

1. A plankton highway along the western coasts of the UK

Main policy implications

This work has demonstrated that the stratified regions around the western coasts of the UK and Ireland have particular unique properties and constitute distinct eco-hydrodynamic regions. Such oceanographic regionality is directly relevant to a range of aspects likely to be considered in the Marine Bill, especially Marine Spatial Planning (http://www.defra.gov.uk/corporate/consult/marine_bill/index.htm). Use of such knowledge is fundamental to the characterisation ('typology') of UK shelf waters (relevant to the proposed European Marine Strategy Directive), and increasing awareness is required of these oceanographic complexities with regard to, for example, the consideration of indicators of ecosystem status (Tett et al., 2004a, b; Larcombe et al. 2004), fisheries management and marine nature conservation.

In summer, the density-driven flows at the boundaries of the stratified regions cause a major regional flow, which acts to limit transport between neighbouring eco-hydrodynamic regions. For example, summer transport between the Celtic Sea and the Irish Sea is very limited, while there is strong transport along their boundary (St Georges Channel). There is thus limited potential for transport of plankton across these pathways, but high potential for transport along them, as indicated by the occurrence of *Karenia mikimotoi* along this pathway (Raine, 1993). This mechanism has the potential to transport 'non-indigenous' species into and around UK waters, into environments that may, in the future, be favourable to their persistence.

Plankton species composition is different between well-mixed and stratified regimes and consequently many toxic harmful algal blooms only occur in stratified water. Management and assessment of such waters requires measures and an approach appropriate to the properties of each eco-hydrodynamic region. The occurrence of Harmful Algal Blooms (HABs) in shelf waters off the S & W coasts of the UK are not directly related to nutrient inputs from the UK mainland, but appear to be a natural consequence of the oceanographic conditions along a regional transport pathway between France, SW England, through the Celtic Sea and around the southern coast of Ireland. Thus, there is no need to increase those management measures currently in place in SW England and S. Wales which address local concerns. Further, these types of

HABs themselves should not be used as indicator of water quality.

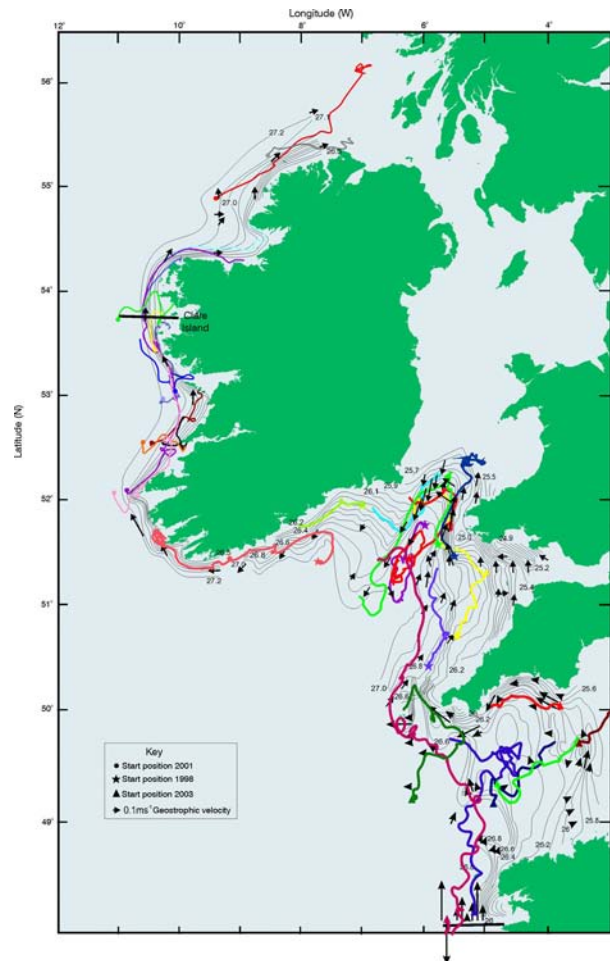


Figure 1.1. The combined pathway from the results of three field programs, with drifter tracks overlain on the contours of bottom density field.

Main science findings

From early summer (late May) to autumn (mid October), a continuous oceanographic pathway exists from the NW Brittany (Ushant), across the Western English Channel, south along the Cornish coast, around the Lizard Peninsula, along the N Cornish and Devon coasts, across St. Georges Channel, and then around the SW and W coasts of Ireland. These flows occur at the boundaries of the stratified regions and have significant magnitude, of $\sim 0.1\text{--}0.2 \times 10^6 \text{ m}^3/\text{s}$ (by comparison, the mean flow of the Amazon River is $0.2 \times 10^6 \text{ m}^3/\text{s}$). Such transport remains within its source eco-hydrodynamic region, and the pathway acts as a barrier to limit transport between neighbouring eco-hydrodynamic regions (e.g. stratified to mixed). For example, summer transport between the Celtic Sea and the Irish Sea is very limited, while there is strong transport across their boundary (St Georges Channel).

Background

Situated towards the western margin of the NW European continental shelf, the waters of the SW approaches, Celtic Sea and western Ireland exhibit hydrographic and biological properties characteristic of both coastal and Atlantic regimes. Detailed work with towed undulating CTDs and ARGOS buoys has taken place off Ireland, where, in the south and northwest, the edge of the continental shelf approaches to 30 km and 60 km of the coast, respectively (Fig. 1.1). Exposed to Atlantic weather, wind speeds average 12 m/s in January and are also high during the calmest month of June, at 7 m/s (Anon, 1999). Consequently, wind would be expected to play a significant role in determining the residual circulation of the region's waters (e.g. Pingree and Griffiths, 1980; Pingree and Le Cann, 1989). Whilst offshore, the strength and extent of the predominantly density-driven European continental slope current has now been established (e.g. Pingree *et al.*, 1999; White and Bowyer, 1997), a description of the coastal circulation remained elusive, yet is important because much commercial exploitation, such as aquaculture, occurs in the inshore waters.

Off the Irish coast, the shelf sea-bed drops sharply to 80–100 m at 20 km offshore, from where it slopes more gradually to the shelf edge. Here, apart from near headlands, shelf tidal currents are generally weak (<0.3 m/s at spring tides) and insufficient to overcome the input of surface buoyancy through solar heating (Simpson and Hunter, 1974; Fernhead, 1975), so that in summer, the region stratifies thermally (Huang *et al.*, 1991; McMahon, *et al.*, 1995). The conventional view of the circulation of this region is one of a relatively quiescent dense (cold and salty) pool of bottom water beneath a warm and largely wind-driven surface layer. Analysis of infra-red satellite imagery indicates that the plume of the River Shannon forms a northward buoyant flow in Galway Bay (Huang *et al.*, 1991), the speed of which is regulated by the wind.

Recent work in the Celtic Sea (undertaken under Defra project AE1214) described the presence of fast (> 20 cm/s), narrow (10–20 km) “geostrophic jets” (baroclinic jets), associated with cold (or salty), dense pools of bottom water which remain trapped beneath the summer thermocline. These jets flow in a cyclonic sense (turn to the left), with peak speeds at or above the thermocline level consistent with existing understanding of the flow dynamics (e.g. Garrett & Loder, 1981). The well-organised cyclonic circulation is resistant to wind and extends continuously for ~700 km, from the Scilly Isles toward St. George's Channel and

around the coast of southern Ireland. Under A1225, further observational and modelling work has been performed (Carrillo, 2001; Brown *et al.*, 2003; Young *et al.*, 2004).

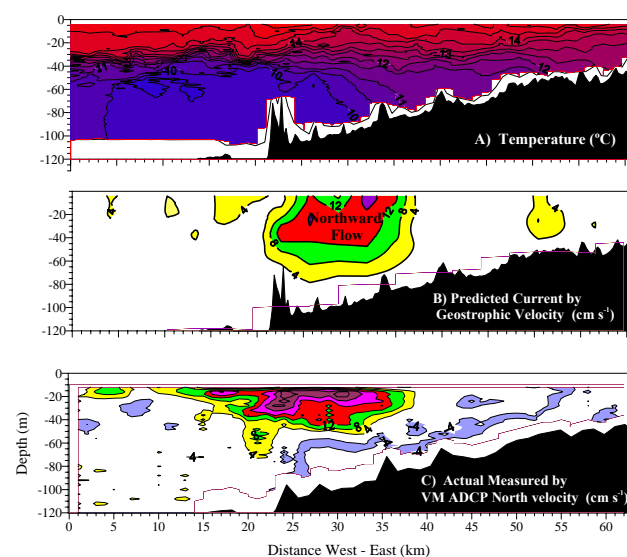


Figure 1.2. Section from Clare Island West Coast Ireland, showing: a) temperature structure, revealing the thermocline and the bottom front, b) the speed of the northward geostrophic flow, estimated from the bottom fronts, c) the measured residual speed, once the tides have been removed.

Physical observations

Two field programs have been conducted: in the western Channel in June and August 2003, and along the west coast of Ireland in July 2001, partly funded by the Irish Marine Institute (full details in Fernand *et al.*, in press).

Satellite-tracked drifters drogued at 30 m depth indicate a regional northward flow, which closely follows the contours of bottom density (Fig. 1.1). Bottom density is a good indicator of the position of bottom fronts which drive flows in the water column above them. In the south, off Brittany, the drifters indicate that flow is strong (average 12 cm/s) and narrow (~15 km wide). Across the channel, the flow weakens to ~4 cm/s and links with a stronger flow which occurs along the southern Cornish coast. Along the west coast of Ireland, flow speeds are 7.2 cm/s, but even the persistent winds in the area accounted for only 25% of the speed during the period of drifter deployments. The remainder is due principally to the density-driven flow. Whilst flows around headlands are locally significant, they do not contribute significantly to regional transport.

In the Western Channel region, these summer flows can be separated into three regimes:

- fast flows (>10-14 cm/s) near the Ushant front;
- slow wind-driven flows (<4 cm/s) in the central region, at ~latitude 49.5° N and east of 5° W;
- moderate flows (~6-10 cm/s) near the Cornish coast.

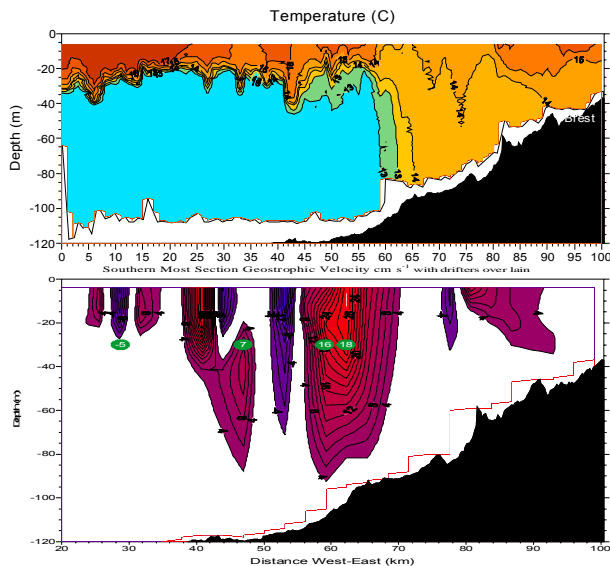


Figure 1.3. Section off Brittany (the Ushant Front) measured by undulating CTD: a) Temperature, b) derived geostrophic velocities with drifter velocities overlain (green dots show speed of northward flows).

