.652 |
| Bias | −1.058 | −1.087 | 0.153 | 0.170 | −5.251 | −5.106 |

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**Table 2.** As in Table 1 for phosphate and silicate. The units for the RMSE and Bias are mmol m$^{-3}$.

|  | AMM7-NE | | AMM7-NE–MRCS | | MRCS-PE | |
| --- | --- | --- | --- | --- | --- | --- |
|  | Monthly | Seasonal | Monthly | Seasonal | Monthly | Seasonal |
| 1. Phosphate |  |  |  |  |  |  |
| Correlation | 0.476 | 0.534 | 0.288 | 0.322 | 0.470 | 0.532 |
| RMSE | 0.261 | 0.228 | 0.303 | 0.265 | 0.616 | 0.570 |
| Bias | −0.126 | −0.125 | −0.124 | −0.117 | −0.434 | −0.413 |
| 2. Silicate |  |  |  |  |  |  |
| Correlation | 0.244 | 0.280 | 0.219 | 0.212 | 0.563 | 0.613 |
| RMSE | 2.776 | 2.391 | 2.765 | 2.314 | 3.741 | 3.444 |
| Bias | −0.698 | −0.695 | −0.207 | −0.111 | −0.753 | −0.723 |

**Table 3.** Summary of daily surface $\log_{10}$ (chlorophyll) statistics calculated on the on-shelf region (Fig. 2) for both AMM7-NE and MRCS-PE for the 2-yr hindcast. The units for the RMSE and Bias are $\log_{10}$ (mg m$^{-3}$).

|  | AMM7-NE | MRCS-PE |
|---|---|---|
| Correlation | 0.294 | 0.255 |
| RMSE | 0.645 | 0.613 |
| Bias | 0.009 | −0.209 |

**Table 4.** Surface daily $\log_{10}$(chlorophyll) statistics of AMM7-NE model and satellite values versus in situ data at the Cefas SmartBuoy locations. The units for the RMSE and Bias are $\log_{10}$ ($mg\,m^{-3}$).

| | Gabbard | | Liverpool Bay | | Oyster Banks | | Warp | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | sat | model | sat | model | sat | model | sat | model |
| Correlation | 0.600 | 0.310 | 0.490 | 0.050 | 0.080 | −0.180 | 0.490 | −0.100 |
| RMSE | 0.380 | 0.390 | 0.590 | 0.610 | 0.740 | 0.920 | 0.650 | 0.870 |
| Bias | −0.220 | 0.080 | −0.400 | −0.190 | 0.300 | 0.390 | −0.190 | −0.220 |

**Table 5.** Surface daily $\log_{10}$ (chlorophyll) statistics for AMM7-NE model versus satellite data at the Cefas SmartBuoy locations. The units for the RMSE and Bias are $\log_{10}$ (mg m$^{-3}$).

|  | Gabbard | Liverpool Bay | Oyster Grounds | Warp |
|---|---|---|---|---|
| Correlation | 0.190 | 0.080 | −0.030 | 0.150 |
| RMSE | 0.390 | 0.370 | 0.450 | 0.480 |
| Bias | 0.260 | 0.100 | −0.060 | −0.030 |

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**Fig. 1.** The domains and nests used for the new NEMO (AMM7-NE, top) and POLCOMS (MRCS-PE, bottom) coupled systems. The colours indicate the depth of bathymetries.

