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Physical processes mediating climate change impacts on regional sea ecosystems

J. Holt[1], C. Schrum[2,3], H. Cannaby[4,*], U. Daewel[2,3], I. Allen[5], Y. Artioli[5], L. Bopp[6], M. Butenschon[5], B. A. Fach[4], J. Harle[1], D. Pushpadas[2,3], B. Salihoglu[4], and S. Wakelin[1]

[1]National Oceanography Centre, 6 Brownlow Street, Liverpool, L3 5DA, UK
[2]Geophysical Institute, University of Bergen and Bjerknes Centre for Climate Research, Allegaten 41, 5007 Bergen, Norway
[3]Nansen Environmental and Remote Sensing Center and Bjerknes Centre for Climate Research, Thormøhlensgate 47, 5006 Bergen 31, Norway
[4]Institute of Marine Sciences, METU, Erdemli MERSÝN, Turkey
[5]Plymouth Marine Laboratory, Prospect Place, Plymouth, PL1 3DH, UK
[6]Laboratoire des sciences du climat et de l'environnement (LSCE), IPSL, CEA-UVSQ-CNRS, UMR8212, Gif-sur-Yvette, France
[*]now at: National Oceanography Centre, 6 Brownlow Street, Liverpool, L3 5DA, UK

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Correspondence to: J. Holt (jholt@noc.ac.uk)

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Abstract

Regional seas are exceptionally vulnerable to climate change, yet are the most directly societally important regions of the marine environment. The combination of widely varying conditions of mixing, forcing, geography (coastline and bathymetry) and exposure to the open-ocean makes these seas subject to a wide range of physical processes that mediates how large scale climate change impacts on these seas' ecosystems. In this paper we explore these physical processes and their biophysical interactions, and the effects of atmospheric, oceanic and terrestrial change on them. Our aim is to elucidate the controlling dynamical processes and how these vary between and within regional seas. We focus on primary production and consider the potential climatic impacts: on long term changes in elemental budgets, on seasonal and mesoscale processes that control phytoplankton's exposure to light and nutrients, and briefly on direct temperature response. We draw examples from the MEECE FP7 project and five regional models systems using ECOSMO, POLCOMS-ERSEM and BIMS_ECO. These cover the Barents Sea, Black Sea, Baltic Sea, North Sea, Celtic Seas, and a region of the Northeast Atlantic, using a common global ocean-atmosphere model as forcing. We consider a common analysis approach, and a more detailed analysis of the POLCOMS-ERSEM model.

Comparing projections for the end of the 21st century with mean present day conditions, these simulations generally show an increase in seasonal and permanent stratification (where present). However, the first order (low- and mid-latitude) effect in the open ocean projections of increased permanent stratification leading to reduced nutrient levels, and so to reduced primary production, is largely absent, except in the NE Atlantic. Instead, results show a highly heterogeneous picture of positive and negative change arising from the varying mixing and circulation conditions. Even in the two highly stratified, deep water seas (Black and Baltic Seas) the increase in stratification is not seen as a first order control on primary production. The approaches to downscaled experiment design and lessons learned from the MEECE project are also discussed.

1 Introduction

Regional seas are the areas where society interacts most directly with the marine environment and as such have substantial socio-economic importance. For example, it is here that the large majority of the extraction of Living Marine Resources is concentrated (Stock et al., 2011; Watson and Pauly, 2001) and that the need to identify and ensure "Good Environmental Status" is most pressing. How global scale climate change might impact regional, coastal and shelf seas is therefore one of the key issues currently facing environmental science. It is well established that the Ocean–Atmosphere General Circulation Models (OAGCMs) used in the CMIP[1] and IPCC[2] processes are primarily designed to provide reliable information at an ocean-basin to global and decadal to centennial scales. The participating climate models in CMIP5 that include a representation of the marine ecosystem generally have a resolution of $\sim 1^{\circ}$ or coarser in the ocean (Bopp et al., 2013; Taylor et al., 2012). This is substantially inadequate for resolving regional sea processes, and so some form of downscaling is required. Given the non-linear and interconnected nature of the system, this generally requires dynamical rather than statistical approaches. The ultimate goal is to provide reliable projections into the future to, for example, aid policy decisions or inform the public debate on the need for mitigation action. It is not, however, just an issue of resolution: a suite of specific dynamic and ecosystem process act in regional seas, which along with their particular geographic setting act to shape the climatic impacts and lead to responses that may be very different from the wider global ocean. In this paper we explore the physical processes that might be expected to mediate the impacts of climate change on regional sea ecosystems and how they are modelled, focusing on primary production as the engine that drives the marine ecosystem. Drawing on the experience of the MEECE project[3], we contrast five very different regional seas (Fig. 1): North Sea, Celtic

[1] Coupled Model Intercomparison Project; cmip-pcmdi.llnl.gov

[2] Intergovernmental Panel on Climate Change

[3] Marine Ecosystem Evolution in a Changing Environment; www.meece.eu

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Seas, Baltic Sea, Black Sea and Barents Sea, along with results from a region of the Northeast Atlantic. Three different coupled hydrodynamic-ecosystem model systems are employed to dynamically downscale the output of a global Earth System Model (ESM). We compare this with the picture that is evolving for the global ocean with the aim of identifying the contrasting vulnerability of these regions to different vectors of change.

Dynamic downscaling is increasingly used to explore the impacts of climate change in regional seas in both physics only (e.g. Adlandsvik, 2008; Olbert et al., 2012) and coupled physics-ecosystems (e.g. Holt et al., 2012a; Neumann, 2010; Omstedt et al., 2012) studies. An alternative approach is to develop fine scale and multi-scale approaches to global modelling. For example, Gröger et al. (2013) rotate the pole of an otherwise coarse resolution ocean component of an OAGCM to give higher resolution in European seas. However, such an approach limits the potential to utilize regionally adapted models. Given the need to run multiple process experiments in this uncertain and evolving field, and the need for multiple regions of interest, the use of global models as the general tool for regional seas climate impact studies is still many years off (Holt et al., 2013).

There is a well recognised need to explore the uncertainty in climate change impact studies. The robustness of the information that can be provided is largely rooted in the numerical experiment design. This has several facets, include the future scenario, the treatment of natural variability, the choice of driving OAGCMs, the approach to forcing the regional model and the structure and parameters of the regional model itself. The treatment of uncertainty arising from these facets would ideally take a probabilistic approach, with multiple simulations conducted to span the uncertainty space. This can, to some extent be achieved with comparatively simple downscaled models where the forcing is the dominant component and the internal processes are well modelled, storm surges being a good example (Howard et al., 2010; Lowe et al., 2009). However, in a multidisciplinary forced system the dimensionality of this space is large and exploring this uncertainty just at a “minimum-maximum” level is exceptionally challenging, let alone defining a Probability Density Function. Hence, we must turn to process understanding to identify the nature of impacts in a semi-quantitative fashion. The identification of the significant pressures on the system, the processes that mediate these and the resulting sign of change is an important first step.

In Sect. 2 the mechanisms for biophysical interactions are reviewed in the context of potential climate forcing and response in these five regions. In Sect. 3 the results from the five model systems in a common forcing experiment are compared. In Sect. 4 the various approaches to downscaling global climate models to regional seas are considered. The common themes in the results, specific short comings and ways forward are discussed in Sect. 5.

2 Mechanisms for biophysical interactions

Most physical processes active in regional seas are to some extent impacted by global change resulting from anthropogenic increases in greenhouse gas (GHG) emissions, and these impacts will in turn affect the biogeochemistry and lower trophic levels of the ecosystem. Detailed descriptions of these physical processes can be found in Robinson and Brink (1998) and Holt et al. (2014a). The impact of climate change in regional seas is largely a boundary value problem and so it is necessary to consider the external forcing in some detail. Here we take a Pressure–State approach; this is subset of the Driver–Pressure–State–Impact–Response framework (DPSIR[4]), noting that we do not directly consider here the human dimensions of Drivers and societal Response to change, or the detailed ecological Impact on the system. There are feedbacks, for example between the ocean and atmosphere physical system (e.g. Schrum et al., 2003) and between the regional seas and global physical and biogeochemical cycles. However, on the decadal/regional time/space scales considered here we presume these

[4]http://ia2dec.ew.eea.europa.eu/knowledge_base/Frameworks/doc101182/

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are not of first order importance, and we focus on regional seas as “driven” systems, while attempting to identify (but not quantify) feedbacks in the wider Earth System.

The systems considered here have natural variability on many time scales (seasonal to decadal scales are our focus here), and one of the important challenges is to distinguish this variability from longer term change induced by anthropogenic GHG emissions. From a purely impacts and process point of view, this variability is as important as GHG emissions induced change. However, being able to attribute change to anthropogenic GHG emissions is important in informing the mitigation debate. Moreover, this “signal to noise” ratio (e.g. Deser et al., 2012; Hawkins and Sutton, 2009) dictates the earliest forecast horizon at which the climate change signal can be detected, which has important implications for adaptation measures.

The Pressure–State view needs also to be considered in light of the time scales needed for the system to adjust to changing external conditions. The required adjustment times can be long (multi-year to multi-centennial), particularly when processes related to benthic recycling and deep-basin to surface exchange are considered, so the distinction between natural variability and trend can be blurred by this signal propagation as much as by long term modes of external variability. For example the deepwater exchange times for the Black Sea are ~ 400 yr (Murray et al., 1991) and for the Baltic Sea ~ 30 yr (Meier et al., 2006).

The anthropogenic GHG driven Pressures naturally divide into three vectors: atmospheric, oceanic and terrestrial. The response of the coupled physical-lower trophic level system to climatic forcing depends on three paradigms of biophysical interaction:

i. Transport processes that set the overall elemental (of carbon, nitrogen etc) and chemical energy budget available for biological activity of a particular region.

ii. The seasonal and mesoscale processes that mediate the phyoplankton’s exposure to light and nutrients.

iii. Direct physiological response to the environment (e.g. temperature).

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In general terms, the distinction between Paradigms (i) and (ii) relates to time scales of the transport relative to biogeochemical processes. They are short in (ii) biology and chemistry responds on the time scale of the transport, and long in (i) the transport sets the background conditions, on seasonal and longer timescales, largely independently of the more rapid biogeochemical processes. Long term transport processes tend to be advective (i.e. moving as a constituent property of the water), whereas processes mediating the phytoplankton's exposure to nutrients and light (ii) can be diffusive, related to horizontal and vertical mixing or advective, e.g. coastal upwelling and coastal currents near river inflows. These can also be related to seasonal sea ice development, which is influenced by a combination of air–sea heat fluxes, advection and turbulent mixing. These paradigms need to be considered in the appropriate oceanographic context, notably the transport and mixing regime, the presence/absence of sea ice and the time scale of exposure to wider oceanic conditions. Owing to the relatively coarse resolution of the model systems we consider (~ 10 km) we do not specifically consider the near-coastal zone here; this is a general deficiency in marine climate impact studies. For Transport process (i) we consider changes over the flushing periods of surface waters resulting from changes in circulation, ventilation and exterior conditions, including long term/large scale terrestrial influence. We only very briefly consider the direct temperature effects on growth and reaction rates (iii), as this is largely a chemical and biological effect, with little relation to the hydrodynamics once the changes in the temperature field are established. Moreover, if we wished to consider the ecosystem at the species level we would additionally have to consider changes in transport timing, rates and patterns (Drinkwater et al., 2010), but again this is not considered further here.

We next explore the relevant forcing and responses in some detail.

2.1 Forcing: atmospheric

All air–sea fluxes potentially mediate climate change: momentum and water fluxes, short and long wave radiation, latent and sensible turbulent heat fluxes (e.g. Gill, 1982). These all will be dependent on changes in air temperature, wind speed and the hydro-

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logical cycle. Two robust changes in atmospheric conditions under global warming are an increase in air temperature and in lower troposphere water vapour (Held and Soden, 2006). These would be expected to lead to a decrease in both sensible and latent heat flux from the ocean until the ocean reaches a dynamic thermal equilibrium, although the former is not necessarily clear in the IPCC Assessment Report (AR) 4 models (Held and Soden, 2006). For shelf seas this equilibration is rapid (seasonal), while for the deep basins this is very slow, being determined largely by the over-turning circulation. Changes in wind speed are also projected by the OAGCMs. However, accurately simulating details of the regional atmospheric circulation, such as the Northeast Atlantic storm track, often challenges these models (Lowe et al., 2009). For example, a multi-model ensemble of IPCC AR4 models (Lowe et al., 2009) shows both intensifying and decreasing strength, and both northward and southward movement of the storm track. In contrast the perturbed parameter ensemble of a fine resolution regional climate model (HADRM3) in that report shows a consistent slight weakening and southward movement of the storm track. How this picture has changed in the recent CMIP5 experiments has yet to be established.