Thus, in summer, there is significant transport from the Brittany coast across the channel and a moderate density-driven flow westwards along the Cornish coast, which links into the Celtic Sea. Whilst observations of the Celtic Sea flow system have been reported previously (Brown *et al.*, 2003), modelling of this system is ongoing and has proved useful in determining the forcing factors, for example in distinguishing between density (baroclinic) and wind-driven (barotropic) flow. Results indicate that, in St Georges Channel, 82% of the summer flow is due to the geostrophic jet (Young *et al.*, 2004). Oceanographic sections through the water column off Brittany and the west coast of Ireland (Figs. 1.2 & 1.3) reveal the cause of this density transport. Both sections show the principal features of bottom fronts beneath the main thermocline and a flow associated with these bottom gradients. Independent observations (using Acoustic Doppler Current Profilers ADCPs & drifters) and model results indicate that these geostrophic currents exist, and although there are differences between the results, such as the precise speeds, these differences are small.

Biological consequences of the pathway

Harmful algal blooms (HABS) have occurred in many pelagic ecosystems for many centuries, well before the likely influence of significant human activity, however, during the last few decades, these events have apparently increased in number, real extent and biomass (Anderson, 1997). HABS have many forms and effects. Massive primary productivity by non-toxic algae can, when the algae decay, provoke an oxygen deficiency which strongly disturbs the ecosystem, while a number of other species, such as *Dinophysis*, are poisonous at low concentrations.

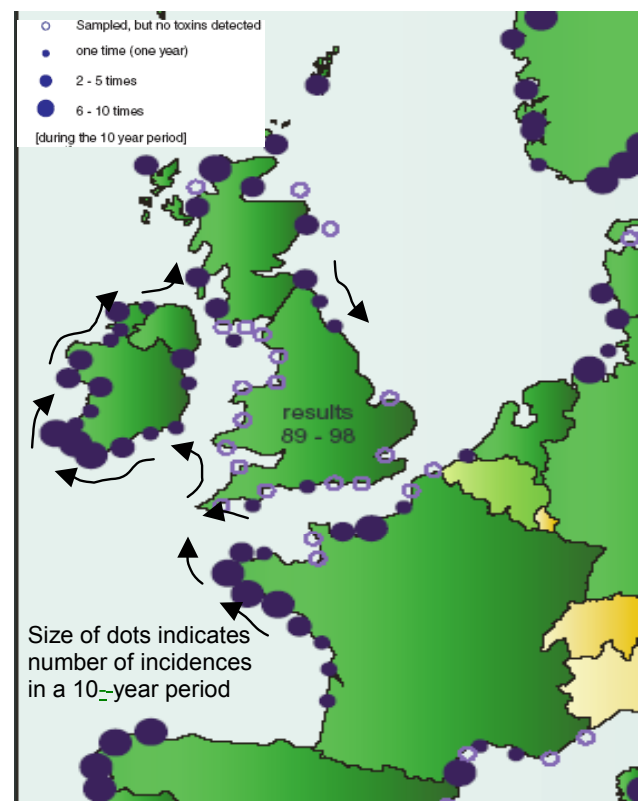


Figure 1.4. The occurrence of *Dinophysis* spp. (data from ICES records). Empty circles indicate testing but no presence.

Diarrhetic Shellfish Poisoning (DSP) is prevalent on the western European shelf, and is due to the dinoflagellate *Dinophysis* (Fig. 1.4). The highest occurrences of *Dinophysis* are along the regional transport pathway, along which favourable conditions exist for growth, primarily that of strongly stratified environments, which act to inhibit turbulence. However, an outbreak will require a source population and its advection along the pathway. It is also notable that outbreaks of Paralytic and Amnesic Shellfish Poisoning (PSP, ASP) are also concentrated along the pathway. A range of other evidence exists for the occurrence of these pathways, such

as the presence of *Amphidoma caudata* around the NW coast of Ireland (e.g. Gowen et al., 1998).

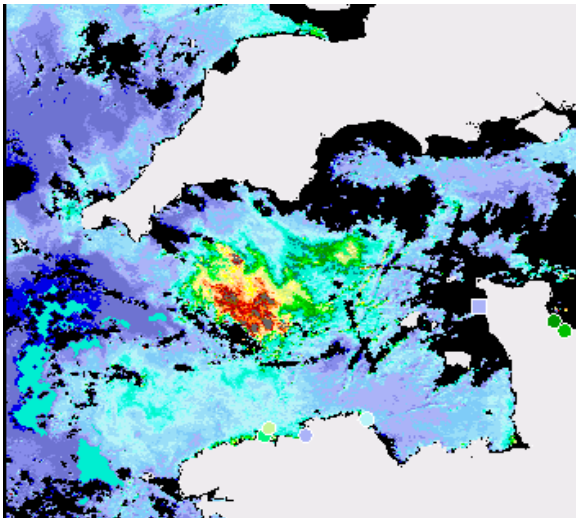


Figure 1.5. Sea Wifs satellite image of Chl-a concentrations in surface waters (courtesy F. Gohin, Ifremer). Red, yellow and green colours show the main part of the bloom (centre of image).

In addition to those species associated with shellfish poisoning, other HAB species such as *Karenia mikimotoi* (previously known as *Gyrodinium aureolum*) occur regularly in the Western Channel (Holligan, 1979). Here, monospecific blooms occur of concentration ~ 50 mg/l Chlorophyll a (chl-a) and $\sim 10^7$ cells/l, located on the thermocline and up to the surface.

Karenia is associated with loss of fish (Arzul, 1995) and shellfish, for example, in the Bay of Brest in 2001, blooms of *K. mikimotoi* caused a loss of 4×10^6 individuals from scallop nurseries (Erard-Le Denn et al., 2001) and the mortality of 800-900 tonnes of the mussel *Mytilus edulis* (Gentien, 1998).

Building on previous findings (e.g. Raine et al., 1993; Gowen et al., 1998), the University of Galway and Irish Marine Institute collaborated in this work, providing plankton and oceanographic expertise, and IFREMER in Brest developed a model for *K. Mikimotoi* which was coupled to a hydrodynamic model (Brunier et al., in press). Field surveys in June 2003 coincided with the presence of a high-biomass bloom which was 50 km across and clearly visible from its chl-a signature (Fig.1.5).

In-situ observations of the bloom have contributed to the success of the modelling effort by providing data for validation, particularly regarding the light regime, and in detailing the sub-surface extent of the bloom. Having established confidence in the capability of the model to replicate observations (compare the data of Fig. 5 with the model results

of Fig. 6) it can be used to determine the sensitivity to various oceanographic parameters. Results indicate that the growth and mortality of *Karenia mikimotoi* are most sensitive to turbulence, with low turbulence conditions being ideal for growth. While the length of the bloom (~ 30 days) is ultimately determined by available nutrients, which do eventually get depleted, the start and magnitude of the bloom is primarily determined by the occurrence of strongly stratified environments with sufficient light. Thus, nutrients do not limit the geographical extent or magnitude of the bloom. Using background concentrations of oceanographic nutrients, the model reproduces the bloom's geographical extent, indicating that oceanic blooms of this type probably occur independently of additional nutrient sources, such as from rivers. This modelling result is consistent with many years of observations, which indicate that inter-annual variance in the blooms appears to be linked to strength of stratification and reduction in mixing, rather than supply of nutrients (Brunier et al., in press).

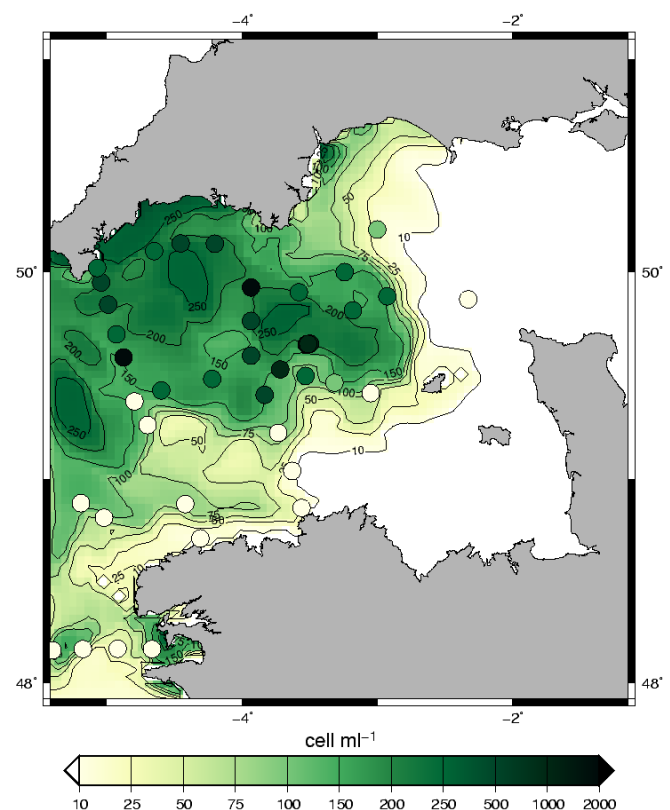


Figure 1.6. Contour plot of modelled concentration of *Karenia* cell counts, with observed values marked as dots, using the same colour scale. The spatial distribution is well simulated by the model, although the concentrations are underestimated.

Application to management

The occurrence of HABs often requires the closure of shellfisheries due to the presence of toxins and the potential danger to public health.

HABs are primarily a result of the appropriate oceanographic conditions which promote their growth, for example; the limited nutritional needs of *Dinophysis spp.* are fully met by background oceanic supply, and turbulence is the primary control upon the duration of large blooms of *Karenia mikimotoi*.

While it has been suggested that ratios of nitrate:phosphate can affect toxicity, such as causing large-blooms of *Chrysochromulina* in the North Sea (Dahl et al., 2005), the nutrient ratio does not appear to affect the growth of these species in the waters of the western channel (Gentien et al., 1998). Controls on nutrient inputs already exist in the SW UK to manage local issues, but our results indicate that controlling the anthropogenic nutrient sources or the balance of nutrients beyond this is unlikely to affect the occurrence of such blooms in the region.. A growing body of international evidence, including work from GeoHab (Global Ecology and Oceanography of Harmful Algal Blooms), indicates that HABs occur in a wide range of aquatic habitats, including those with very low and very high concentrations of nutrients. Thus, these types of HABs themselves should not be used as indicator of water quality.

