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Oceanic controls on the primary production of the northwest European continental shelf under recent past and potential future conditions

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Abstract

In this paper we clearly demonstrate that changes in oceanic nutrients are a first order factor in determining changes in the primary production of the northwest European continental shelf on time scales of 5–10 yr. We present a series of coupled hydrodynamic ecosystem modelling simulations, using the POLCOMS-ERSEM system. These are forced by both re-analysis data and a coupled ocean-atmosphere general circulation model (OA-GCM) representative of possible conditions in 2080–2100 under an SRES A1B emissions scenario, along with the corresponding present day control. The OA-GCM forced simulations show a substantial reduction in surface nutrients in the open-ocean regions of the model domain, comparing future and present day time-slices. This arises from a large increase in oceanic stratification. Tracer transport experiments identify a substantial fraction of on-shelf water originates from the open-ocean region in the south of the domain, where this increase is largest, and indeed the on-shelf nutrient and primary production are reduced as this water is transported on shelf. This relationship is confirmed quantitatively by comparing changes in winter nitrate with total annual nitrate uptake. The reduction in primary production by the reduced nutrient transport is mitigated by on-shelf processes relating to temperature, stratification (length of growing season) and recycling. Regions less exposed to ocean-shelf exchange in this model (Celtic Sea, Irish Sea, English Channel, and southern North Sea) show a modest increase in primary production (of 5–10 %) compared with a decrease of 0–20 % in the outer shelf, central and northern North Sea. These findings are backed up by a boundary condition perturbation experiment and a simple mixing model.

1   Introduction

Coastal and shelf seas and their ecosystems form a vital part of the environment. They support substantial economic activity, e.g. a large fraction of global fisheries occur in

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these seas (Watson and Pauly, 2001), and important biogeochemical cycles, e.g. many coastal and shelf seas are observed to be a net sink of atmospheric CO_2 (e.g. Thomas et al., 2004). However, this still remains a significant source of uncertainty in the global carbon budget (Borges, 2005). Fixation of carbon by photosynthesis (primary production) is one of the most fundamental processes underlying both these aspects. Hence our ability to understand and ultimately predict this process, its variability and change is crucial to many aspects of environmental policy, for example the European Commission's Marine Strategy Framework Directive and the indicators of Good Environmental Status therein[1].

In this paper we explore the controls on the primary production of the northwest European Continental shelf (NWS; Fig. 1) on decadal time scales, through coupled hydrodynamic ecosystem modelling using the POLCOMS-ERSEM system (Allen et al., 2001; Holt and James, 2001). We consider both present day/recent past conditions and an example of a possible future climate scenario. The latter is used to illustrate this region's susceptibility to change under substantially altered global conditions. Our focus here is on the interaction of these seas with the open-ocean, and the consequences of variability and change. A detailed analysis of the internal cycling, and its response to change, is left to future work.

We now briefly review some features of this region important to this study. The NWS is a broad temperate shelf forming the eastern margin of the northern North Atlantic. It includes several shelf sea regions that are identified in Fig. 1. The dynamics of the region are controlled by the seasonal heating cycle, atmospheric fluxes, tides, river inputs and exchanges with the open-ocean. Much of the open-shelf is seasonally stratified, with tidal mixing fronts separating these regions from well mixed/sporadically stratified shallower regions either nearer the coast or on banks and shoals. River discharge plays an important role in near coastal regions, leading to regions of freshwater influence; although compared with other shelf sea regions globally, river flows are low. The large scale ocean-shelf exchange is controlled by seasonal upwelling in the south of

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[1] http://ec.europa.eu/environment/water/marine/ges.htm

the region (see Gomez-Gesteira et al., 2011 and references therein), and the poleward slope current and Ekman transport in the North (Holt et al., 2009; Huthnance et al., 2009). This exchange is supplemented by sub-mesoscale processes (e.g. filaments, and internal tides; Huthnance, 1995), which are not considered further here.

5   This physical background controls, to a large extent, the spatial/temporal patterns of primary production in this region; accepting that this assertion may reflect our limited understanding of "top-down" control in this context.

Much of these seas are inorganic nutrient limited and hence the supply and recycling of these nutrients generally controls the primary production. In coastal regions the

10 combined inputs of significant riverine nutrient loads and optically active constituents (suspended particulate material, SPM, and coloured dissolved organic matter, CDOM) can lead to light limited regimes that can also exhibit exceptionally high levels of production (e.g. Cadee and Hegeman, 2002). In winter months phytoplankton growth is inhibited by high levels of mixing (Huisman et al., 1999) and short day length. During

15 spring, increasing solar irradiance and reduced mixing and consequent stratification can trigger intense phytoplankton blooms. These deplete surface nutrient supplies, but intermittent cross-thermocline mixing (e.g. from spring neap tidal variability; Sharples, 2008) can maintain mid-water production in stratified regions throughout the summer months, as long as the thermocline is within the euphotic zone. In well-mixed and near-

20 coastal regions the production is more erratic, being controlled by a complex inter-play of optical, mixing and river plume conditions. During autumn, storms and surface cooling (convection) mix the seasonally stratified water. This can trigger an autumn bloom. However, the de-stratification generally proceeds from south to north (Holt and Proctor, 2008), with the northern regions remaining stratified until December. Hence, light lev-

25 els can limit the intensity of the autumn bloom. Bacterial and zooplankton consumption of phytoplankton and detrital material in both pelagic and benthic systems recycles the nutrients and can also fuel further production.

The distribution and fluxes of inorganic nutrients are therefore critical to understanding primary production. The NWS receives nutrients from:

1. oceanic inflow, which is in turn supplied by deep winter mixing and coastal up-welling (predominantly in the south of the region);

2. river inputs resulting from human, agricultural and industrial sources (e.g. Artioli et al., 2008);

5   3. atmospheric inputs.

The oceanic components have been identified as dominating nutrient budgets in this region by several model based studies (Proctor et al., 2003; Vermaat et al., 2008; Artioli et al., 2008; Pätsch and Kuhn, 2008), while Hydes et al. (2004) notes the importance of oceanic nutrient input to the NWS in an analysis of data from five cruises west of
10 Great Britain and long time series observations in the Irish Sea. Vermaat et al. (2008) identify variability in oceanic input (characterised by the North Atlantic Oscillation) as a significant source of variability in North Sea nutrients, but also note the inflow is a substantial source of uncertainty in their budgets. The time scale associated with the oceanic input are generally long compared with the seasonal cycle. For example,
15 Hydes et al. (2004) identifies the transit time for Atlantic water crossing the Celtic Sea into the Irish Sea to be 6 yr, while the transports estimates used by Huthnance (1997) imply a North Sea flushing time of ~1 yr.

There are several observational and empirical approaches to investigating primary production, for example through ship based measurements using incubations and
20 chlorophyll based relations (e.g. Cadee and Hegeman, 2002; Joint and Pomeroy, 1993) and through satellite Ocean Colour based models (Carr et al., 2006). Here we explore the dynamical modelling approach, using a coupled hydrodynamic-ecosystem model of the NWS. We use the Proudman Oceanographic Laboratory Coastal Ocean Modelling System (POLCOMS; Holt and James, 2001) coupled to the European Regional Seas
25 Ecosystem Model (ERSEM; Blackford et al., 2004). While the uncertainties associated with such models are well documented (see Stow et al., 2009 and references therein), they provide a complete budget for the biogeochemical and physical fluxes that is not available from other approaches. Hence they provide an invaluable tool for systems

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understanding and exploring hypotheses. Moreover, they can operate under "what if?" scenarios representing particular environmental and/or anthropogenic change.

Potential impacts of climate change on the physical oceanography of these shelf seas are reviewed by Holt et al. (2010). Here we can identify three specific mechanisms (drivers) whereby large scale change might impact primary production in the NWS: through changes to the nutrient supply (and its spatial/temporal distribution), through changes to the temperature, and consequent changes in chemical and physiological rates, and through changes to on-shelf stratification. Increases in stratification act both to reduce vertical nutrient fluxes during the summer and to increase the length of the growing season. For example in a HadRM3 forced simulation, Holt et al. (2010) find the stratified period in the North Sea increases by ∼10 % towards the end of the 21st century (under an SRES A1B scenario) compared with present day conditions. In a region where in-season nutrient recycling and cross-thermocline transport play an important role, changes to the length of the growing season might be expected to have a significant effect on the total annual primary production.

