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Cordula Scherer and Richard Gowen

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EFF Project: Ecosystem Based Management of Irish Fisheries and other resources (CA/033766/11)

Work Package 4:

Determining the status of the microplankton community in the western Irish Sea

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Contents

Summary

The aim of the work presented in this report was to assess the state of the microplankton in the seasonally stratifying region of the western Irish Sea. To determine whether there was evidence of top down (fisheries) and bottom up (nutrient enrichment) induced change and whether the state of the microplankton was representative of GES for the purposes of the MSFD.

To assess the state of the microplankton the approach recommended by Gowen et al. (2013) was followed and the microplankton data were interpreted in the context of the ecohydrodynamic conditions in the western Irish Sea. The final step in the assessment that is whether the microplankton was representative of GES was based on expert judgement. Data on the physical and chemical oceanography of the western Irish Sea together with data on the microplankton have been assembled from peer review publications and unpublished data held by DARD/AFBI.

There is a recurrent annual cycle of seasonal stratification in the western Irish Sea which characterises the region as a distinct ecohydrodynamic water body. There is a low level of anthropogenic nutrient enrichment although time-series analysis shows that there is a decreasing trend in the winter concentration of dissolved inorganic phosphorus and that there is no long-term trend in winter nitrogen. The microplankton data show that there is a recurrent annual cycle of phytoplankton production. The beginning and duration of the production season is controlled by the sub-surface light climate as a function of solar radiation and surface mixed layer depth. During the production season there is a succession of species: diatoms typically dominate the spring bloom and dinoflagellates increase in abundance during the summer and early autumn. In some years there is an autumn bloom which is dominated by diatoms.

Based on the data we concluded that the microplankton community in the seasonally stratifying region of the western Irish Sea does not experience bottom up or top down pressure and in our expert opinion, we also concluded that under prevailing conditions the microplankton is in good environmental status and could be used as reference conditions for other seasonally stratifying regions in UK waters.

Rational

In 2011, the Department of Agriculture and Rural Development (DARD) awarded a European Fisheries Fund (EFF) grant to AFBI to provide advice on the implementation of an ecosystem approach to the management of Irish Sea fisheries and other resources. The study was divided into four work packages: (1) to document the science and best practice relating to the implementation of an ecosystem approach to managing marine fisheries and other ecosystem services; (2) to undertake three ecosystem surveys of the Malin Shelf sea area; (3) to investigate fisheries yield/ microplankton production relationships; (4) to determine the status of the western Irish Sea micro-plankton community.

This is a report to DARD on work package 4. The key aim was to determine the status of the microplankton community in the western Irish Sea. The method to achieve this aim was to take existing (published) and new (unpublished data held by AFBI and DARD) data gained by surveys and remote sampling at and around the mooring station 38A. It was further to apply a modelling approach to quantify any changes in Irish Sea micro-plankton over the last decades using AFBI long term mooring data. The agreed measure of success was a report to DARD (August 2013) providing an authoritative assessment of the status of the microplankton.

1. Introduction

1.1 General Background

The term phytoplankton is the name given to the microscopic floating plants that are found in freshwater and marine waters. Collectively these species are responsible for the bulk of the primary production (carbon fixed during the process of photosynthesis) in the world's ocean and this supports the pelagic food web and benthic production. Other microorganisms in the plankton include mixotrophic[1] and heterotrophic[2] species that play an important role in the cycling of organic matter in the pelagic component of marine ecosystem. Collectively, the autotrophs, mixotrophs and heterotrophs make up the microplankton.

Changes in the phytoplankton brought about through climate change (Edwards 2005) and both bottom up and top down anthropogenic pressures on the microplankton can alter energy flow and influence ecosystem structure and functioning (see Scherer and Gowen, 2013a and references cited therein: Report to DARD (CA/033766/11)). Negative feedback from such changes can in turn influence the delivery and sustainability of ecosystem services to humans, especially fisheries (Ware and Thomson 2005).

The aim of the work presented in his report was to assess the status of the microplankton in the western Irish Sea and determine whether there was evidence of top down, fisheries (and bottom up – nutrient enrichment) induced change. An additional outcome of the assessment of the status of the microplankton was to determine whether status was representative of GES for the purposes of the MSFD and whether the microplankton of the western Irish Sea could be used as reference conditions for other water bodies in UK waters with similar physical, chemical and biological (ecohydrodynamic) characteristics.

1.2 Assessing the status of the microplankton in the western Irish Sea

In October 2005, the European Marine Strategy Framework Directive (MSFD) was presented by the Commission of the European Union (EU) and came into force in 2006 (2008/56/EC). The overall aim of the MSFD is to protect and where necessary re-store

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[1]Mixotrophs are autotrophic (fix carbon by photosynthesis) but are also capable of using organic matter.

[2] Heterotrophs require organic matter as a source of energy and nutrient elements.

the European seas: ensuring sustainability for human use and providing safe, clean, and productive marine waters. The directive covers all European waters up to 200 nautical miles from the coastal baseline and there is therefore a small geographical overlap with the Water Framework Directive (WFD). It includes the water column, sea bed and its sub-surface geology and under the directive, assessments of environmental (ecological) status will be based on eleven quality descriptors (QDs) which are: biological diversity (QD 1), non-indigenous species (QD 2), population of commercial fish/shell fish (QD 3), elements of marine food webs (QD 4), eutrophication (QD 5), sea floor integrity (QD 6), alteration of hydrographical conditions (QD 7), contaminants (QD 8), contaminants in fish and seafood for human consumption (QD 9), marine litter (QD 10), introduction of energy (including underwater noise) (QD 11). All member states are expected to achieve *"good environmental status"* (GES) in the marine environment by 2020 (2008/56/EC). GES is defined as *"the environmental status of marine waters where these provide ecologically diverse and dynamic oceans and seas which are clean, healthy and productive within their intrinsic conditions"*.

To develop the necessary framework of targets and indicators for the MSFD, the UK Department of Environment and Rural Affairs (Defra) established a programme of work that included two scientific workshops. At the second workshop (Birmingham, 29-30th March 2011), a 'pelagic subgroup' discussed methods of detecting change in the plankton found in the coastal waters and seas around the UK. The subgroup recommended a 'lifeform functional group' approach (Tett et al. 2008) that developed from a Defra-funded study (led by Cefas, CSA 6754/ME2204) but identified several matters that required further consideration. To address these, Defra funded two workshops at the Agri-Food and Biosciences Institute (AFBI) in Belfast in June 2011 (Gowen et al. 2011) and in March 2013 (Gowen et al. 2013). The plankton is considered under QD1, 4, 5 and QD 6 and at the second workshop participants agreed and recommended an approach to assess the status of plankton communities in UK waters. This approach formed the basis of the assessment presented in this report.

This report is a final report to DARD for work package 4 of project CA/033766/11. As agreed with the project steering group committee members, this report will be used as the basis for assessing the state of the plankton in other coastal regions of the UK as part of a Defra funded (AFBI project code 45073) project to establish plankton targets and indicators for the MSFD. However, the assessment presented here (together with the other assessments) will be the subject of peer review in March 2014 and may therefore be updated.

2. Methods

Participants at the March 2013 workshop agreed that to simply consider the composition of the plankton at selecting sites against a notional expectation of what species should be present was an inadequate means for determining the state of the plankton. Instead, the group concluded that a much more robust approach to assessing state would be to interpret plankton data in the context of the ecohydrodynamic conditions of the water bodies within which the plankton live and to which species are adapted. However, the expert group pointed out that until there is a better understanding of what represents GES and how it can be determined objectively for the plankton, it would be necessary to use expert judgement to determine whether the state of the plankton was representative of good environmental status.

Detailed information on the methods used to collect data and samples and the analyses used for particular variables can be found in the publications cited in this report. The data that have been compiled to support the assessment are presented in the following three sections.

To assess the state of the microplankton in the western Irish Sea, in (Section 8) we asked a series of questions in an attempt to determine whether: (i) the data on the microplankton in the western Irish Sea are consistent with current understanding of the dynamics (and factors influencing those dynamics) of the microplankton in temperate shelf seas; (ii) there has been any long-term climate or anthropogenic driven change in the western Irish Sea microplankton. In accordance with the view of the expert group, we have used our expert judgement to conclude whether or not the state of the plankton in the western Irish Sea is representative of GES.

3. Physical oceanography of the Irish Sea

3.1 Introduction

The Irish Sea is a small (2534 km^3) inner shelf sea that connects to the more open shelf waters of the Celtic Sea to the south by St George's Channel and to the Malin Shelf in the north via the North Channel (Fig. 3.1). A deep trough 80-100 m extends north south through the western Irish Sea. The deepest part of the sea is in Beaufort's Dyke (~300 m) in the North Channel. To the east the water is generally less deep (< 50m) and there are extensive shallow (~20 m) coastal areas. The specific features and locations mentioned in the text are shown in Fig. 3.1.

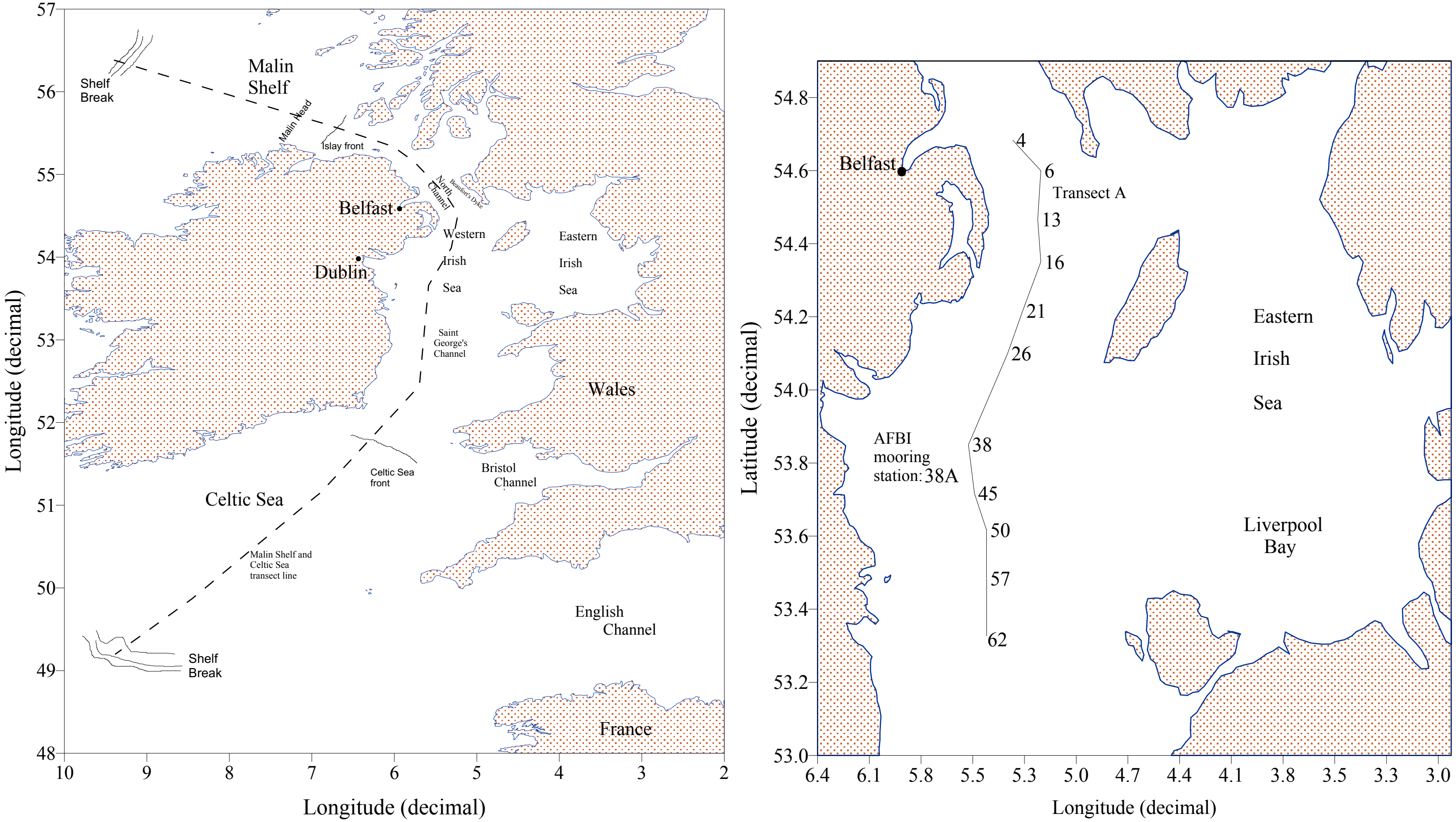


Figure 3.1: Maps of the western shelf region of the UK and Ireland (left) and of the northern Irish Sea (right) showing features mentioned in the text.

3.2 Adjacent Sea areas

The seawater of the shelf and coastal seas of North West Europe has its origin in the Atlantic Ocean. Small-scale processes modify the temperature and salinity characteristics of this oceanic water as it is transported onto the continental shelf and into shelf seas. This is particularly true of the Irish Sea and many of the physical (and chemical) characteristics of the Irish Sea reflect its relative isolation from the ocean.

Early measurements of surface temperature and salinity show that the Celtic Sea is more saline and warmer than the Irish Sea (Bassett, 1910; Matthews, 1914). For the period 1903 to 1931, Bowden (1955) gave the annual mean surface temperature in the Celtic Sea as 12° C compared to 10.5-10.75° C in the Irish Sea. Data collected recently as part of Work package 2 of this project (Scherer & Gowen, 2013) also shows this feature (Fig. 3.2) and also show that the outer Malin Shelf region is warmer than the Irish Sea in winter (data shown in Fig. 3.2) and in summer. The figure also illustrates the geographical isolation of the Irish Sea from the Atlantic Ocean.

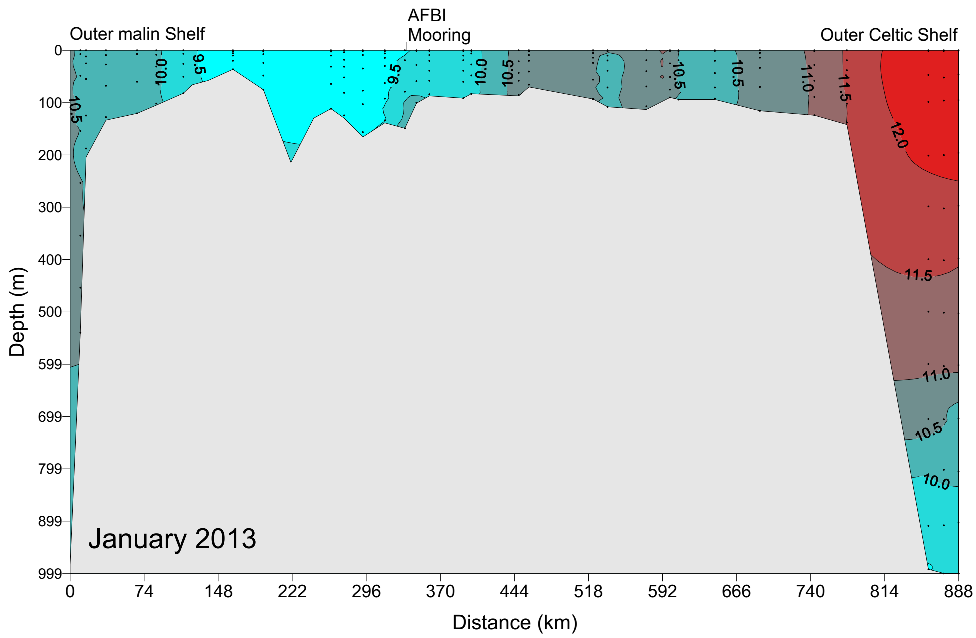


Figure 3.2: A contour plot showing the distribution of temperature from the shelf break off the Malin Shelf through the Irish Sea and Celtic Sea to near ocean waters off the Celtic Sea shelf break. (Data were collected in January 2013/AFBI unpubl. data).

The salinity of water at the shelf break region of the Celtic Sea and Malin Shelf is ~35.50 and 35.42 respectively. On occasion high salinity water can penetrate into the Irish Sea from the south (Gowen et al., 2002). However, a gradual reduction in salinity as Atlantic water is transported from the shelf break region into the Irish Sea and mixes with riverine inflow and runoff from the land is more typical. Recent measurements of salinity across the Malin Shelf (Scherer and Gowen, 2013) are consistent with earlier observations (Ellett & Edwards, 1983) in showing that oceanic water (salinity ≥ 35.00) water generally lies to the west of Malin Head Fig. 3.3).

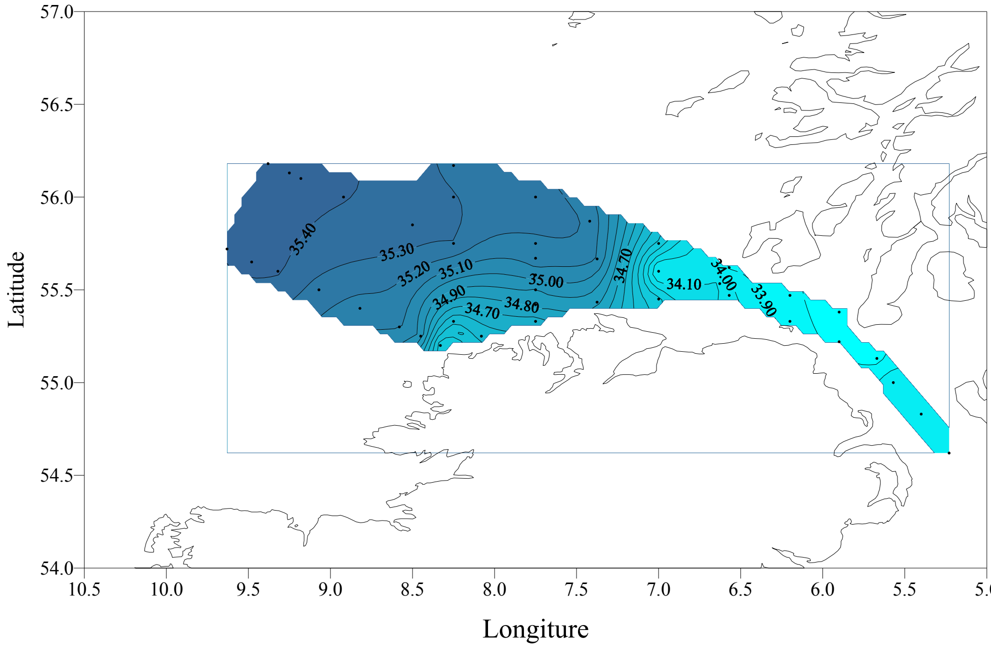


Figure 3.3: The near surface distribution of salinity on the Malin Shelf in January 2013. The filled dots show the positions of sampling station. The contour interval is 0.1 (AFBI unpubl. data).

3.3 Flow and residence time

Flow through the region is generally considered to be northwards (Bassett, 1909) with water from the Atlantic and Celtic Sea providing the source water for the Irish Sea. However, once ocean water has moved onto the shelf, flow is not regular. Early estimates of flow through the Irish Sea between Dublin and Holyhead range from 1.3 km d^{-1} (Knudsen cited in Bowden, 1950; Brown, 1991) to 0.3 km d^{-1} (Bowden, 1950).

Assuming a Dublin to Holyhead cross sectional areas of 7.2 km^2, these flows equate to a volume transport of between 2.1 and 9.2 km^3 d^{-1}. Volume transport through the North Channel has been estimated to be between 2 and 8 km^3 d^{-1} (Dickson and Boelens, 1988); 3.5 and 5.2 km^3 d^{-1} (Simpson and Rippeth, 1998); 8.6 km^3 d^{-1} (Brown and Gmitrowicz, 1995) and 6.7 km^3 d^{-1} (Knight and Howarth, 1998).

Strong winds in winter might be expected to increase exchange across the shelf break regions of the Celtic Sea and Malin Shelf. However, such winds tend to increase the flow of the slope current (which travels along the slope of the European continental shelf edge west of Ireland and Scotland) rather than increasing the movement of water onto the shelf (Pingree and Le Cann, 1989). As ocean water is transported onto the shelf it can be considered to age as it moves across the shelf into the Irish Sea. Based on changes in nutrient concentrations and ratios in ocean water as it extends onto the shelf, Hydes et al. (2004) estimated that water in the Celtic sea was 2 years old but had aged to 6 years by the time it has reached the middle of the Irish Sea. Using the same approach water in the outer region of the Malin shelf was estimated to be 400 days years old and 600 days old in the inner shelf region near Malin Head. The residence time of time of water in the Irish Sea is in the order of 12 months (Dickson and Boelens, 1988). The estimated age of the water in the central Irish Sea therefore seems overly long. However, the 6 years includes the transit time from the shelf break. Furthermore, it is apparent that the exchange of water between the Irish Sea and adjacent sea areas is influenced by wind events (Knight and Howard, 1998).