The long term trends in the atmospheric conditions are superposed on the natural modes of variability, which determines whether or not a clear anthropogenic climate change signal can be detected. In many of these regions, this is compounded by the fact that Northern Europe has some of the strongest atmospheric variability globally (e.g. Hawkins and Sutton, 2009) and the North Atlantic has wind speeds matched only by the North Pacific and Southern Ocean (Josey et al., 2002). There are several modes of variability important for Northern Europe, while these have been termed "oscillations", they are better characterised by switches between different quasi-stable states, rather than having a well defined period. Three key modes in the eastern North Atlantic region, the North Atlantic Oscillation (NAO), the Atlantic Multi-decadal Oscillation and the Atlantic Meridional Mode are reviewed by Grossmann and Klotzbach (2009). The dominant modes influencing the Black Sea are the East-Atlantic/West-Russia pattern, which is reported to influence short term (1–5 yr) variability in the sea surface temper-

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ature record, and the North Atlantic Oscillation, which is believed to influence longer term variability here (Capet et al., 2012).

To provide a specific example, Fig. 2 shows a single realisation comparing a present day time slice and potential conditions at the end of the 21st century (the general timescale under consideration here). This is taken from the IPSL-CM4 model (Marti et al., 2006) used to force the regional model simulations given below. It shows distinct spatial patterns relevant to the regional seas under consideration here. Notably, an increase in air temperature that is much stronger in Arctic regions and, to a lesser extent, over the European continent than over the Northeast Atlantic. The change in wind stress shows a very varied picture, with a notable increase in the Arctic, Norwegian coast and Baltic, otherwise a decrease. The shortwave radiation shows a modest increase except in the Arctic and western Norwegian sea, where it strongly decreases. This figure also emphasises how few grid cells of the atmospheric model cover each region.

2.2 Forcing: oceanic

Oceanic drivers of climate change relate to the phenomena of shelf-edge exchange (Huthnance, 1995; Huthnance et al., 2009) for the open shelf sea areas (e.g. North Sea, Barents Sea and Celtic Sea). How the open ocean affects the more enclosed seas (e.g. Baltic Sea, Black Sea and potentially Irish Sea) is strongly dependent on the detailed exchange processes at the "pinch points" (see Sect. 2.5). In this context the ventilation/overturning circulation of the deep basins has an analogous role to ocean-shelf exchange; i.e. it determines the flushing of the water body in which primary production occurs.

At the large scale, the open shelves can be characterised as being either predominantly upwelling or downwelling. The shelf seas of the North East Atlantic, north of $\sim 48^{\circ}$ N, are generally downwelling (Holt et al., 2009) arising from the prevailing wind direction driving an on-shelf surface Ekman transport and the poleward slope current driving a benthic off-shelf Ekman transport. This implies that their oceanic nutrient re-

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supply is critically dependent on its resupply to surface water in the open ocean, for example by deep winter mixing. This is in distinct contrast to upwelling shelves where this resupply is controlled by the ocean-shelf transport itself.

Large scale change can affect the ocean-shelf and ocean-regional sea exchange in two ways: the magnitude and nature of the fluxes can change and also the oceanic properties can change, and this anomaly can be advected into the region. The exchange fluxes and across shelf circulation we consider responses rather than external forcing and so are discussed below. Most relevant to the discussion here are changes to the distribution of open ocean nutrients. These changes relate to changes in oceanic stratification (e.g. Capotondi et al., 2012), and also potentially to changes in large scale ocean circulation. The reduced surface ocean nutrient levels, and the consequences of this for primary production, is one of the most extensively document potential impact of climate change on marine ecosystems (Sarmiento et al., 2004; Steinacher et al., 2010). Winter mixing (e.g. by convection) provides a key mechanism for this change. As noted above, permanent stratification in the open ocean is necessarily increasing due to global warming, since the open-ocean-atmosphere system is not in balance with changes in lower atmosphere heat and water vapour content. While changes in temperature stratification is a globally applicable effect, changes in haline stratification are expected to play an important role at a basin scale, generally following the amplification of the hydrological cycle (Held and Soden, 2006). For example, the IPCC AR4 models investigated by Capotondi (2012) suggest an increase in haline stratification is important in the North Atlantic and Arctic regions.

Increasing permanent stratification reduces winter mixing, decreases winter mixed layer depths, and so reduces the total amount of nutrients entrained into the winter mixed layer. Hence the amount of nutrients available for phytoplankton growth decreases, as seen in the CMIP3 models (Steinacher et al., 2010). This is shown schematically in Fig. 3: as the mixed layer deepens from summer values (h_s) to winter values (h_w) a quantity of nutrients $\sim (h_w - h_s)$ is entrained into the surface layer to provide the basis for the following season's production. Simplistically this amount de-

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creases linearly with decreases in h_w, arising from climate change. It is important to note that this change is driven by permanent stratification and winter mixing; the role of seasonal stratification is considered below. On a global scale winter deepening of the mixed layer is a universal phenomenon, except close to the equator or in ice covered regions (see de Boyer Montégut et al., 2004). Hence, it is not surprising this is seen as a leading order effect globally.

A reduction in upper ocean nutrient levels arising from climate effects on winter mixing and permanent stratification would naturally be expected to impact on adjoining shelf/regional seas that receive a significant fraction of their nutrients from surface oceanic waters, as is the case for downwelling shelves such as the Northwest European continental shelf (Hydes et al., 2004; Vermaat et al., 2008). This has been seen in future scenario simulations (Gröger et al., 2013; Holt et al., 2012a). However, this impact is highly uncertain, depending as it does on both the fidelity of the global ocean biogeochemical model and the details of the vertical mixing (Sinha et al., 2010; Steinacher et al., 2010). So, for example, Gröger et al. (2013) and Holt et al. (2012a) agree qualitatively as to the sign of this affect, but differ widely in its magnitude.

The effects of climate change on the nutrient concentrations of water transported on-shelf in upwelling regions are less clear. However, a model investigation, focusing on the Pacific (Rykaczewski and Dunne, 2010), suggests an increase in these nutrient concentrations. This arises because of lengthened ventilation times, due to increased oceanic stratification, and so enhanced recycling.

Changes in the large scale ocean circulation and details of the gyre structure potentially have important implications for the characteristics of the water transported on-shelf. For example, the northwest European shelf lies at the boundary between the sub-tropical and sub-polar gyres. Large scale shifts in this boundary may strongly influence the nutrient concentrations of the water transported on-shelf. However, these details are not well represented in coarser resolution climate models and biases in, for example, the position of the Gulf Stream and the North Atlantic current are common (e.g. Molinari et al., 2008). Hence a detailed investigation of these impacts must await

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higher resolution coupled ocean-atmosphere models (Delworth et al., 2011) or larger scale climate impacts models (Holt et al., 2014b).

2.3 Forcing: terrestrial

Riverine inputs of freshwater form buoyancy driven coastal currents that make up an important component of the shelf sea circulation. Examples include the "Coastal River" of continental European from the mouth of the Seine to the German Bight and also the Norwegian Coastal Current. The dynamics of these currents are reasonably well established and depend on the dynamic balance of advective, diffusive/frictional and buoyancy processes (Chapman, 2000; Chapman and Lentz, 1994; Narayanan and Garvine, 2002). However, our knowledge of how potential changes in the hydrological cycle might impact the dynamics of coastal seas is seriously limited. This arises because the dominant scales here are at the margins of resolution for shelf scale modelling in general. Shelf scale models that permit motions at the Rossby Radius (~ 1–5 km) in coastal regions (e.g. Holt and Proctor, 2008) are rare and only recently have been applied to physics only climate impacts studies (Mathis, 2013; Mathis et al., 2013; Olbert et al., 2012). Even eddy permitting models struggle to simulate the detailed dynamics of the dispersal phenomena (e.g. Kok, 1997), which generally need sub-km scale models. Hence, most climate impact downscaling studies have a poor representation of near coastal conditions. When considered alongside the uncertainty in the changes to riverine forcing itself (arising from climatic and direct anthropogenic factors), it is apparent that this is an area in serious need of attention. Hence, for this driver we must limit our consideration to terrestrial impacts driving changes in large scale elemental budgets (Paradigm i), rather than immediate, seasonal, effects (Paradigm ii).

The Baltic and Black Seas are both examples of regional seas highly impacted by riverine inputs. The Black Sea drains a catchment 2×10^6 km^2 and receives waste water from 100 million people (Mee, 1992). The total discharge into the region is 1.2–1.5×10^5 m^3 s^{-1} (Ludwig et al., 2009), with the largest rivers draining into the northwest shelf region. Temporal variability in phytoplankton biomass in the northwest Black Sea

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is consequently dominated by changes in river discharge and advection over both seasonal and interannual timescales. The volume and chemical characteristics of Danube river water entering the Black Sea is heavily moderated by anthropogenic activities, which constitute the dominant control on the nutrients inputs. The Baltic Sea drainage basin is similar to that of the Black Sea in area ($\sim 1.7 \times 10^6$ km^2) and includes 14 partly heavily industrialized, highly populated countries and 14 larger river basins. The average annual river discharge is also $\sim 1.5 \times 10^5$ m^3 s^{-1}, but with large seasonal variations (Hansson et al., 2010). Since the rivers carry large amounts of nutrients, the Baltic Sea ecosystem is highly impacted by changes in river nutrient loads and potentially exposed to eutrophication especially in the coastal areas (e.g. Schernewski and Neumann, 2002). A major attribute of the Baltic Sea is the imbalance between freshwater supply by rivers and precipitation and evaporation, causing, in conjunction with the restricted exchange with the North Atlantic, an estuarine circulation and a permanent halocline. In contrast the northwest European shelf receives a much smaller river discharge ($\sim 9.2 \times 10^3$ m^3 s^{-1}), but this still makes a substantial contribution to the total nutrient input into this region (Artioli et al., 2008).

Potential changes to terrestrial inputs arise from a combination of natural and anthropogenic phenomena. Projected changes to the hydrological cycle can be translated to changes in freshwater discharges through the use of river routing and other hydrological/land surface modelling approaches (e.g. Bell et al., 2007; Lindstrom et al., 2010). Future changes to anthropogenic terrestrial drivers, relating to changes in population size and distribution (e.g. Carpenter et al., 2005), and land use are likely to be very significant. Specific coastal scenarios for these can be constructed (e.g. Pinnegar et al., 2006), but translating these to quantitative forcing is problematic.

2.4 Responses: seasonal and mesoscale

Phytoplankton growth in mid- to high latitudes can be characterised by several stages, which largely define the biophysical interactions. During late autumn and winter phytoplankton growth is limited by a lack of light arising from low irradiance levels (depending

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on latitude and cloud cover) and/or deep mixed layer depths (arising from wind mixing and convection). These constraints are relaxed by the seasonally increasing irradiance and reduced surface turbulence, so prompting phytoplankton growth. The change in turbulence levels is a primary source of variability and can occur with or without the on-set of stratification or a shoaling mixed layer (Chiswell, 2011; Huisman et al., 1999; Taylor and Ferrari, 2011). How the growth proceeds, and its sensitivity to external forcing depends on the prevailing mixing environment. In general we can consider three stages: pre-bloom growth (PB), spring bloom (SB) and summer growth (SG). These stages are illustrated in Fig. 4, and used quantitatively below. It is useful to consider the biophysical interaction in terms of different mixing/stratification regimes: permanently stratified with shallow or deep winter mixing, seasonally stratified, well mixed and frontal regions. In addition, seasonally ice covered regions like the north-eastern Barents Sea and the northern Baltic Sea form additional provinces within these regimes, which are characterized by an extended light limitation period and reduced productivity compared to ice free regions at similar latitudes. Since a decrease in sea ice is a very robust feature in future climate projections (Overland and Wang, 2007), increasing productivity is expected to be a first order response to future climate change in seasonally ice covered regions. The potential strength of this change, however, is modulated by the local biogeochemical conditions.

2.4.1 Permanently stratified regional seas

The two regional sea areas dominated by permanent stratification in this study (the Baltic and Black Sea) are both characterised by restricted exchange with the open ocean. A third region (the Norwegian Trench) is, in contrast, characterised by rapid exchange with northeast Atlantic.