These three drivers operate on a wide range of time scales up-wards from the phytoplankton growth time of a few days (Bissinger et al., 2008). In the present context we are concerned with inter-annual scales and these drivers might be expected to act both through climate variability and climate change.

Our focus here is on the first of these drivers: changes to the nutrient supply. Climatic influence on nutrient supply has received substantial attention in the global ocean context through the reduction in winter mixing and expansion of the oligotrophic gyres seen by several coupled Ocean Atmosphere General Circulation Models (OA-GCMs). For example, the four models considered by Steinacher et al. (2010) all agree on a reduction in primary production in the North East Atlantic by the end of the 21st century in an SRES A2 scenario, owing to increased stratification and reduced nutrient supply. In global scale models reduced nutrient supply due to stratification can be out-weighed by the temperature response and the increased growing season in mid to high-latitudes, to give an overall increase in primary production (Sarmiento et al.,

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2004). The importance of the temperature response has also been highlighted by Taucher and Oschlies (2011). Other potential drivers, such as changes to optical properties, have as yet received scant attention.

It is well appreciated that most global models that include an ecosystem component have inadequate resolution and process representation to simulate shelf seas with any accuracy (Allen et al., 2010). The common approach is therefore to use limited area regional models with external oceanic boundary conditions. This allows improved resolution and process representation (e.g. of tides and benthic ecosystems), however, many such models have tended to focus exclusively on the shelf sea(s) in question both through limited area and limited boundary condition information. Examples of studies of individual sea regions for process investigation include the North Sea (Kuhn et al., 2010; Pätsch and Kuhn, 2008) and Irish Sea (Holt et al., 2004). This is perfectly adequate for simulations that are no longer than the seas' flushing time, as is the case in these examples. But for longer simulations, for example to explore decadal change, the ocean-shelf coupling needs to be explicitly included through extended domains and improved boundary condition information. This is particularly the case when considering properties (e.g. salinity and nutrients) that are not strongly constrained by atmospheric feedback. In contrast temperature and seasonal stratification can be adequately modelled with 1-D models (Sharples et al., 2006) and 3-D models of limited area and boundary condition information (Young and Holt, 2007; Meyer et al., 2011). Hence, such models can be usefully employed in climate change downscaling studies to investigate changes in atmospheric and riverine forcing (e.g. Schrum et al., 2003; Skogen et al., 2011), but miss a potentially important vector of change, namely that arising from changes in oceanic conditions. Addressing this shortcoming, and exploring its implications, is one of the specific objectives of this work. An additional advantage of the regional scale domain we are considering here, is to include several shelf sea regions and allow a consistent comparison between them, particularly some areas (such as the Celtic Sea), which have seen little modelling attention in this context.

In the next section we briefly describe the POLCOMS-ERSEM model and the specific experiments considered here. Section 3 describes the controls on the present day and potential future primary production, and the ocean-shelf coupling is further explored in Sect. 4. Conclusions are drawn in Sect. 5.

2 Model description, validation and experiments

POLCOMS is a three-dimensional hydrodynamic model using a quasi finite-volume approach discretised on a B-grid in spherical-polar-terrain following coordinates. The Atlantic Margin Model (AMM; Fig. 1) configuration considered here has a resolution of 1/9° latitude by 1/6° longitude grid (~12 km) with 42 s-coordinate levels (Song and Haidvogel, 1994) in the vertical. This configuration is further described by Wakelin et al. (2009).

ERSEM (Fig. 2) is a well established, generic lower-trophic level/biogeochemical cycling model. Eight plankton functional types are represented, including phyto-, zoo-plankton and bacteria, along with the cycling of C, N, P, Si through pelagic (Blackford et al., 2004) and benthic ecosystems (Blackford, 1997). The latter is critical for nutrient cycling in shelf seas. The implementation of ERSEM considered here essentially matches that described in Blackford et al. (2004) with the treatment of abiotic (SPM, CDOM) absorption described by Wakelin et al. (2011). The parameter set matches that used by Blackford (2004), except here we limit the carbon to chlorophyll ratio to better match observations (Geider et al., 1997; Artioli et al., 2011).

The POLCOMS-ERSEM system has been used extensively in several NWS model domains in the context of understanding model uncertainty (Holt et al., 2005; Lewis et al., 2006; Allen et al., 2007a), understanding regional processes (Proctor et al., 2003; Blackford et al., 2008; Holt et al., 2004) and for operational oceanography (Siddorn et al., 2007).

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2.1 Model experiments

Here we consider four model experiments: a reanalysis forced simulation (ERA40) and three OA-GCM forced simulations (CNTRL, A1B and A1Bb). We use ERA40 to explore present day variability, the difference between CNTRL and ERA40 to explore the consequences of forcing this regional model with a coarser resolution OA-GCM and the difference between A1B and CNTRL to explore the behaviour of the system under possible future conditions. Experiments ERA40 and CNTRL are compared with observations and other models in Sect. 2.2. Experiment A1Bb is used to further explore the importance of oceanic nutrient change for the on-shelf production. For this work we adopt a time-slice approach commonly used in climate impact studies, whereby mean conditions in a future period are compared with mean conditions in a present day reference period to give a measure of the climate change signal, on the assumption that conditions in both time-slices are approximately stationary. This signal can then be compared with natural variability, model (structural and parameter) uncertainty and emissions uncertainty to assess the significance of this signal (Hawkins and Sutton, 2009). Because we only consider the first of these here and make no assessment of the likelihood of the future conditions (both in terms of the emissions scenario or the forcing OA-GCM) these simulations should be considered a "sensitivity" experiments, rather than a projection, illustrating the system's response and the relative importance of different vectors of change. An alternative approach is to sequentially perturb different aspects of the forcing to identify different response processes (Skogen et al., 2011). While this is insightful, the decadal simulations needed to investigate ocean-shelf coupling prohibit a full range of perturbation experiments, so we instead opt of a single self consistent set of forcing. The model experiments are now described in some detail.

2.1.1 ERA40

This is a 45-yr (1960–2004) simulation with surface forcing from ERA-40 reanalysis (until September 2001) and subsequently ECMWF operational analysis. Surface fluxes

are calculated by COARE v3 bulk formulae (Fairall et al., 2003) in all the experiments considered here. Lateral boundary conditions are taken from a 1° NEMO ocean re-analysis (Smith and Haines, 2009) and a North Atlantic Tidal model (providing 15 constituents; Flather, 1981). Aspects of this simulation have previously been reported by Holt et al. (2009) and a subset of data from this simulation is freely available[2]. Full details of the physical model forcing, including detailed analysis of the accuracy of the temperature simulation can be found in Holt et al., 2011). Ecosystem boundary conditions use monthly values from the World Ocean Atlas (WOA; Garcia et al., 2006) for nitrate, silicate and phosphate, imposed with an up-wind advection boundary condition. Other variables use a "zero-gradient" boundary condition; this is equivalent to a one-dimensional (vertical) model at the boundary grid cell. River nutrient loading matches that used by Lenhart et al. (2010), with raw data for the UK, Northern Ireland, Ireland, France, Norway, Denmark and the Baltic processed by van Leeuwen (CEFAS, UK) and raw data for Germany and the Netherlands was processed by Pätsch and Lenhart (2004). The Baltic exchange at the Belts is treated crudely as an inflow source using a mean annual cycle of depth averaged transport, salinity and nutrients. A constant spatial field of atmospheric nitrogen deposition (oxidized and reduced) is provided by EMEP (Cooperative Programme for Monitoring and Evolution of the Long-range transmission of Air Pollutants in Europe; as is also used in some models considered by Lenhart, 2010).

2.1.2 CNTRL

This is a 23-yr present day simulation forced by the IPSL-CM4 OA-GCM (Marti et al., 2006) as run for the ENSEMBLES project[3], for the nominal present day period 1980–1999 (1980 is repeated three times before this period is simulated). The OA-GCM provides: 6-hourly surface atmospheric air temperature, winds, pressure and

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[2]http://www.myocean.eu/web/24-catalogue.php

[3]http://www.ensembles-eu.org/

relative humidity; daily shortwave radiation (which we modulate with a diurnal cycle) and monthly ocean currents, sea level, temperature and salinity. Tides, rivers, abiotic absorption, and nutrient boundary conditions match those in ERA40. We note this OA-GCM has a significant negative temperature bias in NWS (~ -2 °C), which may unduly influence changes in those processes non-linearly dependent on the temperature e.g. growth rates and stratification. Hence we correct this bias using a time constant 3-D correction field (for temperature and salinity, derived from WOA data) applied to the initial and boundary conditions, and a 2-D correction to the air temperature derived from ERA40. This is partially successful in removing this bias (see below).