The situation in summer is rather more complex. The seasonal development of tidal mixing fronts on the Malin Shelf (Simpson et al., 1979; Gowen et al., 1998) in the Irish Sea (Simpson and Hunter, 1974) and Celtic Sea (Fasham et al., 1983) together with changes in the patterns of water circulation (Hill et al., 1994; Horsburgh et al., 1998) make it difficult to quantify the summer flow through the Irish Sea.

3.4 The seasonal cycle of temperature and salinity

Seasonal changes in water temperature in the Irish Sea are governed by the annual cycle of solar heating and cooling. An example of the seasonal cycle of near surface and bottom water temperature is shown in Fig. 3.4 (data from 2004). Minimum near surface and near bottom temperatures of 7.7° and 7.6° C were recorded on 24th March respectively. The maximum near surface temperature (16.6° C) was recorded on the 17th August but the maximum near bottom water temperature (13.7° C) was not reached until the 5th November. Data collected from the AFBI instrumented mooring in the western Irish Sea between 1996 and 2013 shows that there is some inter-annual variability in the timing and values of the maximum and minimum near surface and near bottom water temperatures but that the seasonal changes are a recurrent annual feature (Fig. 3.5).

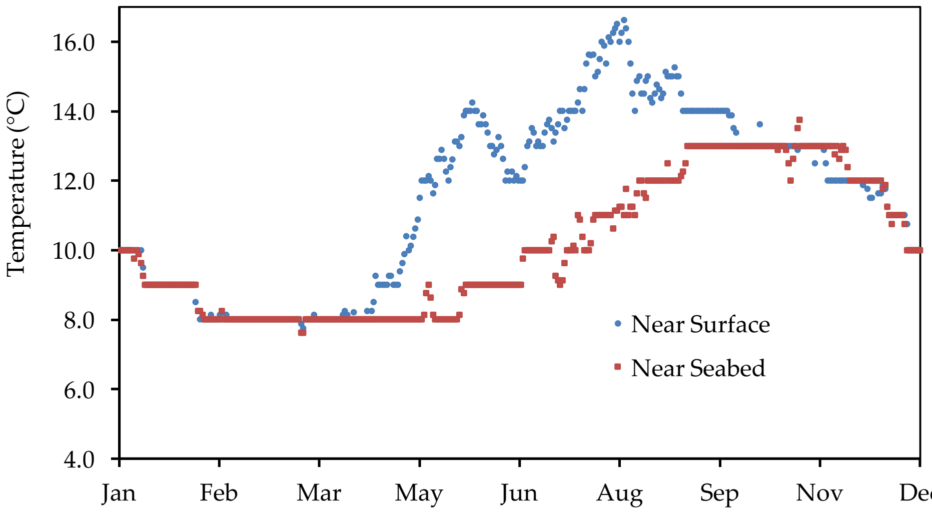


Figure 3.4: The seasonal changes in near surface and near seabed temperature (°C) at the AFBI mooring site in the western Irish Sea. (Data from 2004)

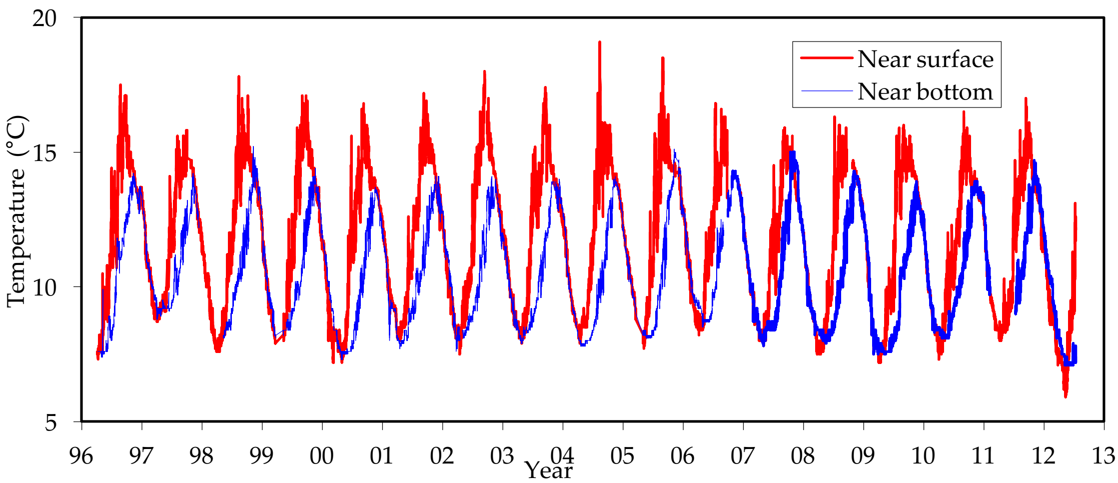


Figure 3.5: Seasonal changes in near surface and near seabed temperature (°C) at the AFBI mooring site in the western Irish Sea between 1996 and 2013.

The lowest salinity is found in the eastern Irish Sea and this reflects the inflow of freshwater. Of the total riverine discharge into the Irish Sea (31 $km^3 y^{-1}$) some 24.9 $km^3 y^{-1}$ (80 %) flows into coastal waters of the eastern Irish Sea (Bowden 1955). The Liverpool Bay region is much influenced by freshwater inflow and can be defined as a '*Region Of Freshwater Influence*' (ROFI) meaning that there is tidal straining of the horizontal salinity gradient and sporadic lenses of fresher water that are moved by wind and mixed away when stirring increases. In the eastern Irish Sea, isohalines are orientated north south (Fig. 3.6) and reflect the origin of freshwater inflow and are suggestive of limited exchange between the eastern and western Irish Sea, although the distribution of radionuclides indicate some east west transport (Leonard et al., 1997). Most of this low salinity water leaves the Irish Sea via the North Channel

(McKay et al., 1986; Balls, 1987; Brown and Gmitrowics, 1995) although under certain meteorological conditions, the northerly flow can be reversed and at such times a tongue of low salinity water eastern Irish Sea water may be advected across the top of the Isle of Man (Lee, 1960).

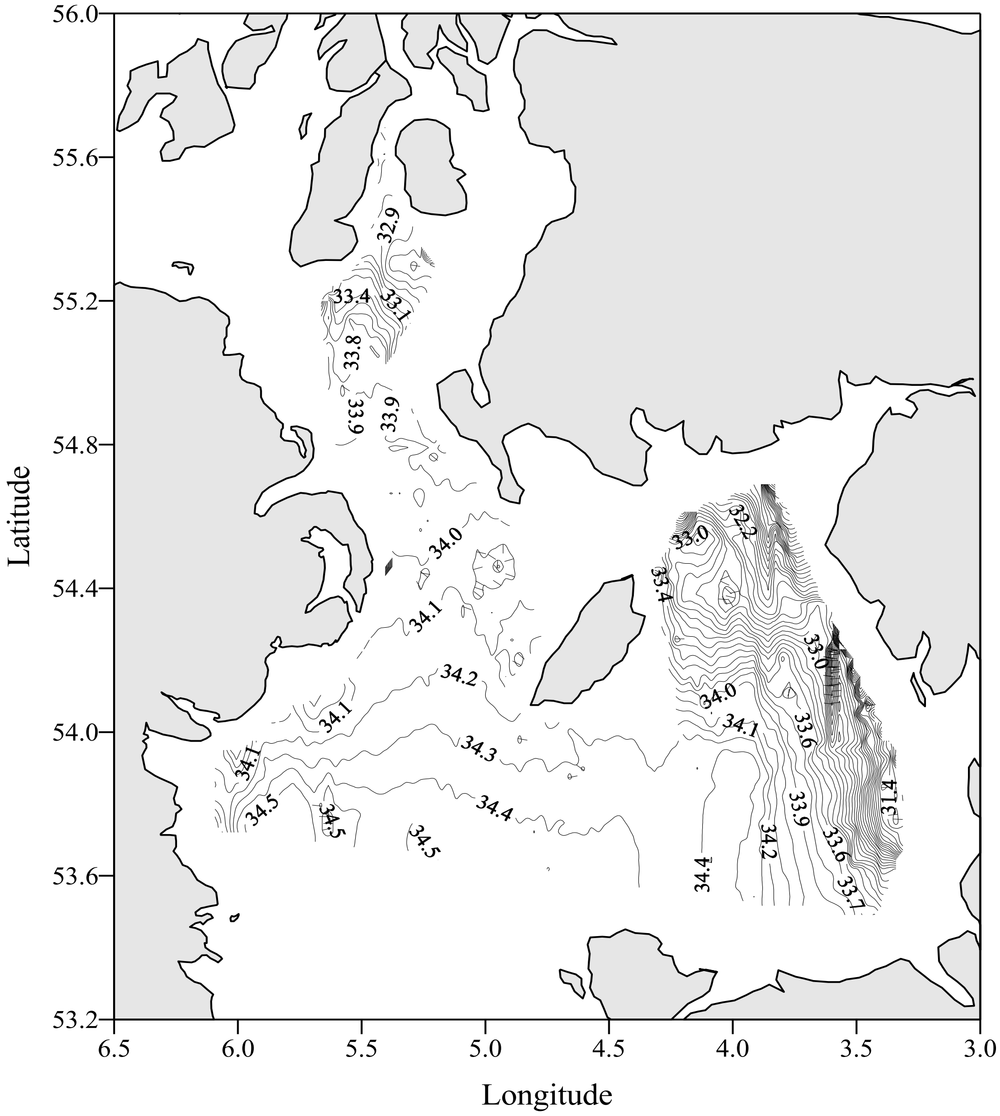


Figure 3.6: The spatial distribution of near surface salinity in the Irish Sea during January 1990. The contour interval is 0.1).

For offshore waters of the western Irish Sea, the annual mean surface salinity given by Bowden (1955) for the period 1903 to 1931 was 34.1 to 34.4. The mean near surface salinity at the AFBI instrumented mooring at station 38A is 34.20. The south north salinity gradient in the western Irish Sea (Fig. 3.6) is indicative of a tongue of relatively high salinity water extending northwards from the Celtic Sea. This feature has been documented from earlier investigations of the Irish Sea (Bassett, 1909; Matthews, 1913) and can therefore be regarded as a consistent winter feature. The salinity at station 38A (34.20) indicates that ~3% of the water is freshwater. Over the year, the seasonal range in salinity is small, 0.91 in 2006 (Fig. 3.7) with seasonal maxima in winter and minima in late spring and summer.

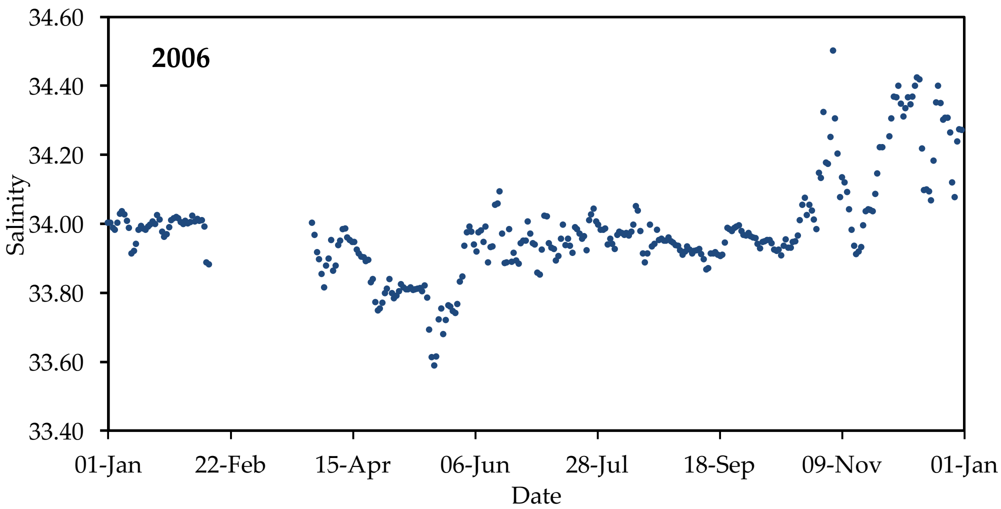


Figure 3.7: The seasonal variation in near surface salinity at station 38A in the western Irish Sea in 2006.

3.5 The seasonal development of stratification

The bathymetry of the Irish Sea, regional differences in tidal amplitude and freshwater inflow give rise to distinct hydrographic regions (Gowen et al., 1995). In St George's Channel, much of the eastern Irish Sea and in the North Channel turbulence generated by strong tidal flows is sufficient to maintain a vertically mixed water column throughout most of the year. In contrast, early investigations of the physical oceanography of the Irish Sea documented the presence of summer stratified water to the south east of the Isle of Man (Matthews, 1913). In this region, deep water (80 m) and weak tidal flows (< 0.5 m s-1) limit the downwards transfer of heat and the water column stratifies (Fig. 3.8).

Stratification begins to develop in April (Fig. 3.8) although there is some inter-annual variability in the timing of the onset of stratification and this influences the timing of the plankton production season. Maximum stratification (up to ~6.0° C) is typically observed in August. It is evident that the bottom water is not completely isolated during summer since there is a gradual increase in temperature over the summer. In 2002 for example, the bottom water temperature increase from 9.0° C on the 19th of May to 12.0° C on the 30th August. This warming may be due to vertical heat flux or movement of bottom water. Stratification begins to erode during late summer.

In 2002, the near surface to near bottom temperature difference was ≤ 1.0° C on the 11th October and had fallen to 0.2° C on the 17th of that month.

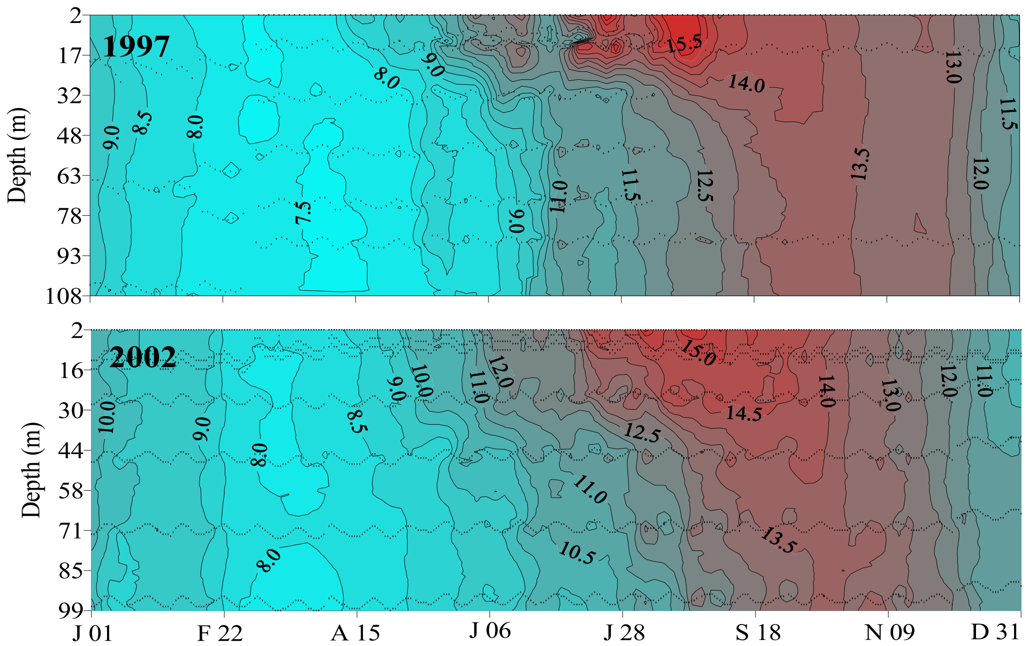


Figure 3.8: Contour plots showing the seasonal development of thermal stratification at station 38A in the western Irish Sea in 1997 and 2002. The contour interval is 0.5 °C.

North- south transects of the western Irish Sea places the temperature structure at the AFBI mooring site in a wider geographical context (Fig 3.9). Data for the section were collected during a survey in June 1992. The most intensely stratified region is to the south west of the Isle of Man (stations 26 to 50). Here, warm surface water (13.7° C) was separated from deeper cooler water by a thermocline with a temperature gradient (ΔT) of 2.9° C, over 10 m between 15 and 25 m. Below the thermocline there was a 'cold water dome' of bottom water which is separated from the surrounding, warmer bottom water by bottom density fronts. North of station 16 and south of station 57, tidal flows are stronger and there is greater mixing. As a consequence, and despite the greater depth in area of the North Channel, there is a greater transfer of heat down the water column. At station 6 for example, surface temperature in June 1992 was 11.7° C (compared to 13.7° C at station 38) and there was no evidence of isolated cold bottom water. South of the region of intense stratification, shallower water and increased tidal flows result in greater transfer of heat down the water column. Surface water at station 57 was 11.0° C and the surface to bottom difference was only 0.2° C.

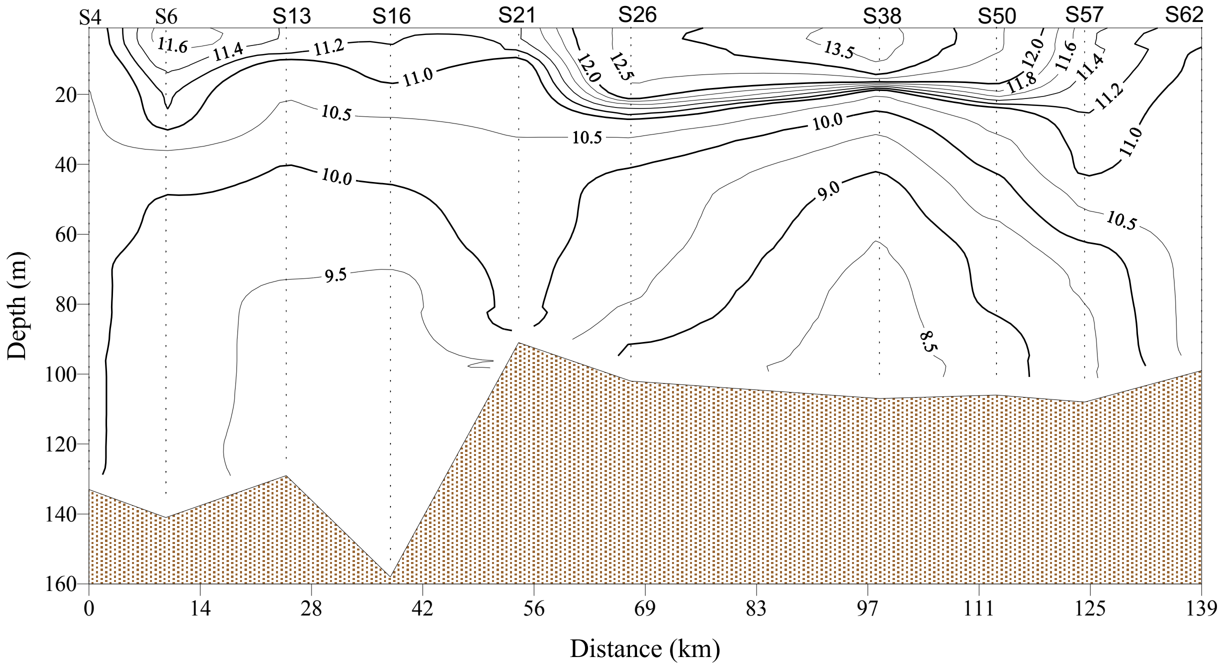


Figure 3.9: The vertical distribution of temperature through the western Irish Sea in June 1992. The contour interval is 0.5°C. (See Figure 3.1 for station positions).

Vertical gradients in salinity are evident throughout the deeper part of the western Irish Sea (Fig. 3.10). These gradients are small but can play an important role in stabilising the water column such that heat is trapped in the surface layers and rapid stratification of the water column takes place in early spring. By comparing the contribution that temperature and salinity make to the density of the water (and values of the potential energy anomaly (φ = phi)[3], Gowen et al. (1995) estimated that salinity can account for ~50 % of the stratification during early spring. However, as the surface layer warms, salinity becomes less important in stabilising the water column.