The Black Sea is a highly stratified basin, characterised by a thin relatively fresh surface layer of riverine origin, overlaying saline waters of Mediterranean origin. A permanent halocline at 150–200 m depth prevents deep winter convection. The seasonal characteristics of phytoplankton growth in the Black Sea are characterized by high

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interannual and multiannual variability, and comparatively weak seasonality, e.g. seasonality explains only 35 % of the variance in the remotely sensed chlorophyll *a* time series (Vantrepotte and Melin, 2009). This arises because the shallow mixed layer depths (~ 5 m in summer to ~ 70–140 m in winter; Oguz, 2008) are not so great as to provide a strong constraint on phytoplankton growth during the winter months. Nezlin et al. (2002), in an analysis of the remotely sensed data record, suggests that, away from the northwest shelf, the Black Sea has a seasonal cycle of phytoplankton biomass akin to that typical of subtropical regions (e.g. Longhurst et al., 1995). This record suggests that surface phytoplankton biomass peaks during September and October in the open Black Sea and remains high throughout the winter months, decreasing during spring with the onset of seasonal stratification (McQuatters-Gollop et al., 2008; Nezlin, 2008; Nezlin et al., 2002). Spring blooms (e.g. as reported by Demidov, 2008; Oguz et al., 2001) may be triggered by a combination of increased light levels and reduced mixing, but the sustained winter production limits the build up of surface nutrients and so the strength of the spring bloom. Surface nutrients are resupplied from depleted summer levels by convective and wind driven mixing in autumn and winter (Oguz et al., 1996), triggering the strong autumn bloom.

The seasonal characteristics of phytoplankton growth in the Baltic Sea are highly sub-basin dependent. The thermocline is generally shallow (compared to the euphotic depth), so nutrients below the summer thermocline are generally accessible and production tends not to be limited by stratification. The seasonal characteristics are a combination of spring-bloom-, polar-bloom-, and eutrophicated coastal systems. Sediment water exchange, oxygen deficiency, and denitrification and nitrogen fixation are all particularly important for the Baltic Sea ecosystem and modulate phytoplankton production by modulating the N/P ratio in the water column, and thereby the limiting processes for phytoplankton production (Rodhe et al., 2006). Moreover, the retreat of sea ice, the maximum ice extent and the different length of the ice free period, which varies greatly locally, play key roles in structuring the seasonal phytoplankton dynamics in the Baltic Sea.

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Beyond these characteristics, the largely enclosed nature of these basins has an important impact on their seasonal response. The Black Sea is characterised by a basin-wide cyclonic circulation, with an intense "rim current", a cyclonic geostrophic current that approximately follows the 200 m contour (Oguz et al., 1992). This mean circulation is driven by the predominantly positive wind stress curl, and moderated by thermohaline processes (Korotaev et al., 2011). Interannual variability in the strength, gradients and direction of wind stress fields moderates the strength of the cyclonic circulation and this in turn influences other physical characteristics of the basin, including exchanges between the Northwest shelf and the open water. Capet et al. (2012) link intensification of the cyclonic circulation to increased export of riverine materials from the highly eutrophic northwest shelf to the deep basin, which influences primary production on and off the shelf.

The Baltic Sea can in general be divided into a central Baltic Sea basin and the adjacent gulfs. The central Baltic Sea is thought to be forced by an interaction between bottom topography and buoyancy (Sarkisyan et al., 1975) and is characterised by a general cyclonic gyre, while anticyclonic gyres can be found in the Bornholm Basin, the Gdansk Basin and north of the Gotland Basin (Lehmann et al., 2002). The circulation is highly variable and strongly dominated by changes in the large scale atmospheric forcing and associated changes in the regional wind field (Lehmann et al., 2002). During NAO^+ conditions, strong Ekman currents drive increased up and downwelling along the coasts, while under NAO^- conditions ventilation is strongly reduced (Lehmann and Myrberg, 2008). Upwelling in the Baltic Sea is highly relevant for ecosystem dynamics by replenishing depleted nutrients in the surface layer, and while it acts locally it affects the entire basin. Since Baltic Sea deep waters are often anoxic and nitrate depleted the mechanism changes the N/P ratio in the surface waters and hence favours the production of nitrogen fixing cyanobacteria (e.g. Daewel and Schrum, 2013; Janssen et al., 2004).

Hence, it is apparent that alongside change to the permanent stratification, these regions are highly susceptible to changes to the wind strength, gradients and direction,

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and consequent impacts on circulation and upwelling, in a way that is not so apparent in the open ocean.

2.4.2 Seasonally stratified regional seas

The seasonally stratified open shelf is the largest region of the northwest European continental Shelf. This shelf is characterised by being well mixed for several months during the year and so (except for the Norwegian Trench) lacks permanent stratification. The dominant balance in the seasonally stratified regions is between seasonal heating and tidal mixing; this sets the seasonal stratification cycle. Wind mixing then determines the evolution of this thermal stratification through the year, for example deepening during summer storms and shoaling during calm periods. Figure 4 shows example time series for locations in the stratified North Sea and Celtic Sea. The patterns are similar, but differ in detail. Also apparent is the strong interannual variability to the extent that the mean annual cycle differs significantly (e.g. in bloom amplitude) from any particular year.

The efficiency of a bloom in seasonally stratified conditions (both in regions exhibiting seasonal and permanent stratification) is dependent on how much of the available nutrients can be used before stratification starts limiting the vertical diffusive flux needed to replenish the nutrients in the euphotic zone (shown schematically by the shaded area in Fig. 3). Hence a bloom that starts earlier than the on-set of stratification sufficiently strong to inhibit this vertical flux would be expected to be more efficient. Hence, this efficiency would be sensitive to the details of the stratification and mixing conditions during the bloom, and how they change, depending on changing buoyancy flux and wind conditions. This critically challenges the vertical mixing schema used in 3-D models, and their ability to simulate actual mixing values, rather than simply acting as a switch between stratified and non-stratified conditions (Palmer et al., 2013).

While the seasonal evolution of stratification and phytoplankton blooms is similar to that in the open ocean, the influence of climate change on regions that lack permanent stratification is far less certain, as this first order response is absent (as shown

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schematically in Fig. 3). In this case only changes in the seasonality of the heat flux influence shelf sea thermal stratification. In a simple two layer system with only weak diapycnal mixing, the summer stratification is essentially set by the difference between spring and summer temperatures, and so relative changes in these under climate warming conditions will determine the changes in thermal stratification: summer warming faster (slower) than winters leads to an increase (decrease) in stratification. This is illustrated in Fig. 2, which shows the difference between summer and spring air temperature in the IPSL-CM4 model, i.e. the tendency for the forcing to generate seasonal stratification, and how this changes. It demonstrates that, in this case the forcing is such that an increase in seasonal stratification would be expected, but this is a detail of the forcing that is not necessarily robust and a different OAGCM may equally give a change of opposite sign.

There is, however, a positive feedback in the system that favours an increase in stratification. Namely the non-linear equation of state means that at warmer temperatures the same temperature difference leads to a larger density difference, e.g. an 8 °C surface to bottom temperature difference corresponds to a 9 % larger density difference at an SST of 20° than at 18 °C. This would further inhibit mixing of heat during the on-set of stratification and so lead to increased warming in the surface layer. The importance of this feedback has not yet been fully explored, but model simulations of future scenarios have tended to show an increase in stratification (see examples below and Adlandsvik, 2008; Holt et al., 2010). It should be noted, however that, while temperature plays the dominant role in the seasonal stratification in these seas, salinity and changes to $E-P$ forcing can play an important role in future changes to stratification (Holt et al., 2010), again this is in a positive sense in the examples given below. These processes are amenable to investigation with one dimensional water column models (e.g. Molen et al., 2013), which greatly reduces the computational expense of the simulations, but of course misses other vectors of climate change impacts.

Wind has a complex effect with regard to changes in shelf sea stratification and ecosystem response. Increased (decreased) wind speed in spring might be expected

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to delay (hasten) the onset of thermal stratification. This would not necessarily have the same effect on the timing of the spring bloom and so changes in wind strength might be expect to change the relative timing of the bloom and the onset of stratification, and hence the bloom efficiency, as identified above. Increases in wind during the summer would tend to increase diapycnal mixing (e.g. through inertial shear spiking; Rippeth, 2005), but would also deepen the thermocline. The former would lead to enhanced nutrient fluxes and midwater production, whereas the overall effects of the latter are less clear. On deepening the mixed layer would entrain nutrient rich waters, leading to burst of enhanced production. Subsequently production at a deeper thermocline would be more light limited, but spring-neap nutrient pumping (Sharples, 2008) may be enhanced particularly in shallow regions where surface and bottom mixed layer interact. Increased wind mixing in the autumn would hasten the breakdown of stratification, potentially leading to the autumn bloom occurring in higher irradiance conditions, so strengthening it. Hence, wind effects are highly dependent on the details of the seasonality, and the particular mixing environment in question. In the example shown on Fig. 2, there is a marked decrease in spring wind stress, and a generally increasing, but more mixed, picture in summer; again this is not necessarily a robust change.

2.4.3 Well mixed and frontal Regions

Aside from changes in depth mean temperature and salinity, climate change impacts in regions that are generally well mixed and the frontal regions between these and seasonally stratified areas would be expected to be highly dependent on detailed fine scale and high frequency processes. Again, the exploration of these regions is generally hampered by the lack of sufficiently fine resolution model simulations. Figure 4 shows an example from the German Bight in the North Sea. In these seas, light and nutrient limitation act in combination throughout the year resulting in a multiple series of blooms depending on variations in mixing conditions (e.g. the spring-neap tidal cycle or wind induced mixing). For an analysis of the spring conditions here see Tian et al. (2011).

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Climate change impacts in such regions are again more nuanced. Stratification effects are likely to be less important, except in cases where frontal positions are only weakly constrained by tidal mixing and bathymetry, such as in the German Bight, where wind mixing and haline stratification play a stronger role than in the open-stratified regions of the North Sea (Schrum, 1997). In these cases, movements of frontal positions, by changes in wind speed and direction, are likely to have very strong local effects due to the large horizontal gradients of, e.g., nutrient distributions. The depth variation of temperature change with heat flux implies shallower waters are warming faster than deeper (Holt et al., 2012b). This would be expected to lead to an intensification of frontal gradients and hence of frontal jets (e.g. Brown et al., 1999) and associated baroclinic eddies (Badin et al., 2009), particularly if the bottom waters of the stratified region are warming more slowly.

Lohmann and Wiltshire (2012) hypothesize that variability in the transport of optically clear water into the German Bight is a key driver of climate variability in diatom production in this region. However, the effects of climatic change on inherent optical properties (arising from suspended sediments and coloured dissolved organic material) are yet to be investigated. Their treatment in dynamical models is generally problematic, and recourse is often made to climatological remote sensed observations (Wakelin et al., 2012) or empirical relations with salinity (Le Fouest et al., 2010), neither of which are particularly amenable to future climate impact studies.

It should also be noted that changes in sea level will have some effect on tidal amplitudes and the implications of this deserve further investigation. For example, Pickering et al. (2012) show a 2 m sea level rises leads to a ~ 5 cm increase in M_2 amplitude in the central North Sea and Southern Bight, and a similar decrease in-between.

2.5 Response: regional scale transport setting elemental budgets

The regional scale transport of water and its constituent properties (heat, salt, carbon, nutrients) from the open ocean and across the regional sea basin controls the overall elemental budget. In deep, nearly closed basins, the mixing and upwelling of deepwater provides a similar role, alongside transport at the straits, in setting the budgets of the surface layer. In this context, the regional seas naturally divide depending on their exposure to open-ocean exchange. In decreasing order of exposure are: narrow upwelling shelves (e.g. off Iberia), open shelf edge region (e.g. Malin, Hebrides shelf), broad strongly advective shelves (central/northern North Sea, Barents Sea), broad weakly advective shelf seas (e.g. Celtic Sea), coastal/frontal shelves (e.g. Irish Sea, Southern North Sea, English Channel), and nearly enclosed basins (Black Sea, Baltic Sea).

The models used for climate impact studies (typically 5–15 km resolution) tend to have a rather crude representation of ocean-shelf exchange processes. The general upwelling and downwelling circulation, governed by Ekman transport and continuity, is simulated, and so is its response to changing wind patterns. However, both will be limited by model resolution. This is particularly the case in upwelling regions. Here the horizontal scale is given by the first internal Rossby Radius, and so the detailed structure (Alvarez-Salgado et al., 2002; Peliz et al., 2002) and its effects and response are not included. Similarly the representation of along slope currents, which are important for several aspects of ocean-shelf exchange, is limited by the resolution of the shelf-slope. Beyond these general features, the myriad of meso-scale and submesoscale processes mediating ocean-shelf exchange (Huthnance, 1995) are generally excluded, and so therefore is their response to climate change. These include: internal tides (Baines, 1982), cascades (Ivanov et al., 2004), on-shelf eddies and tidal excursions. Taken with the difficulty in accurately modelling these regions due to the juxtaposition of steep slopes and stratification (Holt et al., 2014b), this is a highly uncertain vector of change, which deservers further detailed study.