2.1.3 A1B and A1Bb

A1B is a future climate scenario representative of possible conditions in 2080–2100 under a business as usual emissions scenario: SRES A1B (Nakicenovic and Swart, 2000). Again the first year is repeated three times before running this period. Forcing matches CNTRL using the same OA-GCM simulation run forward to this period. This OA-GCM simulation includes the PISCES ecosystem model (Aumont et al., 2003) and we perturb the open-boundary nutrient values (nitrate, silicate and phosphate) by the fractional change between this time-slice and CNTRL; the bias between the PISCES nutrient values and WOA data prohibits the use of an absolute change. River flows are perturbed by changes in regional rainfall from the OA-GCM, whereas riverine nutrient loads and atmospheric inputs are unchanged.

For the purposes of this work, the climate change signal between A1B and CNTRL is well characterised by the change in temperature (not shown) and potential energy anomaly (Fig. 3). The latter gives a measure of stratification appropriate for both shelf seas and open-ocean, and is defined as the energy required to mix the top 400m of the water column (see Holt et al. (2010) for further details). The sea surface temperature (SST) change shows a strong seasonal signal being larger in the summer and autumn than winter and spring. Spatially the changes are largest in the North Sea (~ 4 °C in the central North Sea in summer) and smallest west of Biscay (~ 0.5 °C in winter). This

is accompanied by an increase in both seasonal and permanent stratification (Fig. 3). There is a substantial increase in stratification in open-ocean regions of the model throughout the year. During the summer the greatest increase in oceanic stratification is towards the south of the domain. The shelf remains generally well mixed during winter, but there is a significant increase in stratification during the summer particularly in the Irish Sea, North Sea and English Channel. While there is a significant fractional change in the "well-mixed" regions, values here remain low.

Experiment A1Bb matches A1B, except in this case the nutrient boundary conditions are not changed compared with CNTRL (i.e. just WOA nutrients are used). This partially constrains the open-ocean portion of the model to present day nutrient values.

In all experiments we treat the first 5 yr (justified below) as "spin-up" to allow the model to adjust to its lateral boundary and surface forcing conditions, so the results present here are means for 40 yr for ERA40 and 18 yr for CNTRL, A1B and A1Bb.

2.2 Validation

As with any model simulation, these results need to be considered in the context of observed properties to inform the reliability of the conclusions. The uncertainties in the POLCOMS-ERSEM system have been extensively investigated in comparison with contemporary observations for seasonal scale simulations (Allen et al., 2007a, b; Holt et al., 2005; Lewis et al., 2006) and detailed analysis of the representation of inter-annual variability in this simulation is underway (e.g. Holt et al., 2011). Hence, these are not considered here. Instead we follow the approach of Holt et al. (2010) and focus on an assessment of the mean state for temperature, salinity, nitrate and chlorophyll, drawing on the substantial volume of in-situ data for this region held at the Wold Ocean Data Base[4] for the period 1980–2000. We concentrate on values in the 13 regions shown in Fig. 1. Table 1 shows the mean bias (model minus observations) and the cost function, χ, defined as the RMS error divided by the standard deviation of the

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[4]http://www.nodc.noaa.gov/OC5/WOD/pr_wod.html

observations. Surface observations are averaged onto the model grid for each month and then these statistics are calculated across each region. Here surface values are defined by the top 8 model s-levels. Hence, the mean bias indicates the overall sign and magnitude of the discrepancy between model observation and χ assesses the model's ability to reproduce the mean annual cycle and the spatial variations. Cost function values are typically ∼1 across the regions and variables, except for temperature, which has values between 0.4 and 0.7. Hence salinity, nitrate and chlorophyll have RMS errors close to the spatial and temporal variability. The regions of the highest error for nitrate and chlorophyll are Skagerrak/Kattegat, Norwegian Trench (reflecting the poor representation of Baltic inflow), and Armorican shelf; these regions are not considered in detail in this investigation. There is no systematic increase in errors when comparing CNTRL with ERA40, indicating that forcing with this coarser resolution OA-GCM does not substantially degrade the simulation. However, there is a consistent negative temperature bias in the CNTRL experiment, indicating that a more sophisticated bias correction approach may be needed.

Validation of the net primary production (netPP) is more problematic. This is defined here as the total carbon uptake by phytoplankton minus the phytoplankton respiration, annually and depth integrated, but limited to the upper 200 m. Direct measurements are rare and themselves subject to substantial uncertainties. Satellite derived estimates are based on empirical modelling assumptions, are subject to contamination with other inherent optical properties and may also have a treatment of respiration inconsistent with the model values. However, they do provide our best spatially resolved estimate and so this is the subject of ongoing work. Comparisons with other model studies (e.g. Skogen and Moll, 2000) can provide a guide to areas to investigate further, but can equally re-affirm erroneous model results. Hence, for our purposes observed values of netPP from the literature, drawn from a range of approaches, provides the best guide to model performance, accepting that these few observations grossly under-sample the spatial and inter-annual variation. We compare these with CNTRL and ERA40 values by region in Table 1. This demonstrates that both ERA40 and CNTRL produce annual

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netPP within the observed range in each region except for the Skagerrak/Kattegat. The netPP values in CNTRL are systematically less than those in ERA40. This most likely arises from both the air temperature and wind speed being less in the OA-GCM forced run than the reanalysis forced run. Compared with a SeaWiFs based primary production model (Smyth et al., 2005), we consistently underestimate the annual netPP, for the reasons noted above. Compared with the NORWECOM and ECOHAM1 models in the North Sea (Skogen and Moll, 2000), POLCOMS-ERSEM, produces similar netPP values in the southern, central and northern North Sea, but does not show the large values ($\sim$200 g C m^2 yr^{-1}) seen in outer shelf regions of NORWECOM. POLCOMS-ERSEM shows coastal values that are closer to the (higher) values in NORWECOM than ECOHAM1, but has a less marked netPP minimum in the central North Sea than NORWECOM (being closer to ECOHAM1 here).

3 Present day and potential future primary production

The mean annual net primary production for ERA40 and CNTRL is shown in Fig. 4 along with the fractional difference between A1B and CNTRL, and between A1Bb and CNTRL. The ERA40 and IPSL-CM4 forced simulations show very similar spatial patterns of netPP ($r^2 = 0.95$). They differ in magnitude, particularly around the coast of Ireland, in the Celtic and Irish Seas and the English Channel. As noted above, the CNTRL simulation underestimates the primary production in all these areas compared with ERA40.

The A1B simulation shows a reduction in netPP in most of the open-ocean regions, the shelf edge, northern and central North Sea. This decrease ranges from $\sim$20 % in Biscay to <5 % in central North Sea. The primary production increases in Celtic Sea, Irish Sea, southern North Sea and west of Scotland by 5–10 %. It also increases in an open-ocean patch in Biscay, around the coast of Iceland and along the Wyville-Thomson ridge. Regional mean values are shown in Table 1, which also indicates where the difference in the mean is statistically significant compared to the inter-annual variability.

The experiment without using PISCES boundary nutrient data (A1Bb) shows a very different picture: an increase in netPP across much of the domain of typically 0–20 %, except in the central and northern North Sea, the southwest corner and the central open-ocean region, where there is a decrease of typically 0–20 %. We should keep in mind that this is a rather unnatural experiment, since the boundary conditions are constrained towards present day values and so are constantly out of balance with the response of the open-ocean regions to local forcing.