[3]The potential energy anomaly: a measure of the amount of mechanical work (J m-3) necessary to vertically mix the water column and values of < 10 and > 20 J m^{-3} indicate mixed and stratified water respectively (Simpson et al., 1979; Simpson, 1981)

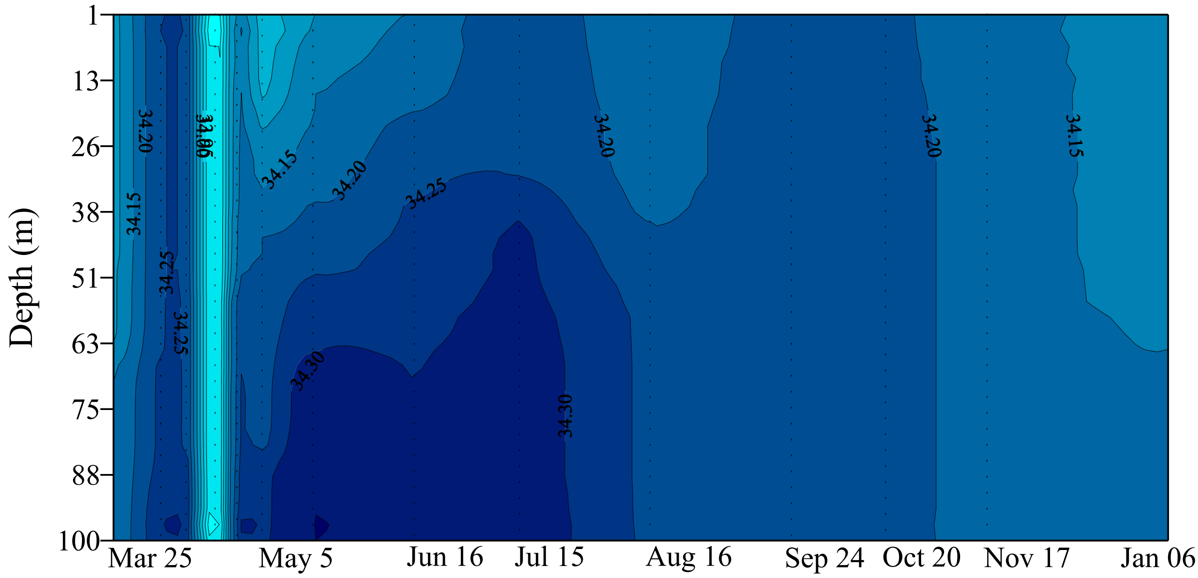


Figure 3.10: A contour plot showing the horizontal and vertical distribution of salinity at station 38 in the western Irish Sea during 1992. The contour interval is 0.15 and the dashed lines are the sampling dates.

The seasonal development and spatial extent of stratification was investigated by Gowen et al. (1995) by recording the changes in vertical gradients in density at a grid of stations in the western Irish Sea during 1992. The density data were used to plotting contour diagrams of φ (Fig. 3.11). In 1992, stratification developed first to the south west of the Isle of Man in early May. The area of stratified water expanded rapidly and by late May occupied most of the offshore region of the western Irish Sea. For the region as a whole, stratification was most intense during July (Fig. 3.11) and it is evident that there were two centres of stratification. The larger of the two areas is located to the south west of the Isle of Man and the second between the Isle of Man and the Northern Ireland coast. The area of weaker stratification between these two centres may be due to an area of shallower water and greater mixing. Throughout the region, stratification was weaker in August and the more northerly region of stratification had been eroded. In the vicinity of stations 4 and 6, the period of stratification may only last 3 months compared to 5 months at the AFBI mooring site. The observations of the seasonal development and erosion of stratification made in 1992 by Gowen et al. (1995) are supported by data collected during an intensive series of surveys conducted in 1995 by Horsburgh et al. (2000).

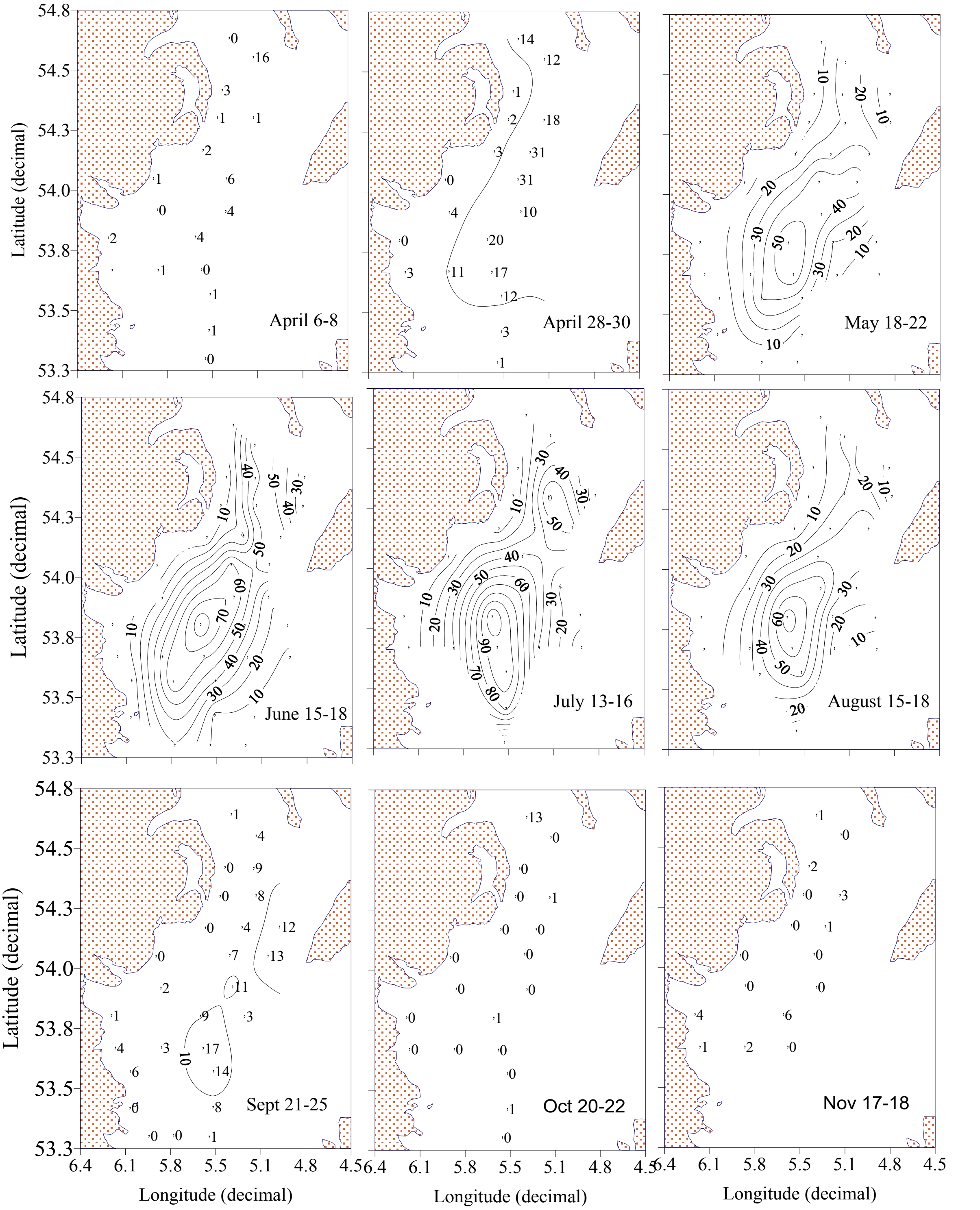


Figure 3.11: Contour plots of the potential energy anomaly (Phi, ϕ) illustrating the seasonal development of stratification in the western Irish Sea in 1992. The contour interval is 10 J m $^{-3}$ (from Gowen et al., 1995).

Bottom fronts separate the 'cold water dome' from warmer bottom water (Fig. 3.12) and drive a cyclonic gyre of near surface water (Hill et al., 1994). Recent investigations of the gyre including the results of drifter studies have been reviewed by Horsburgh et al. (2000). As noted above, vertical gradients in salinity may play an important role in the initial stages of stratification and the gyre may establish in April when temperature gradients are small. The bottom fronts that drive the gyre are more stable than the near surface fronts and thermocline and the gyre can persist into October when the surface features have been eroded. Data from drifters show that the gyre encompasses both centres of stratification (Fig. 3.11) although the degree of coupling between then is less clear. According to Hill et al. (1994) northerly flows can reach up to 20 cm s^{-1} on the eastern flank of the gyre but southerly flows are weaker (9 cm s^{-1}) on the western flank; the transport time of drifters around the gyre is ~42 days with a mean speed of 10 cm s^{-1}. Towards the centre of the gyre, near surface waters appear to become isolated although loss of drifters from the region (particularly in early summer) suggests than some exchange between the gyre and adjacent waters does occur (Hill et al., 1994).

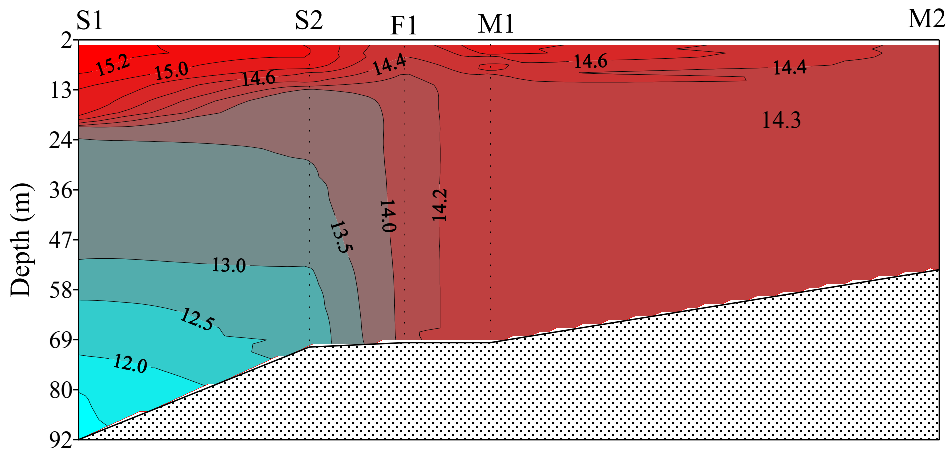


Figure 3.12: The thermal structure of the western Irish Sea front showing the bottom front in 1999 (from Trimmer et al., 2003).

The south eastern boundary of the gyre forms the western Irish Sea tidal mixing front (Simpson and Hunter, 1974) between the seasonally stratified western Irish Sea and mixed eastern Irish Sea water (Fig. 3.12). The front extends from the southern point of the Isle of Man to Dublin and in can be identified by the 14.2° C isotherm (Fig. 3.13). The transition from stratified to mixed waters occurs over a distance of ~20 km. The front becomes established in April-May, once the water column in the western Irish Sea begins to stratify, and persists until at least August (Simpson and Hunter, 1974). However as discussed above, stratification of the water column begins to weaken in August. It is rapidly eroded and by September/ October the surface front loses its integrity. Recent measurements of benthic mineralisation rates (Trimmer et al., 2003) show a striking correspondence between the position of the front and the transition in benthic activity over a distance of 13 km. Since the benthic characteristics on either side of the front reflect the longer-term pattern, this sharp demarcation in sedimentary characteristics supports the conclusion of Simpson and Bowers (1979) that there is limited (5 km) movement in the position of the front.

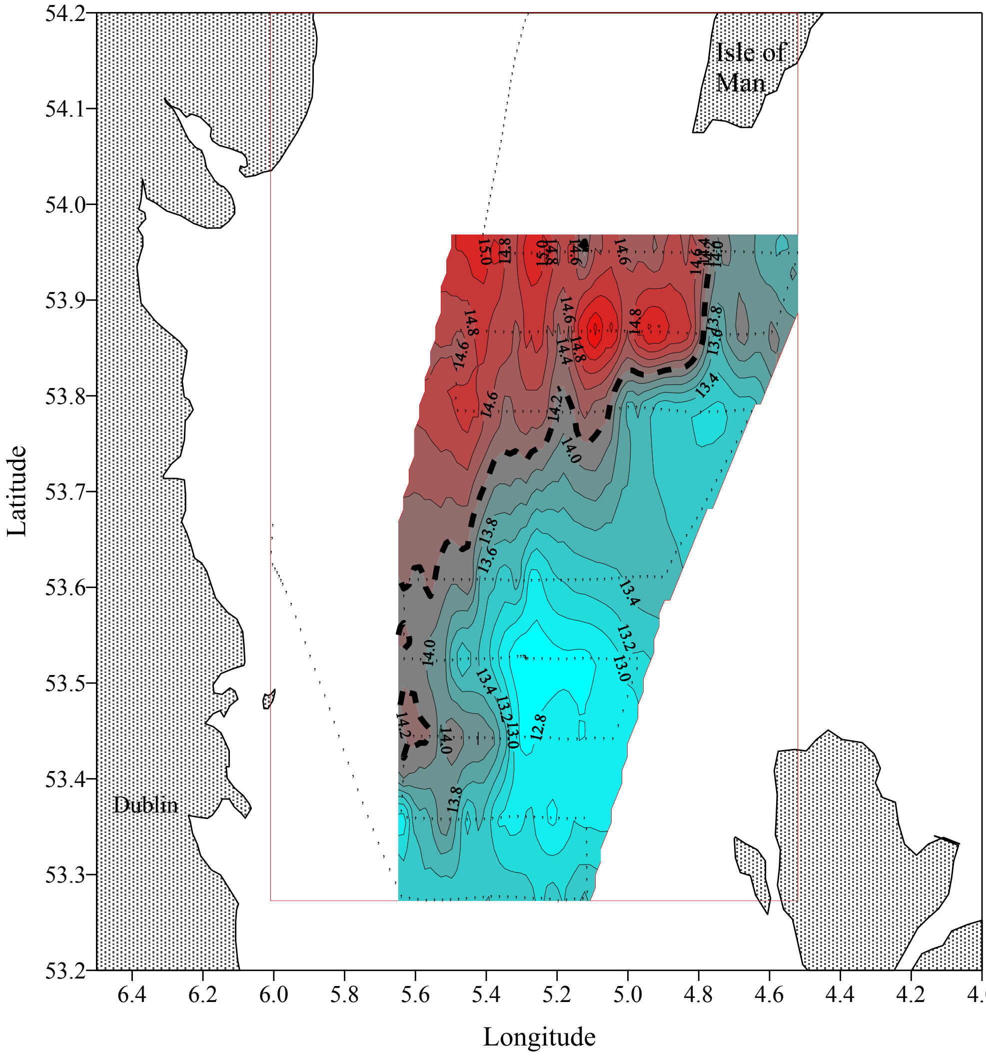


Figure 3.13: The surface distribution of temperature (°C) showing the position of the western Irish Sea front (denoted by dashed line which represents the 14.2°C isotherm). The contour interval is 0.2°C. (DARD/AFBI data collected during July 2001).

The seasonally stratifying region of the western Irish Sea is a depositional area. The reduction in turbulence associated with stratification allows seston (living planktonic organisms and non-living detrital material) to settle out of the water column (Fig 3.14). The depositional nature of the western Irish Sea is reflected in the composition of bottom sediments (fine silt/clays) and there is important chemical and biological coupling between the water column and sediment. For example, Trimmer et al. (2003) found that the sediment on the stratified side of the front had higher concentrations of chlorophyll and higher rates of oxygen uptake and nutrient efflux compared to the sediment on the mixed side. The gyre may augment the depositional nature of the western Irish Sea by retaining seston within the region and increasing the likelihood that material will settle out.

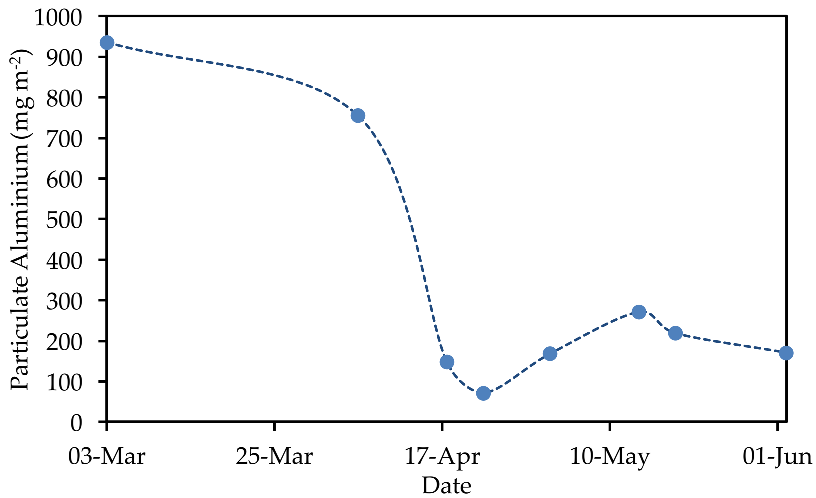


Figure 3.14: Changes in the stock of particulate aluminium (mg m^{-2}) in the upper 25 m of the water column in the stratified region of the western Irish Sea during spring 1997.

3.6 The sub-surface light climate

As discussed later in section 5, the sub-surface light climate plays an important role in determining the onset and duration of the phytoplankton production season in coastal waters and shelf seas. Examples of the vertical profile of down-welling photosynthetically active radiation (PAR) from the seasonally stratifying region of the western Irish Sea are shown in Fig. 3.15. From such measurements the attenuation coefficient (k_d) can be calculated and used to calculate the depth at which irradiance is 1% of surface irradiance. This depth is the euphotic zone depth: the surface layer within which there is sufficient light for photosynthesis. Estimates of k_d and euphotic zone depth from the irradiance profiles in Fig. 3.16 are given in Table 3.1. From this small data set mean euphotic zone depth is 25.7 m which encompasses the surface mixed layer and thermocline (Figs. 3.8, 3.8 and 3.12).

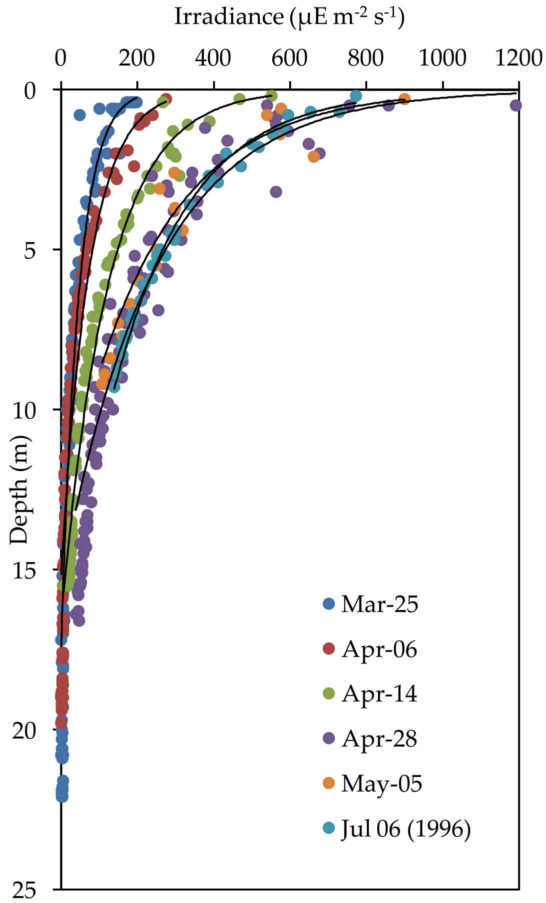


Figure 3.15: Examples of the attenuation of down-welling photosynthetically active radiation in the seasonally stratifying region of the western Irish Sea during spring 1992 and in July 1996.

Table 3.1 Estimates of the attenuation coefficient of down-welling photosynthetically active radiation and the corresponding euphotic zone depth.

Date	Attenuation coefficient (m^{-1})	Euphotic zone depth (m)
Mar 25	0.1994	23.0
Apr 06	0.2415	19.1
Apr 14	0.1947	23.7
Apr 28	0.1691	27.2
May 05	0.1281	35.9
July 05 (1996)	0.1846	24.5

3.7 Summary

The Irish Sea is a small geographically isolated inner shelf sea and this is reflected in the age of water in the western Irish Sea which may be up to 6 years old relative to near ocean water at the Celtic Sea shelf break. Deep water and weak tidal flows in the western Irish Sea allow the water column to stratify ($\varphi \geq 20$ for 120 days) for up to 5 months between April and September. Stratification results in a surface mixed later of ~25 m, which is separated from cold bottom water by a thermocline. During spring and summer the euphotic zone is typically the same as mixed layer depth. Bottom density fronts drive a near surface gyre with a rotation of approximately 42 days. The seasonally stratifying region is a depositional area in which seston settles to the seabed and this is reflected by the fine silt/clay bottom sediments.