The on-shelf Ekman transport on the Northwest European continental shelf is driven by the prevailing south westerly wind, so variation in the Northeast Atlantic storm track position and strength would be expected to influence this. However, this requires a driving atmospheric model capable of accurately simulating this track, and this is highly uncertain (as noted above). The mean slope current is driven by the north-south baro-

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clinic pressure gradient (Huthnance, 1984) and its variability is largely wind forced. It is responsible for an off-shelf near bed transport through an Ekman drain (Souza et al., 2001). While this current may be sensitive to changes in the details of the North Atlantic Gyre structure, its forcing is integrated over such a large scale (Iberia to Hebrides) that it is unlikely to change greatly. On long time scales a steady state approach such as the LOICZ well-mixed box (Gordon et al., 1996), suggests that the fluxes themselves are only important in relation to other inputs/losses of the system (e.g. ocean-shelf flux compared with river inputs, atmospheric deposition and denitrification; Holt et al., 2012a), and so is likely have a less direct effect than the changes in external concentrations in setting budgets. However, the exchange/transformation processes during this transit can be crucial, challenging the "well-mixed" assumption in this approach. Moreover, changes in fluxes will alter the relative importance of benthic exchanges, and changes therein, e.g. a reduced ocean-shelf flux would amplify the importance of a temperature induced increase in benthic nutrient efflux.

The Barents Sea is a large broad part of the Arctic shelves. It is strongly controlled by advection: inflowing warm, salty and nutrient rich Atlantic water is subject to water mass transformation and leaves the Barents Sea towards the Arctic Ocean as dense and cold water (e.g. Årthun et al., 2011). The north-eastern part of the Barents Sea is dominated by the presence of Arctic water and sea ice. A pronounced frontal system separates the seasonally stratified ice free and highly productive south-western region from the year round stratified, seasonally ice covered and less productive north-eastern region. The position of the polar front, and so the area occupied by these two regimes, is advectively controlled by the overall amount of incoming Atlantic Water. Hence this sea would be expected to be sensitive to changes in inflowing water in marked contrast to the LOICZ well-mixed box view considered above.

The Black and Baltic Seas are deep basin regional seas with limited connection with the wider oceans. In both cases these exchanges have been identified as important to the biogeochemistry and ecosystems of the seas as a whole (e.g. Murray et al., 1991; Rodhe et al., 2006). However, modelling the changes in strait flows is exceptionally

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challenging, due to the narrow horizontal scale, steep topography (Hofmeister et al., 2011) and often non-hydrostatic processes.

North Sea and Baltic Sea are connected by a system of narrow belts, straits and shallow sills (18 m at Darss Sill; 8 m Drogden Sill) restricting the exchange of water masses. The freshwater imbalance of the Baltic Sea favours a permanent outflow of relatively fresh surface water from the Baltic to the North Sea and further limits the inflow of haline and oxygen rich North Sea water into the Baltic Sea. Significant inflows from the North Sea, so called Major Baltic Inflows (MBIs), occur only occasionally under specific weather conditions (Gustafsson, 1997; Omstedt et al., 2004). The restricted exchange leads to a water residence time in the Baltic Sea of about 30 yr (Omstedt and Hansson, 2006; Rodhe et al., 2006). An analysis of long time series of oceanographic and atmospheric parameters by Schinke and Matthäus (1998) indicated that specific atmospheric conditions (e.g. pressure system and wind) are required to promote MBIs and that the strength of the event is additionally determined by the amount of river runoff. The potentially long time intervals between the MBIs cause the Baltic Sea deep waters to be stagnant over long periods, becoming anoxic and nitrate depleted and simultaneously phosphate enriched by sediment processes. The dependency of Baltic Sea deep-water renewal to atmospheric conditions makes the Baltic Sea ecosystem dynamics highly vulnerable to potential changes in climate dynamics. However, the narrow connection between the two seas requires a sufficient resolution of the atmospheric forcing to represent MBIs accurately, which is particularly challenging with respect to the resolution of OAGCMs (Feser et al., 2011).

The Black Sea is connected to the Aegean Sea via the Dardanelles Straits–Marmara Sea–Bosporus Straits system. Exchange through the Bosporus Straits can be summarised as an upper layer outflow of relatively fresh Black Sea surface water amounting to $\sim 19 \times 10^3\,m^3\,s^{-1}$ and a lower layer inflow of saline Mediterranean water amounting to $\sim 9.5 \times 10^3\,m^3\,s^{-1}$, i.e. a net outflow of $\sim 9.5 \times 10^3\,m^3\,s^{-1}$ (Ozsoy and Unluata, 1998; Unluata et al., 1990). Temporal variability in this exchange is closely linked, over seasonal and longer timescales, to variability in precipitation and river inflow (Peneva et al.,

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2001), which moderate the water level gradient along the straits as well as density stratification in the Black Sea. Modelling exchange through the Bosporus Straits system is extremely challenging, particularly due to the presence of sills near its two ends and a contraction in the centre, where the width of the straits decreases to 700 m at the narrowest point. The successful numerical representation of hydraulic controls on exchange through the Bosporus, which include dissipative hydraulic jumps, is a relatively recent achievement (Oguz, 2005; Sozer, 2013). The numerical description of Bosporus exchange flows over interannual and longer time-scales remains a key challenge to the assessment of climatic variability in the region.

Clearly Black Sea and Baltic Sea exchange flows cannot be represented by global climate models and for this reason these seas are either excluded from or poorly represented by the OAGCMs included in the IPCC AR4 and AR5.

In contrast to the deep basins the circulation of the Black Sea and Baltic Sea, and the highly advective nature of the Barents seas, the circulation on the northwest European continental shelf is strongly constrained by the topography, tidal mixing and the geography. Conservation of potential vorticity limits the excursion of the slope current on-shelf, and the shelf break acts as an effective barrier to ocean-shelf exchange. The North Sea circulation is generally cyclonic, and while there are some suggestion of this having more than one mode depending on wind direction (Kauker and von Storch, 2000), the barotropic circulation is constrained by the coastline and topography to follow the general direction of coastal trapped wave propagation. The baroclinic circulation generally flows in the same direction. Hence, while this has yet to be studied in detail, the expectation is the circulation patterns here would change quantitatively, but not qualitatively into future.

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3 Contrasting the climate change impacts on primary production in five regional models

Here we explore, in some specific examples, the various biophysical interactions and Pressure–Responses identified above, with the aim of elucidating the important mechanisms and identifying key uncertainties, deficiencies in approach and gaps in our understanding. The model simulations are drawn from the MEECE project, and so have a degree of harmonisation between them. All three model systems use a generally similar approach of direct coupling between a regional hydrodynamic model and a lower trophic level ecosystem model that divides the ecosystem into several nutrient, producer and consumer boxes, and cycles one or more elements among these. They differ in details of the numerical solution of the equations of motion and how the ecosystem is partitioned. Rather than providing a detailed description for each model references are provided in Table 1 and details of the simulations can be founded in MEECE (2013). For expediency, we focus on the POLCOMS-ERSEM model of the northwest European shelf (NWS) for much of the further analysis. Future climate forcing is provided by the IPSL-CM4 OAGCM (Marti et al., 2006), chosen because of ready access to high frequency forcing data that includes a biogeochemical component. Each model uses a timeslice approach to compare potential conditions at the end of the century (2080–2099, identified as A1B) under the SRES A1B "business as usual" scenario (Nakicenovic and Swart, 2000) with typical present day conditions (1981–2000, identified as CNTRL). Two approaches are employed: a direct forcing approach in which future and present conditions are both taken from the OAGCM or a delta change approach whereby a reanalysis forced simulation is used for the present conditions and a mean monthly change is imposed on this for the future conditions. Issues relating to these approaches are discussed further in Sect. 4.

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3.1 Change in net primary production

Figure 1 shows the average net primary production (netPP) for these five models and the driving OAGCM. The difference in detail between the regional models and the global model shows the potential for "added value" by regional models, i.e. they provide information that was not available from the global model alone. Quantifying the extent to which this is achieved requires a more detailed, case by case assessment of the mean state and variability than can be included here. However, these models have each been assessed in reanalysis forced simulations (Table 1), showing that the general spatial patterns such as these are well represented. It is reassuring that the POLCOMS-ERSEM NWS and ECOSMO North Sea models show good qualitative agreement where they overlap, with POLCOMS-ERSEM giving somewhat higher values than ECOSMO. An exception is in the Norwegian Trench and Skagerrak regions where the POLCOMS-ERSEM model shows a minimum in production not seen in ECOSMO. This may well be due to an inadequate treatment of Baltic inflow in the POLCOMS-ERSEM model.

The overall climate change effect on netPP is shown in Fig. 5 as the absolute difference in mean values between the two timeslices. The global model shows a general decrease in primary production at mid latitudes and an increase at high latitudes, reflecting the regimes suggested by Steinacher et al. (2010). The regional models, in contrast, each show a mixture of both positive and negative change. This arises because the regional models are able to produce a more detailed process response than the global, with multiple processes acting depending on the detailed regional conditions. Again the POLCOMS-ERSEM and ECOSMO model show qualitative agreement in the North Sea, with positive change in the southern region near the coast of continental European and negative change in the central and northern North Sea. Based on the review of processes and responses provided above, we can hypothesize the causes of change in each region. This is summarised in Table 2, separating each model domain into the general regions that shows positive and negative change. While some regions

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show a relatively straightforward response, such as the change in nutrient inputs and increased stratification in the northern North Sea. Other regions show multiple drivers, such as the complex combination of factors that lead to a projected increase in netPP in the Celtic Seas. The response of the Black Sea is an important special case, as unlike the other regions a change in the circulation pattern is thought to be a primary driver of change here (Cannaby et al., 2014).

To facilitate a common analysis, a simple heuristic framework is used. We divide the annual phytoplankton growth into three periods by identifying: bloom start time (T1): netPP is greater than 20 % of the annual maximum (following Platt et al., 2009); bloom stop time T2) when surface nitrate is less than 20 % of winter maximum; and growth end time (T3) when netPP is less than 20 % of the annual maximum. The three periods (see Fig. 4) are then pre-bloom (PB; T3 to T1), spring bloom (SB; T1 to T2) and summer growth (SG; T2 to T3). This approach aims to separate out the production that occurs during the transition from winter to summer mixing and light conditions, from that occurring during the summer conditions (e.g. seasonally stratified or shallower mixed layers). Hence, T2 is chosen to mark the time when seasonal surface nutrient depletion becomes apparent. Because the seasonal cycle is much less marked in the Black Sea, these thresholds are set to 60 % for this region.

By exploring properties averaged over these three stages the response to climate forcing can be seen in more detail. Table 3 presents the netPP, growing season, and potential energy anomaly (PEA, an integral measure of stratification; Simpson and Bowers, 1981) divided temporally between these three stages and spatially between regions showing positive and negative overall netPP change. The annual change in diatom production is also shown. We do not include the Barents Sea in this analysis because the change in productivity can be associated with changes in water mass distribution and sea ice cover, and hence this common approach is not appropriate. The PEA (Fig. 6) and netPP (Fig. 7) results are also shown as bar charts.

The PEA change is generally positive for all regions and areas showing both positive and negative change in netPP. The exceptions are in the North Sea ECOSMO model,

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where the PB and SG period with positive and the SB period with negative change show a small (1–6 %) decrease in PEA. The SB period with negative change in Celtic Sea also shows a 1 % reduction. The positive changes in PEA are much larger than the negative changes, and reflect the general tendency of this forcing to enhance both permanent stratification in the open ocean and deep-basin seas, and also enhance the seasonal stratification in the shelf seas (Fig. 2). The former would be robust to changes in forcing OAGCM, the latter is unlikely to be. In the North Sea (both models), Celtic Sea, northern section of North Atlantic, the largest change in PEA is in the PB period. This period includes autumn and winter stratification and may well reflect change to the precipitation forcing.

The changes in the spring bloom (SB) production show a mixed picture, but generally follow the overall sign of netPP change in that region. An exception is in the Baltic Sea where it shows a weak decrease, compared with an overall increase across the region, particularly during the SG period. The POLCOMS-ERSEM North Sea and Celtic Seas results show a consistent increase in netPP during SB even in decreasing regions, while the ECOSMO North Sea results show a small decrease during the spring bloom in overall decreasing regions. In all the areas showing a negative overall netPP change the summer growth is also negative. This reflects a basic response to increased seasonal stratification (Fig. 6) of reducing the thermocline production. The production in the pre-bloom (PB) period, and its change, is small in all cases on-shelf, partly reflecting the construction of the stages, but also showing that the “tails” of the distribution, arising from the overall seasonal cycle, are not greatly changed. Hence the general increase in PEA during the PB period does not affect the netPP in this analysis, accepting that the netPP can also change with the timing of the periods. In contrast the southern region of the North Atlantic shows a substantial decrease in PB netPP.