2. Oceanographic pathways in the North Sea

Main policy implications

As noted above, the forthcoming UK Marine Bill is proposing to adopt an ecosystem approach which will include the tool of marine spatial planning. Use of such a tool necessarily requires a strong evidence-based understanding of the dynamics of the oceanographic flows on the UK shelf.

One clear example is that of the fate of nutrients transported through UK waters, including trans-boundary issues in the N. Sea (see also sections 1, 4 & 5). In summer, there is rapid cycling of dissolved nutrients, so that there is no clear link between those dissolved nutrients introduced into the sea off the Tees and the productivity of waters in the central and southern N. Sea. At present nutrient concentrations, hypoxia in the bottom waters of the Oyster Grounds is primarily the result of the duration of stratification, rather than human-induced organic enrichment. The issue is complicated further because nutrients are also transported in particulate form, the understanding of which is, at present, insufficient to quantify the contribution of UK-derived nutrients to such hypoxia and to assess the significance.

Modelling work indicates that, in the future, the duration of stratification is likely to be extended (section 5) so that an additional winter input of nutrients may risk exacerbating such hypoxia. Quantification of this is the subject of ongoing Defra-funded work (E3202) and includes consideration of the impacts of anthropogenic sources of nutrients. Resolution of these issues will require further work to resolve this complexity.

Main science findings

In the North Sea, in summer, strong (12 cm/s) organised flows exist from the NE English coast (i.e. North of the Flamborough front), past the northern edge of the Dogger Bank and NE to the Skaggeak. There are also strong flows (10 cm/s) directed SW along the southern flank of the Dogger Bank. This flow continues anticlockwise around the edge of the stratified region at the south of the Oyster Grounds, and, in summer, acts to contribute to isolation of the bottom waters there. This isolation, coupled with the relatively shallow depth (and associated productivity), means that oxygen depletion is likely in the bottom waters.

In the stratified North Sea, the cycling of nitrates and ammonia by phytoplankton in summer is very rapid, at ~1 day in the chlorophyll maximum and ~7 days in the surface layer (Weston *et al.*, 2005), so that although the summer transport pathways are strong, direct transport of dissolved nutrients from the NE English coast to the central and southern N. Sea is unlikely. In the stratified region the most likely transport mechanism of nutrients is in particulate form, and while a number of mechanisms can contribute to such transport, these are weak (because the tides are relatively weak) and occur over long timescales. There is a strong contrast with well-mixed regions, where the cycling of nitrates is much slower (Weston et al., 2004) so that significant transport of dissolved nutrients can occur.

Background

A narrow (~10 km) and shallow (<30 m) coastal sub-tidal platform extends ~300 km along the coast between Flamborough Head and the Firth of Forth. To the east, the sea-bed shelves smoothly to greater than 70 m, reaching a maximum of over 110 m in the Farn Deep. Inshore, peak tidal velocities are ~0.6 m/s, falling to typically 0.3 m/s in the deeper region and near Dogger Bank (Gmitrowicz and Brown, 1993). Offshore, the combination of deep water and weaker tidal currents means that the water column stratifies during the spring and summer. Stratification

begins in April-May, isolating a pool of cold, dense, winter water below the thermocline. Density-driven oceanographic flows are created (similar to those presented in Section 1), including the formation of bottom fronts and jets along the 50 m contour from the Firth of Forth to Flamborough Head, where the flow passes offshore toward the Dogger Bank.

Past descriptions of the mean residual circulation in the central North Sea indicate a broad and weak (<4 cm/s) anticlockwise flow that passes down the east coast of the UK before extending eastward from the coastline of East Anglia (e.g. Lee and Ramster, 1981; Davies, 1983; Backhaus and Reimer, 1983; Prandle, 1984; Durance, 1989). More recently, Defra-funded work (contract AE1214) has identified strong jet-like flows specifically related to stratification north of the Dogger Bank, mostly along the 50 m isobath (Brown et al., 1999, AE1214).

Observations

Field programs have concentrated on flows in three areas: the Oyster Grounds (Fig. 2.1), the German Bight and between the top of the Dogger Bank and the Skagerrak (Fig. 2.2). For the latter area, drifters flowed along this pathway at an average of 12 cm/s, indicating that conservative tracers (e.g. PAHs and heavy metals such as cadmium and chromium) could be advected from the NE English coast into Danish and Norwegian waters (at ~3° E) in 33 days, and, thereafter, to the tip of Jutland in a further ~60 days. Incidences of DSP and PSP occur along this pathway (Fig. 1.2). PSP is caused by *Alexandrium tamaranse* and has a cyst stage that can be advected by the currents discussed here. Details are in the Final Report of contract AE1214 (<http://www.defra.gov.uk/AE1214>) and in Brown et al. (2001).

One important issue that remained from previous work (e.g. AE1214) was the continuity of the flow around the 'tail end' (NE end) of the Dogger Bank in the trans-boundary region between UK, Dutch, Danish and German waters. Few easterly-moving drifters turned to the south around the tail end (only 1 of 10) while most drifters (4 of 5) deployed on the southern flank of the Dogger Bank travelled to the SW (Fig. 2.3). Other drifters, deployed at the southern edge of the Oyster Grounds, exhibited transport to the NE. Correlation of drifter trajectories with the wind (Chambers et al., 2004) showed that the drifters were only partly wind-forced, which, because the tidal residual is weak in the region (Van Aken et al., 1987) indicates that the flow is probably baroclinically driven (i.e. driven by density).

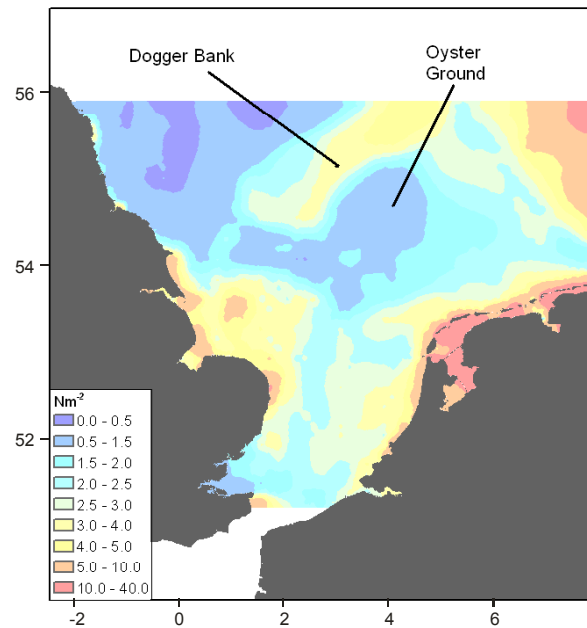


Figure 2.1. Peak modelled combined wave-current bed stress (N/m^2) in the southern N. Sea (Final Report, contract AE1224).

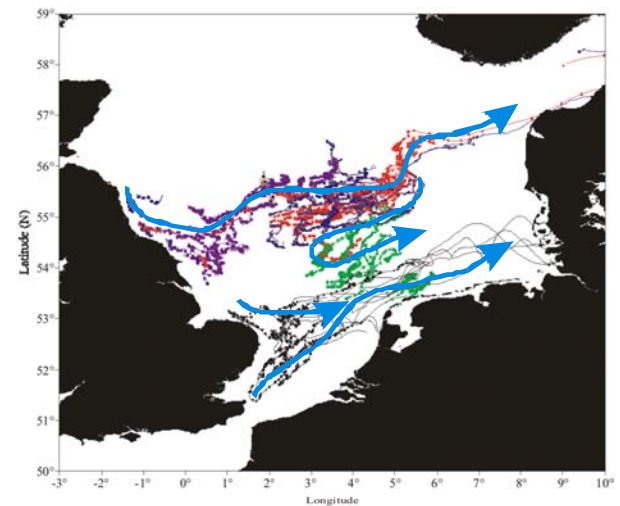


Figure 2.2. Drifter tracks (including summer and winter datasets) in the central and southern N. Sea.

Further east, the flow structure in the German Bight is heavily influenced by salinity. Central Europe experienced an extremely wet month in June 2002, with a number of major rivers in full flood. Measurements indicate that salinity dominated the density field at up to 50 km from the Danish coast (Cefas cruise Corystes 8/02; see Fig. 3.2). Frontal structure in this region is defined as much by salinity as by thermal mixing. Inclusion of freshwater inputs is a challenging but appropriate task for oceanographic models, partly because freshwater input often contains high nutrient concentrations.

The fate of nutrients – uptake of nitrogen and ammonia

This project has demonstrated that the uptake rates of nutrients are very different between stratified areas and well-mixed areas (Weston et al., 2004; Weston et al., 2005; see also Final Report for A1221). In the well-mixed southern North Sea, which is dominated by diatoms, turnover times¹ are highly variable for nitrates, but show a clear seasonal cycle with long turnover times in winter (>1000 days) and shorter times in Spring (~70 days). Only in August is the turnover time short (~13 days; Table 2.1), when median uptake rates of nitrate are 0.12 mmol N m³/day. The impacts of additional nutrients into these water bodies can be gauged by considering the duration required to uptake 5 mmol/m³ of NO₃, assuming that those rates measured *in situ* are applicable.

Table 2.1. Nitrate 'turnover times' (days) for *in situ* concentrations and for a standard concentration of NO₃ of 5 mmol/m³, for the southern N. Sea (well mixed) and north of the Dogger Bank (stratified) (adapted from Weston et al., 2004).

	Feb	Mar	May	July	August	Sep
Well-mixed waters - <i>In situ</i> concentrations	> 1000	794 ± 394	72 ± 60	65 ± 72	13 ± 17	30 ± 26
NO ₃ at 5 mmol/m ³						
Well-mixed waters					75 ± 54	
Stratified waters - Surface					7 ± 14	
Stratified waters - Chlorophyll max.					< 1	

In the stratified regions, uptake rates are very rapid, much greater than in well-mixed regions, and there is vertical variation. In August, median rates of uptake in the chlorophyll maximum zone were 4.8 mmol N m³/day while, at the surface, the uptake rate was 0.72 mmol/m³/day. Thus, nutrients that are introduced into the chlorophyll maximum in August are rapidly utilised (<1 day), recycled and incorporated into organic matter, with subsequent generation of organic detritus. Those nutrients that are placed into the surface will be transported further but are likely to be recycled in 7-10 days. The cycling of nutrients in the late spring - early summer remains unclear, although results of uptake experiments undertaken in April 2005 indicate that productivity is high (Fig 4.2) and uptake of nutrients is

probably rapid, however, it was a limited set of observations.