4 Dissolved Inorganic Nutrients

4.1 Introduction

Dissolved inorganic forms of nitrogen and phosphorus are essential nutrients for the growth of phytoplankton (and higher plants). In addition, diatoms and silicoflagellates require silicon (Si, as dissolved silica or silicic acid, $Si(OH)_4$) for cell wall formation. Nutrients may 'limit' both the growth and the yield of phytoplankton populations. The former relates to the rate of increase in biomass, and the latter to the absolute amount of biomass generated per unit of nutrient available. The relationship between nutrients and populations of micro-organisms can be described by a number of theories (Monod, 1942; Dugdale, 1967; Droop, 1968; Droop, 1983; Davidson and Gurney, 1999; Flynn, 2005).

In temperate coastal waters and shelf seas, dissolved inorganic nutrients reach their annual maximum during winter when the rate of re-supply exceeds the demand by phytoplankton. For this reason, investigations of nutrient sources and the nutrient status of coastal waters are typically based on winter data. In this report, dissolved inorganic nitrate + nitrite is denoted as TOxN; dissolved inorganic phosphate as DIP and silicate as Si.

4.2 Adjacent Sea Areas

The Atlantic Ocean is the source of water for the Celtic and Irish seas and this oceanic water determines the background nutrient levels for the two seas. Present day Atlantic concentrations of dissolved nutrients have been established as a result of large scale biological, chemical and physical processes which have been active over geological time-scales. However, as noted above the residence time of water in the Celtic and Irish Seas is in the order of years, and this timescale implies that considerable recycling of dissolved N, P and Si will take place within these shelf seas.

Gowen et al. (2002) and Hydes et al. (2004) presented winter (January/ February) nutrient data from near surface waters at the Malin Shelf and Celtic Sea shelf break (Table 4.1). The more recent winter data in Table 4.1 are from surveys of the Malin Shelf (Scherer and Gowen, 2013) undertaken as part of EFF project (CA/033766/11) of which this report is part and AFBI surveys of the Celtic Sea. Quasi-synoptic data collected in January 2013 have been plotted as a section from near ocean waters off the continental shelf west of the Malin Shelf through the Irish and Celtic seas to near ocean waters of the South West approaches (Fig. 4.1). A consistent feature of near surface concentrations of dissolved inorganic nutrients is that winter concentrations are higher in near ocean waters of the Malin Shelf. Hydes et al. (2004) attributed this to deeper winter mixing off-shelf which introduced more nutrients into near surface waters at the Malin Shelf compared to the depth of mixing in near ocean waters beyond the Celtic Sea shelf break. More recent data supports this view and the temperature data plotted in Fig. 4.2 show the greater depth of winter mixing in near ocean waters off the Malin Shelf.

A second feature of the quasi-synoptic winter nutrient data shown in Fig. 4.1 is the lower concentration (6.0μM) of TOxN in the western Irish Sea compared to the outer shelf and near ocean. One reason for this might be because deep winter mixing off the shelf restores winter nutrient concentrations to surface waters more quickly that recycling restores inorganic nutrient concentrations in the inner shelf (Hydes et al., 2004). The finding that concentrations of TOxN in the western Irish Sea were significantly higher in March compared to January/ February (Gowen et al. 2002) supports this view.

Table 4.1: Winter concentrations (μM) of dissolved inorganic phosphorus (DIP), nitrate + nitrite (TOxN) and silicate (Si) in near surface (upper 20 m) waters of the shelf break region of the Celtic Sea and Malin Shelf.

	Concentration (μM)			Ratios		Source
Date	DIP	TOxN	Si	TOxN:DIP	TOxN:Si	
Celtic Sea						
Feb 1994	-	7.80	-			Gowen et al. 2002
Feb 1998	0.46	6.65	2.57	14.5	2.5	Gowen et al. 2002
Jan 1999	0.43	7.56	3.29	17.6	2.3	Gowen et al. 2002
Jan 2009	0.43	7.34	2.52	17.1	2.9	AFBI data
Jan 2011	0.55	8.17	3.24	14.7	2.5	AFBI data
Jan 2012	0.48	6.27	2.36	13.1	3.3	AFBI data
Jan 2013	0.48	6.91	1.90	14.4	3.6	AFBI data
Open Ocean (off the Malin Shelf)						
	0.68	11.00	4.75	16.2	2.3	Hydes et al. 2004
Malin Shelf						
	0.53	7.40	3.30			Hydes et al. 2004
Jan 2012	0.73	10.49	3.42	14.4	3.1	AFBI data
Jan 2013	0.64	10.29	3.66	16.1	2.8	AFBI data

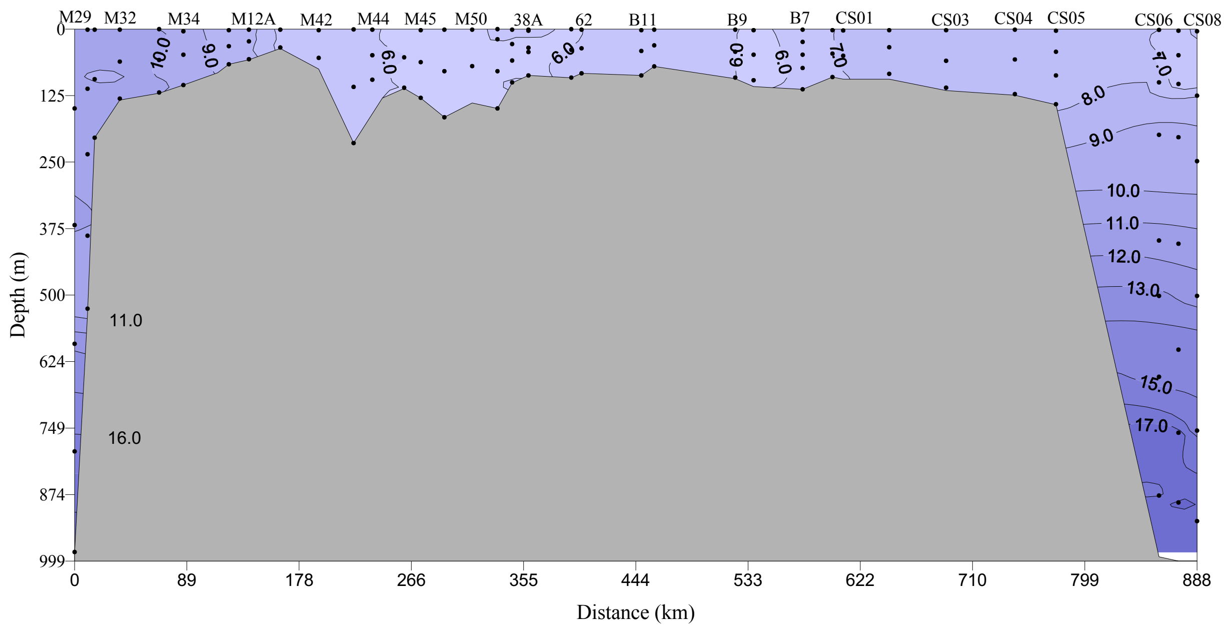


Figure 4.1: A contour plot showing the distribution of TOxN (μM) along a section from near ocean waters off the Malin Shelf (station M29) through the western Irish Sea (AFBI mooring site, station 38A) to near ocean waters off the Celtic Sea shelf edge (Station CS08) during January 2013. (The approximate location of the transect is show in Figure 3.1)

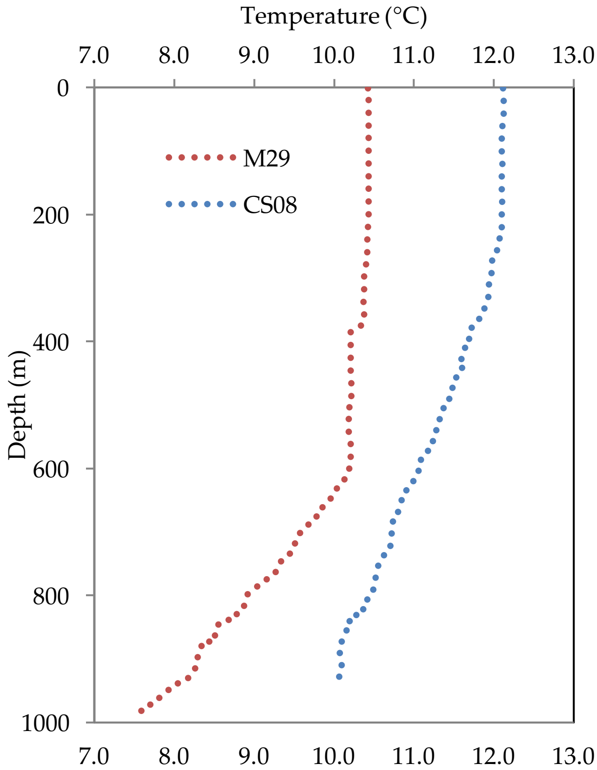


Figure 4.2: Vertical profiles of temperature (°C) in near ocean waters at station M29 (Malin Shelf) and CS08 (Celtic Sea) in January 2013.

4.3 The Irish Sea

Near surface winter concentrations of nutrients in the Irish Sea exhibit spatial and temporal variability. Concentrations are typically higher in the eastern Irish Sea (Fig. 4.3) and reflect the high concentrations of nutrients in freshwater flowing into the region. At the Liverpool Bay station worked in 1997 for example, the maximum winter concentrations of TOxN and P were 29.2 and 1.7 µM respectively (Gowen et al., 2002). There are pronounced seasonal cycles in the concentration of all three nutrients in the Irish Sea (Fig. 4.4) and the AFBI time-series of nutrient data from station 38A shows that this seasonal pattern is a recurrent annual feature of the western Irish Sea (Fig. 4.5).

Typically, there is a slow build up of nutrients over the winter and maximum concentrations in offshore waters of the western Irish Sea reach their maximum in March. Gowen and Stewart, 2005 gave mean (1998-2002) March concentrations of: 8.3 µM TOxN, 0.7 µM DIP and 6.6 µM Si). This is followed by a rapid removal of nutrients from the surface mixed layer. The ratios (TOxN:DIP and TOxN:Si) of this nutrient drawdown are typically 11.5 and 1.26 for TOxN:DIP and TOxN:Si respectively (mean values for 1992, 1997-1999 and 2001). The timing of this drawdown is variable. Taking the date on which the near surface concentration has fallen to 50% of the maximum winter concentration as the mid-point of the drawdown then between 1992 and 2013 (insufficient data for 1994, 1999 and 2000) the mean midpoint was 21st April and ranged from 30th March to the 23rd May (Fig. 4.6).

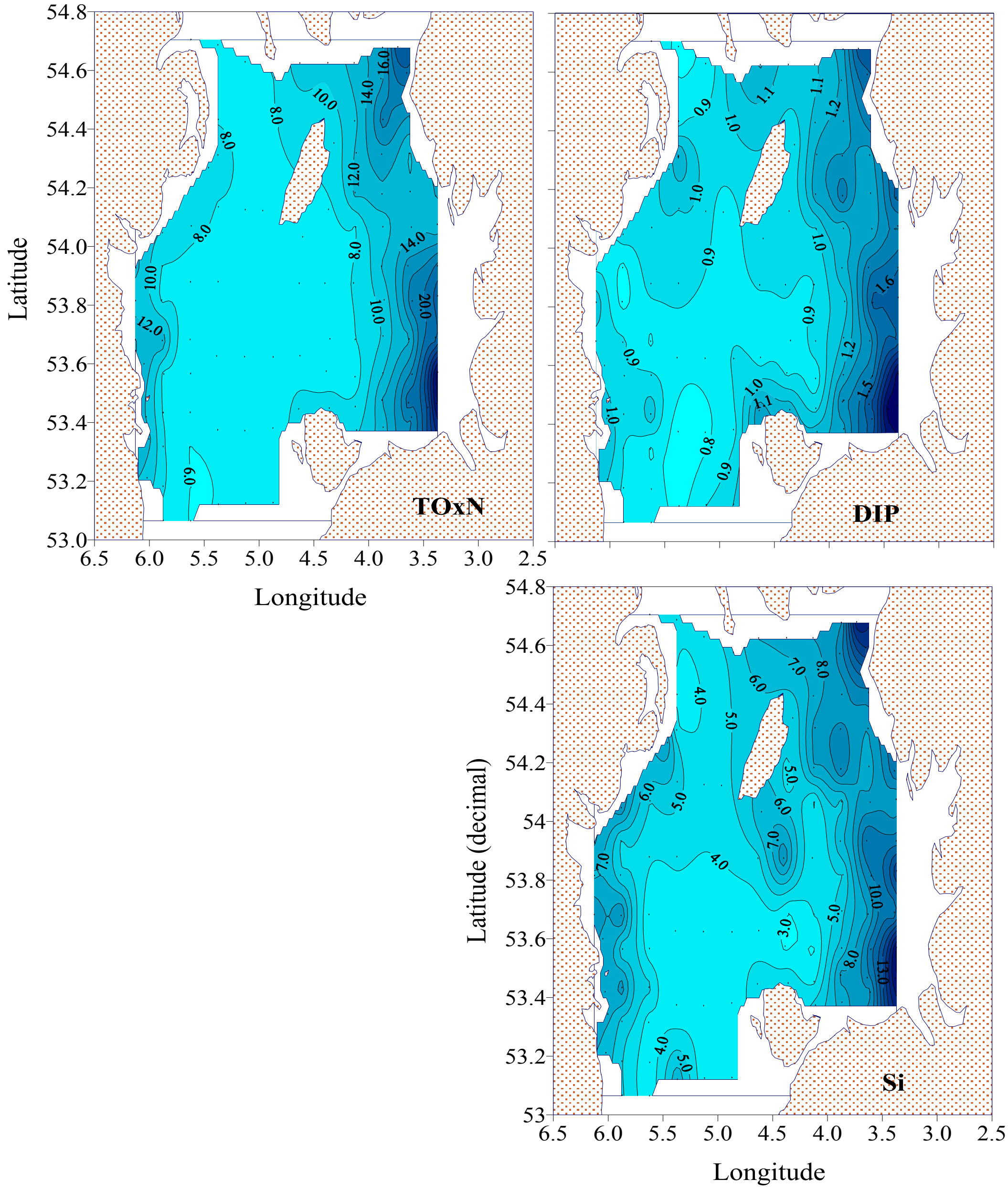


Figure 4.3: The spatial distribution of TOxN, DIP and Si (μM) in near surface waters of the Irish Sea during January 2000.

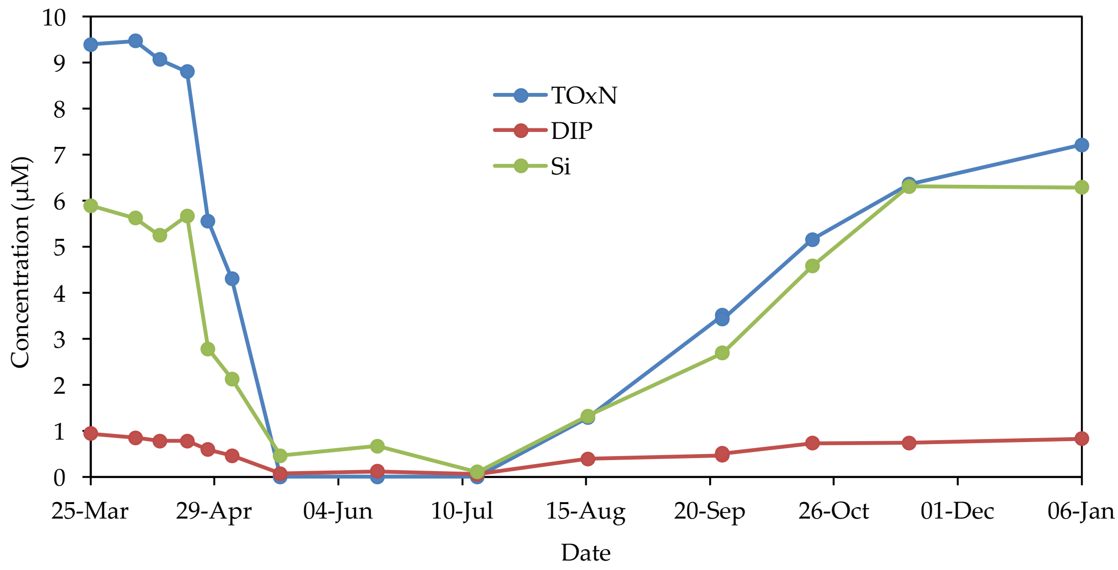


Figure 4.4: The seasonal cycle of inorganic nutrients at station 38 in the western Irish Sea during 1992.

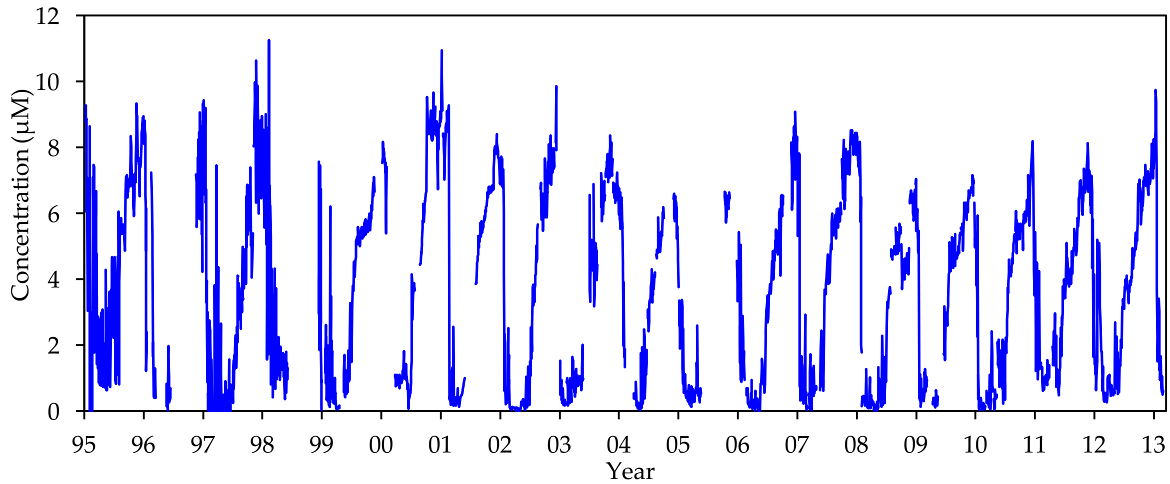


Figure 4.5: The TOxN time-series at the AFBI mooring site (station 38A) in the western Irish Sea.

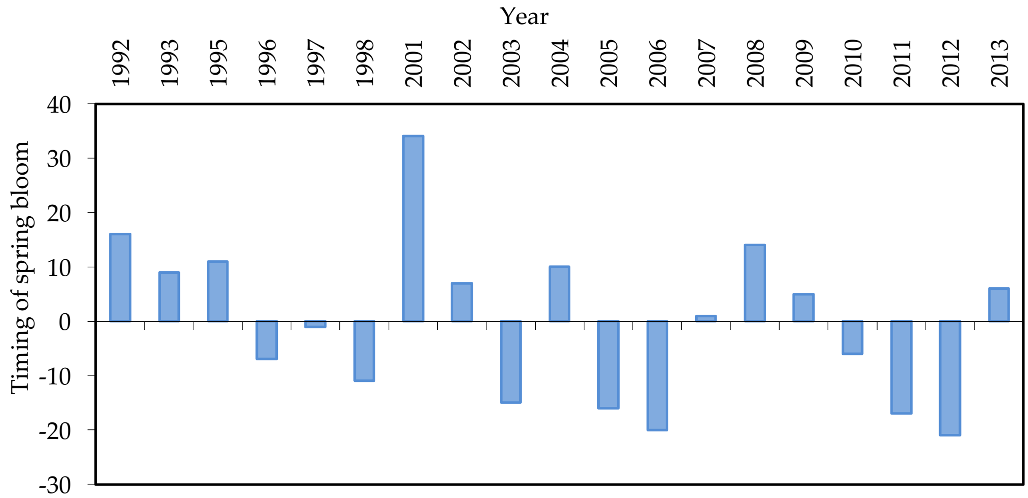


Figure 4.6: Inter-annual variability in the timing of the spring drawdown of winter nutrients in the western Irish Sea (see text for details). There were insufficient data for 1994 and 1999.