The most marked changes in growing season (T1 to T3) are in the Black Sea and the southern sector of the Northeast Atlantic (Table 3). The other regions show small changes, with lengthen (shortened) growing seasons in regions showing increased (decreased) netPP. This change is in the counter-intuitive direction for the Black sea:

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the positive region shows a marked decrease in growing season, and the negative region shows a marked increase. This indicates that changes in stratification are not the dominant driver of regional scale variability in the response of primary production in the Black Sea. This is supported when we consider that the region in the west of the Black Sea, where the increase in seasonal stratification is most pronounced, encompasses both high negative and high positive responses in primary production (Cannaby et al., 2014). Hence, while basin-wide increases in productivity are linked to an increase in seasonal stratification and an associated increase in the residence time of riverine nutrients within the surface mixed-layer, regional variability within the basin requires a different explanation. Cannaby et al. (2014) attribute the regional scale response of the Black Sea to changes in the wind driven circulation, which in turn influences the distribution of Danube plume waters. In contrast the southern sector of the Northeast Atlantic shows a substantial increase in the length of the growing season in both the positive and negative regions. Here bloom initiation is controlled by mixing rather than day-length so shallower winter mixed layer depths (Fig. 8; see below) can lead to an earlier bloom. Further north, early-spring day-length becomes a factor and growing seasons are not greatly changed.

To illustrate changes to the physical environment Fig. 8 shows the changes in potential energy anomaly, mixed layer depth (using the integral definition proposed by Holt and Proctor, 2003) and wind stress for the POLCOMS-ERSEM model. As noted above, the change in pre-bloom PEA is positive across the domain except in well mixed regions. In contrast the increases in PEA on-shelf during the spring bloom are limited to English Channel, Irish Sea and the frontal regions of the southern North Sea. The Celtic Sea shows a weakening in spring bloom PEA, deepening in mixed layer, coincident with an increase in wind stress. The central/northern North Sea shows a weak reduction in spring bloom PEA and deepening MLD, but coincident with a reduction in wind stress. The southern part of the North Atlantic shows an increase in spring bloom wind stress along with a strong increase in stratification. This supports the assertion (above) that the earlier bloom is caused by changes MLD rather than wind stress; the

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increase in wind stress during the spring bloom period reflects the seasonality in wind stress outweighing the climate change signal (Fig. 2). Together this leads to a modest increase in SB netPP (Fig. 7), even where the overall change is negative.

Figure 9 shows the fractional change in netPP (again for POLCOMS-ERSEM) averaged over the PB, SB and SG periods for diatoms and non-diatoms, normalised by the total netPP in the control run, so these six field sum to give the total fractional change. The diatoms show a modest (5–10 %) increase across much of the region for these three periods, and regions of much higher increase. This is particularly apparent in the Celtic and Irish Seas, and the frontal region of the German Bight during the spring bloom.

The non-diatoms show a more varied behaviour. The pre-bloom period (autumn and winter growth) shows a general decrease, particularly in Biscay and the sub-tropical gyre due the substantial increase in stratification here. The spring bloom period is characterised by an increase in most coastal regions with little change elsewhere. The Celtic Sea shows a reduction in non-diatoms corresponding to the increase in diatoms, i.e. a change in community structure. The increase in the frontal spring bloom production in the southern North Sea is to some extent counteracted by reduced summer growth. This period shows quite uniform reduction across the model, away from near coastal region. Production during the SG period is largely fuelled by wind and tidally driven diapycnal mixing at the base of the summer thermocline. Hence the general increase in stratification and reduction in wind stress across the domain (Figs. 8 and 2) tends to reduce production.

The substantial increase in diatom fraction in the Biscay, Celtic Seas and North Sea most likely arises from an increase in growth rates from light and air temperature increases before the on-set of strong stratification (see below). This permits a greater fraction of the winter silicate to be utilised, demonstrating the importance of the "bloom efficiency" identified above. Hence we see a specific two-way coupling between the ecosystem and the biogeochemistry. The increase in the diatom fraction means that more production ends up in larger, faster sinking particles, which are substantially less mobile. Hence there is in increase in the total nitrogen inventory in these less advective regions and a "nutrient trapping" process. This is a common response of all the POLCOMS-ERSEM model regions shown in Table 3, except the Northern part of the Northeast Atlantic. The Black and Baltic Seas also show an overall increase in diatoms, whereas the ECOSMO model in the North Sea shows a decrease.

3.2 Forcing-response experiments

To explore the relative importance of various external drivers, here we present a further series of POLCOMS-ERSEM experiments following Holt et al. (2012a). The approach we adopt is to start with the self consistent set of future forcing (from the IPSL-CM4 model) and systematically remove aspects of the climate change signal by running the POLCOMS-ERSEM model with individual future forcing variables replaced by present day values, taken from a random year of the control period (1981–2000). The difference between the standard run and this experiment then quantifies the climate change effect attributable to this forcing variable. This differs from a more conventional sensitivity experiment (e.g. Skogen et al., 2011) in the treatment of non-linearities. Here we identify the effects of an aspect of the forcing and all non-linearities associated with it under future conditions. In the alternative approach the non-linearities are associated with present day conditions, so the non-linear climate response is missing. We consider five forcing experiments, each an 18 yr simulation following 5 yr of spin up, for: wind (W), short wave radiation (L), air temperature and relative humidity (A), boundary nutrients (B) and precipitation (P). In addition we also consider an experiment to investigate the temperature dependence of the ecosystem model (T). This experiment is similar to that used in a global context by Taucher and Oschlies (2011); the change due to physiological/chemical temperature effects are quantified using a pair of timeslice experiments with the ecosystem model rates fixed to their values at 10 °C.

The change in net primary production associated to each of these experiments is shown in Fig. 10. This shows boundary nutrients have a predominantly negative effect in this case, as identified by Holt et al. (2012a). Air temperature and relative humidity changes comprise a combination of stratification and growth rate effects, these generally follow the regions of positive and negative overall change (Fig. 5): positive in Celtic and Irish Seas, English Channel and southern North Sea, negative otherwise. Wind effects again show a similar pattern but weaker pattern. The short wave radiation effects (L) are uniformly positive and a direct response to the forcing (Fig. 2). Similarly precipitation shows a generally weak but positive effect, suggesting a reduction in salinity stratification. This is at odds with the ensemble mean picture given by Capotondi et al. (2012), but simply reflects the single choice of forcing model.

The direct temperature effect on netPP in this model is a modest increase, resulting from more rapid growth during the spring bloom, and enhanced recycling, but presumably countered by enhanced grazing. This is accompanied by a more substantial reduction in annual mean phytoplankton biomass (not shown), suggesting a more detailed analysis of the dependence on temperature of the flow of carbon and nutrients through the system is required (e.g. Taucher and Oschlies, 2011). The parameterisation of temperature effects are very simple in this model with all group sharing the same parameter value, hence all aspects of the system are changed by an equal amount and tend to cancel in terms of the annual production, but the not biomass. A more sophisticated approach, for example that differentiates between autotrophic and heterotrophic processes (e.g. Wohlers et al., 2009), might be expected to give a larger response.

4 Experiment design for downscaling climate change impacts to regional seas

Here we consider in more detail some of the facets of downscaled experiment design identified in Sect. 1. The future climatic scenarios are prescribed in terms of the GHG emissions either through a socio-economic story line (as in SRES; Nakicenovic and Swart, 2000) or as a particular change in radiative forcing (as in CMIP5). Alongside anthropogenic GHG driven climate change there are many modes of natural variability, but predicting this on time scales of years to decades is exceptionally problematic. OAGCMs may reproduce the character of these modes well and so give good statis-

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tics for long control runs (several centuries), which in turn can give good statistics for impacts studies. However, the length of simulations typically used for downscaling studies is generally short compared to these long control runs, so contamination by natural variability is always a possibility and caution is needed before attributing a particular impact to anthropogenic GHG emissions.

The choice of driving OAGCMs should be dictated by model fidelity in terms of representing global and regional climate and its variability, compared with present day properties appropriate to the questions being asked of the downscaled model. The quality of the regional model output will always be limited by that of the driving model, so this is a first order consideration. This can be decided either by a selection process judging each OAGCM according to a set of observation based criteria (Overland and Wang, 2007) or by using multiple models and weighting the output according to such criteria so to generate ensemble statistics (as in Steinacher et al., 2010). Care is needed in both cases to remove interannual variability from the observations so as not to unjustifiably favour a model that serendipitously agrees in phase with the variability in the observations (Stock et al., 2011). This can be problematic for all but the most basics variables (e.g. sea surface temperature), due to widely varying data densities over the last decades, and it may simply not be possible to derive a "true" mean state from the observations without some natural variability remaining. Hence, the selection or weighting processes should draw on mechanistic understanding of the individual OAGCMs to choose/weight one model over another, or focus on gross qualitative deficiencies rather than detailed differences.

There are two classes of dynamically downscaled experiments: transient and timeslice simulations. The former drives the downscaled model with lateral and surface boundary conditions taken from the OAGCM, starting from the present-day and running for typically many decades into the future (e.g. Olbert et al., 2012). After an initial adjustment period during which the model evolves from the initial conditions (the "spinup"), the simulation can be analysed for the full range of variability and trends. For example, it can be assessed for how well interannual variability can be averaged out to give statistically significant long term change. The obvious limitation of this approach is the computational resource required and this can limit the number of different runs that can be made. Other issues are that the scope for manipulating the driving data is more limited and that full frequency forcing data is required. In the timeslice approach as used in MEECE and many other studies (e.g. Adlandsvik, 2008; Holt et al., 2010) the model is driven by both future and present day conditions in two separate experiments. After a spinup period in both, the two can be compared for statistically significant differences. This approach is significantly more flexible than the transient approach, with several options for manipulating the driving data, for example climate delta approaches, reconstructions and bias corrections. This also has options for alleviating data access issues, e.g. approaches that use mean seasonal conditions between a future and present climate model, added to reanayslsis forcing (the delta change method), only needs monthly output from the OAGCM. Further details on these options can be found in MEECE (2011).

The timeslice approach comes with two specific issues. First is the adjustment to future conditions: the approach assumes that, after the spinup period, the model is not sensitive to the initial conditions, or else this sensitivity will manifest itself as a false climate change response. This is not necessarily a good assumption in regions dominated by stochastic processes (e.g. the mesoscale eddy field in the open ocean) or for processes that are slow to adjust e.g. basins that are only weak flushed and the benthic system. This can, to some extent, be ameliorated by deriving future initial conditions from the driving model. However, the OAGCMs rarely have a good representation of the benthic system, so the issue of benthic spinup and adjustment is an ongoing concern with the timeslice approach. The second issue is the relationship between longer terms modes of natural variability and the difference between the timeslice can be difficult to assess, since only a "snap shot" of the variability is available from the simulations. Together these issues suggest that, while the timeslice approach is very useful for investigating the response of the system to a wide range of changes, the transient approach is generally more suited to future projection. The ideal strategy maybe to

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run multiple timeslices initialised from points on a baseline transient simulation (e.g. a medium emissions scenario).

Alongside the OAGCM forced simulations, simulations forced by atmosphere (e.g. Uppala et al., 2005) and ocean (e.g. Smith and Haines, 2009) reanalyses provide an important benchmark, against which the performance of the regional model can be judged. These allow direct comparison with contemporary observations, but are comparatively short in duration. Forcing by long present day or pre-industrial climate control runs and, potentially by longer reanalysis runs (e.g. 20CR[5]) are required to obtain a full appreciation of the natural variability in the system.

Atmospheric conditions can also be dynamically downscaled using a high resolution atmospheric model, which then forces the coupled hydrodynamic ecosystem model. This is a very useful approach when considering processes that are strongly dependent on the details of the atmospheric simulation (e.g. storm surges and surface waves; Lowe et al., 2009) or when the global model has difficulty in representing even the basic features of the regional atmospheric circulation. This method is practically and computationally more demanding than those considered above and as with most downscaling approaches, this still leads to dynamically inconsistent forcing. The most sophisticated downscaling approach is to use a high resolution regional coupled ocean-atmosphere simulation (as used by Meier, 2006). This downscaling method is dynamically consistent and should be seen as an ideal to aspire to, but is substantially more technically and computationally demanding than the other approaches, and scope for multiple simulations is limited. To our knowledge this approach has yet to be applied to the fully coupled atmosphere–ocean–ecosystem case.