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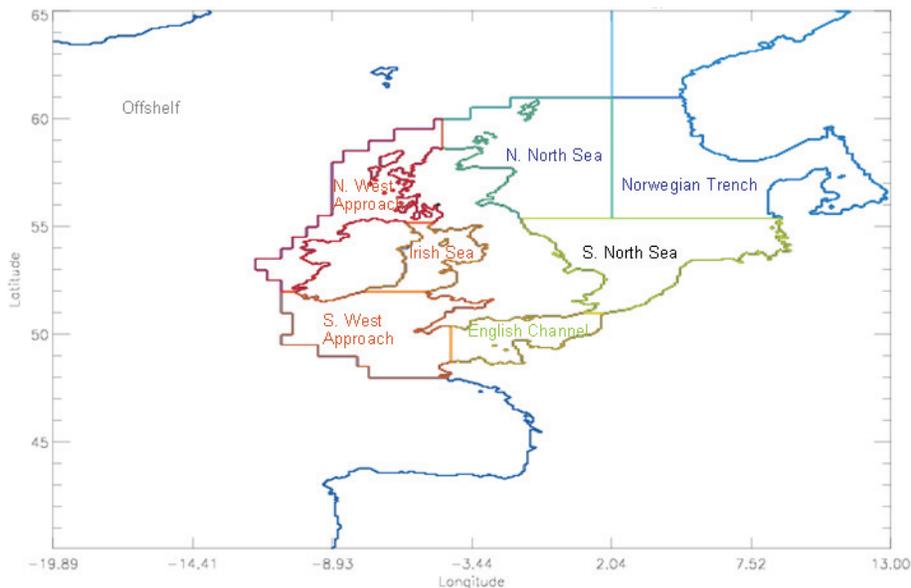
**Fig. 2.** Area mask used to produce the Taylor plot and some statistics. The on-shelf region used in the text includes all of the other regions except offshelf.
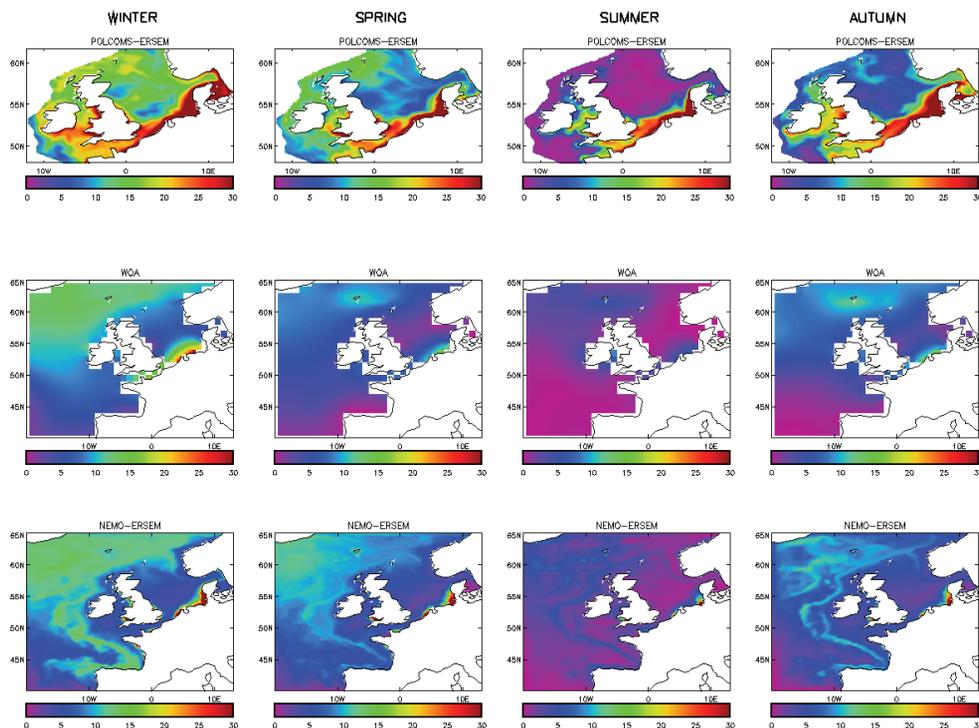
**Fig. 3.** Seasonal averages of nitrate values (mmol m$^{-3}$) for MRCS-PE (top row) compared to the WOA09 fields (middle row) and AMM7-NE (bottom row). The MRCS-PE and AMM7-NE fields are for 2008. Winter = December 2007–February 2008; Spring = March, April and May 2008; Summer = June, July and August 2008; Autumn = September, October and November 2008.
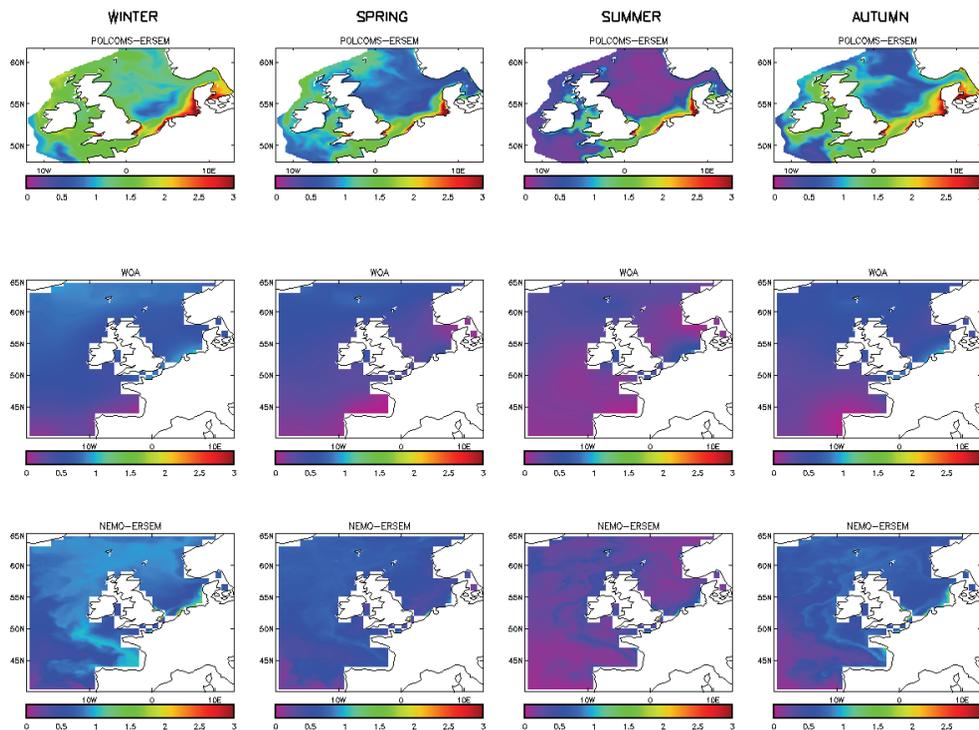
**Fig. 4.** As in Fig. 3, the seasonal average surface phosphate (mmol m$^{-3}$) for 2008 for MRCS-PE (top) and AMM7-NE (bottom) compared with the WOA09 climatology (centre).
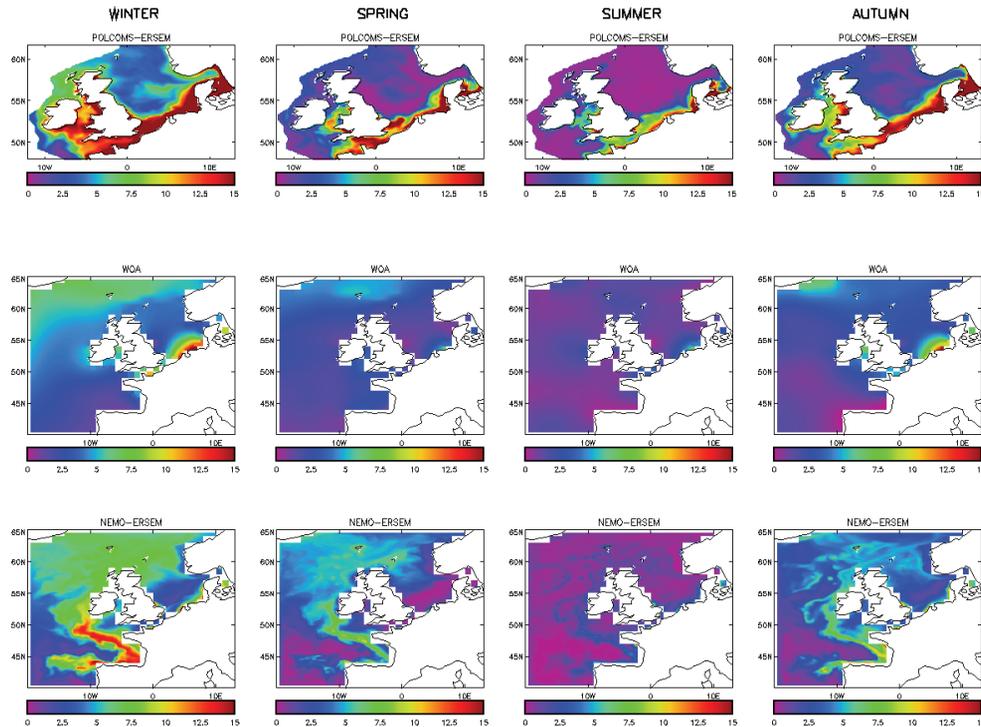
**Fig. 5.** As in Fig. 3, seasonal average surface silicate (mmol m$^{-3}$) for 2008 for MRCS-PE (top) and AMM7-NE (bottom) compared with the WOA09 climatology (centre).