Measurements made at station 38A in 1999 and 2000 show that over the spring period 88 and 95 % of the TOxN were removed from the upper 30 m of the water column. There is also a net removal of nitrogen from the water column. During the spring of the same two years, between 22 and 35% of the total nitrogen stock was removed from the euphotic zone (Table 4.3).

Table 4.2: Changes in the stock (concentration as μM summed over the upper 23 m of the water column to give the stock as mmol m^{-2}) of different nitrogen fractions at station 38 in the western Irish Sea during spring 1999 and 2000.

	Nitrogen fraction (mmol m^{-2})			
Date	Dissolved inorganic	Dissolved organic	Particulate organic	Total
1999				
March 03	287.4	141.6	43.4	472.5
April 07	23.4	222.3	195.3	441.0
May 11	35.1	224.0	107.1	366.5
June 22	67.7	263.0	102.7	433.4
2000				
April 06	186.9	263.1	32.2	482.2
May 01	194.3	191.1	42.6	428.0
May 09	8.2	183.1	87.1	278.4
May 11	9.3	255.9	65.1	330.4

As noted in section 3, thermal stratification of the water column in the western Irish Sea isolates the bottom water. The drawdown of nutrients observed in the surface mixed layer does not occur in the bottom water and a 'pool' of nutrient rich water persists throughout the summer in the western Irish Sea (Fig. 4.7).

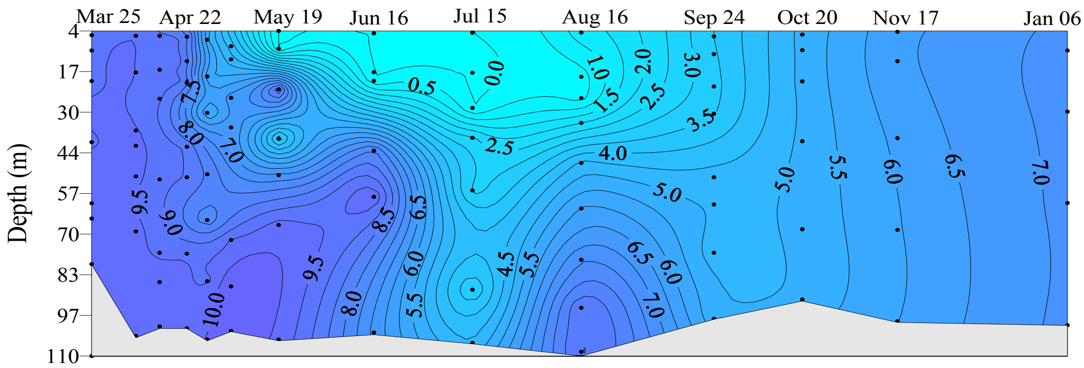


Figure 4.7: A contour plot of nitrate showing the seasonal depletion in the surface mixed layer. (DARD/AFBI data collected from the seasonally stratifying region of the western Irish Sea during 1992).

Concentrations of all three nutrients remain low in the surface mixed layer throughout the summer (≤ 0.3 μM TOxN, 0.2 DIP μM and 0.7 Si μM) but by late summer concentrations begin to increase. The breakdown in stratification brings about the redistribution of nutrients with the mixing of nutrient rich bottom water to the surface. In 1992 for example, DIN, DIP and Si were uniformly mixed throughout the water column by October. However, autumnal mixing does not return nutrient concentrations to their winter maxima. Recycling in the water column and sediment efflux contribute to the restoration of the winter maxima.

Changes in the concentrations of the different nitrogen fractions in the water column during the autumn and early winter provide evidence for recycling within the water column. Nitrogen is transferred from the dissolved organic fraction to the dissolved inorganic fraction. Between November 2, 2000 and January 8, 2001, the concentration of DON decreased by 100 mmol m^{-2} whereas TOxN increased by 343 mmol m^{-2}. The fact that the latter exceeded the decrease in DON indicates that over the winter period there was a net increase in the total nitrogen stock within the Irish Sea. Some of this new nitrogen comes from the sediment through the remineralisation of organic matter in the sediment (Trimmer et al. (1999) measured a nitrate efflux rate of 10 μ mol m^{-2} h^{-1}).

The cycling of silicate does not follow the same pathway as N and P. Silicate is used in the cell walls of diatoms and silicoflagellates and is not digested by zooplankton grazing on phytoplankton. As a result much of the particulate silicate settles to the seabed as phytodetritus (living and dead algal cells) and zooplankton faecal pellets. In the sediment, silicate is returned to the dissolved form by dissolution. Estimates of silicate efflux from western Irish Sea sediments (Irish coastal waters) range from 42 to 123 mol m^{-2} h^{-2} (Gowen et al., 2000).

4.4 External Nutrient Sources

Inorganic nutrients in the Irish Sea may come from three external sources: marine (Atlantic), freshwater (anthropogenic and natural sources) and atmospheric. If as has been suggested, winter concentrations in near ocean waters at the Celtic Sea shelf break set background concentrations of nutrients in the Irish Sea, it follows that differences between Atlantic water and Irish Sea concentrations will reflect internal nutrient cycling and the influence of anthropogenic sources. Such differences have been used to quantify the contribution that anthropogenic nutrient sources make to nutrient levels in the Irish Sea (Gowen et al., 2002; Hydes et al., 2004) and assess the eutrophication status of the Irish Sea (Gowen et al., 2008).

Estimating the Atlantic source term is not a trivial task and some of the difficulties were discussed by Gowen and Stewart (2005). One of the key unknowns is the on-shelf movement of oceanic water and volume transport through the Celtic Sea. Much of the transport might be expected to occur during the winter however, as noted in section 3, stronger winter winds tends to transport water parallel to the shelf break rather than onto the shelf and the presence of a shelf break salinity front in the winter (Hydes et al., 2004) may further restrict movement of ocean water onto the shelf. Gowen and Stewart (2005) estimated the daily input of dissolved inorganic nutrients into the Irish Sea to be 540 t TOxN, 78 t DIP and 840 t Si and gave what they considered to be crude estimates of the annual input as: 82,000 TOxN, 12,000 t DIP and 127,000 t Si. Most of the freshwater nutrient input to the Irish Sea is via river inflow. The annual input of dissolved nutrients via the main UK and Irish rivers flowing into the Celtic and Irish seas is estimates as 150000 t TOxN, 12000 t DIP and 34000 t Si (Gowen et al., 2002). The atmospheric input of DIN is 43000 t (Gillooly et al., 1992) and the input of atmospheric DIP (in soil dust) is 2000 t. It would therefore appear that the anthropogenic input of TOxN to the Irish Sea is approximately equivalent to the natural input from the Atlantic.

A comparison between Atlantic and Irish Sea winter concentrations shows that the latter is enriched with DIP and Si (Gowen et al., 2002). Evidence for TOxN enrichment of the western Irish Sea is less clear. The mean January/February shelf break concentration of 7.15 μM TOxN (Table 4.1) compares with moored water sampler data (1996 to 2002 [not 1999]) of 7.44 μM (n = 126). March/ early April concentrations of TOxN are higher (1997 to 2001, 8.57 μM (n = 88)) suggesting enrichment relative to the January /February shelf break concentration. However, comparing March/ early April western Irish Sea data with January/ February shelf break data assumes that the latter represent the winter maximum and this may not be the case if there is a late winter increase in the depth of winter mixing (Hydes et al., 2004).

Concentrations of dissolved inorganic nutrients are much higher in freshwater than in marine waters. As a consequence, small volumes of freshwater have a disproportionately large influence of nutrient concentrations in coastal waters. The following assessment assumes that the main source of freshwater to the western Irish Sea is from Irish rivers. For this region, the mean near surface autumn/winter (September 2001 – March 2002 moored CTD data) salinity was 34.20. This represents a dilution of 3.7% compared to an oceanic salinity of 35.50. Irish rivers flowing into the western Irish Sea have DIP and TOxN concentrations of ~3.0 and 220 μM respectively (PARCOM data source). The silicate concentration is likely to be 83 μM (Gowen and Stewart, 2005). The contribution of freshwater nutrients to near surface western Irish Sea water is shown in Table 4.3.

Table 4.3: Estimates of the influence of anthropogenic nutrients on the winter concentration in the western Irish Sea.

Nutrient	Concentration		Contribution		Western Irish Sea concentration	
	Oceanic	Riverine	Oceanic (96.3%)	Riverine (3.7%)	Predicted	Measured
DIP	0.45	3.00	0.43	0.02	0.54	0.75
TOxN	7.15	220.00	6.89	8.14	15.03	8.75
Si	2.65	83	2.55	3.07	5.62	6.32
				TOxN:DIP	26.7	11.7
				TOxN:Si	2.67	1.38

Of the three nutrients, silicate had a predicted concentration that was closest to the measured concentration (- 12%).The reason for this might be because the biogeochemical cycling of silicate involves fewer chemical forms and loss terms compared to TOxN and DIP. For DIP, the measured concentration is higher implying a loss of DIP from the system or underestimate of the freshwater term. Riverine waters are high in particulate phosphate and for Irish rivers, DIP is only 50- 60% of the total phosphorus load (PARCOM data source). It is likely therefore that the freshwater supply of DIP is higher than that suggested by DIP alone, although the final input of DIP will depend on the equilibrium between the particulate and dissolved forms. The predicted concentration of TOxN for surface waters of the western Irish Sea is 15.03 μM (85% more than the mean measured value). It would therefore appear that the supply of TOxN to the western Irish Sea is greater than can be accounted for by near surface concentrations.

The results of the above assessment can be shown graphically by plotting near surface nutrient concentrations against salinity and comparing each plot with a theoretical mixing line between oceanic water (salinity 35.50, 0.47 μM DIP, 7.15 μM TOxN and 2.65 μM Si) and freshwater (zero salinity, 3.0 μM DIP, 220 μM TOxN and 83 μM Si). For DIP and Si the measured values are close to the theoretical mixing line but for TOxN measured concentrations are much lower than predicted (Fig. 4.8). The transport of 'old' Atlantic water into the Irish Sea and recycling of N in estuaries would reduce both source concentrations of TOxN. In addition, sediment denitrification would remove nitrogen from the system. Denitrification may be the single most important process by which comparatively low concentrations of TOxN are maintained in the western Irish Sea. A denitrification rate of 18 mol m^{-2} h^{-1} (Trimmer et al., 1999) equates to an annual loss of 2.2 tonnes of nitrogen per km^2. If the area of muddy sediment is 3504 km^2, then 7735 t of nitrogen would be lost from the system which is similar to the annual nitrogen load from the Boyne (PARCOM data source).

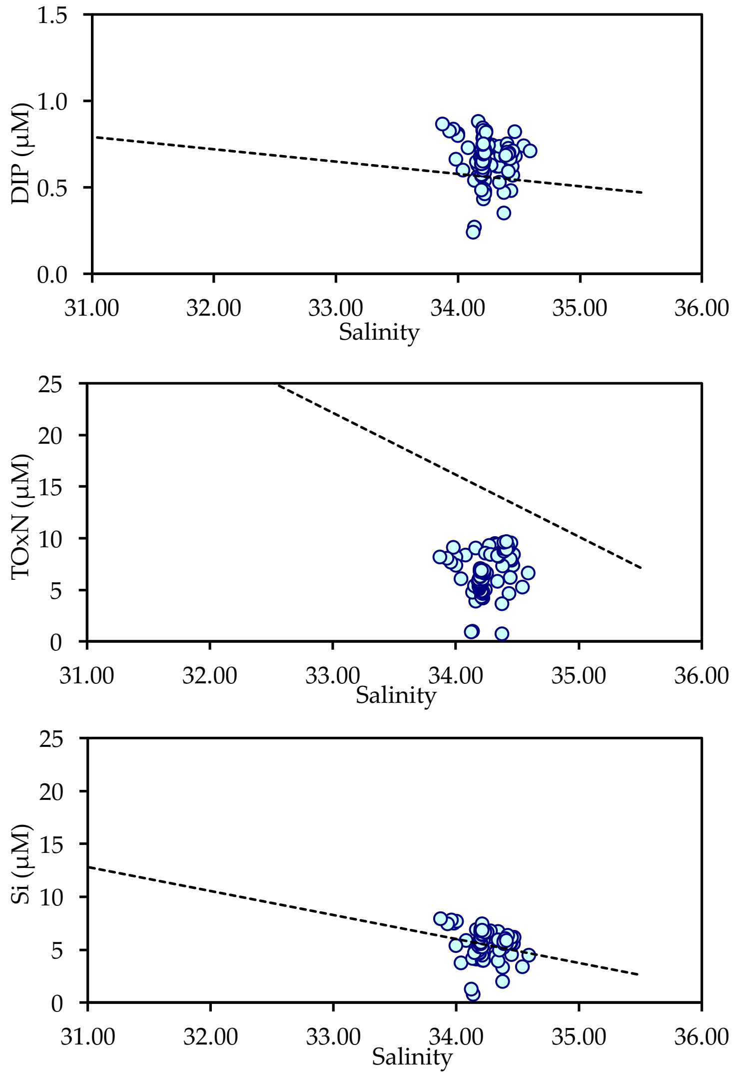


Figure 4.8: A comparison between theoretical salinity nutrient mixing relationships (dashed lines) and measured concentration in the western Irish Sea (Nutrient data were collected between 1998 and 2002).

4.5 Long-term change

Long-term change in the nutrient status of the Irish Sea was investigated by Gowen et al. (2002) and Gowen et al. (2008). In both studies the time-series of nutrient data collected by the Port Erin Marine Station from a location approximately 5 km from the shore was analysed for long-term trends. In the first study data between 1955 and 1999 (DIP), 1960 and 1999 (nitrate) and 1959 to 1999 (Si) were analysed and Gowen et al. (2002) concluded that there was as an indication that DIP had declined since the late 1980s, nitrate had remained stable since the mid 1970s and there was no long-term trend in Si. In the second study data from the beginning of each time-series up to 2005 were analysed using the same statistical technique (Mann-Kendal test for monotonic trends). Based on the longer data set, Gowen et al. (2008) concluded that the reanalysis confirmed the lack of any trend in nitrate since the mid 1970s and the decrease in DIP since 1989.

4.6 Summary

There is a pronounced and recurrent seasonal cycle of dissolved inorganic nitrogen (nitrate + nitrite) phosphate and silicate in near surface waters of the western Irish Sea. Maximum concentrations (1998-2002 mean concentrations: 8.3 μM TOxN, 0.7 μM DIP and 6.6 μM Si) are found in March. This is followed by a rapid removal of these nutrients from near surface waters and concentrations remain low in the surface mixed layer (≤ 0.5 μM TOxN, 0.2 DIP μM and 0.7 Si μM) throughout the summer. By late summer concentrations begin to increase.

Concentrations of all three nutrients in the western Irish Sea are elevated relative to near ocean concentrations but the level of nitrogen enrichment is constrained by sediment denitrification. Analysis of the Isle of Man time-series shows that the winter concentration of DIP has decreased since 1989 and the winter concentration of TOxN has been stable since the late 1970s.

5. Microplankton

5.1 Introduction

Microplankton encompasses all the planktonic unicellular micro-organisms in fresh and marine waters. Approximately 4,000 species make up the phytoplankton worldwide (Sournia, 1991) and these microscopic floating plants are responsible for the bulk of primary production in coastal waters and shelf seas beyond the limits of macro algal and higher plant (sea grass) growth. The phytoplankton forms the base of the pelagic food web but in addition to the phototrophic plants, mixotrophic and heterotrophic organisms play an important role in the cycling of organic matter through the pelagic component of marine ecosystems. Collectively these micro-organisms are referred to as the microplankton.

5.2 The seasonal cycle of biomass and production in the western Irish Sea.

Estimates of phytoplankton biomass (as the green pigment chlorophyll hereafter denoted as Chl) were made during an early study of the western Irish Sea be Slinn (1974) who reported summer concentrations of approximately 4 mg m^{-3} in early June and lower concentrations in July (>1 mg m^{-3}). Richardson et al. (1985) measured summer (1984) Chl concentrations of between < 2 and > 4 mg m^{-3} in the western Irish Sea. However, the first detailed study of the seasonal cycle of phytoplankton biomass and production was carried out in 1992 by Gowen et al. (1995) who showed that there was a pronounced seasonal cycle of phytoplankton biomass in the seasonally stratifying region of the western Irish Sea. Comparing these early observations with more recent data (Fig. 5.1) shows that the pattern of phytoplankton growth in this region of the Irish Sea is a recurrent annual event. The way in which the production season evolves in the water column is illustrated in Figure 5.2.

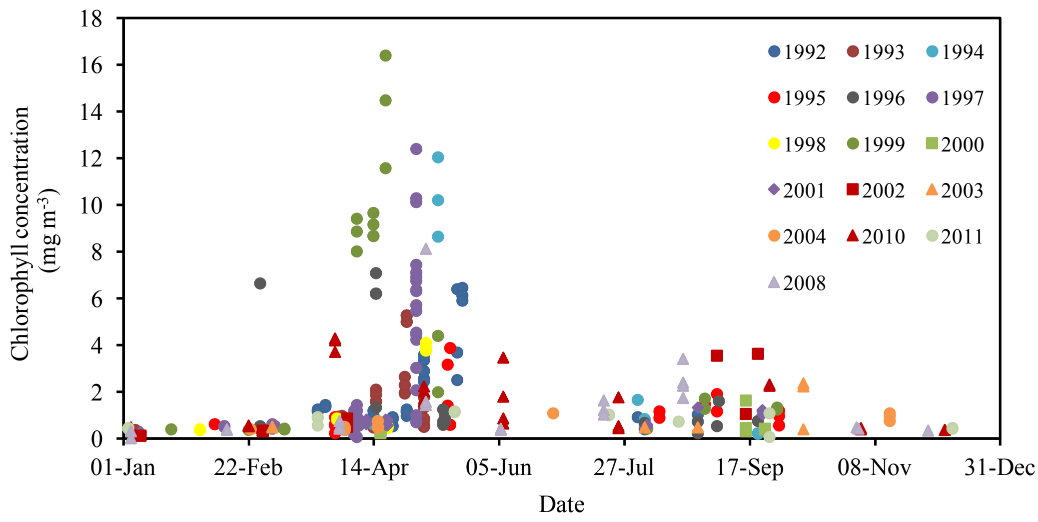


Figure 5.1: The seasonal cycle of phytoplankton biomass at station 38A in the seasonally stratifying region of the western Irish Sea. The data were collected between 1992 and 2011. (DARD/AFBI unpubl. data).