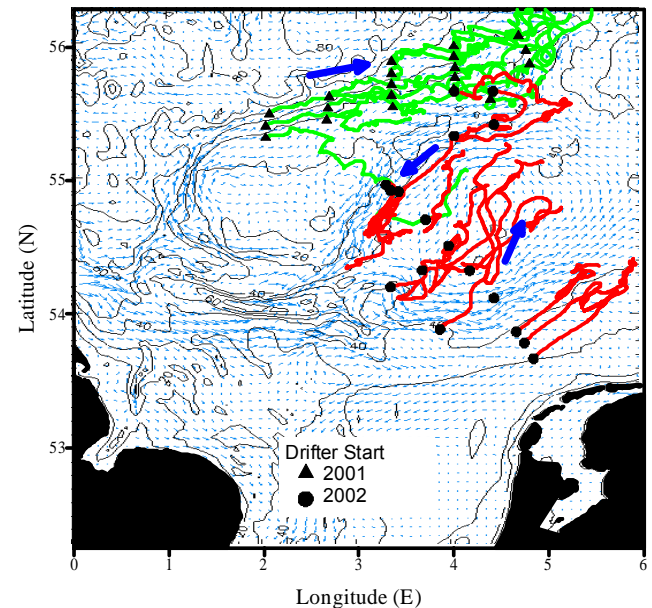


Figure 2.3. Depth-integrated density-driven residual flow (array of small blue arrows) for July 2002, with drifter tracks (~30 days duration) from 2001 and 2002. Large blue arrows indicate general flow directions.

Oyster Grounds

The summer of 2003 saw high air temperatures in the UK and over central Europe, and a long period of summer stratification in some UK waters. Results from an autumn cruise in the Oyster Grounds demonstrated that the region was stratified until as late as 1st October (Fig. 4.3), with very low oxygen concentrations (2.07 mg/ml) in basal waters. These are the lowest levels ever recorded in the region and, if widespread, are potentially dangerous to fish. The cause of this hypoxia is the decay of organic matter, which can either be due to local productivity or through influx of organic matter near the bed.

Productivity in the water-column

During spring, a surface bloom occurs. Following this bloom, until autumn, productivity occurs along the thermocline (see section 4). Even in October, nutrients are still present in the bottom waters (Fig. 2.4) to support this productivity. Whilst summer stratification occurs, both living and decaying organic matter tends to sink to the bottom waters, where it is consumed. Because these bottom waters are isolated, horizontally by bottom fronts and vertically by the thermocline, an oxygen deficit results. This deficit increases during the summer, persisting until the breakdown of stratification in the autumn. In those years when nutrients remain in the bottom waters, the

¹ The 'turnover time' is the time taken to use up the available source of nitrogen.

breakdown of stratification may lead to an autumn bloom. Thus, at present nutrient concentrations, the occurrence of hypoxia in bottom waters is primarily the result of the duration of stratification. However, modelling indicates that, in the future, the duration of stratification is likely to be extended (section 5) so that additional nutrients are likely to exacerbate such hypoxia. Quantification of this is the subject of ongoing Defra-funded work (E3202) and includes consideration of the impacts of anthropogenic sources of nutrients

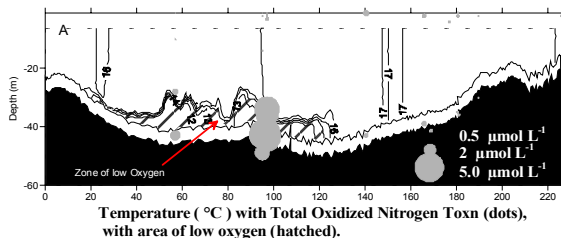


Figure 2.4. NW-SE section through the Oyster Grounds basin (1st October, 2003) showing the thermal stratification and the zone beneath the thermocline of low oxygen concentrations and high concentrations of total oxidised nitrogen (TOXN). Contour lines are temperature (°C), grey circles are TOXN (μmol/l).

Influx of organic matter - the role of sediment transport

The Oyster Ground is located at a local minimum of combined wave-tide bed stress (Fig. 2.1) and is generally understood to be a region of temporary accumulation of sedimentary material, with accumulation and reworking occurring respectively during periods of low and high wave activity. Such material includes organic detritus (e.g. plankton) and minerogenic sediments. Theoretical work has been developed to investigate sediment transport here and at similar sites (e.g. Farne Deep, Hurd Deep, Western Irish Sea), and a general expression has been derived for the net tidal flux of suspended material, including a wind-driven 'stirring' factor (Aldridge, submitted). The results allow the importance of each sediment transport mechanism to be quantified as a function of particle size. For easily transported fine particles, such as organic matter, sediment transport is dominated by the interaction of the tidal currents, the residual flow and the surface elevation, while for heavier particles, the asymmetry of peak tidal currents plays a dominant role. These results are consistent with previous work (e.g. Dronkers, 1986). This proposed mechanism indicates that it is possible for fine material to be advected into the Oyster Grounds region, and be retained there. The relative contribution of this mechanism compared to direct transport and settling from productivity in the water column requires clarification.

Further work

Further work is required to quantify the relative magnitudes of *in situ* versus transported productivity, including modelling which couples the transport pathway to that of productivity, with a particular emphasis on stratified regions. There is a need for new observations of transport of particulate organic material and for the development of a robust model of suspended particulate material (SPM). Such a model could then be linked to a the coupled of GETM (General Estuarine Transport Model) to ERSEM (European Regional Seas Ecosystem Model) as is envisaged in the Defra-funded Ecosystem Connections project (ME3205).

3. Applying improved hydrodynamic models

Main policy implications

Where they incorporate the correct mechanisms, physical oceanographic models allow us to predict a range of key oceanographic conditions in the UK's shelf-seas. Such physical models are increasingly linked to ecological models, leading to improved understanding of ecosystem structure and function, and better prediction of the response of the ecosystem to natural and anthropogenic forcing. The presence of robust models, only achieved by validation with high resolution observations, allows Cefas to advise DEFRA appropriately on a variety of marine issues, especially those which require underpinning by an accurate physical understanding and simulation.

A key finding of this project is the identification that correct simulation of gradients across the thermocline is vital to robust modelling of plankton dynamics. Such gradients have been well-replicated by Cefas' application of the GETM model, whereas most shelf-wide operational models provide relatively poor vertical resolution. The productivity and dynamics of plankton are fundamental to marine life around the UK.

Modelled predictions of nutrient transport may soon become acceptable tools for management (e.g. OSPAR assessments), including being used to distinguish between natural and anthropogenic effects, although the simulation of salinity requires further work. Flow fields on the UK shelf are a result of wind-driven flow, tidal residual and density-driven flow, and it is only the latest generation of 3-D baroclinic models, such as

Cefas GETM, which simulate all three mechanisms well (Fig. 3.1).

Supporting the technical development and use of such models for management is thus essential, and, for Defra to receive robust advice based on oceanographic and ecosystem models, it is also important to retain the close links between field observation, modelling, validation and application.

Main science findings

Across most of Europe, a consensus has been achieved on the significant physical factors controlling flow patterns and the physical structure of the N. Sea. Most European institutions now use baroclinic 3-D models and comparison and validation datasets are now shared between some institutions.

The latest generation of 3-D baroclinic models (e.g. GETM, which includes the GOTM turbulence scheme) are able to replicate horizontal gradients of temperature well and are generally better than the older baroclinic models (e.g. POM) at representing vertical gradients.

Most modern 3-D baroclinic models (see list at base of section) replicate measured surface and bottom temperatures typically to better than 0.5°C (1 SD) which is sufficiently accurate for the simulation of many ecological processes. Even so, while models can simulate effectively spatial patterns of salinity, absolute values are typically only accurate to ± 1 , and consequently, flows associated with salinity gradients are also poorly simulated. This is particularly important because the distribution of salinity is a primary indication of freshwater input, and therefore a measure of land-based nutrient supply.

In this project, the use of real riverine inputs, rather than seasonal averages of a suite of catchments, significantly improved the replication of the salinity structure both in the North and Celtic Seas. The higher accuracy associated with these latest models provides some confidence that models can be used to fill gaps in temporal and spatial observations for key parameters, such as temperature.

Background

Historically, most published and established oceanographic modelling performed by Cefas has used POM, because it was available for use on standard computers and had a long and proven pedigree. It has proved suitable for a wide range of applications, such as particle-tracking (Young

et al., 2004, Fig. 3.1) and climate change work (section 5). However, it has now become necessary to perform work with an ecosystem approach, integrating physical and ecological models, and such integration requires high levels of computing power, which has recently become available using parallel processors. New models have been written to take advantage of parallel processing, of which GETM is the most applicable in our context. This report thus includes results from both Cefas POM and GETM models, the latter being subject to an international process of development and evaluation (e.g. OSPAR workshop on eutrophication modelling, University of Hamburg, September 2005).

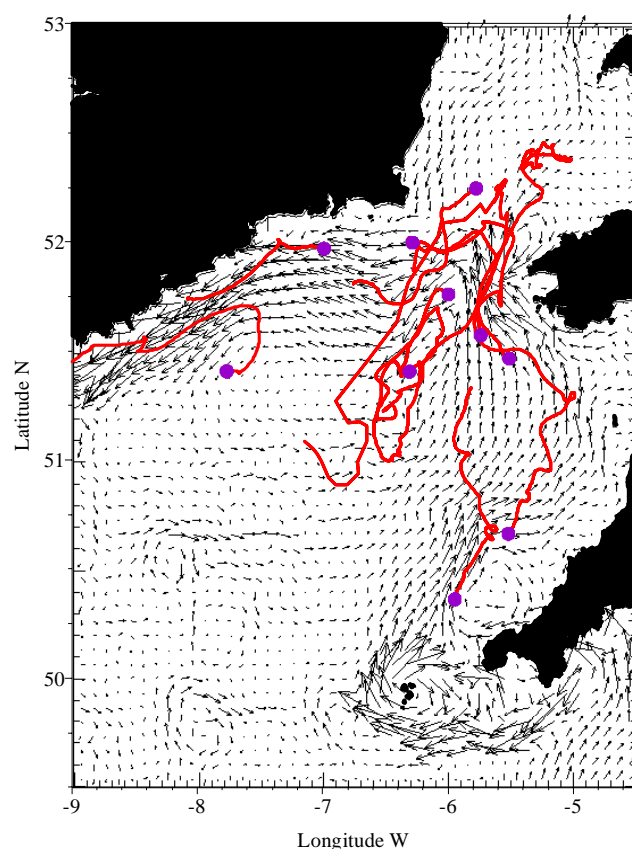


Figure 3.1. Modelled depth-integrated flow field for the Celtic Sea in July 1998, with drifter tracks (red, each of ~40 days duration). Note that the model replicates well the observed flow from the Cornish coast north to the Gower Peninsula, west across St Georges Channel towards the SE coast of Ireland.

Validation

Validation is the process by which we determine how well model results fit field observations, thus indicating model quality, confidence in the results and model applicability. Below, we discuss the main elements which need to be included in models, and comment on the performance of the POM model (modified by Cefas as part of A1225)

and of the GETM model, in describing various oceanographic parameters in the Celtic Sea and N. Sea respectively.