To illustrate the importance of model experiment design and to raise the issue of whether or not we can yet produce reliable estimates of change, Fig. 11 shows three different time-slice views of the change in net primary production (netPP) using the POLCOMS-ERSEM model, These are direct and delta change forcing from the IPSL–CM4 OAGCM and direct forcing by the HadCM3 OAGCM (Gordon et al., 2000; Pope

[5]http://climatedataguide.ucar.edu/reanalysis/noaa-20th-century-reanalysis-version-2

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et al., 2000). While there are many similarities between these results in terms of the overall pattern, the differences are marked to the extent that, in several regions, choice of forcing approach gives a similar order of change to choice of forcing model. It is reassuring, however, that while there are large differences, the spatial correlation between the two runs using IPSL-CM4 is higher ($r^2 = 0.3$), than that between the IPSL-CM4 and HADCM3 forced runs ($r^2 = 0.1$). The differences between these simulations arise because of differences in future state, present state and how natural variability has been sampled in each case.

To give first assessment of the robustness of these results, this figure also shows the regions where the three simulations agree in sign, and whether this is positive or negative. This identifies two distinct regions on-shelf. The region of agreed negative change largely follows the path of the inflow of water from the Northeast Atlantic into the North Sea. The regions of agreed positive change are in the Celtic and Irish Seas, English Channel and Southern North Sea.

5 Discussion and conclusions

The impacts of climate change in regional seas are far from straightforward. A myriad of physical processes can potentially act as vectors transferring the larger scale oceanic, atmospheric and terrestrial variability and change to regional sea physics, biogeochemistry, lower trophic level ecosystems, and so up the foodweb. These processes act on a wide range of time scales, being strongly dependent on the prevailing conditions of an individual regional sea basin. Here we have explored some of the physical mechanisms driving this interaction, drawing on a set of regional model simulations to provide illustrations. These processes are summarised in Fig. 12, along with a hypothesised sign of change in netPP. We would not expect that statistical relationships between forcing and response (e.g. Popova et al., 2010) could be used to reproduce the rich diversity of behaviour seen in this study, nor given that we are using comparatively simple models, be able to reproduce the plasticity of response that might be expected of a future ecosystem. It should he emphasised that each of these simulations only represent a single possible view of future conditions, and no quantitative assessment of the likelihood of this occurring has been made.

Considerable focus has been given in the global context to the impacts of changes in permanent stratification on vertical nutrient resupply (Capotondi et al., 2012) leading to a decrease in primary production (Bopp et al., 2013; Steinacher et al., 2010) and while there has been some acknowledgements of direct temperature effects and changes to growing season these have received less attention(Sarmiento et al., 2004; Taucher and Oschlies, 2011). This arises from the fact that they relate to less robust aspects of ecosystem models (in the case of direct temperature effects) and climate models, in the cases of growing season effects. In regional seas, however, these permanent stratification effects are less clear and we must consider all potential processes, with priority being dictated by regionally specific conditions. This is particularly the case in seas that are shallow compared with turbulent boundary layer thicknesses and so are well mixed for part of the year. In this case this leading order effect is absent. Hence this property may shelter these seas from some direct impacts of climate change. In the permanently stratified seas we have been considering here (the Black Sea and Baltic Sea) the impact of climate change on stratification is highly modulated by changes in circulation and overturning/mixing in its effect on nutrient resupply and primary production. These more dynamic processes are seen to be the leading order effect in these cases and under the single forcing scenario considered here.

Hence, the view is of several competing processes acting with both positive and negative sign (Fig. 12). While this really needs to be considered on a case by case basis, some general principle can be identified. When there are multiple effects of different sign these will tend to mitigate the climate change impact, suggesting some regional seas will generally be less vulnerable to climate change effects than the open ocean. This can act both locally and spatially, i.e. advective and diffusive transport will tend to reduce effects across gradients of negative and positive impact. This will not be the case in enclosed regional seas, where a single dominant effect can have a large impact that is not mitigated by exchange with neighbouring regions of a different sign. Hence, we might expect the enclosed regional seas to be more highly impacted. This is indeed the case for the Black sea and Baltic Sea in these experiments. In both cases these are driven by changes in wind effects leading to changes in circulation patterns in the former and upwelling rates in the later, i.e. both highly dependent on the detailed conditions in the basin.

Another consequence of multiple, competing processes is that uncertainties are enhanced. Simplistically, uncertainties for uncorrelated processes with add in quadrature even if the effects are of different sign and cancel, i.e. fractional uncertainty can substantially increase. This is compounded by the fact that many of the processes considered here relate to less well modelled, regionally specific, aspects of the OAGCM forcing such as the hydrological cycle and details of the wind fields. Hence, the climate change signal in these is substantially less certain than, for example, changes in air temperature.

We should reiterate that the resolution considered in these models is marginal for the consideration of many processes, particularly near coastal, frontal and in shelf-slope regions of the ocean margins; in fact where we would expect the primary production to be highest. A simple scale analysis suggests a $\sim h^{0.5}$ relationship between horizontal scale and water depth, i.e. a $\sim$ 10 fold decrease in scale from 4000 m to 40 m. Hence, 1/10° regional model in shallow water is in some sense comparable to a 1° global model. The models domains used here are well-established and so have not fully taken advantage of the continued growth in computer power over recent years, in terms of their grid resolution and there is now an opportunity to address these issues, accepting that increases in resolution must be tensioned against the need for multiple process experiments, longer simulations and ensembles.

Finally, there are several lessons to be taken away from this exploration of processes and the results from MEECE project, which may inform future work:

1. While common analysis and comparative approaches are very important they should be complemented by detailed regionally specific analysis. This analysis

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should eventually inform larger area and global studies with the aim of developing generic approaches.

2. The relationship between natural variability and anthropogenic GHC driven change is central to projecting impacts, but we need to consider centennial timescales to build a deep understanding of the relationship. This points clearly to transient simulations over timeslices.

3. Climate change impacts in regional sea ecosystems largely relate to both the general properties of the forcing and the details; this implies a closer engagement between global climate modelling and regional downscale modelling. Moreover as resolution is refined, particularly as we move into near coastal regions, the human dimension has to be considered in any future projection effort.

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Table 1. List of models and references.

Region	Model	References		
		Hydrodynamic model	Ecosystem Model	Downscaling experiments and configuration All: MEECE (2013)
Black Sea	POM BIMS_ECO	Blumberg and Mellor (1987)	Oguz et al. (2001); Korotaev et al. (2011)	Cannaby et al. (2014)
Barents Sea	ECOSMO	Schrum et al. (2005)	Daewel and Schrum (2013); Årthun et al. (2011)	Daewel and Schrum (2013); Årthun et al. (2011)
North Sea and Baltic Sea	ECOSMO	Schrum and Backhaus (1999); Backhaus (1985); Kochergin (1987); Schrum (1997); Barthel et al. (2012)	Daewel and Schrum (2013)	Daewel and Schrum (2013)
Northwest European Continental Shelf	POLCOMS-ERSEM	Holt and James, (2001); Wakelin et al. (2009); Holt et al. (2012a) Wakelin et al. (2012)	Allen et al. (2001); Blackford et al. (2004); Wakelin et al. (2012)	Holt et al. (2012a)

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Table 2. Sign of change of key forcing variables from IPSL-CM4 (A1B compared with CNTRL), and hypothesis for cause of positive (+ve) and negative (−ve) change in netPP.

Forcing	Black Sea	Barents Sea	Baltic Sea	North Sea	Celtic Seas
Air temp.	+ve	+ve	+ve	+ve	+ve
Wind: Spring	−ve	+ve/−ve	−ve	−ve	−ve
Summer	+ve	−ve	+ve	+ve	+ve
Overall	−ve	+ve	+ve	+ve	−ve
Precip.	+ve	+ve	+ve	+ve	+ve
SWR	+ve	−ve	+ve	+ve	+ve
Nut. BC		+ve		−ve	−ve
netPP Response: +ve	**East/North**: Increased nutrient retention on NW shelf	**Central**: Reduced ice cover (increased in-water PAR); increased Atlantic water and nutrient inflow	**Central**: Increased wind driven ventilation and upwelling	**Coastal**: Increased growing season; increased recycling; increased SWR	**Central/Coastal**: Lengthen (more efficient) spring bloom; increased recycling; increased SWR
−ve	**West/South**: Reduced nutrient transport from NW shelf	**Coastal**: Changed pathway of Atlantic Water inflow, more northward flow.	N/A	**Central/Northern**: Reduced oceanic nutrient input; increase seasonal stratification	**Outer shelf**: Reduced oceanic nutrient input; increase seasonal stratification

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Table 3. Summary of response from the common analysis. At each grid cell the model values are integrated temporally over the periods described in Sect. 3. These are then averaged spatially over the areas showing an overall increase and an overall decreased in netPP. Variables shown are: percentage area of positive and negative change; netPP and fraction change between timesclices; growing season and change in days; netPP and PEA for the three periods, two areas and whole region. Annual diatom production and fraction change for two areas and whole region.

Model		BIMS_ECO			ECOSMO				POLCOMS-ERSEM											
		Black Sea			Baltic Sea	North Sea			North Sea			Celtic Seas			NE Atlantic: North of 53.2°N			NE Atlantic: South of 53.2°N		
Response		All	+ve	−ve	All	All	+ve	−ve	All	+ve	−ve	All	+ve	−ve	All	+ve	−ve	All	+ve	−ve
Area %			64	36	100		24	76		38	62		61	39		27	73		13	87
netPP	$gCm^{-2}yr^{-1}$	72	76	66	55	84	123	71	122	129	117	125	127	122	102	100	103	122	138	120
	Δ_f %	5	23	−31	17	−12	5	−20	−2	5	−7	2	6	−6	−5	13	−11	−13	13	−18
Growing season	days	273	273	162	227	203	237	192	180	200	167	151	166	126	70	70	69	124	137	122
	Δ days	−34	−48	57	−10	0	7	−2	4	9	0	6	6	6	0	12	−4	64	76	62
Pre-bloom netPP	$gCm^{-2}yr^{-1}$	11	10	13	4	8	7	9	14	13	14	21	18	26	30	28	30	31	32	31
	Δ_f %	70	118	10	41	−2	−2	−2	4	0	6	3	8	−2	−1	3	−3	−40	−32	−41
Sprg bloom netPP	$gCm^{-2}yr^{-1}$	37	40	34	12	46	105	27	52	80	35	47	54	35	22	20	22	33	37	33
	Δ_f %	−9	9	−46	−5	−8	6	−20	14	16	13	15	18	7	−7	7	−12	12	45	7
Summer netPP	$gCm^{-2}yr^{-1}$	24	26	19	40	30	12	36	66	59	70	61	61	61	51	52	51	58	70	56
	Δ_f %	−2	10	−32	24	−21	3	−23	−8	4	−15	−6	0	−15	−6	22	−16	−13	18	−19
Diatoms netPP	$gCm^{-2}yr^{-1}$	44	45	42	23	16	14	17	13	10	15	16	14	19	15	15	14	17	22	16
	Δ_f %	11	32	−31	8	−7	0	−8	15	18	13	32	45	10	−2	24	−12	6	59	−1
Pre bloom PEA	Jm^{-3}	79	74	88	161	61	4	79	14	8	17	27	20	39	32	31	32	73	70	73
	Δ_f %	38	32	111	6	17	−1	18	40	10	49	44	38	50	65	61	67	128	135	127
Spring bloom PEA	Jm^{-3}	113	109	118	131	43	14	52	16	20	14	7	8	7	13	17	12	13	15	13
	Δ_f %	22	29	14	2	−5	2	−6	12	4	19	7	12	−1	44	41	45	502	472	508
Summer PEA	Jm^{-3}	207	200	241	203	87	2	115	40	26	48	42	38	48	43	47	41	65	73	64
	Δ_f %	31	32	25	11	4	−4	4	17	18	17	12	13	10	27	41	21	127	140	125

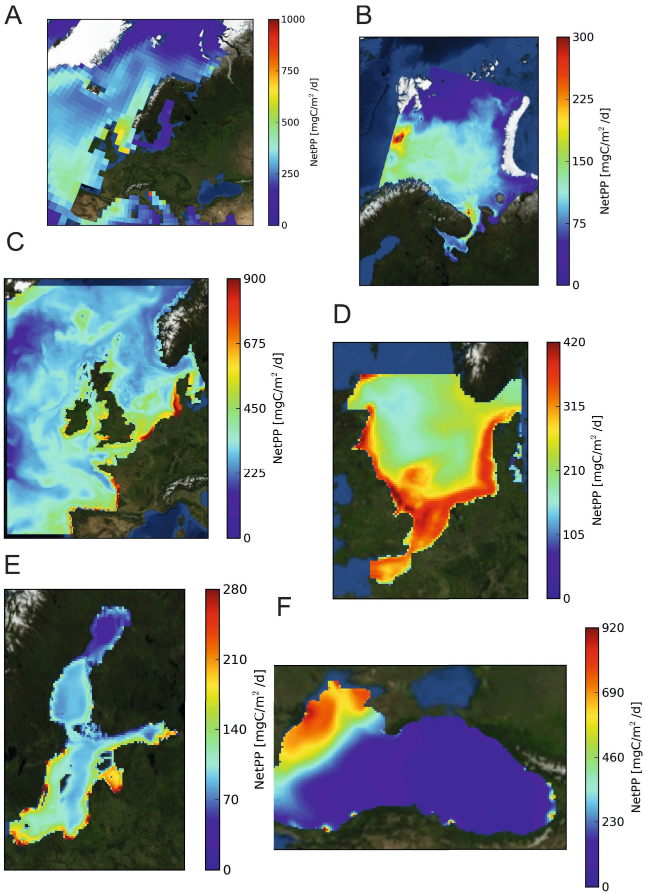

Fig. 1. Average annual netPP for the global OAGCM and the five regional models over a nominal 20 yr present-day period (1981–2000). **(A)** Global; **(B)** Barents Sea (ECOSMO); **(C)** Northwest European Shelf (POLCOM-ERSEM); **(D)** North Sea (ECOSMO); **(E)** Baltic Sea (ECOSMO); **(F)** Black Sea (BIMS_ECO).