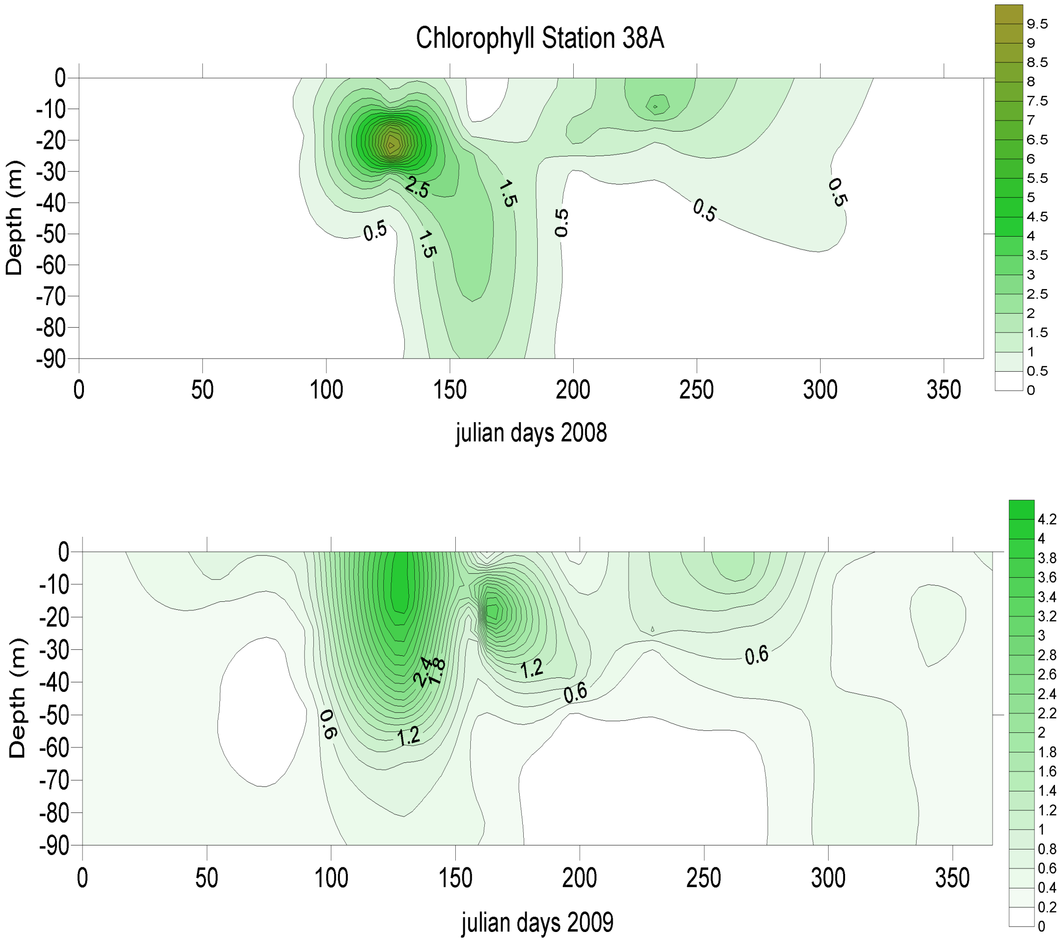


Figure 5.2: Contour plot of the seasonal chlorophyll cycle (mg m^{-3}) at mooring station 38A in 2008 and 2009. The contour levels are 0.5 mg m^{-3}. (from Scherer Ph.D. thesis 2012)

In the seasonally stratifying region of the western Irish Sea the microplankton production season begins in April/ May and coincides with the onset of stratification (Fig. 5.3). The relationship amongst sub-surface irradiance, mixed layer depth and the timing of the spring bloom in the western Irish Sea was investigated by Gowen et al. (1995) who found that a threshold mean surface mixed layer irradiance of between 183 and 245 Wh m^{-2} (equivalent to between 12.2 and 16.3 W m^{-2} for a day length of 15 hours, or 6 to 10% of daily irradiance) was required to trigger the start of the spring bloom.

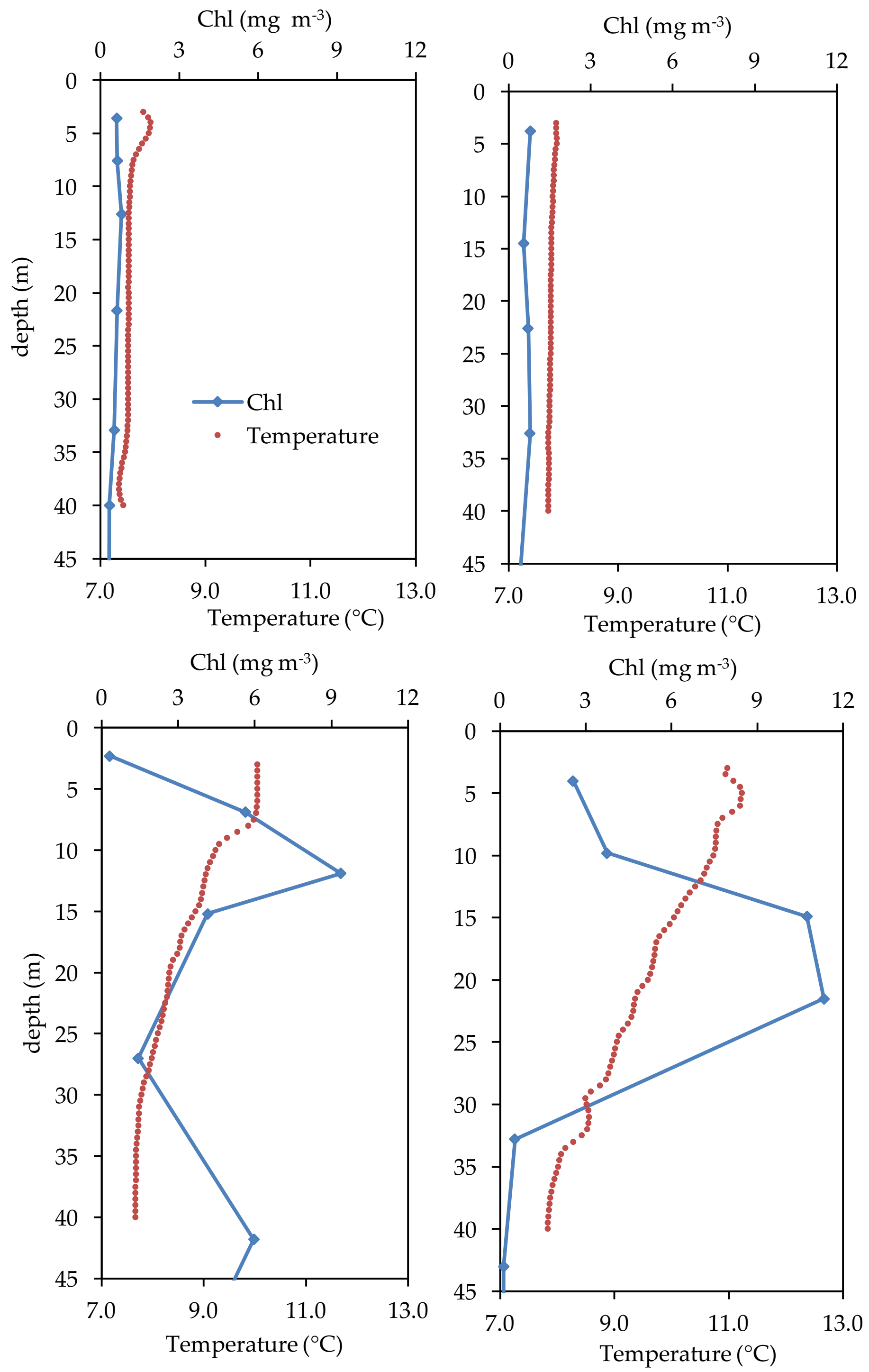


Figure 5.3: The relationship between thermal stratification (temperature in °C) of the water column and the development of the spring bloom (Chl = chlorophyll in mg m^{-3}) in the seasonally stratifying region of the western Irish Sea in 2001. (AFBI unpubl. data)

Based on data collected in 1992 and 1993, Gowen and Bloomfield studied the regional differences in the seasonal cycle of biomass and production in the western Irish Sea. These workers found what appeared to be a wave of production which appeared to begin in shallow (20 m) Irish coastal waters and extend first to the seasonally stratifying region and then to waters of the North Channel (Fig. 5.4). There were also differences in the duration of the production season which was longest (6 months) in Irish coastal waters, lasted 4-5 months in the summer stratified region and only ~3 months in the North Channel. Following the spring bloom, biomass in the surface mixed layer remains low (Fig. 5.1) although there is often a sub-surface peak in chlorophyll situated close to the thermocline. In early autumn, there is a small increase in biomass in some years (Fig. 5.1).

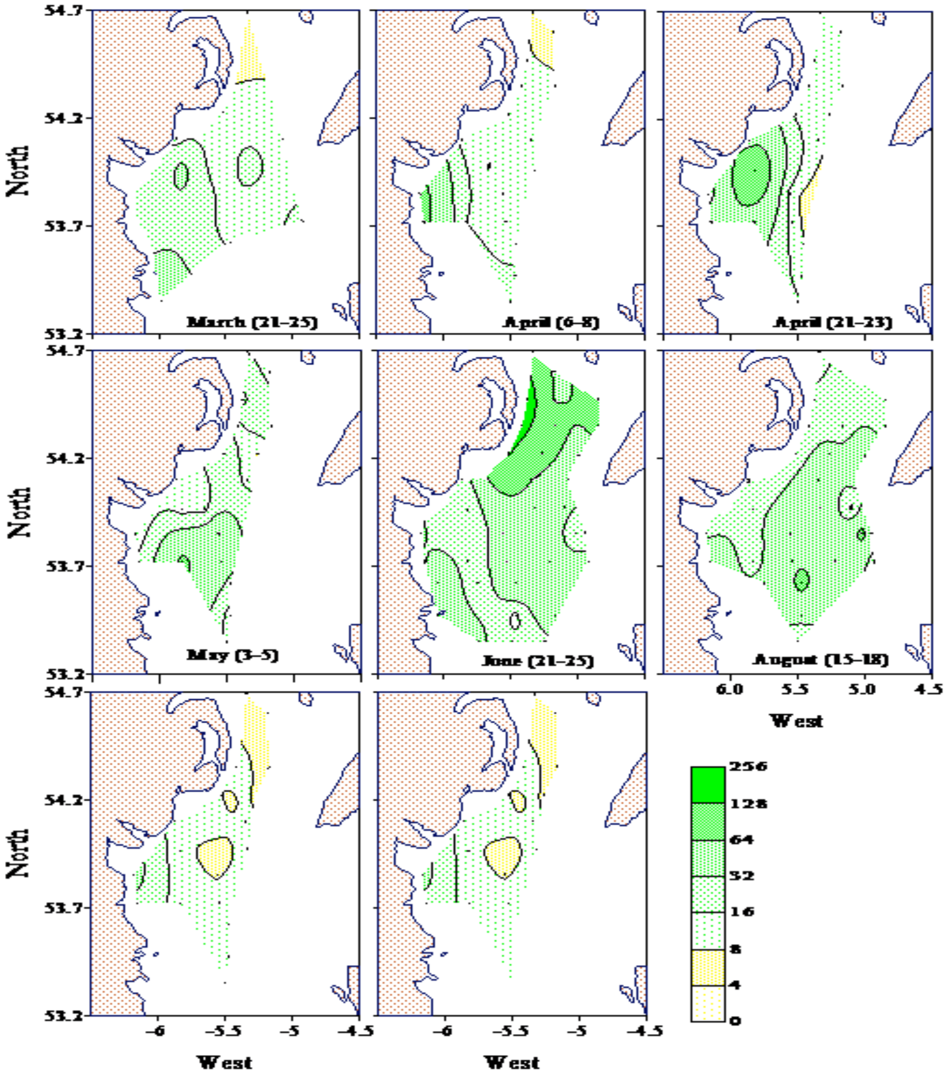


Figure 5.4: Contour plots of euphotic zone, chlorophyll standing stock (mg m^{-2}) in the western Irish Sea during 1992. (From Gowen and Bloomfield, 1996)

The differences in the length of the production season gave rise to regional differences in seasonal production. Gowen and Bloomfield (1996) gave estimates of 194 g C m^{-2} for seasonal production in Irish coastal waters; 140 and 194 g C m^{-2} for the summer stratified region and North Channel respectively. These estimates compare with only 96 g C m^{-2} given by Gowen et al (1995) for mixed waters to the south of the seasonally stratifying region. Scherer and Gowen (2013) combined more recent (2010 and 2011) data on carbon fixation to that from the earlier studies and derived an estimate of annual production of 204 g C m^{-2} y^{-1} with a range from 157 to 291 g C m^{-2} y^{-1}. The estimate of 204 g C m^{-2} for annual gross primary production appears reasonable compared to estimates from the North Sea. Gieskes and Kraay (1975) gave an estimate of 250 g C m^{-2} for the central North Sea and estimates of 119 and 199 g C m^{-2} for the southern and central North Sea respectively were given by Joint and Pomroy (1993).

5.3 Microplankton species abundance and composition

Changes in phytoplankton cell abundance and biomass (carbon) reflect the seasonal cycle of chlorophyll biomass (Fig. 5.5 and 5.6), with a spring increase, summer minimum and in 2009, an autumn bloom.

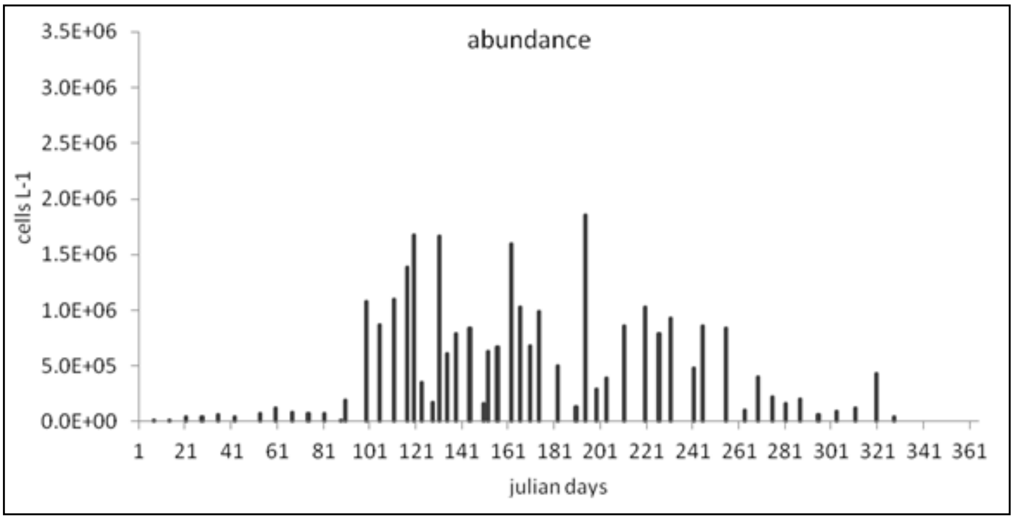


Figure 5.5: The seasonal changes in microplankton abundance (cells L^{-1}) in the western Irish Sea during 2009. (From Scherer PhD thesis, 2012)

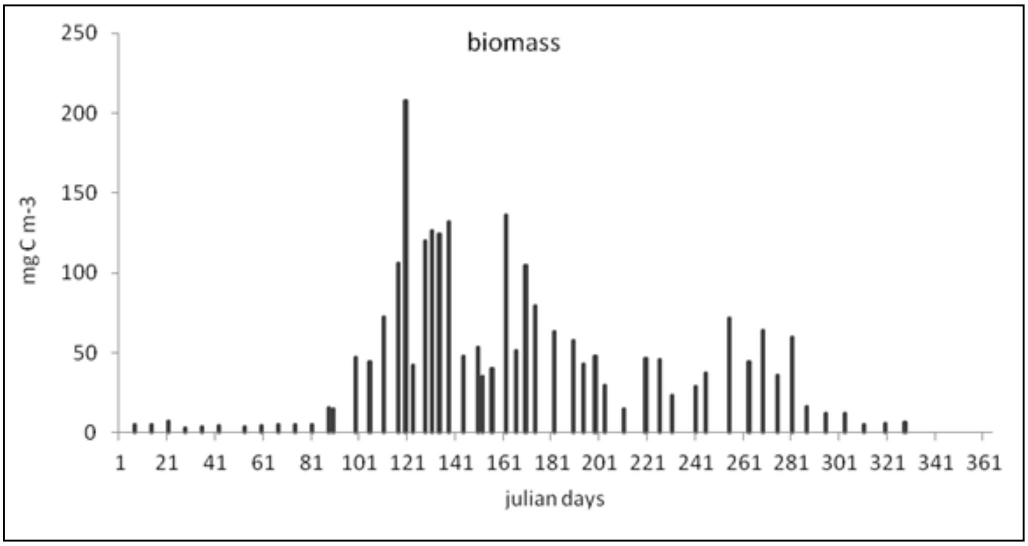


Figure 5.6: The seasonal changes in microplankton biomass (mg C m^{-3}) in the western Irish Sea during 2009. (From Scherer PhD thesis, 2012)

There are relatively few published studies of microplankton in the western Irish Sea and most of these have focussed on the spring bloom. Beardall et al. (1978) reported that the 1977 spring bloom was dominated by diatoms which declined in abundance during the summer and that micro-flagellates were present in high numbers throughout the year. McKinney et al. (1997) undertook a detailed study of diatom abundance at the AFBI mooring site (station 38A) between April and August 1995 and identified a total of 39 diatom species. *Skeletonema costatum* was the most abundant spring bloom species although species of *Chaetoceros, Pseudonitzschia*, and *Thalassiosira* formed an important part of the phytoplankton. Gowen et al. (1998) reported that in 1997 the spring bloom was dominated by microflagellates (≤ 10µm) and the silicoflagellate (*Dictyocha speculum*). Analysis by Scherer (2012) gave a total of 53 diatom species between April and August 2009. The dominant spring bloom species was *Guinardia delicatula*. Gowen et al. (2012) compiled data on the 10 most abundant spring bloom diatom species and found that there was considerable inter-annual variability in the most abundant spring bloom species (Table 5.1).

In general, dinoflagellates in the western Irish Sea appear to be most abundant and reach a higher biomass in summer and autumn (Fig. 5.7). The abundance of large dinoflagellate species of *Gymnodinium* and *Gyrodinium*, together with *Protoperidinium crassipes* and *Protoperidinium depressum* was highest during summer and autumn in 2008 and 2009 (Scherer 2012). There is therefore a succession of species in the western Irish Sea. Scherer (2012) divided the microplankton species into four functional-taxonomic groups: diatoms, dinoflagellates, microflagellates and ciliates and found that there was a marked seasonal succession of these four groups in 2009 (Fig. 5.7).

Diatoms dominated the spring bloom but were much less abundant during the summer. In contrast, dinoflagellates and microflagellate biomass increased during the summer, both in absolute amounts and as a proportion of the total microplankton abundance. Ciliates were a minor component of the microplankton community throughout the year, albeit with a slightly higher biomass in spring.

Table 5.1: The ten most abundant diatoms (cells mL^{-1}) during the spring bloom (April - May) in near-surface offshore waters of the western Irish Sea. (From Gowen et al. 2012)

Species	1995	1998	2000	2001	2002	2003
Asterionellopsis glacialis	2.6	-	-	-	-	-
Cerataulina pelagica	0.7	-	1.2	-	2.2	1.3
Chaetoceros spp.	17.4	2.2	282.9	0.2	250.2	705.0
Cylindrotheca closterium	0.8	0.7	1.1	-	-	0.4
Detonula spp.	-	-	0.9	-	-	-
Ditylum brightwelli	-	0.4	-	-	2.8	-
Eucampia zodiacus	-	-	0.5	-	-	0.4
Guinardia delicatula	0.5	0.2	9.0	0.1	38.5	2.3
Guinardia flaccida	-	-	2.1	-	0.9	-
Guinardia striata	-	-	-	-	-	0.6
Lauderia annulata	1.3	-	-	-	0.9	-
Leptocylindrus danicus	2.0	0.2	-	0.1	2.4	4.2
Leptocylindrus minimus	-	-	-	0.1	1.2	53.5
Paralia sulcata	-	0.1	-	-	-	-
Pennate diatoms (small)	-	0.3	-	0.1	-	-
Pseudo-nitzschia spp.	9.8	1.1	0.7	1.1	11.2	16.5
Rhizosolenia setigera	-	-	-	0.2	-	-
Rhizosolenia styliformis	-	-	0.4	-	-	-
Skeletonema (*costatum*)	173	-	-	3.0	-	-
Thalassionema nitzschiodes	-	0.2	-	0.1	-	-
Thalassiosira spp.	4.1	3.0	0.4	4.8	5.9	63.3

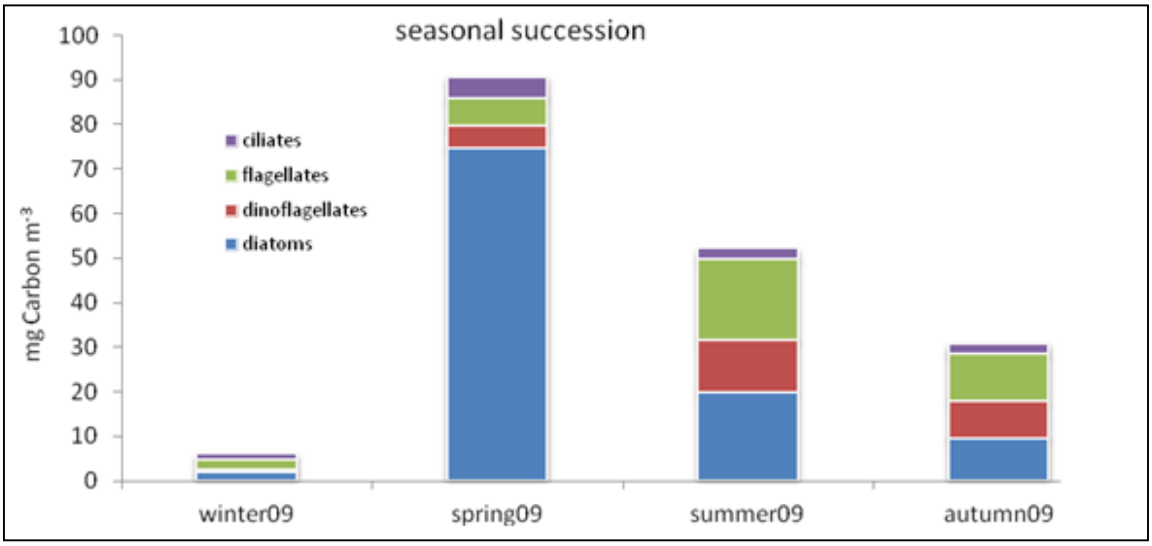


Figure 5.7: The seasonal succession of the four functional-taxonomic microplankton groups: diatoms, dinoflagellates, microflagellates, and ciliates. (From Scherer PhD thesis, 2012)

5.4 Long term trends

If as is generally accepted, nutrient availability (especially nitrogen) determines the level of production during the production season, then an increase in nutrients might be expected to result in an increase in primary production. From the preceding section it is evident that there has been a low level of enrichment (~3 µM N [nitrate + nitrite]) in the western Irish Sea and a small increase in phytoplankton production might therefore have been expected. This argument is consistent with an increase in spring (May-June) chlorophyll (~ 2 mg m^{-3}) reported by Allen et al. (1998) at the Isle of Man time-series station approximately 5 km off the south west coast of the Isle of Man. For the production season as a whole however, Allen et al. (1998) found no change in phytoplankton biomass In contrast, Lynam et al. (2010) reported that a step change increase in a phytoplankton colour index (a proxy for chlorophyll) took place in 1989. However, re-analysis of the Isle of Man data using data up to 2005 showed no significant trend (Gowen et al., 2008). Furthermore, Gowen et al. (2008) compared the Isle of Man chlorophyll data collected between 1966 and 1971 with more recent data from the western Irish Sea (Fig. 5.8) and concluded that there had not been any major changes in the seasonal pattern of phytoplankton biomass or elevation in biomass in the western Irish Sea.