Tides

In the UK's shelf seas, mixing by tides is a major control on the extent of the stratified regions, so it is vital that models first be validated for tidal flows. The Cefas POM model has been assessed by comparing observed and predicted elevations and velocities for the two main tidal constituents (M_2 and S_2) in the North Sea (Young, 2002a, b.). Predicted co-tidal charts of the region are in good agreement with published charts based on observed tidal elevations. Mean errors in predicted elevation amplitudes and phases are respectively 8.92 cm and 5.32° for the M_2 tide, and 2.43 cm and 8.26° for the S_2 tide. This is good and is comparable with other flow models (e.g. POL3DB) and sufficient for most applications, except for the forecasting of storm-surge.

Temperature

Most models replicate surface and bottom temperatures well, usually to ± 0.5 degrees. For a site in the western Irish Sea, the Cefas POM model predicted well the seasonal cycle of thermal stratification (Young et al., 2003). Mean and root-mean-square (RMS) errors in temperatures were respectively 0.25°C and 0.72°C for near-surface, and 0.05°C and 0.44°C for near-bed. These model results are good and within expected inter-annual variability.

Salinity

Analysis shows that the use of real riverine inputs of freshwater (rather than seasonal averages) significantly improves model accuracy. Many models, such as POLCOMS, GETM and COHERENS, indicate that freshwater inputs are under-estimated and that diffuse riverine inputs or groundwater discharges are larger than previously realised, or that model advection is incorrectly represented. This is true for the entire southern N. Sea, and is evident, for example, in the German Bight, where although the horizontal structure is well replicated, the modelled absolute values of salinity are too high (Fig. 3.2c, d).

Flow

Regarding transport, the flow pattern is the most important element. The POM model uses real wind data at 3-hr intervals and generates flow regimes that are the combination of tidal residual, wind-driven flow, baroclinic flow and topographic steering effects. The model reproduces well the drifter trajectories south of the Dogger Bank, in a

region where both wind-driven and baroclinic flows occur (Chambers et al., 2003). In the Celtic Sea, the model (Fig. 3.1) reproduces well drifter tracks, and significantly so in St Georges Channel where the baroclinic component of flow contributed 91% to the net westward flow (Young et al., 2003).

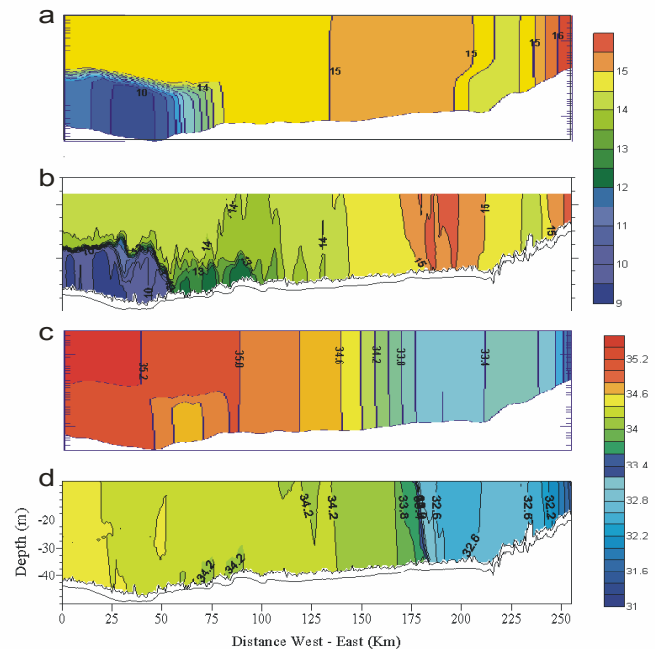


Figure 3.2. Oceanographic structure along line $54^\circ 33' \text{N}$: a) GETM modelled temperature, b) observed temperature; c) GETM modelled salinity, d) observed salinity. Note good simulation of the strong vertical temperature gradients in the stratified region (left of sections a & b) and good replication of salinity structure (c & d) but not absolute salinity (see text for details).

Gradients

Model results can be compared best with vertical gradients and horizontal gradients of temperature and salinity measured by towed undulators (e.g. 'Scanfish'). Features in the Celtic Sea are well replicated by Cefas POM, such as the height above the bed of the thermocline. Elements of the North Sea have proved more challenging, because here measurements indicate the presence of double thermoclines. Such structures are difficult to replicate in models, because of complexities in quantifying mixing by wind.

Key results

A number of oceanographic features relevant to ecosystem processes are replicated well, such as thermocline depth and light regime, which in part determine phytoplankton productivity. The GETM model is good at replicating bottom and surface temperatures (Fig. 3.2a, b) and particularly at predicting the locations of the bottom fronts and

nature of the gradients, which is especially important regarding the use of the model as a diagnostic and predictive tool. The height of the thermocline above the bed is well replicated, indicating that the tidal flows and sea bed roughness are probably both modelled correctly. The new ability to replicate the thermocline well (Fig. 3.2) significantly enhances our future ability to model primary productivity and other trophic levels, and begin to distinguish the effects of likely change in nutrient or climatic pressures.

Examples of applying models

In situ observational programs are expensive and have severe temporal and spatial limitations. Well-validated models can be used to bridge gaps in observations both spatially and temporally and are a highly cost-effective addition to observational programs. One key example is that of the Rhine plume, for which observations, based on the distribution of salinity (e.g. Baars, 2001) indicated that the plume remained close to the coast at all times (Fig. 3.3a). However, simulation of the plume (Fig. 3.3b) through the seasons reveals the likelihood that the plume becomes detached from the coast for short periods (~4 days). There are clear consequences regarding quantifying the relative proportion of riverine nutrients that seasonally reach the southern N. Sea from continental and UK rivers.

The combined use of observations and models has allowed us to demonstrate, for example, that nutrients are not the key parameter controlling the occurrence of blooms of *Karenia Mikimotoi* in the western Channel. Other examples of contributions to increasing our understanding of marine environmental issues are given elsewhere in this report (e.g. section 5).

Our models also support eutrophication work (Mills et al., 2005) as do other models around the UK (Heath et al., 2002). OSPAR is currently evaluating the use of models to directly support the application of the Comprehensive Procedure and is using models to test nutrient-reduction scenarios and trans-boundary nutrient transport. The latter is an issue of particular importance because German and Dutch contracting parties have classified part of their maritime regions as Problem Areas and cited the UK as responsible for contributing to their supposed eutrophic state. Initial results using six different models showed that changes to the eutrophic status of coastal waters were generally insensitive to nutrient reductions.

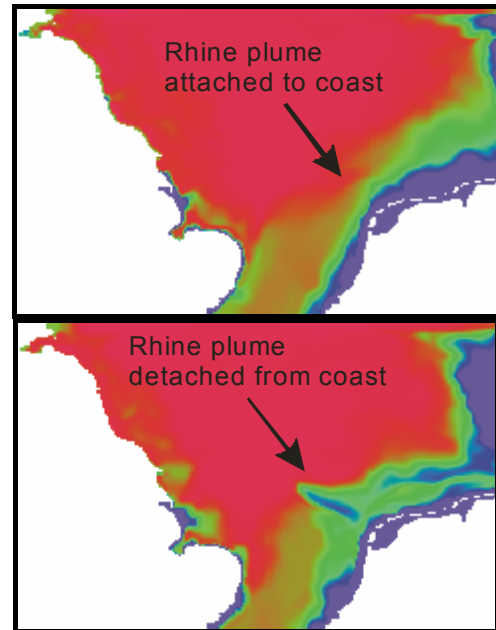


Figure 3.3. GETM model of surface salinity distribution in the southern N. Sea for; a) the general case, and; b) 22 April 2002, highlighting the potential importance of episodic events.

While satellite data provides very good indications of sea-surface temperatures, models are able to provide sub-surface and near-bed values which are required for effective use in ecosystem studies, such as in providing a basis of a tagged database for understanding cod behaviour (Righton, 2005).

List of relevant models

There are 6 main 3-D baroclinic models of the North Sea available at present, each of which has various derivatives under development:

- BSH - Bundesamt für Seeschifffahrt und Hydrographie, Germany;
- NORWECOM - Norwegian Ecological Model system, developed by Institute of Marine Research (IMR), Norway;
- GETM - General Estuarine Transport Model;
- POL3DB - Proudman Oceanographic Laboratory 3-D Model, Liverpool;
- HAMSOM - The Hamburg Shelf Ocean Model, IFM Hamburg, Germany;
- COHERENS - Coupled Hydrodynamic Ecological Model for Regional Shelf Seas, MUMM, Belgium.

4. Structure of the North Sea - why is there high primary productivity?

Main policy implications

The oceanographic structure of the N. Sea determines the nature of primary productivity, which needs to be maintained to support marine life. Stratified areas have high levels of continual summer productivity and a different ecosystem function than well-mixed areas. This means that there are significant differences in productivity between stratified and well-mixed areas, and thus differences in key aspects such as plankton species composition, the distribution of fish stocks and the response to nutrient inputs. The presence of such major differences requires the establishment of appropriate standards and tools at national and international levels for water bodies of such different structure and function.

While winter nutrient input from the land does contribute to the over-winter nutrient pool, the greatest contributor and variable is the oceanic input (Jickells, 2005). It is therefore oceanic, rather than land-based inputs of nutrients that primarily support the high levels of primary productivity observed along the base of the thermocline in the offshore regions of thermally stratified regions of the North Sea, and so changes to controls on land-based nutrient runoff are unlikely to significantly influence primary productivity in these regions (see also section 2).

There are implications for commercial fisheries management of the availability of food (primary productivity) and of habitat, and some have been investigated by work associated with this project. The commercially important species Norway Lobster (*Nephrops norvegicus*) is strongly associated with muddy substrates in stratified areas (e.g. western Irish Sea, Farn Deep, Fladen Grounds) and with oceanographic circulation patterns which tend to retain larvae over such substrates (Hill et al., 1996). In summer, cod are located preferentially in colder waters associated with stratified areas (Righton et al., 2005). Conversely, the edible crab (*Cancer pagarus*) tends to reside in well-mixed areas of the N. Sea and their migration and reproductive habits act to ensure that they and their larvae remain in such waters (Eaton et al., 2003).

At present, estimates of primary productivity in stratified regions derived from satellite imagery are inevitably significant underestimates. It is likely that satellite imagery can be combined in

some manner with targeted monitoring and the present understanding of oceanographic structure and seasonal change to form a useful input to assessments of ecosystem status, but work will be required to achieve this.