To explain these changes in netPP we turn to the nitrogen dynamics in the model. Figure 5 shows the fraction change in winter dissolved inorganic nitrogen (DIN; in ERSEM this is just nitrate and ammonia, other species of inorganic nitrogen are not considered) and annual mean total N (TN; pelagic DIN, dissolved and particulate organic nitrogen and benthic N in water less than 200 m deep) between CNTRL and both A1B and A1Bb. Again integrations are limited to 200 m depth. Between A1B and CNTRL, the DIN concentration across the whole northeast Atlantic (as included in this domain) is decreased by 5–50 %. The exceptions are some localised patches that show a 0–10 % increase and the Norwegian Sea, which shows a 0–5 % decrease. These changes are reflected across much of the continental shelf. However, the Irish, Celtic, northern English Channel and southern North Sea all show an increase in DIN of between 0 and 15 %. What is interesting to note is that this increase is also apparent in the total nitrogen inventory. It is not simply a redistribution of N, as might be expected by simply increasing recycling rates. The pattern of winter DIN change generally matches the netPP change; this is quantified below. The regions of positive netPP change are generally more extensive than the regions of positive DIN change and the band of increased netPP across the northern part of the domain is accompanied by a general reduction in winter DIN. When the change between CNTRL and A1Bb is considered the reduction in winter DIN largely disappears and is replaced by a modest increase to the south of the domain and across much of the shelf. Again this change is reflected in the total N inventory. The pattern of DIN change matches the change in netPP on shelf, but is less clear in the open-ocean.

We can quantify the relation between primary production and winter DIN by evoking the strong correlation that exists in this model between netPP and nitrogen uptake by phytoplankton (overall $r^2 = 83$). Hence this uptake can be used as a proxy for primary production that can be quantitatively related to the available DIN. It is also helpful to
5 move from the detailed spatial fields to regional aggregation, since the reliability of model results generally improves when averaged over an increasing number of grid cells (Shutler et al., 2011). Hence we now consider results integrated over the 13 regions shown in Fig. 1. Turning first to ERA40, Fig. 6 compares the total DIN uptake in nine of these with the available winter DIN. It clearly shows that the winter DIN pro-
10 vides a lower bound on the total uptake. There is excess production beyond this initial supply ranging from ~20 % on the Shetland Shelf to ~4 times in the southern North Sea. At this degree of aggregation all regions are nutrient limited and the properties of any coastal light limited regions are hidden in this averaging. This excess production reflects the various resupply mechanisms active over the seasonal cycle including
15 cross-pycnocline mixing, pelagic and benthic recycling, and riverine and atmospheric nutrient inputs. Annual values for all 40 yr of simulation are shown in this figure. These show a positive correlation between the variability in winter nutrients and annual DIN uptake, although the variability in the uptake tends to be larger.

The next step is to consider how the winter DIN and DIN uptakes change between
20 the present (CNTRL) and future (A1B) time-slices. Figure 7, demonstrates a clear relationship between changes in winter DIN and DIN uptake. This relationship is seen in the absolute differences but is particularly clear in the fractional differences. For most regions the change in DIN uptake matches the change in winter DIN to within one standard deviation of the inter-annual variability of this uptake. The southern NE Atlantic
25 region and the northern North Sea both show a decrease in nutrient uptake that is greater than the corresponding decrease in winter nutrients. This arises from changes in stratification (Fig. 3). All other regions show changes in DIN uptake that is more positive than the change in winter DIN would suggest, in these cases temperature effects mitigate the reduction in winter DIN by increasing recycling rates and lengthening

the growing season in seasonally stratified regions. This outweighs any reduction due to reduced vertical nutrient mixing arising from increased stratification. This mitigation is particularly the case for the Irish Sea and northern NE Atlantic regions. When the oceanic nutrients are constrained to present day values through only using WOA data (and not the OA-GCM model data) at the boundaries (A1Bb; Fig. 7), there is a marked change. In all the regions the decreases in winter DIN are reduced and correspondingly the change in DIN uptake is more positive. Some regions still show a weak reduction in DIN because the constraint to present day values is not absolute; oceanic nutrient concentrations still adjust to local meteorological forcing. However, all regions now show an increase in DIN uptake between CNTRL and A1B, except the Shetland shelf (which shows a ~1.5 % decrease).

Hence variations in winter nutrient supply are an important control on on-shelf primary production. Given that much of these nutrients originate from the open-ocean we turn next to the issue of ocean-shelf exchange in some detail.

4 Ocean-shelf nutrient transport

Before considering the on-shelf nutrient transport in the full POLCOMS-ERSEM model, it is insightful to explore the ocean-shelf water transport using a passive tracer experiment. Here we introduce 6 tracer patches in experiment ERA40 from January 1980 to December 1990, with the objective of identify the general regions of origin for the on-shelf water. Initial value is $1\,\mathrm{m}^{-3}$ throughout the water column in total water depths deeper than 1000 m, as shown in Fig. 8, along with example tracer fields after 5 yr of integration from two of the patches. Time series of mean concentrations in 9 of the regions shown in Fig. 1 (Fig. 8) demonstrate how water from different oceanic regions impinges on-shelf. Riverine and Baltic water is introduced with zero concentration, so the total tracer concentration gives a good indication of the oceanic influence in each region. Open boundary concentrations are fixed at unity, so oceanic concentrations are replenished on inflow with water of the original patch in that location.

The southern and western shelf seas (Armorican Shelf, Celtic Sea, English Channel, Irish Sea and southern North Sea) receive water in varying combinations from regions A, B and C. This is generally dominated by water from region B (Biscay), and region A (Iberian) only makes a minor contribution. These proportions typically reach equi-
5 librium on a 5–10 yr time scale; and do not receive a significant contribution from the northern patches (D–F). The outer-shelves, central and northern North Sea initially receive water from patches C, D, and E. All these regions receive water from patch D first (accompanied by E on the Shetland Shelf), followed by patches C and E. Water from D and E is replaced with water from patch B so this dominates after ∼5 yr. There are
10 two pathways for this replacement. First off-shelf, whereby water in patches C, D and E is replaced by water from patch B owing to the general northward transport here, both in the North Atlantic current and the slope current. Second, on-shelf, whereby water from the Celtic Sea is transported north around the Ireland carried by the shelf edge (Pingree et al., 1999) and Irish coastal (Fernand et al., 2006) currents. From Fig. 8a
15 it is apparent that both of these pathways are active, but the transport into the Celtic Seas from patch B is slow. This may well reflect our inability to resolve the pertinent shelf-exchange processes active in this region with this coarse resolution model (see Huthnance, 1995).

Hence on a 10 yr time scale, a substantial fraction of the water on-shelf (∼80 %) orig-
20 inates from patches C and B (between 43.22° N and 53.33° N) and the corresponding wider ocean regions outside this domain. Both these regions show a substantial increase in stratification (Fig. 3) and reduction in winter nutrients (Fig. 5) in the future time-slice. However, water from the first of the transport pathways noted above may experience several seasons of deep winter mixing, and hence may acquire the nutrient
25 properties of water further north, prior to coming on-shelf.

To explore the detailed spatial structure of the ocean-shelf transport, fluxes of DIN across the shelf break (defined by the 200 m isobath; Fig. 9) are calculated from monthly mean model output of the layer integrals of $u \cdot$ DIN. Where, u is the velocity normal to the 200 m isobaths, with on-shelf values being positive. These are time

averaged during the model simulation and so include both mean and fluctuating (e.g. tidal residual) components but do not include any numerical diffusion arising from the advection scheme. A passive tracer horizontal diffusion term is not explicitly included in this model (Holt and James, 2001). The northwest European continental shelf has an overall downwelling circulation with water being brought on-shelf at the surface and leaving at depth (Holt et al., 2009), both in the large scale circulation and the surface and benthic Ekman layers. These layers are associated, respectively, with the wind driven circulation and the slope current. This downwelling circulation is reflected by the overall DIN transport across the shelf break. When the change in DIN transport between the time-slices is considered (Fig. 9), a reduction in mean DIN transport on-shelf is apparent around the whole shelf break from 53° N to 61.3° N, with only localised increases. This arises primarily from a substantial reduction in DIN around the shelf break above ∼80 m depth, owing to a reduction in oceanic surface DIN. There is a small reduction in volume flux between these experiments. This is particularly notice-able where the slope current intrudes on-shelf at ∼54.5° N in the region of Porcupine bank.

Shelf wide context of ocean shelf exchange

We can summaries the shelf wide impacts of changes in ocean-shelf exchange by considering the various terms in the pelagic DIN equation:

$$\frac{dN_m}{dt} = A + P + B + F_r + F_a \tag{1}$$

Here we amalgamate the full model equations (shown schematically in Fig. 2) to give: A Advective flux divergence, P Pelagic recycling minus biological uptake, B Benthic recycling, F_r River inputs, F_a Atmospheric inputs.