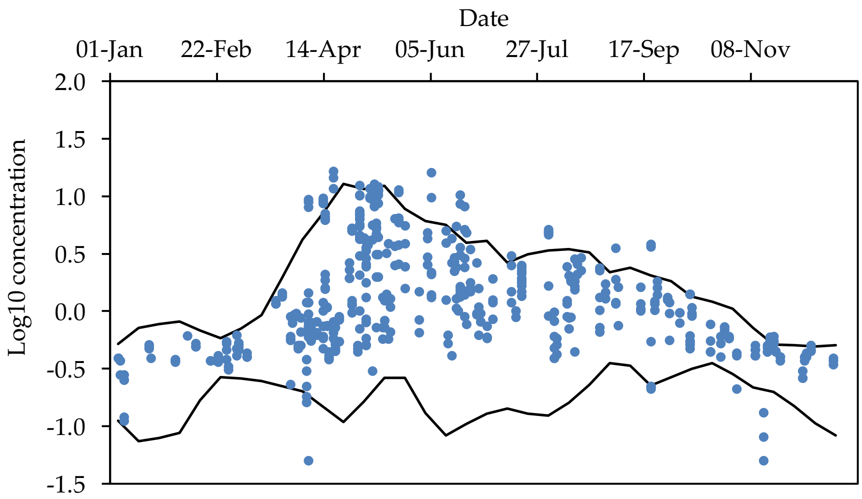
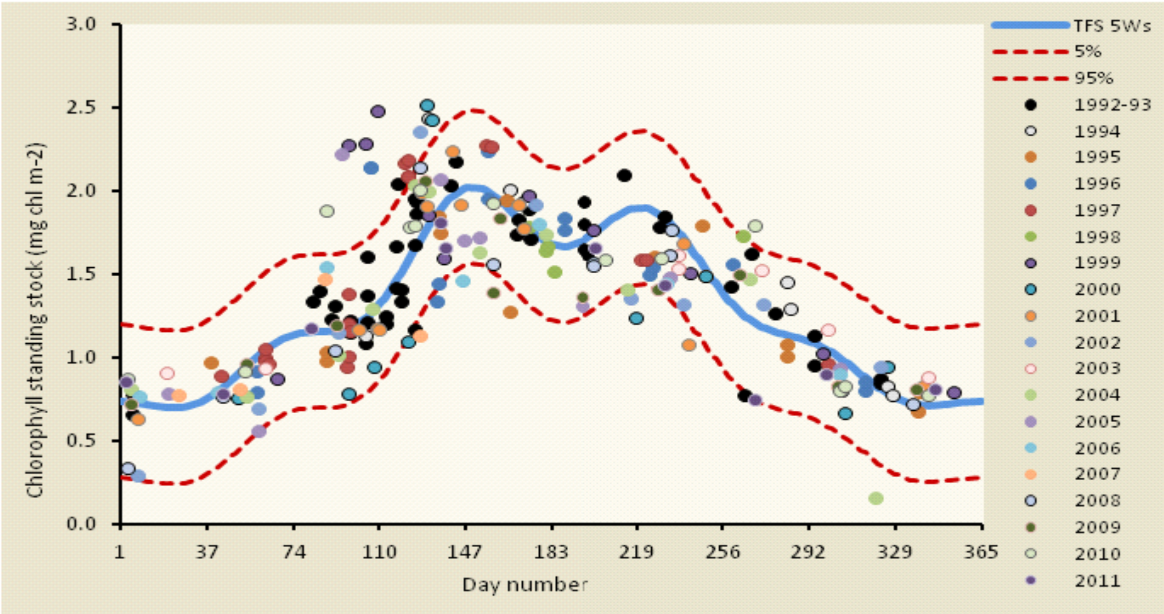


Figure 5.8: A comparison between the seasonal envelope of variability (solid lines) of chlorophyll (mg m^{-3}) from the Isle of Man time-series data (1966-1971) and more recent (1992 – 2004) data from the western Irish Sea (blue filled circles). (From Gowen et al., 2008)

Scherer and Gowen (2013) used the 1992 and 1993 chlorophyll and primary production data of Gowen and Bloomfield (1996) to define the seasonal cycle of biomass and production in the western Irish Sea (Fig. 5.9A and B). These seasonal envelopes of variability were used as reference envelopes against which more recent data were compared. On this basis, Scherer and Gowen (2013) concluded that there was evidence to show that the seasonal cycle and biomass of phytoplankton in the western Irish Sea has not changed over the last 20 years. The absence of a long-term trend of increasing nitrate concentration and the decreasing trend in DIP (Gowen et al., 2008) support the conclusion that there has not been a long-term increase in phytoplankton biomass in the western Irish Sea.



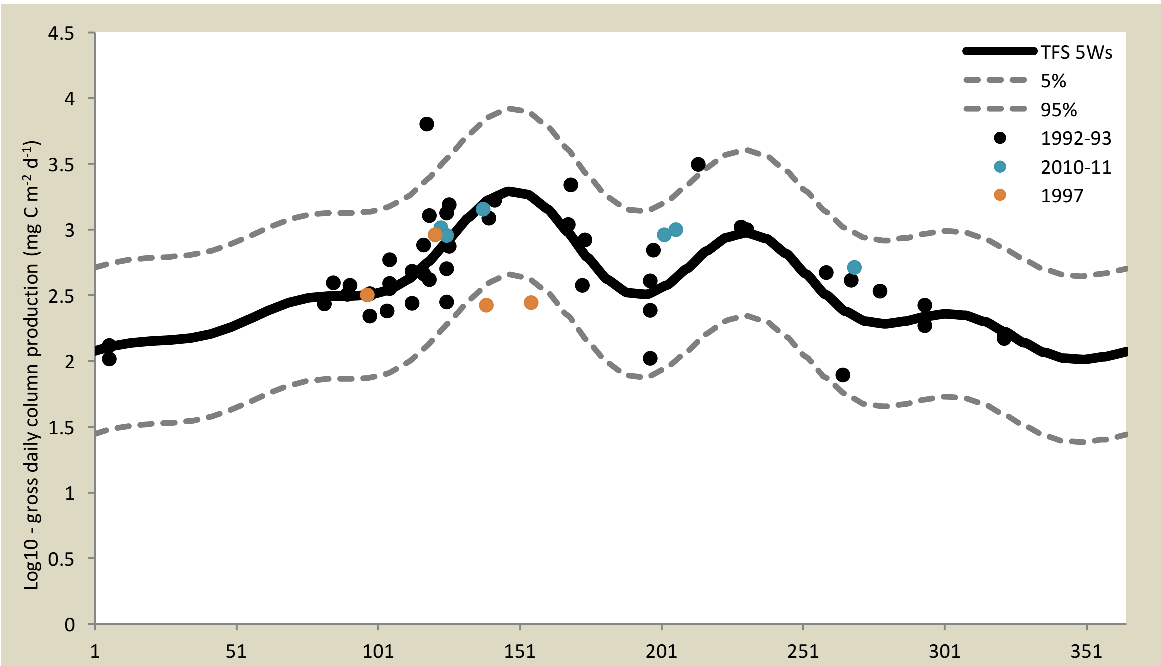


Figure 5.9: The annual cycle of chlorophyll standing stock (mg m^{-2}) (upper graph) and primary production (mg C m^{-2} d^{-1}) (lower graph) in the seasonal stratified offshore region (station 38A) of the western Irish Sea over the last 20 years. (DARD/AFBI unpubl. Data).

There are no time series data on microplankton species abundance or community structure with which to determine whether there have been any long-term changes.

5.5 Summary

There is a recurrent seasonal cycle of phytoplankton biomass and production in the seasonally stratifying region of the western Irish Sea. The production season typically begins with a spring bloom which coincides with the development of a shallow (25 m) surface mixed layer and thermal stratification of the water column in April/May. The production season lasts for up to 5 months; gross seasonal production is in the range of 101 - 140 g C m^{-2} and annual gross production is 204 g C m^{-2} with a range from 157 to 291 g C m^{-2}. The spring bloom is usually dominated by diatoms, although in some years the bloom has been dominated by microflagellates and silicoflagellate. There is a succession of functional groups, from diatoms in the spring to dinoflagellates and microflagellates in the summer and autumn. There is evidence to show that there have not been any changes to the onset and duration of the microplankton production season or the level of phytoplankton biomass in the stratifying region of the western Irish Sea at least since the early 1990s.

6. Zooplankton

The zooplankton are the animal component of the plankton, some are herbivores, feeding upon phytoplankton, while others are carnivorous feeding upon other members of the zooplankton. The zooplankton is comprised of a very wide range of organisms from planktonic copepods (~0.5 - 1 mm in size) to large zooplankton such as jellyfish (~ 0.5 m). Some commercial fish species and the Norway lobster *Nephrops norvegicus* have planktonic larval stages.

Zooplankton in the western Irish Sea is numerically dominated by copepods (Scrope-Howe and Jones, 1985) and small neritic species *Psuedocalanus elongatus, Acartia clausi Oithona similis* and *Temora longicornis* tend to be the most abundant (Gowen et al., 1998). The conspecific species *Calanus finmarchicus* and *Calanus helgolandicus* are generally less abundant than the small species (Gowen et al., 1998). Studies by Scrope-Howe and Jones (1985), Nichols (1995), and Dickey-Collas et al. (1996) showed that the summer stratified region in the western Irish Sea supports a higher biomass of copepods than the coastal and mixed waters of the western Irish Sea. Gowen et al. (1998) observed a seasonal cycle of copepod abundance (Fig. 6.1) which was closely coupled to that of phytoplankton biomass and production.

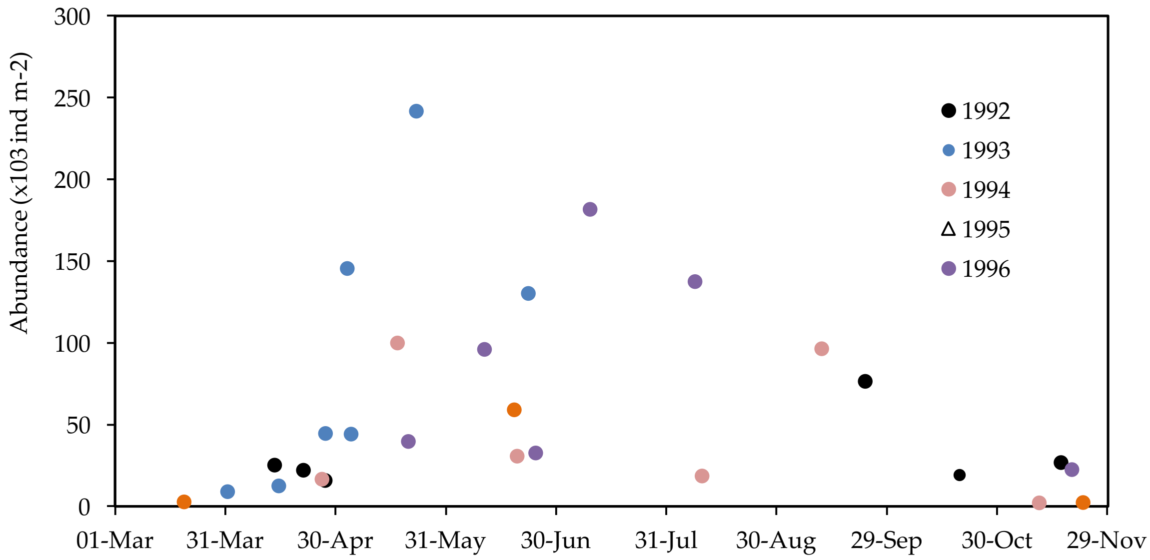


Figure 6.1: The seasonal abundance of planktonic copepods (x 10^3 individuals m^{-2}) in the western Irish Sea between 1992 and 1996. (From Gowen et al. 1998)

At certain times of the year, fish larvae (Dickey-Collas et al., 1996) and the larvae of *N. Norvegicus* (Hill, 2007) are an important component of the zooplankton in the western Irish Sea. Dickey-Collas et al. (1996) also found that the abundance of pelagic fish larvae was positively correlated with depth and the stratification parameter ϕ.

6.2 Long-term change in zooplankton

Kennington and Rowlands (2005) reported CPR data that showed the averaged copepod abundance (for nearly all species) in the Irish Sea has declined from the 1970s to the present. Lynam et al. (2010) also reported the decline in zooplankton. Lynam et al. (2010) further state that due to a rise in temperature since the 1980s the abundance of jellyfish and the importance in their role in the ecosystem has increased.

7. Energy flow through the food web

In the seasonally stratifying region of the western Irish Sea, the water is too deep for benthic plants, attached macro-algae (seaweeds) and benthic micro-algae to grow. Energy flow through the food web is therefore largely derived from phytoplankton production with transfer to both the pelagic and benthic components of the ecosystem. However, there have been few studies of energy flow through the food web in the

Irish Sea. The main studies that have been undertaken in the seasonally stratifying region are those by Gowen et al. (1999), Trimmer et al. (1999; 2003) and Hill (2007).

Gowen et al. (1999) attempted to quantify copepod grazing on the spring bloom and estimated that over the course of the bloom copepods grazed 22% of phytoplankton production. Towards the end of the spring bloom copepods grazed up to 76% of daily production.

The input of phytoplankton derived organic matter to the benthos was reported by Trimmer et al. (1999) who measured an increase in sediment chlorophyll and benthic oxygen consumption soon after the peak of the spring bloom. Hill (2007) also reported a close relationship between the seasonal pattern of chlorophyll in the euphotic zone and the increase of chlorophyll concentration in the bottom water (Fig. 7.1) as well as increased chlorophyll in the sediment. Based on measurements of sediment oxygen demand Trimmer et al (1999) estimated that 41 % of carbon fixed during the spring bloom settled to the seabed. More recently, Scherer and Gowen (2013), estimated the annual input of phytoplankton carbon to the benthos in the seasonally stratifying region of the western Irish Sea to be 17.2 g C m^{-2} and that the 2011 catch of Norway lobster (*Nephrops norvegicus*) represented 31% of the phytoplankton carbon which was available for animals at the third trophic level in the food web.

Further study is required to determine whether there has been any long term change in energy flow and the pathways by which energy is transferred through the food web.

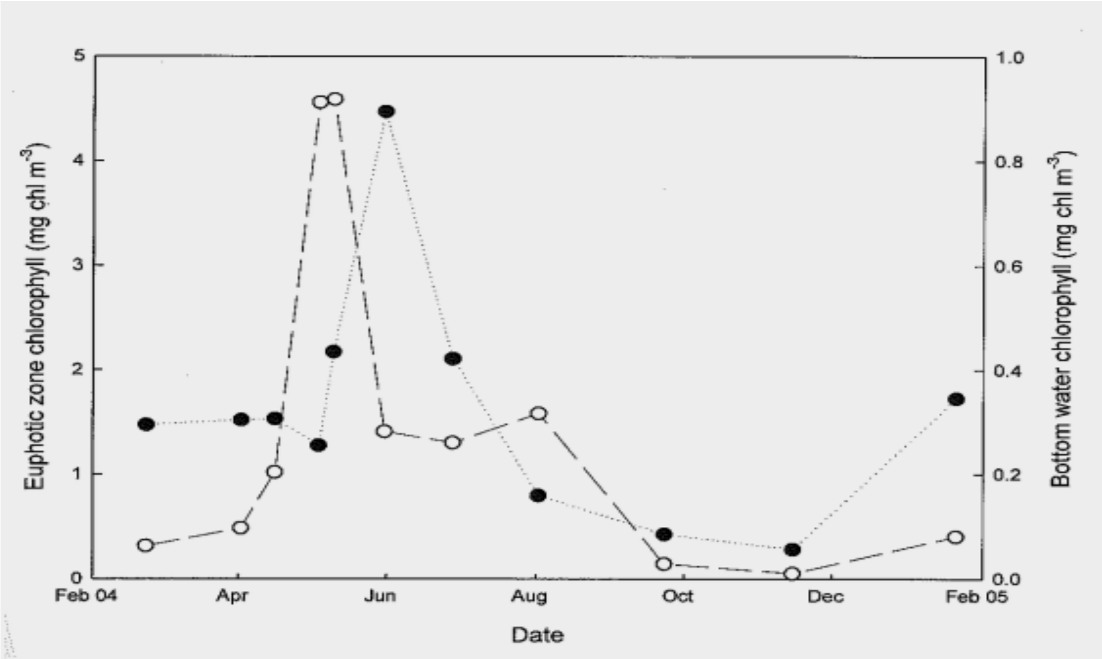


Figure 7.1: Chlorophyll concentration in bottom water (~85 m) (closed circles) and euphotic zone (0 – 23 m) (open circles) at Station 38A in the western Irish Sea from February 2004 to January 2005. (From Hill PhD thesis, 2007)

8. Assessing the state of the microplankton

8.1 Introduction

In preceding sections data on the physical and chemical oceanographic characteristics of the western Irish Sea and the microplankton have been presented. . In this section we have assessed the state of the microplankton by asking a series of questions using the data presented in the earlier sections to support our answers. For the assessment the ecohydrodynamic approach (see methods) was used. That is, the microplankton data from the western Irish Sea were analysed in the context of the structure and functioning of the planktonic component of the pelagic system. Finally, we used expert judgement to determine whether the status of the microplankton in the western Irish Sea is representative of good environmental status.

8.2 Does the western Irish Sea represent a distinct ecohydrodynamic region?

The answer to this question is *yes*. Within the western Irish Sea, water depth and weak tidal flows result in the development of seasonal stratification (Fig. 3.9). This is a recurrent annual event that typically begins in April (although the timing is variable: ± 3 weeks) and lasts for up to 5 months (Fig. 3.5, 3.8). Stratification results in a surface mixed layer of ~25 to 30 m (which corresponds to the depth of the euphotic zone) and isolates bottom water from the surface (Fig. 3.4., 3.9) The onset of stratification and the establishment of bottom density fronts (Fig. 3.12) sets up a cyclonic gyre of near surface water which retains seston within the region. The depositional nature of the seasonally stratifying region allows seston to settle to the seabed and facilitates close benthic/pelagic coupling.

8.3 Is the seasonal pattern of dissolved inorganic nutrients consistent with current understanding of biogeochemical cycling in shelf seas?

The answer to this question is *yes*. It is widely accepted that in most coastal waters, it is the availability of dissolved inorganic nitrogen (N) as ammonium (NH_4^+), nitrate (NO_3^-), and nitrite (NO_2^-) that is most likely to constrain phytoplankton growth (Ryther and Dunstan, 1971), although diatoms and silicoflagellates can be silicate limited. Nitrogen limitation is the expected situation in northern European marine waters, but in some locations, such as parts of the Baltic Sea, phosphorus (P) as dissolved inorganic phosphate (PO_4^{3-}) is considered to be the limiting nutrient (Andersson et al., 1996). Phosphorus limitation has also been demonstrated for the eastern Mediterranean (Krom et al., 2004).