Main science findings

New estimates of primary productivity indicate that 38% of all new productivity in the North Sea occurs along the thermocline during the summer months. The primary nutrient source for this productivity is the bottom water on the UK shelf, which is largely remnant from the winter months. High levels of productivity occur at the thermocline because of the particular interaction between tides, light regime, nutrient pool and bathymetry. The productivity associated with the summer thermocline is sustained for a much longer period than that of the spring bloom and potentially supplies a more reliable source of fixed carbon and energy for higher trophic levels. The increased biomass of chlorophyll resulting from this productivity is not visible from satellite observations.

Background

The North Sea has long been recognised as a highly productive region. There are two distinct regions in the North Sea: a) southern waters and coastal waters that are shallow and strongly tidally stirred and b) northern stratified waters, less strongly influenced by tidal mixing. These regions are separated by a tidal mixing front located off Flamborough Head. In the shallow and strongly stirred regions, the typical seasonal cycle of phytoplankton is characterised by a late spring bloom with possible further blooms in the summer, depending upon nutrient supply.

Historically, stratified regions have been regarded as having a cycle of phytoplankton growth in spring and autumn, with winter and summer minima, but this view is inconsistent with the presence of major fisheries in the N. Sea. Despite occupying only 0.1% of the world's oceans, the North Sea produces 4% of the world's fish stocks (Sundermann et al., 1971). The explanation is the continual high rates of productivity (and food availability) along the base of the thermocline. While fisheries' productivity is now reduced, high primary productivity remains a key feature of the N. Sea, with only major areas of oceanic upwelling (e.g. Benguela, Peru) having greater primary productivity (~1000 mg C/m²/d). Work performed under AE1225 builds upon recent advances in understanding the controlling mechanisms and locations of such primary

productivity (performed under Defra funding (<http://www.defra.gov.uk/ae1219.doc>) and under various NERC-funded projects).

Methods

As well as using the standard methods for determining the vertical structure of the oceans, estimates of primary productivity were determined using a technique of radio-isotope labelling to measure the uptake of ^{14}C Carbon (Korb et al., 2005). Full details are in Weston et al. (2005).

Results

Incubation experiments were used to analyse samples taken from the water column north of the Dogger Bank (Fig. 4.1, line b; Table 4.1). Results indicate that in August 2000, in the stratified region, ~58% of the instantaneous productivity occurs in the chlorophyll maximum zone at the base of the pycnocline at around 30 m depth, rather than near the surface.

Table 4.1. Average primary productivity, integrated over the entire water column (mg of C /m²/day) for different regions along a transect north of the Dogger Bank (Fig. 4.1, line b). SML = surface mixed layer, CM = deep chlorophyll maximum and BML = bottom mixed layer.

Area Type	Entire Water Column	SML	CM	BML
	mg of C /m ² /day	%	%	%
Stratified (N)	741	35.1	57.8	7.1
Frontal (~40 m contour)	1015	44.8	-	55.2
Bank (S)	456	38.1	-	61.9

Importantly, results indicate that productivity in summer in the chlorophyll-maximum zone represents new productivity using nitrates, while that occurring in the surface mixed layer is regenerated productivity which uses ammonia from the decaying products of previous new productivity (i.e. the decaying spring bloom).

The context of these data is the seasonal cycle and the extent of the stratified area of the North Sea. Here, stratification lasts for ~150 days and the stratified region occupies an area of $0.3 \times 10^{12} \text{ m}^2$ (Richardson and Pederson, 1998). This allows an estimate to be made that the chlorophyll maximum zone of the stratified region produces $\sim 5.7 \times 10^6 \text{ t}$ of carbon of new productivity each year, which represents about 38% of the total new productivity in the entire North Sea.

However, stratification alone cannot be solely responsible for the high levels of productivity,

because the stratified open ocean is relatively unproductive. The other necessary conditions are sufficient inputs of light and nutrients into the stable stratified zone (Fig. 4.2). North of the Dogger Bank, maximum productivity typically occurs at depths where light levels are around 5% level of surface irradiance and are within a relatively stable physical environment.

South of the Dogger Bank, in the shallow Oyster Grounds region, waters are only weakly mixed by tides and waves, which results in a thermocline at ~25 m depth (Fig. 4.1). Here, in contrast to the diatom-rich spring bloom, the productivity at depth consists mostly of dinoflagellates, which thrive in relatively stable, low-energy environments (Cullen, 1983).

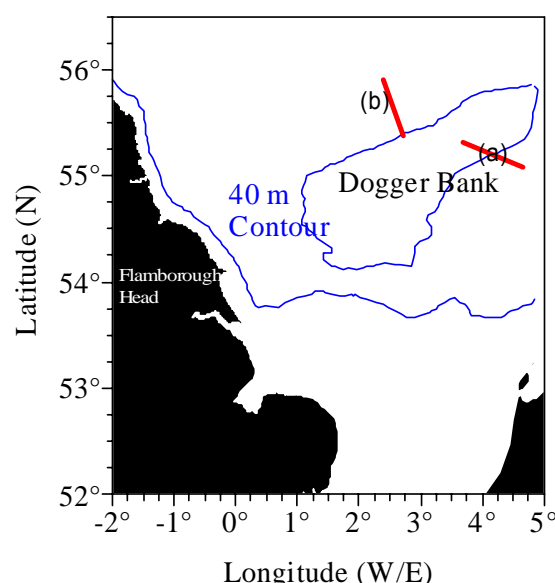


Figure 4.1. Simplified bathymetry of the central N. Sea, showing location of high-resolution sections shown in Figs. 4.2 and 4.3.

North of the Dogger Bank, despite the greater water depth, the depth of the thermocline is similar, because stronger tidal currents produce greater mixing from the bed. Double thermoclines (Fig. 4.2) are a recurrent feature in all the stratified regions around the Dogger Bank. The occurrence of the upper thermocline enhances the stability of the lower thermocline, which, as an environment of relatively low turbulence, favours the growth of dinoflagellates. However, a steady supply of nutrients is required to support the new productivity, which supply can occur by either of three physical mechanisms:

- 1) Mixing across the lower thermocline from beneath, perhaps due to internal waves (with a loss of biological material to layers below);
- 2) Mixing from areas around the bottom fronts, with nutrients moving from cold waters across

the bottom front and into the lower thermocline. This mechanism has been described previously (AE1219 Final Report) where dye-tracing work showed that the mechanism is locally significant (with vertical diffusivities of $2 \times 10^{-4} \text{ m}^2/\text{s}$, 10-100 times greater than the standard vertical flux) but is probably insignificant elsewhere;

- 3) Supply of nutrients into the lower thermocline from adjacent mixed areas of higher nutrient concentrations. Such mechanisms include variations in mixing during the monthly spring-neap cycle and the injection of nutrients through the formation of baroclinic eddies (Bo Pedersen, 1994; Richardson et al., 2000). These mechanisms are under study by PhD research being conducted at Liverpool (funded by AE1225), and preliminary results indicate that nutrients from the well-mixed edge only reach ~15 km into the stratified region within 2-3 days. These mechanisms are only likely to be important in regions with bottom fronts (Badin et al., 2005).

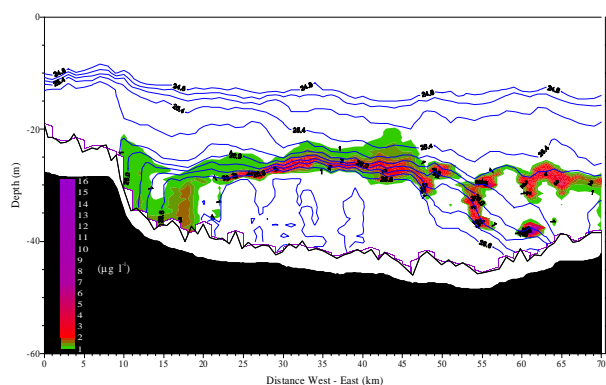


Figure 4.2. Chlorophyll ($\mu\text{g l}^{-1}$) and density ($\sigma_t \text{ kg m}^{-3}$) for a section across the Oyster Ground (Fig. 4.1, line a) in August 2003. Note the double pycnocline and high levels of productivity along the base of the lower layer.

Mechanism 1 above (direct cross-thermocline transfer) is therefore the most likely route for nutrient transfer and can operate over a large area. While highly variable, recent estimates of mixing by turbulence in a similar shelf sea indicate values of around $0.3 \times 10^{-4} \text{ m}^2/\text{s}$ (Rippeth 2005), which is ~0.1 of that near bottom fronts, but with a greater overall effect because it operates over the entire stratified area. In addition to physical mechanisms, the dinoflagellates which dominate the productivity along the thermocline are able to swim using their flagellum, and are therefore able to “dip into the fridge” below to top up their supply of nutrients (Gentien et al., 1995).

The usual understanding is that the spring surface bloom dominates annual productivity (Lalli & Parson, 1997), but recent work indicates that as early as mid April, productivity at depth can be

greater than at the surface (Fig. 4.3). Productivity experiments from one pair of stations demonstrate that the greatest productivity occurs at depths of ~40 m.

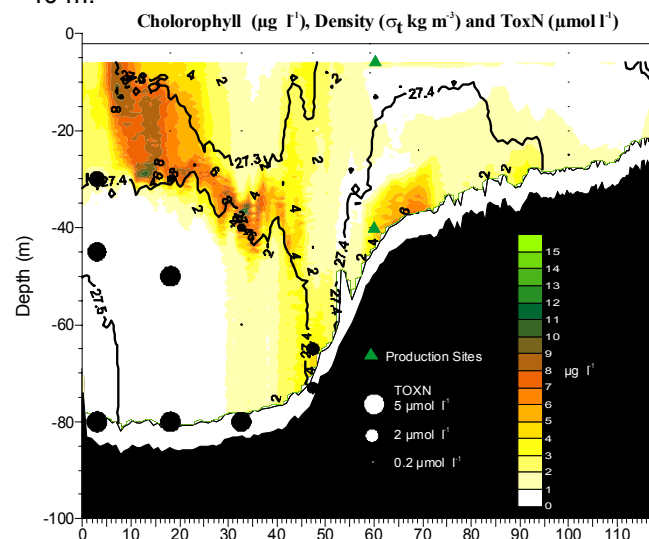


Figure 4.3. Section from North of the Dogger Bank (Fig. 4.1, line b) 28th April 2005, showing high productivity at the surface and subsurface, with high concentrations of available nutrients in the deep waters beneath the pycnocline.

Implications

This work indicates that those nutrients that drive the relatively high rates of productivity at the chlorophyll-maximum zone are derived from shelf bottom waters, which are renewed in the winter months. From an analysis of salinity and the estimates of oceanic and land-based inputs (e.g. Jickells, 2005) the nutrients in the bottom waters originate mostly from the NE Atlantic. For example, the total annual input of nitrogen to the N. Sea is $\sim 650 \times 10^9 \text{ mol/yr}$, of which ~85% is derived from offshore sources (Rendell et al., 1993). In shallow shelf areas, regeneration of nutrients derived from bed sediments may be a significant factor (Trimmer et al., 2005). This is true of areas such as the Oyster Ground, which although adjacent to areas of low salinity and high nutrient load, also have high oceanic-type salinities and associated nutrients.