We only consider depth integrals here, so no vertical diffusion term is needed. We also integrate horizontally over the whole on-shelf region (depth <200 m) north of 48° N (excluding the Skagerrak and Kattegat; i.e. regions 1–4 and 7–10). Time averaged values of these terms are presented in Table 2. This shows that in all runs the model is

close to equilibrium with dN_m/dt being by far the smallest term. This term is consistently negative in these experiments indicating a slow adjustment in the model towards equilibrium. This may well represent the benthic sub-model adjusting on much slower timescales than the pelagic. The term dN_m/dt is about twice as large in A1B as in
5 CNTRL. The primary balance is between the net pelagic uptake and the flux from the benthic sub-model. The deficit from this balance is increased by the advection term and decreased by riverine and atmospheric sources. The relative importance of the terms does not change greatly between runs but there is a noticeable increase in the benthic flux in A1B compared with CNTRL. The mean winter DIN decreases by ∼9 % between
10 these experiments, but increases slightly when CNTRL is compared with A1Bb. The on-shelf flux on the western margin is balanced by an off-shelf flux to Norwegian Trench and into the Skagerrak (also shown in Table 2). The inflow and outflow fluxes of DIN decrease in proportion to the decrease in DIN concentration at the shelf edge.

It is useful to compare the modelled on-shelf nutrient concentration with that pre-
15 dicted by a simple "mixing-box" model. Here we assume river and oceanic water enters the region with volume fluxes $Q_{r,o}$ and nutrient concentrations, $N_{r,o}$. This water is well-mixed on the shelf to give a concentration, N_s, which leaves the shelf with volume flux $Q_o + Q_r$ (to give a constant volume). The steady-state concentration (including the area averaged atmospheric input, F_a) is then given by:

$$20 \quad N_s = \frac{Q_o N_o + Q_r N_r + F_a}{Q_o + Q_r} \tag{2}$$

Values for N_s calculated with the ocean in-flow and shelf-edge nutrient concentrations and the riverine flux of 0.01 Sv (constant across the experiments to ∼5 %) are given in Table 1. It is interesting to note that changes in oceanic and riverine volume fluxes impact the steady state nutrients only in proportion with each other. The values from
25 this very simple calculation agree reasonably well with the full model, with N_s being consistently greater than N_m owing to biological activity. The change between the time-slices is over predicted by the simple model as biogeochemical processes act to reduce the magnitude of change that this simple, steady state, passive model suggests.

5   Discussion and conclusions

Changes in oceanic nutrients are clearly demonstrated here to be a first order factor in determining changes in on-shelf primary production on time scales of 5–10 yr. While it has long been known that oceans supply a substantial fraction of shelf sea nutri-
ents (e.g. Galloway et al., 1996), the consequences for on-shelf primary production of potential future changes has not up until now been clearly articulated. The importance of changes in oceanic nutrient inputs is generally supported by a simple mixing model, and so is robust and not sensitive to the details of the coupled hydrodynamic-ecosystem model we employ.   However, while shelf sea regions are vulnerable to
changes in oceanic nutrient inputs, there are several on-shelf processes that mitigate this and the changes are generally less than either a simple passive tracer or nutrient based analysis would suggest. Generally shelf regions that are most directly exposed to ocean-shelf exchange show a stronger reduction in primary production, whereas those where the exchange is slower show a weaker reduction or a net increase. Ex-
amples of the former include Irish, Hebrides and Shetland Shelves, and the northern and central North Sea. Examples of less controlled regions are the English Channel, Irish Sea, Celtic Sea and southern North Sea.

We can speculate that the mitigation of reduced on-shelf nutrient transport arises from changes to temperature that lead to increased recycling rates in both the pelagic
and benthic systems.   These temperature changes also lead to increased on-shelf stratification and hence potentially increased growing season. The boundary condition perturbation experiment (A1Bb) suggests changes in on-shelf stratification reducing vertical mixing have a secondary effect on primary production in many regions compared with oceanic transport (the central North Sea being a possible exception). We
also note that the total nitrogen inventory is seen to increase in some regions, comparing A1B and CNTRL. This cannot simply be a recycling phenomenon, but must involve a process of nutrient capture. This necessarily involves material in particulate phase. The concentration of dissolved material cannot accumulate, and the boundary

concentrations here are decreasing. In contrast, the particulate phase can accumulate, as it does not necessarily move with the water. This, along with the temperature and stratification effects deserves a much more detailed investigation than can be given here. These mitigation processes will be diagnosed in more detail in future model
5 experiments. They will be explored both in the context of overall primary production changes and with regards to changes to the seasonality, which are potentially important both to phytoplankton production and to higher trophic levels.

The details of the division of the shelf sea regions into those where the netPP is dependent on oceanic control and those where local processes are more important is
10 likely to be sensitive to the choice of model and forcing. This can be characterised by the zero-fractional-change contour in Fig. 4. The sensitivity of position of this dividing line deserves further investigation with respect to changes in OA-GCM forcing (both model choice and emissions scenario choice) and shelf sea model parameter values and structure. For example, here we use an ecosystem model with a sophis-
15 ticated representation of pelagic and benthic recycling, and we can speculate that a model without, for example, explicit representation of bacteria would give very different results. Similarly, the ERSEM model has a static foodweb with fixed interaction strengths between predators and prey, with no ability to simulate changes in behaviour or food preference. This lack of "plasticity", necessarily limits the model's ability to sim-
20 ulate variations in top-down control (Mariani and Visser, 2010), and results in a model ecosystem that is predominantly sensitive to bottom-up changes in the physical and chemical environment. Moreover, the POLCOMS model at this resolution tends to underestimate the ocean-shelf exchange (Huthnance et al., 2009) particularly in regions, such as the Celtic Sea, where this is dominated by fine scale processes that are not
25 represent in the model, such as internal tides (Sharples et al., 2009).

Here we are primarily demonstrating the principles using the "blunt instrument" of a future climate change scenario to provide a self-consistent set of forcing, but with no comment on its likelihood. Of equal importance and inherently more testable against observations would be an analysis of the relative oceanic and local controls arising

from climate variability in the ERA40 simulation. This is underway in a more in depth analysis of the propagation of signals through the pelagic and benthic systems and will be reported on in due course.

These results suggest that the model considered here is minimal in its spatial extent
for investigations of future climate downscaling in many regions of the northwest European Continental shelf: models that do not adequately represent changes in ocean-shelf nutrient transport (e.g. on-shelf 3-D models with fixed nutrient boundary conditions or 1-D water column models) miss an important vector of climate change for many regions. Ideally a model covering a substantially larger area of the North Atlantic
should be used for the climate change downscaling. Such a model is currently under development in the EURO-BASINS FP7 project[5].

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Table 1. Model validation for ERA40 and CNTRL using all WOD data in the domain for period 1981–2004. Mean Bias and cost function χ are shown for the regions in Fig. 1. This is based on ~168 000 temperature and salinity observations, 62 000 nitrate observations and 49 000 Chl-*a* observations.