**Fig. 6.** Comparison of AMM7-NE (black), MRCS-PE (blue) and in situ data (red) at the L4 buoy:
**(a)** nitrate, **(b)** phosphate, **(c)** silicate and **(d)** $\log_{10}$ (chlorophyll).
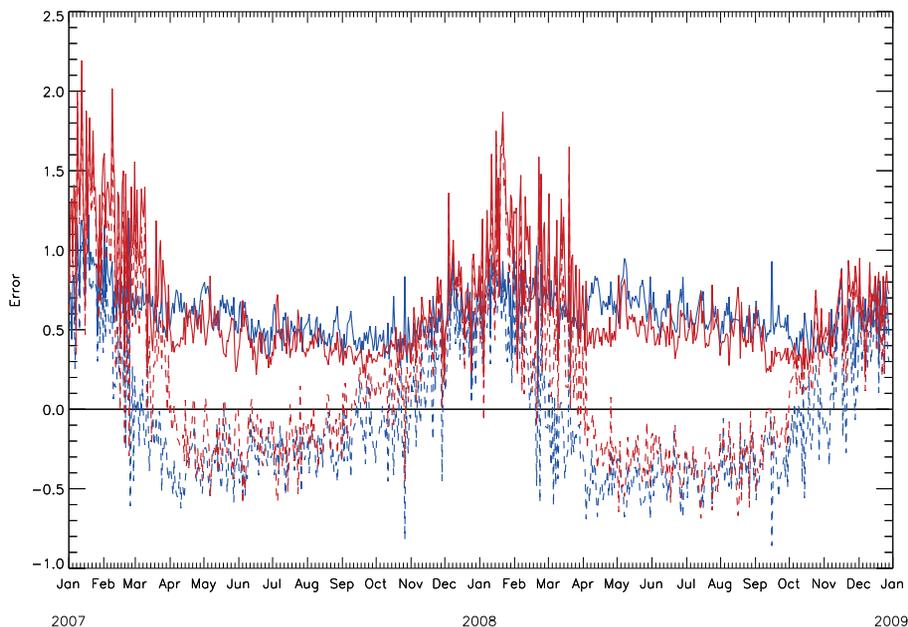
**Fig. 7.** Comparison of error estimates for $\log_{10}$ (chlorophyll) in the on-shelf region (Fig. 2) for MRCS-PE (blue) and AMM7-NE (red). Solid lines = RMSE; dashed lines = bias (obs-model).
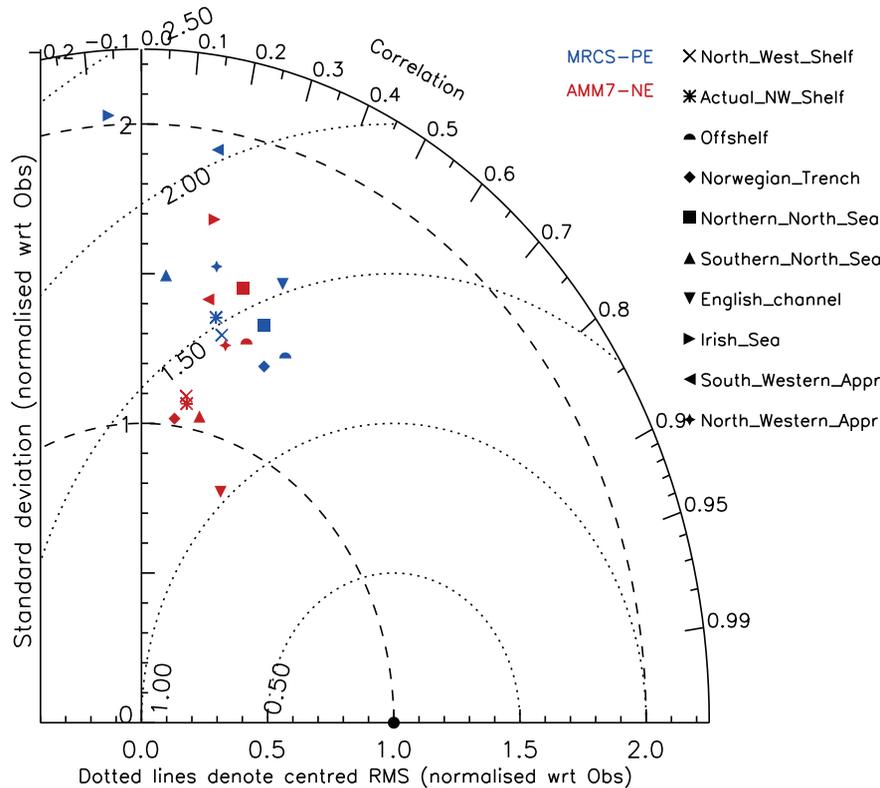