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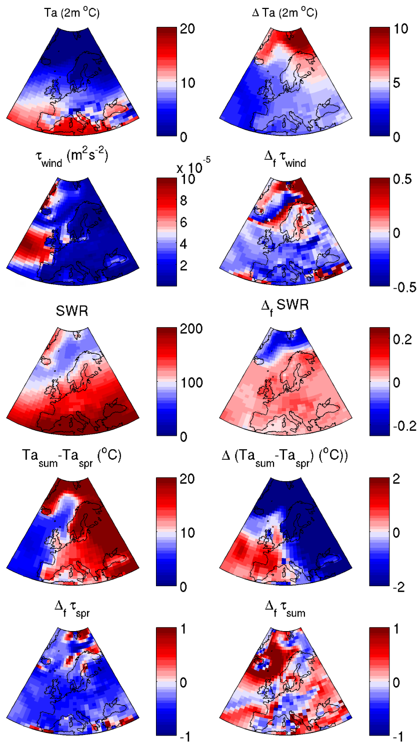

Fig. 2. Mean values from the atmospheric component of IPSL-CM4 for 1980–2000 (CNTRL) and change between mean for 2080–2100 (A1B) and this, absolute difference for air temperature and otherwise fraction change (A1B/CNTRL-1). Variables shown are 2 m air temperature (T_a(2 m), °C), surface wind stress (τ, m^2 s^{-2}) and surface short wave radiation (SWR, W m^{-2}). Also shown is the difference between Summer (July–August) and Spring (March–April) temperatures and the change in wind stress for these periods.

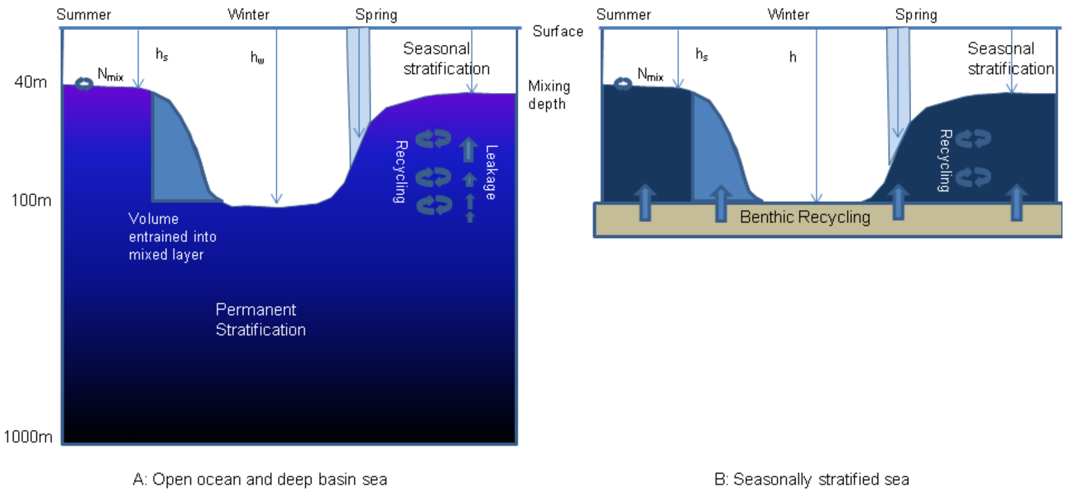

Fig. 3. Conceptual view of the difference in seasonal cycles between **(A)** open-ocean/deep regional sea and **(B)** seasonally stratified sea. "Leakage" generally reflects the long-term overturning circulation.

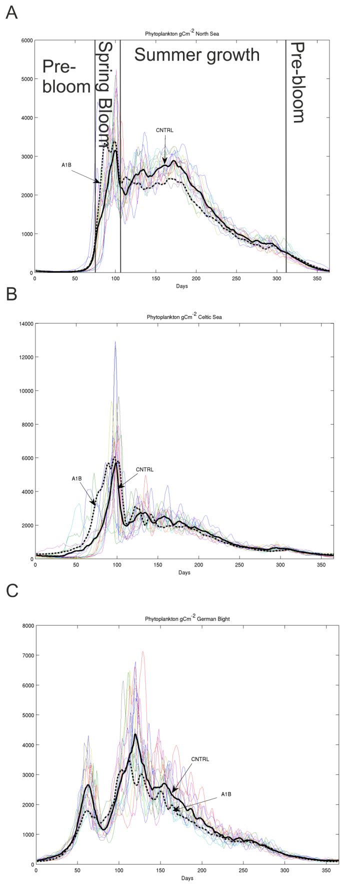

Fig. 4. Examples of the time evolution of depth mean phytoplankton biomass (from POLCOMS-ERSEM) at locations in the seasonally stratified North Sea, Celtic Sea and the well mixed German Bight. Light lines show individual year for two 18 yr model experiments (CNTRL and A1B) and heavy lines show the mean for these experiments.

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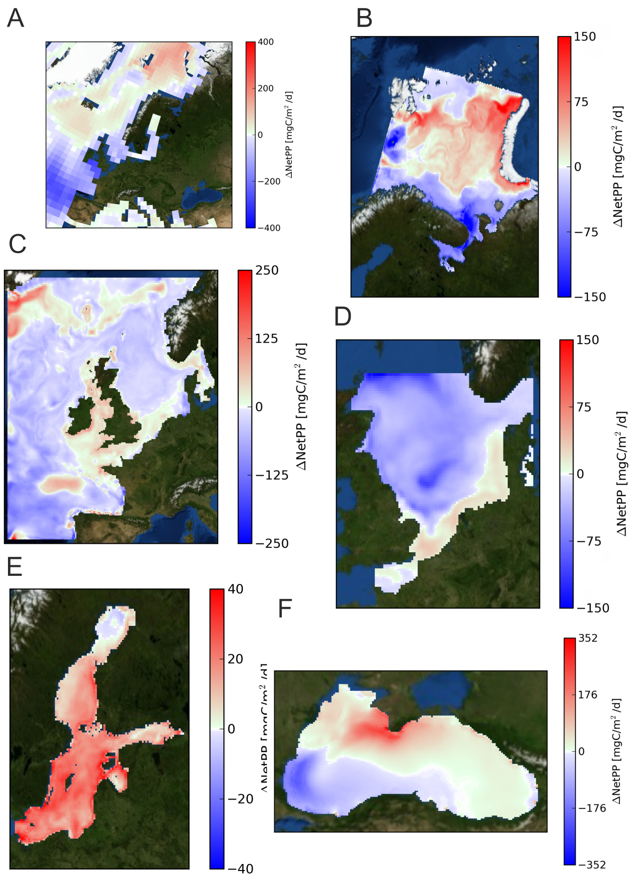

Fig. 5. Change in mean netPP between A1B and CNTRL for the five regional models, and the global OAGCM. All the regional models are forced by the IPSL-CM4 model and use a common timeslice, but the forcing methodology differs between models.

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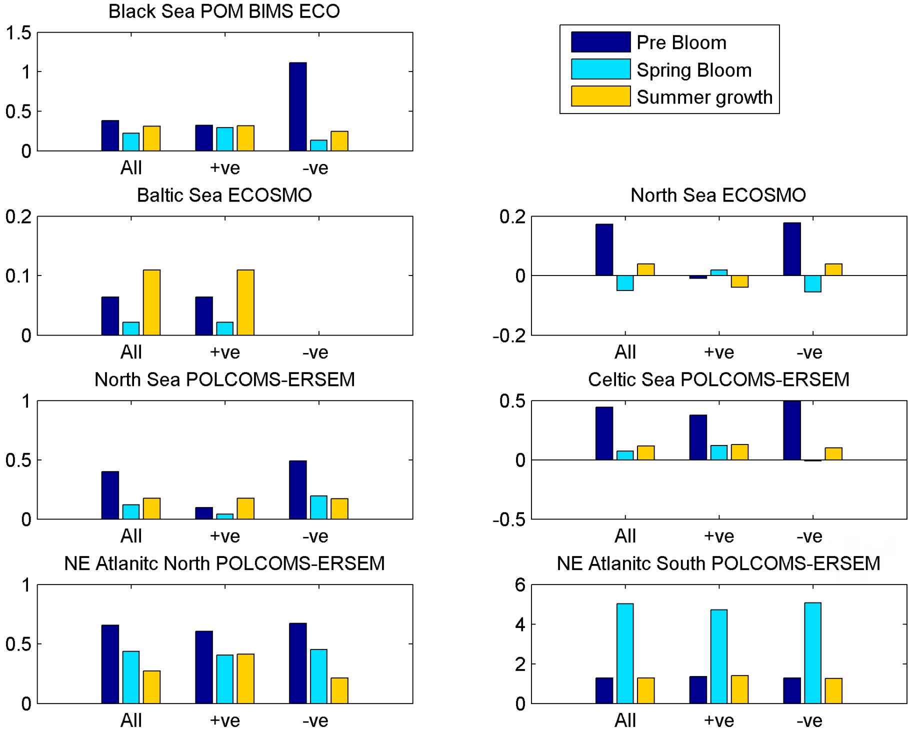

Fig. 6. Bar plots of PEA fractional change for the three stages divided between regions showing positive and negative netPP change.

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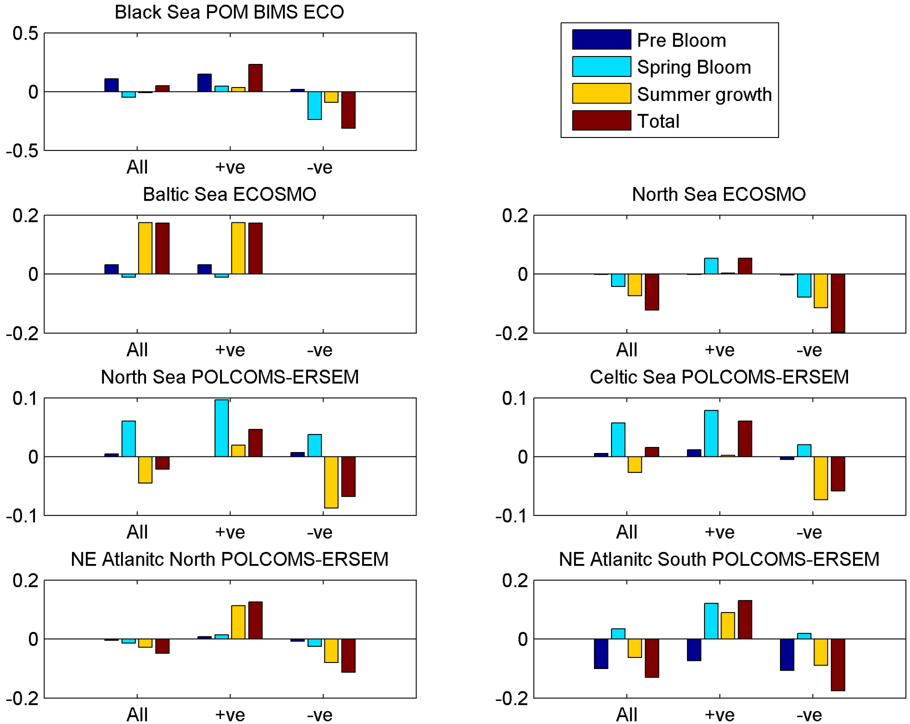

Fig. 7. Bar plots of netPP fractional change for the three stages and also total netPP. The results for the stages are all scaled by the CNTRL netPP, but do not exactly sum to the total due to the conditional sampling approach.