	Temp. Mean bias °C	χ	Sal. Mean bias PSU	χ	Nit. Mean bias mmol m^{-3}	χ	Chl-*a* Mean bias mg m^{-3}	χ	Mean netPP ERA40 gC m^{-3}	Literature
ERA40										
1. Southern North Sea	−0.4	0.3	0.3	0.8	0.0	0.9	−3.0	1.0	149	150–300[1]
2. Central North Sea	0.2	0.4	0.0	0.8	4.1	1.3	−1.2	1.0	118	100–150[1,2]
3. Northern North Sea	0.2	0.4	0.1	0.8	2.6	1.2	−0.4	1.0	108	54–127[3]
4. English Channel	−0.2	0.4	0.2	0.9	−6.0	0.9	−2.3	1.1	151	
5. Skagerrak/Kattegat	−0.6	0.4	0.7	0.5	6.1	2.3	−0.8	1.1	131	135–220[7]
6. Norwegian Trench	−0.2	0.5	0.5	0.8	5.5	1.8	−1.8	1.1	102	
7. Shetland Shelf	0.3	0.5	−0.1	0.9	0.4	0.9	0.2	2.0	105	
8. Irish Shelf	0.4	0.4	0.1	0.6	2.9	1.1	−0.3	0.9	131	
9. Irish Sea	0.2	0.7	0.2	0.8	2.6	1.0	0.1	0.9	145	<100–194[4,5]
10. Celtic Sea	0.9	0.7	−0.2	0.8	0.0	0.9	−0.8	1.0	143	160[6]
11. Armorican Shelf	−0.4	0.5	0.1	0.7	2.5	1.4	0.6	1.1	170	
12. NE Atlantic (S)	0.3	0.4	−0.2	1.1	0.6	0.7	0.0	1.0	122	
13. NE Atlantic (N)	−0.5	0.7	−0.2	0.9	−0.2	0.9	0.7	2.1	112	
CNTRL										A1B
1. Southern North Sea	−1.1	0.4	0.9	0.8	−4.3	0.9	−3.3	1.1	129	**134**
2. Central North Sea	−0.7	0.4	0.3	0.9	4.0	1.3	−1.3	1.0	120	**117**
3. Northern North Sea	−0.9	0.5	0.4	0.9	2.7	1.2	−0.3	1.1	112	**101**
4. English Channel	−0.7	0.4	0.6	0.9	−10.2	0.9	−2.7	1.1	113	115
5. Skagerrak/Kattegat	−1.3	0.5	1.3	0.5	5.9	2.3	−0.8	1.2	137	**142**
6. Norwegian Trench	−1.1	0.6	0.8	0.9	5.3	1.7	−1.8	1.1	96	92
7. Shetland Shelf	−0.8	0.5	0.0	0.9	0.4	0.9	0.2	1.9	104	**94**
8. Irish Shelf	−0.7	0.5	0.2	0.7	3.6	1.3	−0.3	1.0	118	116
9. Irish Sea	−0.9	0.8	0.7	1.1	0.7	1.0	−0.5	1.0	120	**133**
10. Celtic Sea	0.0	0.5	0.2	0.8	−2.6	0.9	−1.0	1.1	121	124
11. Armorican Shelf	−0.5	0.5	0.1	0.8	3.5	1.5	0.0	1.0	151	148
12. NE Atlantic (S)	−0.8	0.5	0.0	1.0	0.9	0.7	0.2	1.2	120	**102**
13. NE Atlantic (N)	−1.5	0.9	0.0	0.9	0.4	1.0	1.1	2.9	103	**98**

Literature values of netPP are from: [1] Joint and Pomeroy (1993); [2] North Sea Quality Status Report. (1993); [3] Steel (1956); [4] Gowen and Bloomfield (1996); [5] Gowen et al. (2000); [6] Joint et al. (2001); [7] Rydberg et al. (2006). Mean netPP for CNTRL and A1B are also shown. These are in bold where the mean values are significantly different (tested at 95 %), given the inter-annual variability.

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**Table 2.** Shelf wide integrals (region 1–4, 7–10 on Fig. 1) of terms in the DIN Eq. (1) and average transports across sections with net flow into and out of the region. Also shown is output from a mixing model calculation (Eq. 2).

		ERA40	CNTRL	A1B	A1B/CNTRL-1
dN_m/dt	Gmolday^{-1}	−0.03	−0.02	−0.05	110.5 %
P	Gmolday^{-1}	−0.92	−0.86	−0.91	5.9 %
B	Gmolday^{-1}	0.87	0.79	0.85	7.2 %
A	Gmolday^{-1}	−0.31	−0.29	−0.31	8.3 %
F_r	Gmolday^{-1}	0.21	0.21	0.20	−3.8 %
F_a	Gmolday^{-1}	0.12	0.12	0.12	0.0 %
DIN Flx in	Gmolday^{-1}	1.27	1.36	1.13	−16.8 %
DIN Flx out	Gmolday^{-1}	−1.52	−1.58	−1.38	−12.7 %
N_{in}	mmolm^{-3}	10.94	10.56	8.81	−16.6 %
N_{out}	mmolm^{-3}	13.30	12.55	10.98	−12.5 %
Vol flux in	Sv	1.34	1.49	1.48	−0.2 %
Vol flux out	Sv	−1.32	−1.46	−1.45	−0.1 %
N_m	mmolm^{-3}	13.22	10.96	9.93	−9.4 %
N_s	mmolm^{-3}	13.70	13.06	11.27	−13.7 %