Here we have described productivity associated with the stratified regions of the North Sea, much of which can't be measured by remote sensing. Significant primary productivity also occurs in coastal and well-mixed regions, which is the subject of ongoing Defra-funded research. It has been suggested that the take-up of carbon is more significant in stratified regions than in those that are well mixed (Rippeth, 2005), because phyto-detritus is more easily taken out of the system in stratified areas. Productivity in these shelf-sea regions is therefore a highly relevant contribution to the global carbon budget.

5. Potential impacts of climate change on the UK shelf seas

Main policy implications

Future climate change in the UK's shelf seas is likely to include marked changes in vertical hydrographic structure, additional to any overall surface warming trend indicated in previous studies (UKCIP02).

At present, we can be reasonably confident that, for the North Sea, seasonal stratification will probably last longer and be more intense, with the most significant oceanographic changes occurring in those geographic areas located presently between stratified and well-mixed waters. The relatively shallow regions of the southern Oyster Grounds, for example, are likely to experience an increased incidence of low oxygen concentrations. For the Celtic Seas, the area that stratifies will be increased and the dominant oceanographic pathways will be slightly strengthened. Ecological impacts will result. The *Nephrops* fishery on the western Irish Sea is likely to be adversely affected by hypoxia events, related to the increased duration of stratification. Oceanic HAB events are likely to be more common, with the likelihood of causing more fish kills and other knock-on ecological effects.

There are, however, a range of issues that are less certain, and which will require further work. The oceanographic changes described by this work may have considerable impacts upon the ecosystem and commercial activities, but these potential impacts are not well understood and further work will be required to resolve them and their significance relative to the changes driven by other pressures (anthropogenic and natural).

In addition, habitats and their biodiversity are likely to change, but the sense, magnitude and value of change remains unknown (see also section 1). Vulnerability to change is likely to increase as an organism's habitat becomes more localised (limiting the chance to adapt by moving) and as its lifecycle becomes longer (limiting the chance to adapt through evolution). There are planning and management procedures which need to consider changes on timescales longer than a few decades, such as the designation of habitats for conservation and issues of non-indigenous species. To support this, future iterations of regional climate-scenarios relevant to the UK's shelf seas should aim to increase vertical resolution and to include bio-geochemical

processes in order to address the ecosystem impacts effectively. The habitats and scale of change will not be limited by political boundaries, so that there is a requirement to act internationally.

Main science findings

Seasonal stratification is a key factor controlling the timing, location and nature of primary productivity in UK waters, and understanding is increasing of its significance to commercial fisheries and the shelf-sea ecosystems. In a few decades from now, the seasonal cycle of thermal stratification in areas of the North and Celtic Seas could last longer (up to 40 days in affected areas) and be more intense than at present (by about 1-2 °C).

The changes are likely to be greatest in those areas at the boundary between stratified and well-mixed waters, such as St Georges Channel and the southern N. Sea. In the Celtic Seas, the increased stratification is likely to lead to more frequent Harmful Algal Bloom events. In relatively shallow regions of the North Sea, such as the Oyster Grounds, and in the Western Irish Sea, there could be increased incidences of low dissolved oxygen concentrations.

Background

Climate change is an ongoing process that involves the marine environment and ecosystems. Evidence for climatic change can be seen in data from the coastal temperature network where a 30-year warming trend is associated with inter-annual variability of the same scale and with apparent shifts in state (Fig. 5.1).

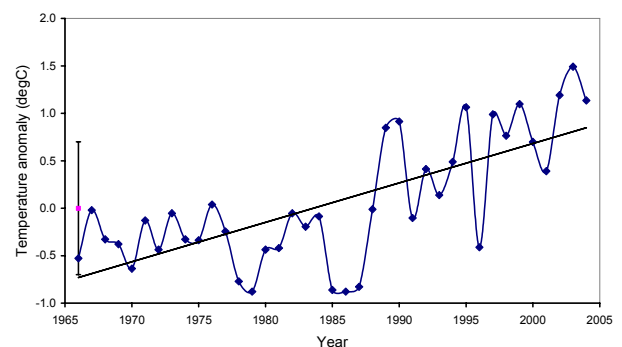


Figure 5.1. An example of changing temperature in UK coastal waters. Observations of annual mean sea temperature anomaly since 1966 at Southwold (source, UK Coastal Temperature Network). There has been a 1.5 °C rise over this 40-year period, with regular inter-annual changes of 0.5-1.5 °C. Note also the 'shifts in state' which occurred around 1988. Error bar on left-most point indicates the standard deviation of the dataset presented.

Work has been undertaken to investigate the potential impacts of climate change on the vertical structure and seasonal transport pathways of the UK's shelf seas. Four "story lines" have been identified by the IPCC (2000) which describe future conditions, on which basis global climate models are run:

- A1 – high emissions;
- A2 – medium - high emissions;
- B2 – medium emissions;
- B1 – low emissions.

Most processes in the atmosphere, ocean and on land that determine climate take place at scales smaller than those resolved in the global climate models (GCMs, 265 x 300 km). Regional models are thus required that use boundary forcing from the large GCM and apply it to high-resolution models. The Hadley Centre Regional Model 3 (HadRM3) covers the European area at a resolution of about 50 km and is used in assessments of climate scenarios for the UK (e.g. by the UK Climate Impacts Programme, UKCIP02). The model provides the meteorological forcing required to run high-resolution models of the UK's shelf seas (3D baroclinic models).

Methods

Our work used the well-validated POM model (Young et al 2004), which is a 3D baroclinic model that replicates stratification and density-driven flows at a horizontal resolution of ~3.5 km. Meteorological output parameters from HadRM3 were used to calculate the surface heat-flux in the shelf-sea model, including: air temperature, wind-speed & direction, relative humidity, solar irradiance and cloud cover.

A comparison was made between current conditions and those under a potential future climate. Two 20-year periods were run as sets of individual years, with re-initialisation on each January 1st to a well-mixed water column at the HadRM3 sea-surface temperature. Inter-annual variability within a given period is large and can mask the climatic trend, so the use of 20-year sets of runs allows the distinction between weather and climate to be made and quantified.

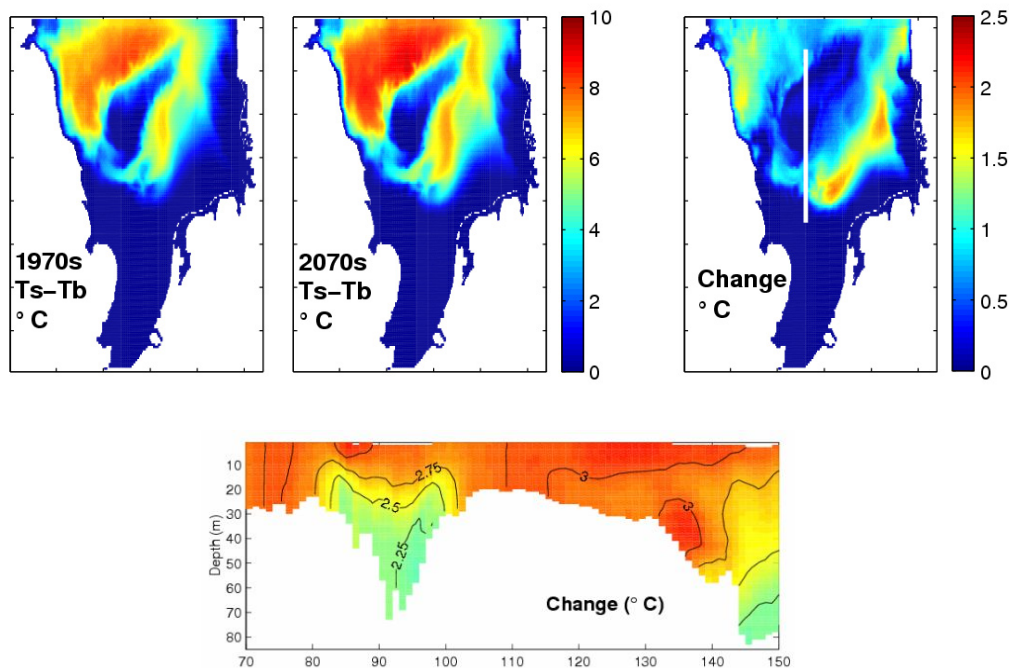


Figure 5.2. Modelled change in thermal conditions in the North Sea: a) September mean bulk-stratification (surface to bottom temperature difference T_s-T_b , °C) for a 1970-1980s (1970s) climate and 100 years further forward (2070s) under a medium high emissions scenario (SRES-A2). The third panel shows the difference between the future and present stratification, where positive values suggest enhanced future conditions. The white line shows the position of a cross-section, b) that shows the September mean temperature difference between the future and present model climates the full 'climate warming' signal is not passed to depth which leads to enhanced stratification.

The first period (1970-1989) was forced by HadRM3 meteorological conditions from a climate that is consistent with the global emissions history (representing a current climate). The second period (representing a future climate) of twenty-years (2070-2089) was forced with the medium-high emissions scenario A2a. Separation of the two periods by 100 years and the use of a medium-high scenario enables: a) investigation of the effect of significant changes in the forcing conditions on the shelf seas, b) indications of potential changes and, c) results to be consistent with UKCIP02 and thus the IPCC. Our future climate work can only represent one potential scenario rather than a 'forecast'.

The UK's future shelf seas

North Sea

Results indicate that the entire water column of the N. Sea will be warmer (by up to 3.5 °C) than at present, in line with the UKCIP02 A2a scenario. However, in areas that stratify, the bottom will warm less than the surface, enhancing stratification by as much as 2 °C (Fig. 5.2). Some areas that are presently considered transitional will stratify in summer.

Stratification inhibits mixing between surface and bottom waters, and the associated decreased turbulence may mean a shift in the plankton towards dinoflagellates rather than diatoms (as presently occurs on the north side of the Dogger Bank).

Lengthened periods of stratification will also increase the isolation of bottom water, particularly in the relatively shallow southern region of the Oyster Grounds (Fig. 5.3). By-products of productivity sink to the bottom and decay, using up oxygen. If the bottom layer of the water column is relatively thin, then an oxygen deficit can develop, as was observed in 2003 (see section 2). Furthermore, the bottom water itself will be 2-3 °C warmer than at present, reducing its ability to store oxygen by around 0.4 mg/l (about 5%) thus enhancing any oxygen deficit. Low oxygen levels are associated with fish mortality and with changes in benthic ecosystems. The stratification changes induced by climate change indicate that low oxygen concentrations might become more frequent, because of the changed 'mean thermal state' or because one or more of the factors involved becomes dominant. While these events are primarily due to natural events, anthropogenic

nutrient inputs will have an increased impact of oxygen levels in these areas.