**Fig. 8.** Taylor plot to compare MRCS-PE (blue) and AMM7-NE (red) surface chlorophyll with satellite-derived chlorophyll. The areas are shown in Fig. 2 and North_West_Shelf represents the entire AMM7 domain.
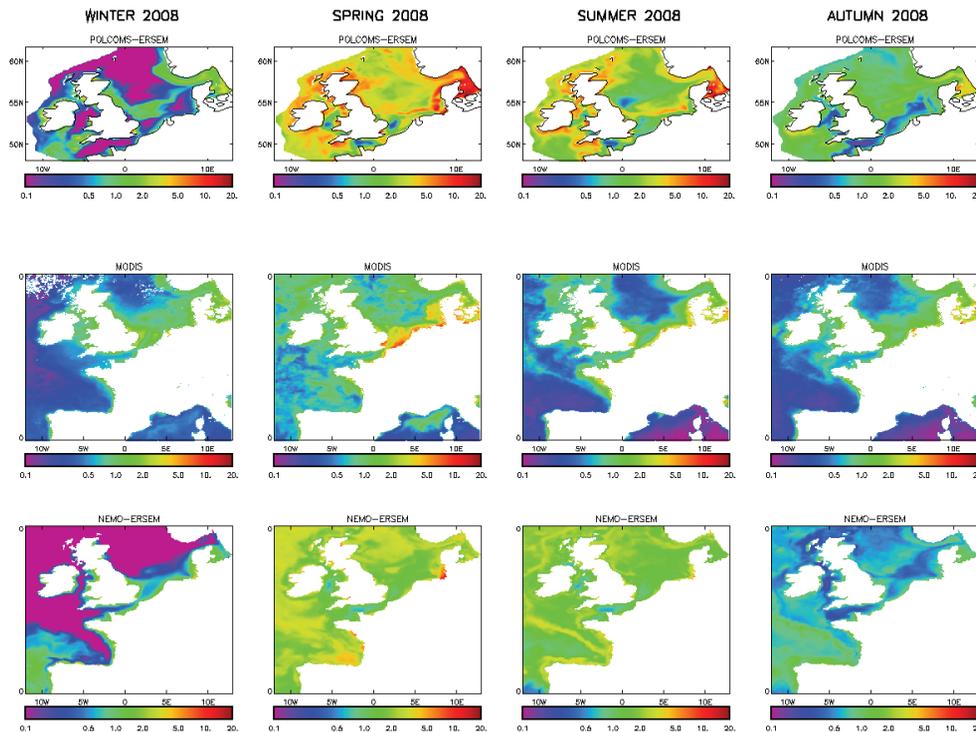
**Fig. 9.** As in Fig. 3. Seasonal average surface log10(chlorophyll) for MRCS-PE (top) and AMM7-NE (bottom) as compared to the satellite-derived chlorophyll (middle).
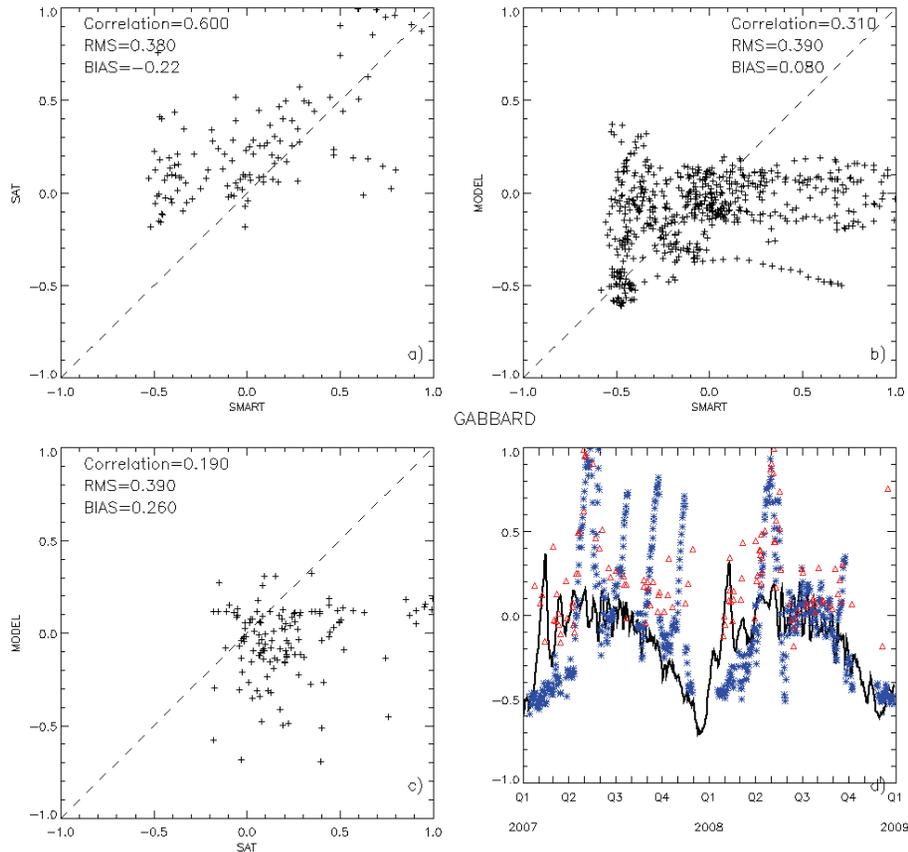
**Fig. 10.** Plots and statistics of $\log_{10}$ (chlorophyll) at the Gabbard SmartBuoy: **(a)** SmartBuoy