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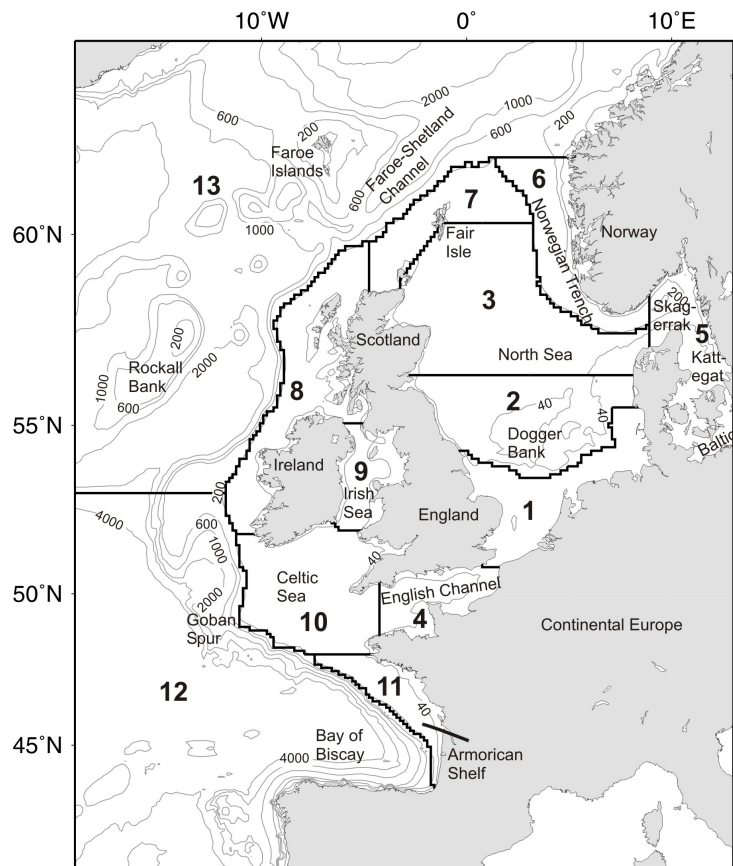
Fig. 1. Model domain, sections for flux calculations and regions for areal integrals.
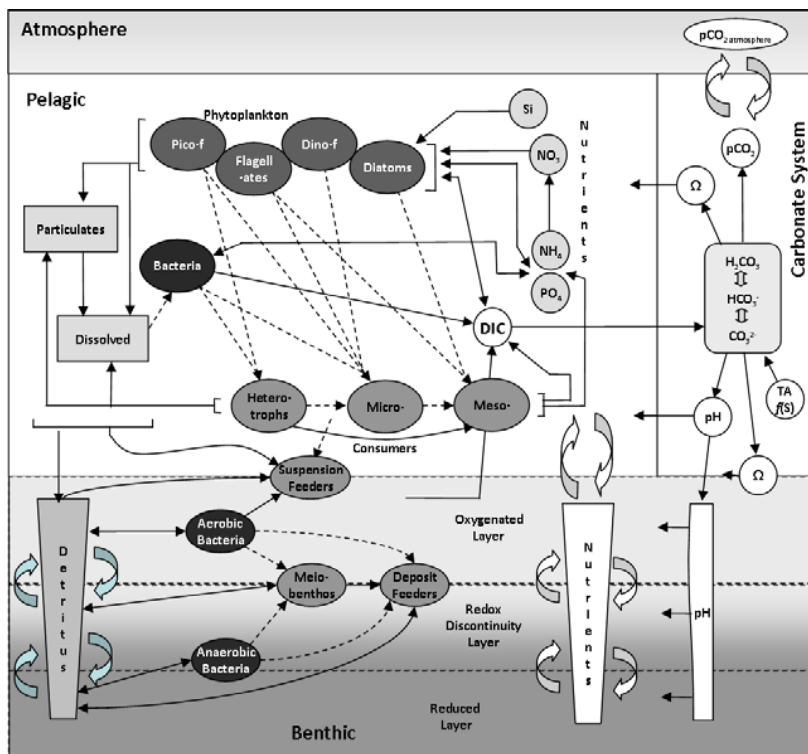
Fig. 2. Pelagic and benthic components of the ERSEM Model.
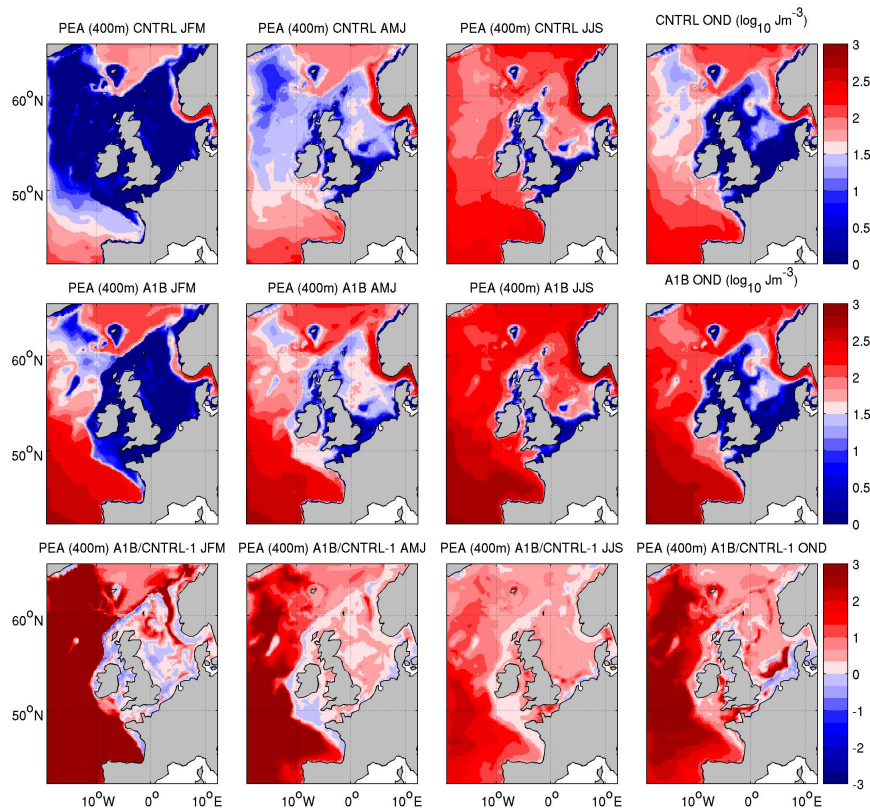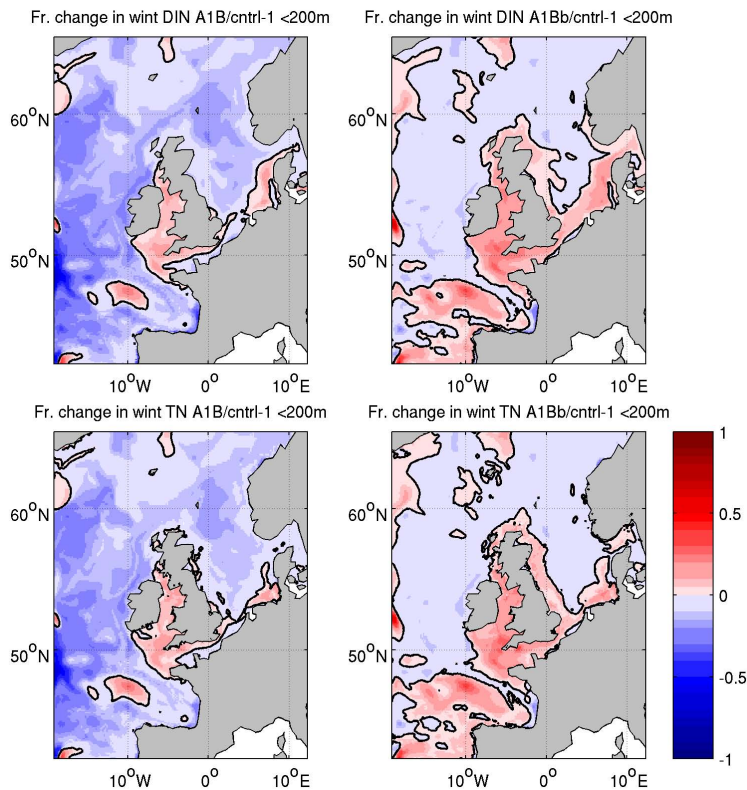
Fig. 3. Seasonal mean potential energy anomaly with integration limited to 400 m (Holt et al., 2010) for CNTRL and A1B (note $\log_{10}$ scale), and the fractional difference between them. For clarity this is limited to changes of a factor of 3, maximum change in oceanic regions is a factor of 5.7.
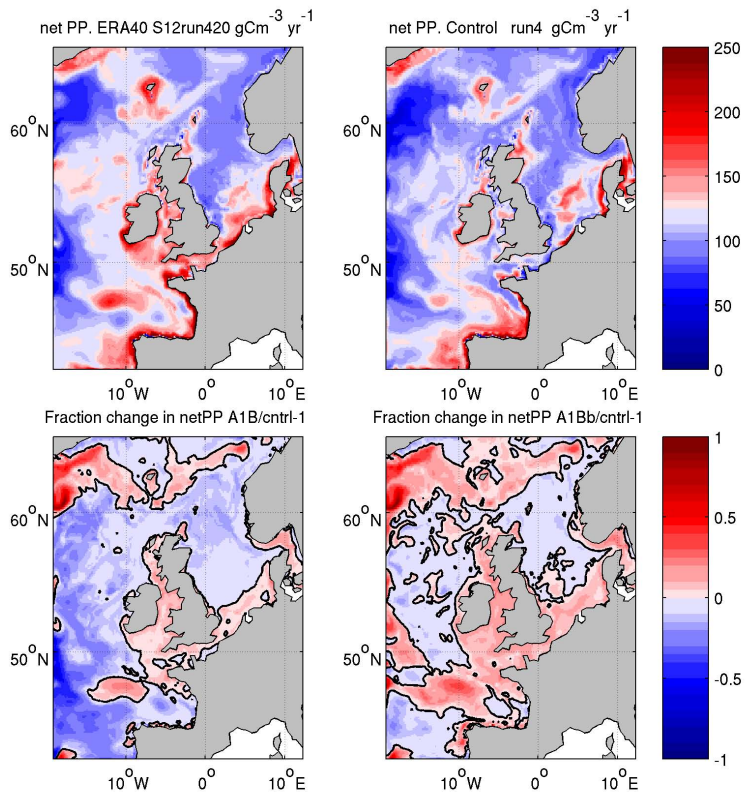
Fig. 4. Depth integrated annual mean net primary production (top): ERA40 (left); CNTRL (right); Fraction change (bottom) between CNTRL and A1B (left); between CNTRL and A1Bb (right).

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Fr. change in wint DIN A1B/cntrl-1 <200m

Fr. change in wint DIN A1Bb/cntrl-1 <200m

Fr. change in wint TN A1B/cntrl-1 <200m

Fr. change in wint TN A1Bb/cntrl-1 <200m

Fig. 5. Fraction change in winter DIN and total N comparing A1B and A1Bb with CNTRL.