Increases in bottom temperatures of 2-3 °C would be likely to have an impact on the survival of bottom-dwelling fish, primarily the gadoid group. Horizontal temperature gradients between well-mixed waters and deep cold pools are slightly increased, leading to an increase in the jet-like flow at the associated bottom front. Typical increases in speed are predicted to be relatively small, at ~2 cm/s, which is around 10% of the present flow speed.

The Celtic Seas

The principal area of stratification will remain the same, but stratification will occur in two areas that are presently transitional, at the mud patch in the eastern Irish Sea and in eastern Carmarthen Bay.

Perhaps more significant is the increased magnitude of thermal stratification, in the western Irish Sea the increase is by about 1 °C with greater increase evident south of St. Georges Channel of around 1.5 °C. This increase in oceanographic stability would enhance the potential for large blooms of HAB Harmful Algal species, such as *Karenia mikimotoi*. The increased duration of stratification (10-30 days) is likely to increase the total magnitude of primary productivity in the western Irish Sea, which combined with its relatively isolated character, may lead to incidences of reduced oxygen concentrations. The western Irish Sea has a significant *Nephrops norvegicus* (Dublin Bay prawns) fishery, and while adults can cope with a wide range of environmental variation (except severe oxygen depletion <2 mg/l) the effect on juveniles is marked at relatively mild levels of oxygen depletion (< 5 mg/l) (Baden et al., 1990).

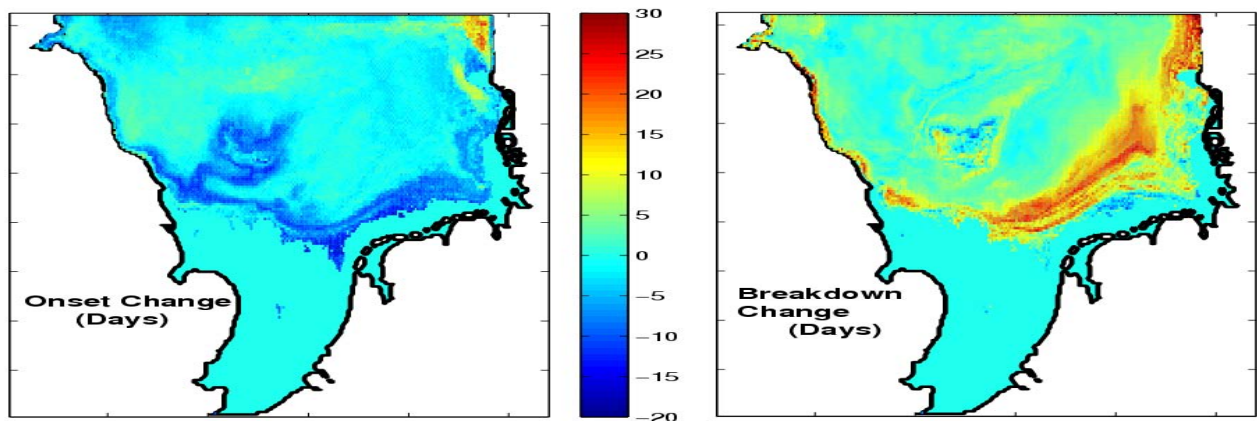


Figure 5.3. Number of days difference between future and present onset and breakdown of bulk-stratification, negative (positive) shows earlier (later) occurrence of event in the future model climate.

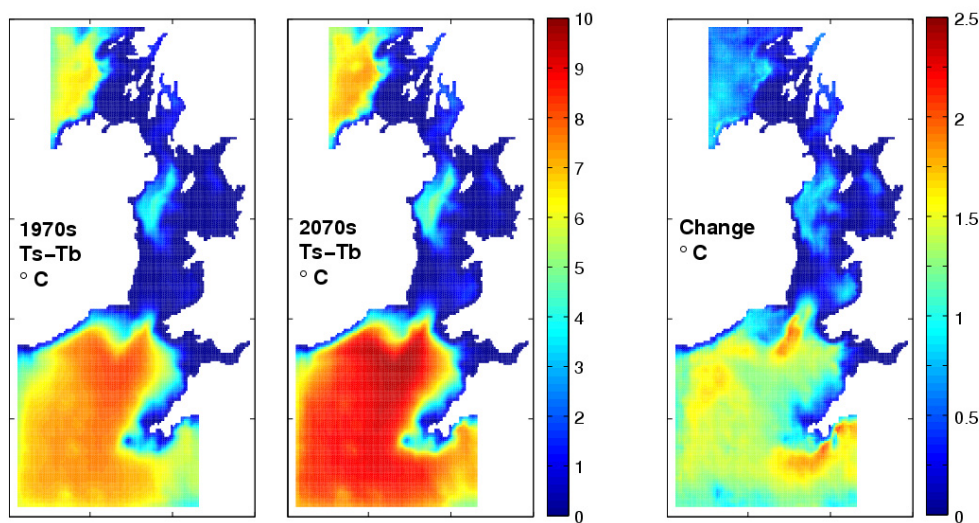


Figure 5.4. Modelled change in thermal conditions in the Irish and Celtic Seas. August mean bulk-stratification (surface to bottom temperature difference $T_s - T_b$, °C) for a 1970-1980s (1970s) climate and 100 years further forward (2070s) under a medium high emissions scenario (SRES-A2).

6. The development of scientific consensus

Developing consensus on the physical structure and flow regimes of UK shelf seas has involved broad scientific interactions using a number of methods, which includes:

- the publication of peer-reviewed scientific papers;
- presentations at scientific institutes and meetings;
- attendance at international fora, especially various ICES groups (including PGNSP, oceanography committee and MDM) and UNESCO GeoHab (see list of publications).

The work also involved the organisation of an international workshop in partnership with EUROCEANS (see below).

This project has involved a mix of extensive and highly-focussed observational field programs combined with appropriate modelling work. These strengths have formed the basis for a variety of collaborative work with various institutions, such as the Irish Marine Institute and the University of Galway on field-based research relating to the strong transport pathway described in section 1. Close collaboration has also occurred with the ecological habitats group of IFREMER (France) to develop a model of the dynamics of the HAB species *Karenia mikimotoi* for the Western Channel (see section 1). In the N. Sea, collaborative work with NIOZ (The Netherlands) and various UK universities occurred during a

cruise in the Oyster Grounds (section 2) with subsequent exchange of data with other institutes.

Models have also played a key role in contributing to the development of a consensus on oceanographic transport pathways. If different models successfully replicate field observations, then the indication is that the correct processes are being accounted for. Elements of the Celtic Sea system are being simulated using 3-D baroclinic models at a range of institutes, such as POL, IFREMER and the IML, all of whom have used data collected within the A1225 program to help validate their models. While models results vary in detail, they indicate similar spatial patterns of flow and a degree of robustness.

For the North Sea, a consensus has been achieved on the significant physical factors which control physical structure (section 4) and flow patterns. The evidence is that most European institutions now use baroclinic 3-D models (section 3) and that the nature of the fundamental oceanographic structures is now agreed (e.g. Moll & Radach, 2003). A key mechanism that has contributed to this consensus is the ICES PGNSP which has brought together a number of institutes which develop and use such models (e.g. BSH, MUMM, NCOF, IMR) to provide quarterly summaries of the state of the N. Sea. One of the ongoing tasks is to compare the different model predictions on a variety of scales. As a result of this process, the observed presence of a strong summer baroclinic flow from the NE coast of England to and across the north of the Dogger Bank has already been simulated by a number of models (e.g. Fig. 6.1, compare with Figs. 2.2 & 2.3).

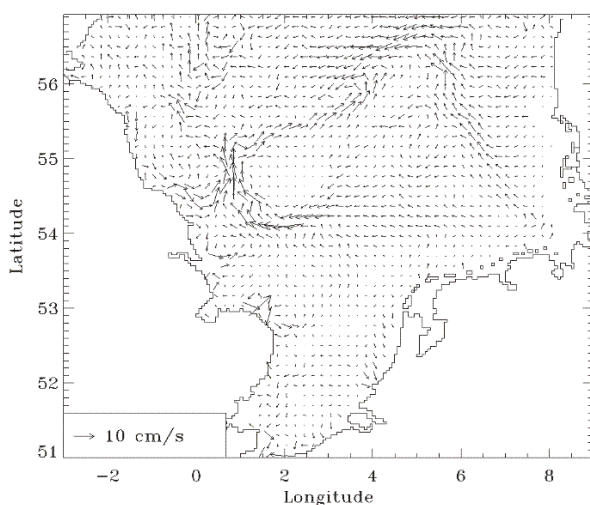


Figure 6.1. Depth-averaged residual flow in summer the N. Sea, as modelled by Coherens (MUMM website).

Shelf-Seas Workshop

A Shelf-Seas Workshop was convened as a joint activity of this project AE1225 and the Shelf-Seas Group of EUROCEANS. The workshop followed a major international conference on Ecosystem Modelling (Advances in Marine Ecosystem Modelling Research, Plymouth, UK, 27-29 June 2005). The Shelf-Seas Workshop was designed to consider the scientific foundations of ecosystem modelling, under three science themes;

- Current status of shelf-seas models;
- Modelling higher trophic levels;
- Observational data needed to challenge models.

Workshop Outcomes

The workshop produced a series of recommendations, including:

- There should be further dialogue and collaboration between observational scientists and modellers across the international community, which could be undertaken by adopting an existing observational site. EUROCEANS would be able to promote the study at this site by facilitating exchange of data;
- It was recognised that there are increasing moves towards an ecosystem approach to managing human activities. Many national marine monitoring organisations are thus considering what variables should be measured to support this approach, especially recognising the increased need for measurements of rates of various key processes, rather than of system state. EUROCEANS should take the opportunity to influence monitoring programs (such as the UK NMMP and those International Fisheries Surveys co-ordinated through ICES) by providing guidance on what additional parameters would best support ecosystem modelling and what standards would need to be adopted.

List of acronyms

BSH	Bundesamt für Seeschifffahrt und Hydrographie (Hamburg)
CEFAS	Centre for Environment, Fisheries and Aquaculture Research
EUROCEANS	European Network of Excellence for Ocean Ecosystems Analysis
GEOHAB	Global Ecology and Oceanography of Harmful Algal Blooms
ICES	International Council for Exploration of the Seas
IFM	Institut für Meereskunde der Universität Hamburg
IFREMER	Institut Français de Recherche pour l'Exploitation de la Mer
IMI	Marine Institute of Ireland
IMR	Institute of Marine Research (Norway)
NCOF	National Centre Ocean Forecasting
NMMP	National Marine Monitoring Program
MUMM	Management Unit of Mathematical Models
PGNSP	Planning Group North Sea Project
POL	Proudman Oceanographic Laboratory
UNESCO	The United Nations Educational, Scientific and Cultural Organisation
UKCIP	United Kingdom Climate Impacts Partnership