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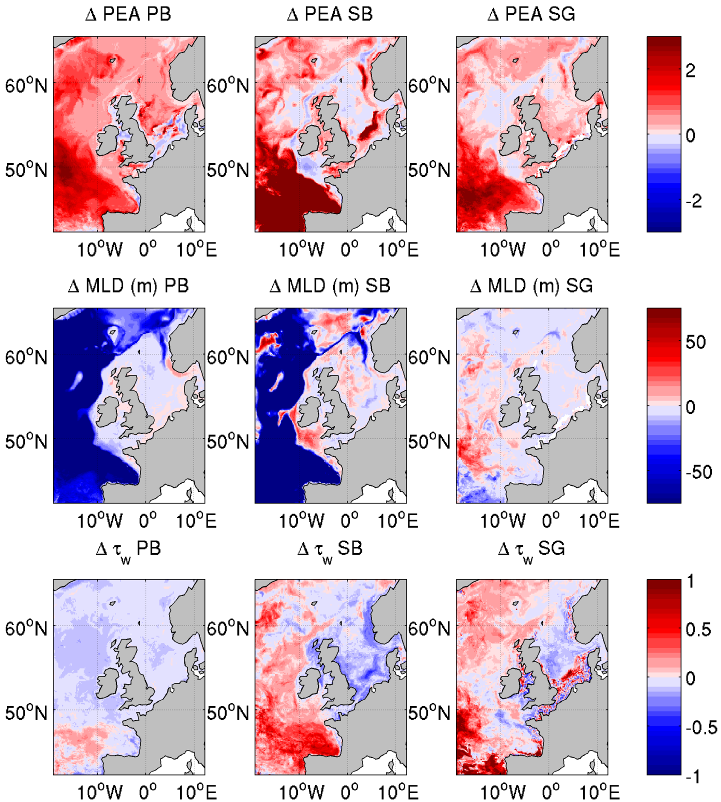

Fig. 8. Fraction change in Potential Energy Anomaly (PEA; limited to 200 m; top) and absolute change mixed layer depth (MLD; middle) and fractional change in wind stress during the growth periods: pre-bloom (PB), Spring Bloom (SB), Summer growth (SG).

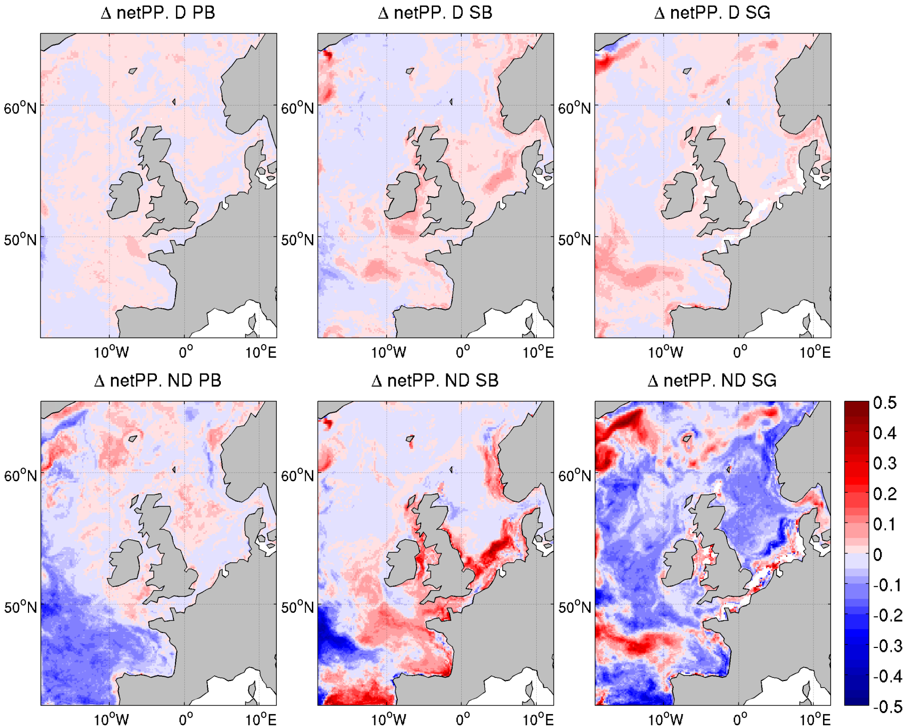

Fig. 9. Fractional change (relative to total in CNTRL) in netPP for diatom (D) and non-diatom (ND) functional groups in ERSEM during the growth periods: PB, SP, and SG.

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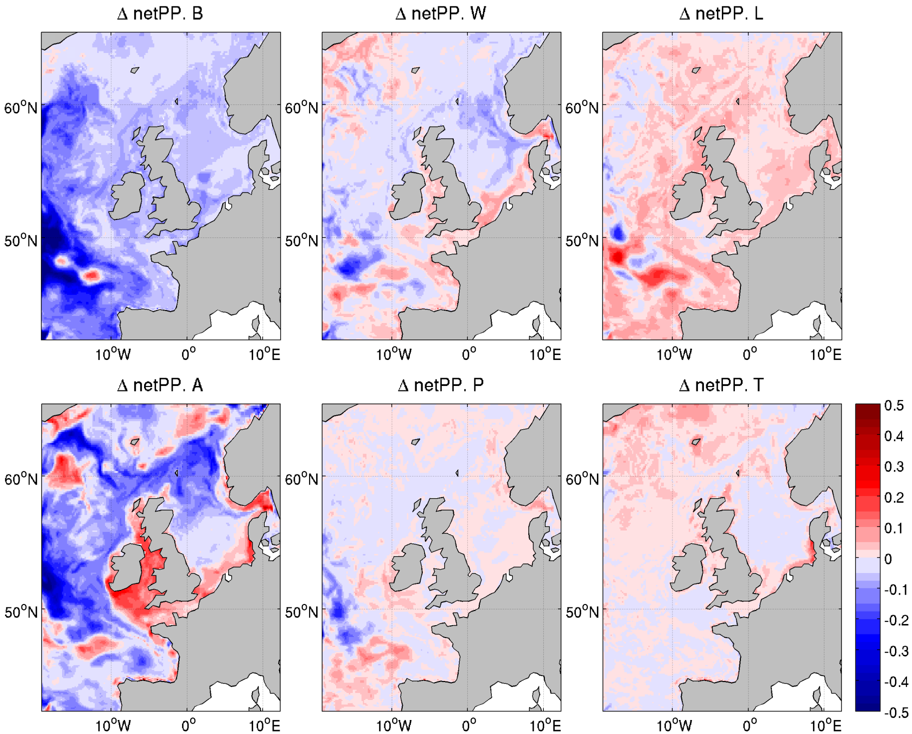

Fig. 10. Forcing experiments with POLCOMS-ERSEM. Fractional change in netPP associated with five external drivers and their non-linear interactions: boundary nutrients (B); wind (W); short wave radiation (L); air temperature and relative humidity (A); precipitation (P), and the direct effects of temperature on growth rates (T).

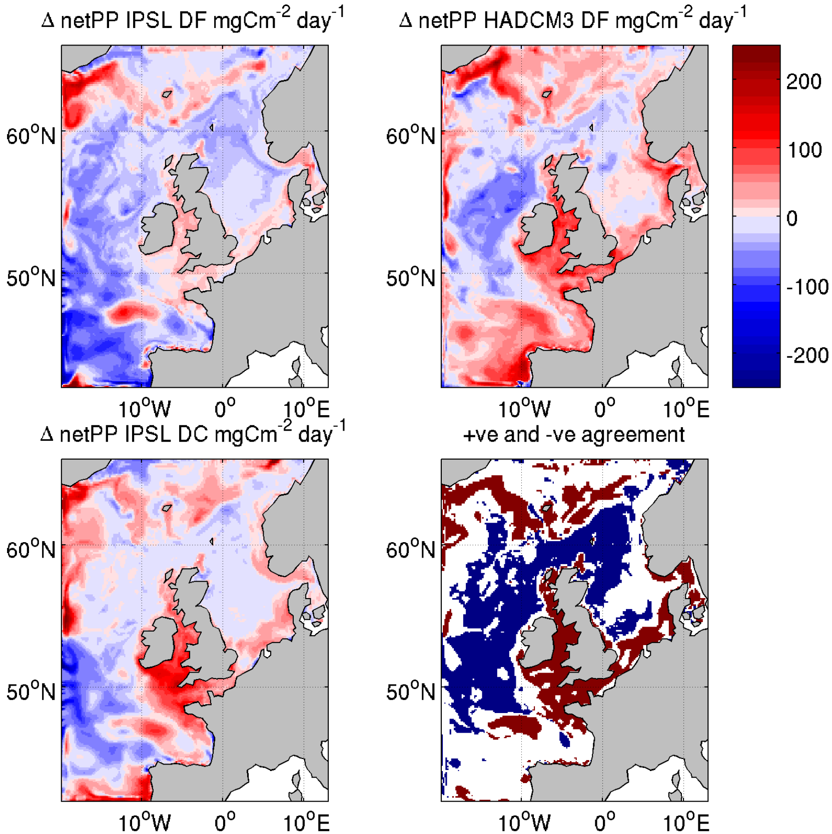

Fig. 11. Change in netPP from three POLCOMS-ERSEM simulations. Top left: direct forced (IPSL-CM4; Holt et al., 2012); Bottom left: delta change (IPSL-CM4 with ERA40 reference); top right: direct forced (HadCM3). Bottom left shows where the three simulations agree on the sign of change being positive (red) and negative (blue).

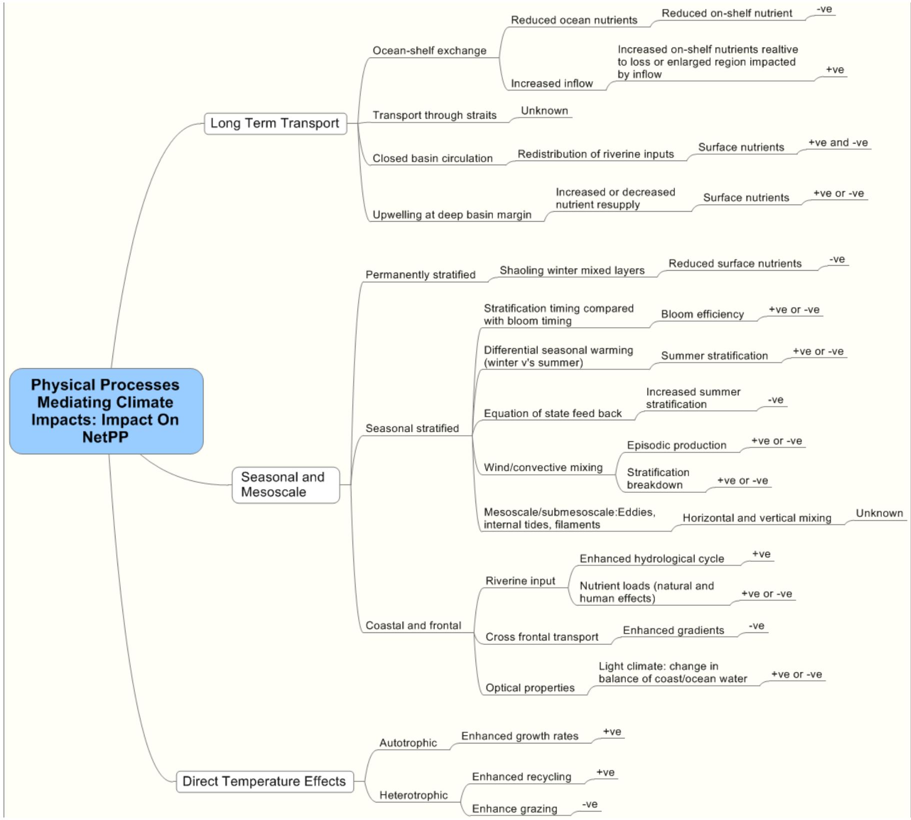

Fig. 12. Summary of physical processes mediating climate change impacts. These are organised according to the three paradigms of biophysical interaction identified in Sect. 1, general process and whether the sign of change in netPP is expected to be positive or negative or either depending on the sign of forcing. This is identified as unknown if the sign of the effect is not straightforward given the sign of forcing.

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