Oceanic controls on primary production

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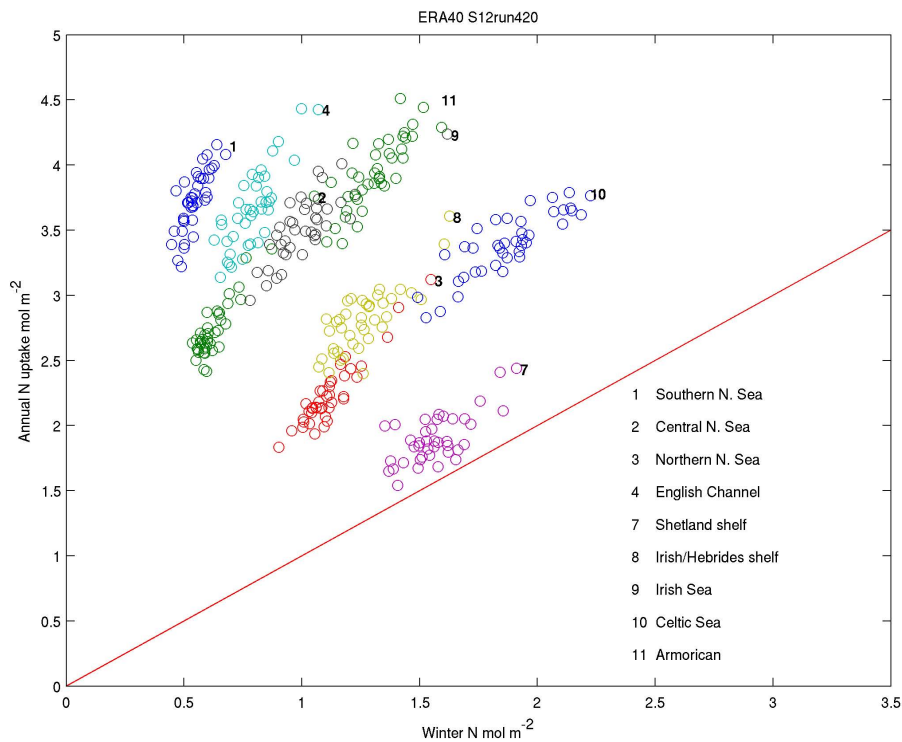
Fig. 6. Total annual DIN uptake and previous winter mean DIN, averaged for the on-shelf regions shown in Fig. 1 for ERA40.
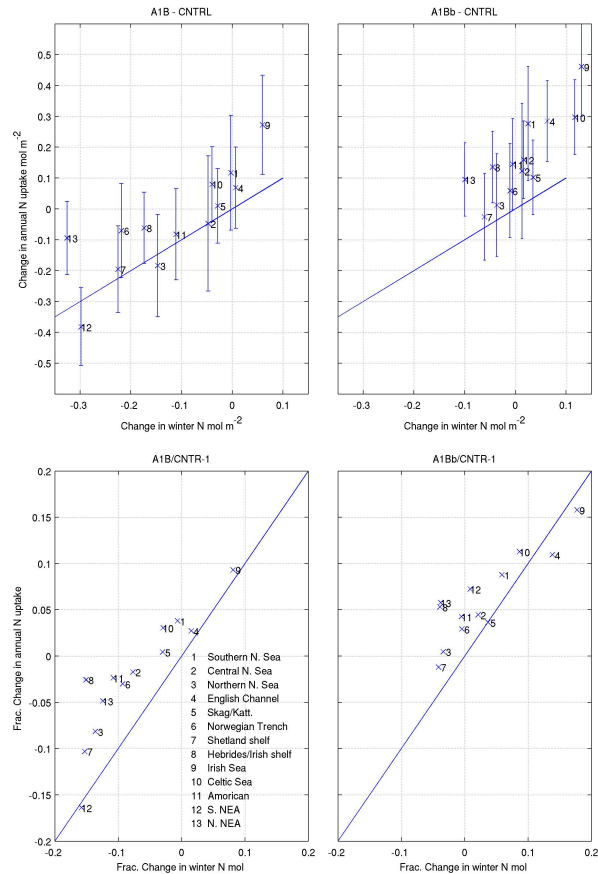
Fig. 7. Total annual DIN uptake and winter mean DIN compared with CNTRL, averaged for the regions shown in Fig. 1 for A1B (left) and A1Bb (right). Absolute and fraction differences are shown in top and bottom panels. Error bars indicate the inter-annual variability of the DIN uptake.

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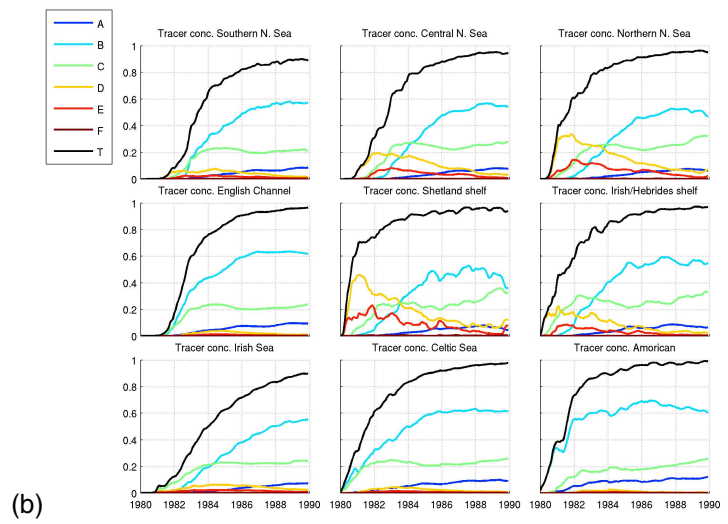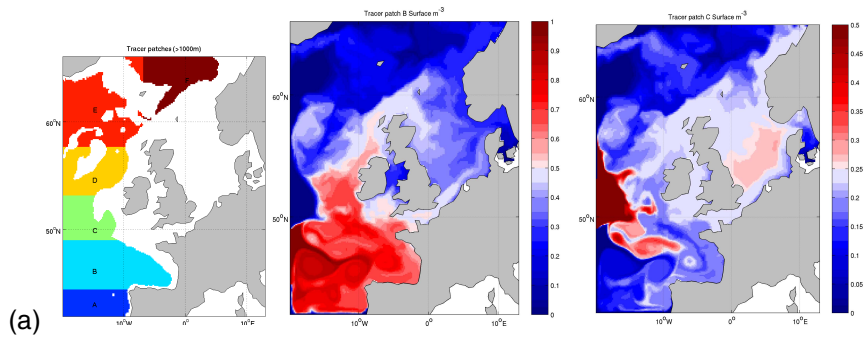
Fig. 8. Passive tracer concentrations from 6 tracer patches initialised in total water depths >1000 m with values of 1 in January 1980 and run forward for 10 yr in the patches shown in A, along with example distributions from patches B and C in January 1985 (note different scales). B shows mean concentrations in 9 of the regions shown in Fig. 1.
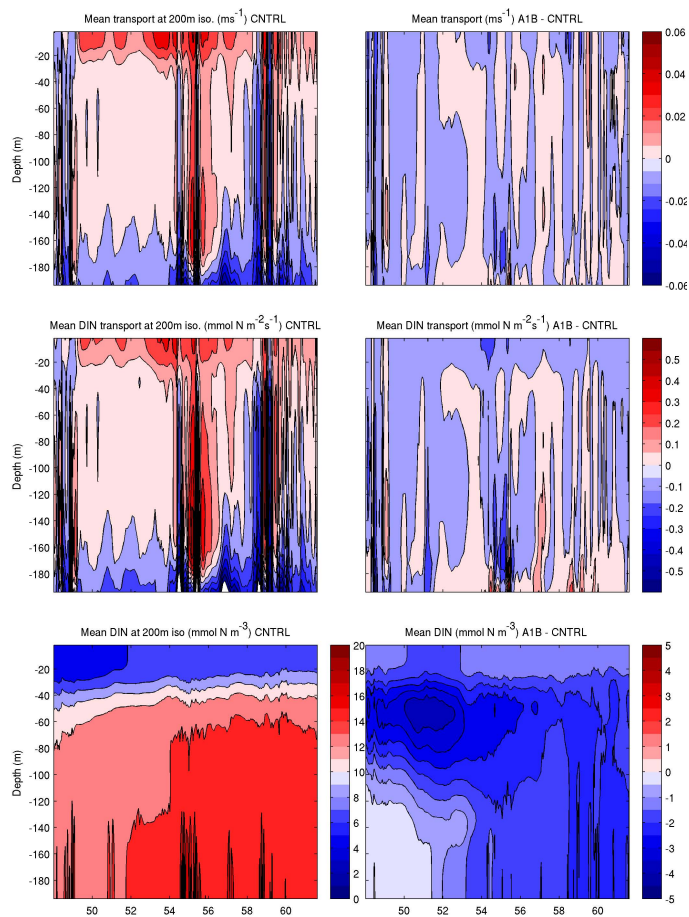
Fig. 9. Mean volume flux, DIN flux and DIN concentration at 200 m isobath: CNTRL; A1B; A1B minus CNTRL. Positive values indicate an on-shelf flux.