versus Satellite; **(b)** SmartBuoy versus Model; **(c)** Satellite versus Model; and **(d)** time series of model (black), SmartBuoy (blue) and satellite (red).

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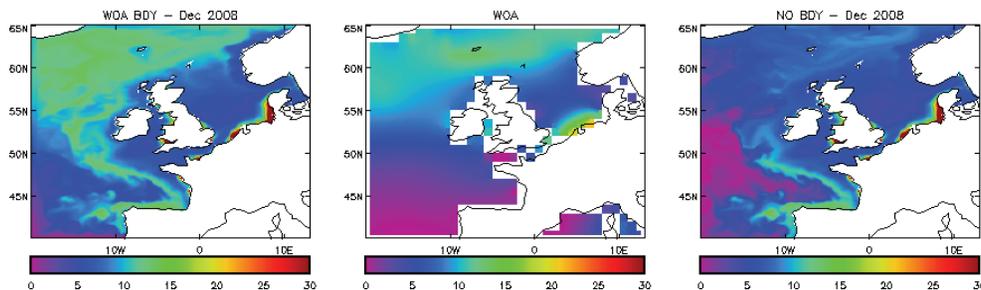
**Fig. 11.** Monthly average surface nitrate values (mmol m$^{-3}$) for the AMM7-NE model with WOA09 BDY (left) and without WOA09 boundary conditions (right) compared with the climatological value (centre). The model fields are from December 2008.