There is a recurrent seasonal cycle of TOxN, DIP and Si with winter maxima (Fig. 4.4, 4.5), a rapid drawdown during the spring and summer minima (Fig. 4.4). The ratios of winter concentrations are similar to the Redfield ratios of 16:1, TOxN:DIP and 1:1 for TOxN:Si. The seasonal pattern observed in the western Irish Sea (Fig.4.4) is consistent with cycle of production and decay observed in temperate shelf seas: (i) uptake of nutrients by phytoplankton (in ratios close to Redfield) at the beginning of the production season; (ii) the isolation of bottom water which restricts the supply of new nutrients to the surface mixed layer during summer (Fig. 4.7); (iii) the re-establishment of winter concentrations as resupply exceeds uptake by phytoplankton. The depletion of TOxN before DIP and Si provides *prima facia* evidence of N limitation (Fig. 4.8) which is the expected norm in most Northern European waters outside of the Baltic Sea.

8.4 Is the seasonal cycle of microplankton production and biomass consistent with current understanding of the processes controlling microplankton biomass and production in shelf seas?

The answer to this is *yes*. The seasonal cycle observed in the western Irish Sea (Fig. 5.1) is similar to that observed in many temperate coastal seas and is consistent with the widely accepted theory that the sub-surface light climate (as a function of the solar cycle of radiation, mixed layer depth and attenuation) and nutrient supply are the two main factors that determine the seasonal cycle of microplankton biomass and production (Gran & Braarud, 1935; Sverdrup, 1953; Pingree et al., 1978; Smetacek et al., 1990; Tett, 1990).

In winter, wind and tidal stirring generally keep the water column vertically mixed and this together with short day length and low angle of the sun means that light limits microplankton growth.

As discussed in section 4, dissolved inorganic nutrients accumulate from different sources during the winter when microplankton growth is minimal. In early spring, increasing day length and angle of the sun lead to an increase in sub-surface irradiance. The development of seasonal stratification results in the formation of a shallow surface mixed layer and when irradiance in this level reaches a critical level, light ceases to be limiting for microplankton growth (Fig. 5.3). At this point, with nutrient concentrations in excess (i.e. above limiting concentrations), the production season begins.

The production season often begins with a burst of growth, the 'spring bloom (Marshall and Orr, 1927) and microplankton is most abundant in the euphotic zone (Fig. 5.2). Production exceeds losses from algal respiration, grazing and sinking and biomass accumulates. However, this event is short lives and as nutrients become depleted, growth slows, the loss terms exceed the rate or new biomass production and biomass decreases (Tamigneaus et al., 1999). During the summer there is limited resupply of nutrients and production is based on regenerated production (Dugdale and Goering, 1967). In the post-spring bloom period, nutrients are recycled through heterotrophic/autotrophic linkages involving the microbial loop (Azam et al., 1981; Malone et al., 1988; Rivkin et al., 1996; Tamigneaux et al., 1999). In autumn, wind mixing can cause a deepening of the thermocline and the entrainment of nutrients into the surface mixed layer. This new nitrogen often triggers an 'autumn bloom' (Fig. 5.5, 5.6).

In the western Irish Sea the burst of growth and rapid increase in biomass (the spring bloom) observed at the beginning of the production season in April/May is a recurrent event (Fig. 5.1, 5.9). Spring bloom biomass can reach levels of up to 16 and 23 mg chlorophyll m^{-3} (Gowen and Bloomfield 1996) and this spring increase coincides with the drawdown in inorganic nutrients. The seasonal production season lasts for five months in the summer stratified regions of the western Irish Sea and in some years a late summer/autumn bloom is apparent triggered by wind mixing that provides new nitrogen from deeper layers. By October microplankton growth has decreased and chlorophyll levels remain low during winter.

8.5 Is the succession of species in the western Irish Sea consistent with what is expected for a seasonally stratifying temperate shelf sea?

The answer to this is *yes*. In the seasonally stratifying region of the western Irish Sea there is a succession of species from diatom such as *Skeletonema costatum* and *Guinardia delicatula* and species of *Chaetoceros, Pseudonitzschia* spp. and *Thalassiosira* spp. which typically dominate the spring bloom (Table 5.1). This is followed by a period of increased dinoflagellate abundance (*Protoperidinium crassipes* and *Protoperidinium depressum* together with species of *Gymnodinium* and *Gyrodinium*) during the summer. The summer assemblage is replaced in autumn by a second diatom dominated assemblage although the dominant species (*Rhizosolenia* spp., *Eucampia zoodiacus, Paralia sulcata*) are different from the spring species. Microflagellates appear to be abundant throughout the production season the western Irish Sea (Fig. 5.7).

This seasonal pattern has been widely reported from different coastal and shelf seas in temperate regions of the world (see review by Smayda, 1980). In the warm temperate waters of the Mediterranean Sea, Margalef (1963; 1967) identified four stages of succession, with each stage characterised as follows:

- small, colony forming flagellates and diatoms like *Skeletonema* and *Chaetoceros*;
- medium to large sized chains of diatoms (e.g. species of *Thalassiosira* and *Guinardia* and small to medium sized dinoflagellates like *Ceratium* and *Prorocentrum*;

- large, cylindrical celled diatoms like *Rhizosolenia* and an increasingly larger dinoflagellate population;
- large motile dinoflagellates dominating the biomass and micro-flagellates representing the highest abundance

Kilham and Kilham (1980) argued that Margalef's fourth stage of succession was rarely if ever reached in temperate coastal and estuarine and waters because the duration of seasonal stratification is too short for the fourth stage to develop. In the western Irish Sea, stratification lasts for ~5 months and Scherer (2012) concluded that the late summer early autumn assemblage was consistent with Margalef's stage 3. Kilham and Kilham (1980) also pointed out that microflagellates are often numerically the most abundant group of species. Jones and Gowen (1980) found that microflagellates were numerically the dominant lifeform in coastal waters around the British Isles but that abundance was not related to the irradiance and stratification regime. Microflagellate abundance in the seasonally stratifying region of the western Irish Sea appears to follow the same pattern. They were generally abundant and numerically dominant throughout the production season (Scherer, 2012).

The pattern of seasonal succession observed in the seasonally stratifying region is consistent with the generally accepted theory that variation in the supply of external energy in the form of light, turbulence and nutrients are the main factors controlling the seasonal composition and succession of microplankton (Margalef, 1978; Smayda, 1980; Reynolds, 1996; Peperzak et al., 1998; Escaravage et al., 1999; Smayda and Reynolds, 2001; Tett et al., 2008). Tilman et al. (1982) and see also (Officer and Ryther 1980; Tett et al. 2003) proposed three broad factors influencing microplankton succession:

- physics: utilisation of differences in the capacity of species or lifeforms to grow in physical environments that differ especially in their vertical mixing intensity;
- nutrient ratios: the relationship between the ratio of nutrient elements needed for growth and the ambient ratio of these elements;
- grazing: variable loss rate due to grazing by protozoans or zooplankton that preferentially take some species or lifeforms rather than others.

8.6 Does the microplankton in the western Irish Sea support higher trophic levels?

The answer to this question is *yes*. Studies by Gowen et al. (1998; 1999) show that during the late 1990s the seasonal peak in copepod abundance occurred in spring (Fig. 6.1) and was after the spring bloom of phytoplankton.. Grazing by copepods accounted for up to 76% of daily gross primary production and overall, 22% of gross spring bloom production.

There is close coupling between the water column and the benthos. Trimmer et al. (1999) observed the seasonal deposition of pelagic production in the benthos in the western Irish Sea and found an increase in sediment phytodetritus and a pulsed increase in benthic oxygen consumption soon after the peak of the spring bloom. Hill (2007) reported a close relationship between the seasonal pattern of chlorophyll in the euphotic zone and the increase of chlorophyll concentration in the bottom water as well as increased chlorophyll in the sediment (Fig. 7.1).

A number of studies show that there is close coupling amongst the seasonal development of stratification, the seasonal cycle of plankton and the plankton life history stages of some higher trophic level animals. White et al. (1988) suggested that the cyclonic gyre of near surface water in the western Irish Sea acts as a retention mechanism for plankton. Dickey-Collas et al. (1996) observed spatial and temporal differences in the distribution and abundance of the larvae and 0-group stage of pelagic fishes. Spawning takes place in shallow inshore waters where there is an early spring bloom (Gowen et al. 1996) but later in the year fish larvae were more abundant in the offshore stratifying region where the spring bloom and peak copepod abundance occur later (Gowen et al. 1996; 1998). Finally, Hill (2007) observed close coupling between the onset of stratification, the timing of the spring bloom and the appearance of larval *Nephrops* in near surface waters of the stratifying region.

8.7 Is the western Irish Sea enriched with anthropogenic nutrients?

The answer to this question is *yes*. The western Irish Sea is enriched with TOxN, DIP and Si relative to near ocean waters at the Celtic Sea shelf break. The Si enrichment is probably natural because rock formations in the UK and Ireland are rich in silica. However, a comparison between the Isle of Man data from the early 1960s and data collected by DARD and AFBI (2000-2004) shows that there has not been any change in the seasonal pattern of TOxN and Si cycling in the western Irish Sea over the last 40 years (Fig. 5.8). The level of TOxN enrichment is low (about 2-3 μM) and the available data indicate that prior to anthropogenic nutrient enrichment, the western Irish Sea may have been nutrient poor (5-6 μM). Salinity mixing diagrams suggest that the level of TOxN enrichment should be much higher (~15 μM) given riverine nitrogen loadings (Fig. 5.3) but most of the additional nitrogen is lost from the western Irish Sea by sediment denitrification.

Analysis of the Isle of Man long-term nutrient data set (IOM) shows that median winter (January and February) concentrations of TOxN have been stable since the mid-1970s and that the median winter concentration of DIP has decreased since 1989.

8.8 Has there been a long-term change in phytoplankton phenology and biomass?

The answer to the first part of the question is *no*. There is evidence of inter-annual variation in the timing of the spring bloom (Fig. 4.6) but a comparison between data from the late 1960s (Isle of Man time-series) and data collected by DARD/AFBI between 1992 and 2004 (Fig. 5.8) and between DARD/AFBI data collected between 1992-1993 and between 1994 and 20 (Fig. 5.9), shows that there has not been a long-term change in the seasonal pattern of phytoplankton biomass.

The answer to the second part of the question is more equivocal. Since the western Irish Sea exhibits a low level of enrichment, if nutrient availability (especially nitrogen) determines the level of production during the production season then a small increase in production is likely to have occurred. This argument is consistent with the significant increase in spring chlorophyll reported by Allen et al. (1998). The more recent study by Lynam et al. (2010) identified an increase (step change) in the CPR phytoplankton colour index which occurred in 1998. However, a comparison between Isle of Man chlorophyll data collected between 1966 and 1971 and more recent data from the stratifying region of the western Irish Sea does not show this increase (Fig. 5.8).

8.9 Does the state of the microplankton in the western Irish Sea represent good environmental status (GES)?

At the present time it is not possible to provide a definitive answer to this question but we conclude that the state of the microplankton in the western Irish Sea is representative of GES. As noted above, until there is a better understanding of what represents GES and how it can be determined objectively for the plankton, it is necessary to use expert judgement to determine whether the state of the plankton was representative of good environmental status. We have attempted to interpret the microplankton data in the context of the ecohydrodynamic conditions in the western Irish Sea: conditions to which the microplankters might be expected to be adapted. In our opinion any anthropogenic perturbation of the microplankton in the western Irish Sea has been minimal and the data presented in this report are consistent with current scientific understanding of microplankton dynamics (seasonal patterns of biomass, production and species) and the factors that control these dynamics in temperate coastal waters and shelf seas.

9. Establishing reference conditions

9.1 Introduction

Having concluded that the microplankton in the seasonally stratifying region of the western Irish Sea is representative of GES, the next step is to use the data to establish reference conditions against which future change can be quantified in the western Irish Sea and which can be used as reference conditions for other seasonally stratifying regions in UK waters.

The plankton experiences an inherently variable environment largely as a result of seasonal and day-to-day variability in weather and water movement. This is particularly true in UK seas, which are for the most part tidally energetic and subject to fluctuating weather conditions as well as seasonal weather patterns. As a consequence, the plankton exhibits variability on a range of spatial and temporal scales and the assemblage of species and populations of individual species are not fixed in time and space but are dynamic. Overlaying this variability there are higher-order constancies: the recurrent annual cycle of phytoplankton growth in coastal waters (Tett and Wallis 1978; Smayda, 1998; Gowen et al., 2008); the succession of lifeforms in seasonally stratifying coastal seas (Margalef, 1978). Despite these higher order consistencies, detecting changes in planktonic communities due to human pressures or climate is not easy. Any method must be capable of quantifying the natural dynamic variability of plankton populations and take account of the seasonal succession of some species.

One obvious approach to characterising the microplankton is simply to list the abundances of all the species present. However, O'Neill (2001) argued that defining ecosystems using species lists was inherently problematic and there is an obvious practical difficulty in that any such list might comprise hundreds of species. It is doubtful therefore that simple lists of species or thresholds of abundance of individual species would adequately discriminate between natural variability and human pressure driven change. In one sense the problem with species lists and data on abundance is that there are often too many data.

There does not seem to be any single species of plankton that can be used as a universal indicator of the condition of the plankton. There are several reasons for this. First, no single species of pelagic animal or plant has a controlling effect on the plankton as a whole. Second, the spatial heterogeneity of the plankton community means that the species important in one region, or under one set of hydrodynamic conditions, may be rare in another region. The third reason is that putative relationships between particular organisms and specific pressures have often been based on limited or over-interpreted evidence (e.g. the use of harmful species of phytoplankton as indicators of eutrophication Gowen et al. 2012).

Gowen et al. (2011) reviewed methods of detecting change in the plankton. Biodiversity indices (Shannon, 1948) or multivariate statistics (Edwards, 2005) have proven to be powerful tools in analysing microplankton data. Devlin et al. (2007) proposed a phytoplankton index (I_E) to classify and assess the UK marine waters under the requirements of the WFD. An alternative method based on the use of plankton lifeforms (assigning groups of species to plankton lifeforms summarises large amounts of information on plankton species without losing information on seasonal fluctuations in species abundance) and system state space theory was introduced by Tett et al. (2008). Of several methods available, Gowen et al. (2011) recommended the latter to Defra as the most useful for detecting long-term changes in the status of the plankton in UK waters for the purposes of the MSFD.

9.2 The lifeform state space approach

The plankton community index (PIp) approach is based on the phytoplankton community index (PCI) introduced by Tett et al. (2007; 2008). A detailed description is also given by Gowen et al (2011). The approach builds on the idea of defining an ecosystem state space in terms of values of state variables, in this case plankton lifeforms (see Margalef, 1978) and mapping the abundance of lifeforms into a multidimensional "state variable space". The main features of the method are: the grouping of species of planktonic organisms into lifeforms; the display of changes in the abundance of each of these lifeforms using a state-space approach (Fig. 9.1);

calculating an index (PI) to quantify possible changes in the state of the plankton relative to baseline or starting conditions (Fig. 9.1).

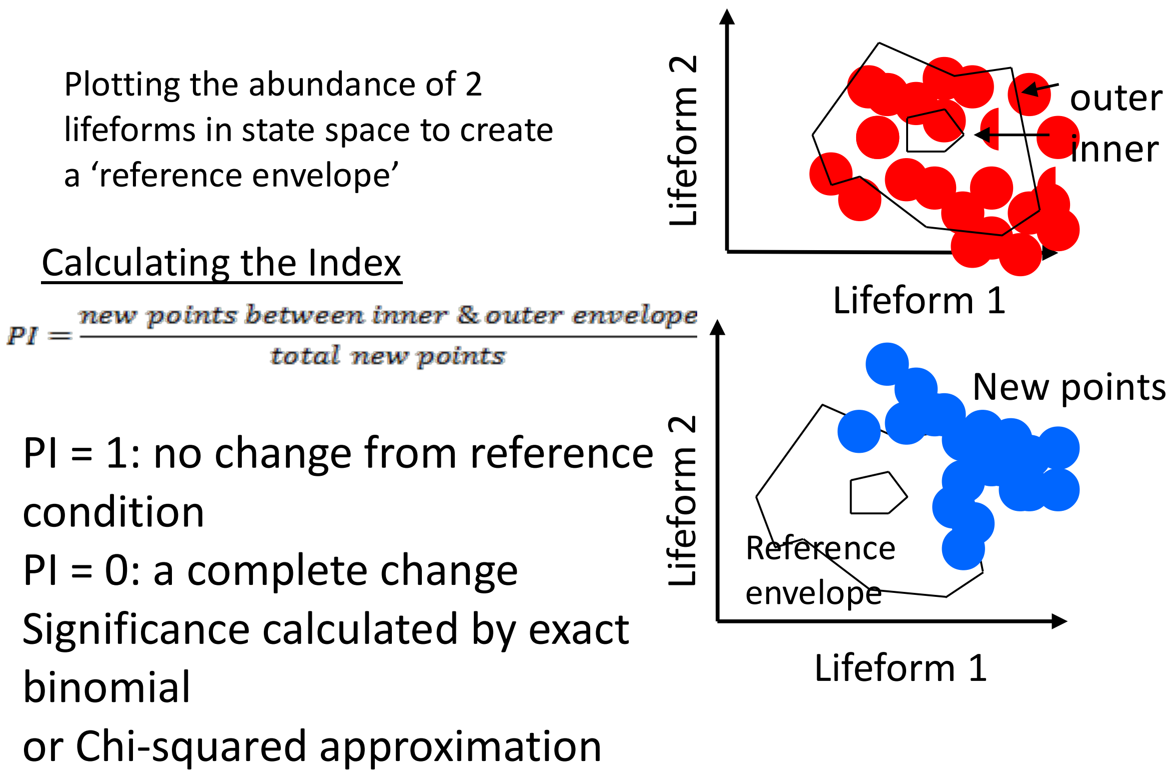


Figure 9.1: Mapping the abundance of lifeforms in state space and calculating an index to quantify changes in the state of the plankton relative to a baseline. Note the term reference envelope does not imply pristine conditions or that the plankton community is representative of GES.

The choice of lifeforms is clearly important. In some cases a lifeform can be based on biogeochemical or ecological function and can include organisms from different taxa. Sieburth et al. (1978) proposed that the best way to place species into useful groups was to ignore taxonomic hierarchies and to separate species into groups based on the level of organisation and the mode of nutrition. Ryther & Officer (1981) listed seven phytoplankter types which they ranked from the most beneficial (centric diatoms) to the most undesirable (bluegreen algae or cyanobacteria). Smetacek (1986) separated tychopelagic diatoms for the large heavily silicified centric diatoms of shallow turbulent waters which are equally capable of living on the sea bed. Riegman (1998) distinguished large diatoms, small diatoms, haptophyta, dinoflagellates, mixotrophic algae and cyanobacteria by ecophysiological properties shared with other members of the same taxonomic group. Lee et al. (2003) distinguished microplankton on their silicate requirement i.e. silicate users and non-silicate users.

Other developments in lifeform theory were reviewed by Tett & Wilson (2003) based on function and taxonomy. Tett & Wilson (2003) distinguished groups of factors that could identify and distinguish lifeforms in relation to ecosystem sustainability. There are five examples:

- Their functionality in relation to biogeochemical cycling of bio-limiting elements like C, N, P, Si, S, O and perhaps Fe and Co. There are two levels that could explain variations in microplankton composition here.
- The first one is qualitative, and concerns the distinctions between algae that require silica and those that do not. The second level is quantitative, and concerns the idea of optimum ratios of nutrient elements required for growth which may differ amongst lifeforms.
- The functionality of organisms in relation to the marine foodweb. Distinction here was made between prey as primary producers (e.g. diatoms) and predators (e.g. ciliates, some dinoflagellates and flagellates).
- The relationship to the physical environment (e.g. turbulence, velocity, light) as considered by Margalef (1978).
- Taxonomy with differences between for example, organisms possessing thick silical cell walls (e.g. diatoms) or cellulose theca (e.g. armoured dinoflagellates) and those that lack these (e.g. naked dinoflagellates, microflagellates).

The development of the state space plots is illustrated in Fig. 9.2. The first step involves mapping each pair of data points for lifeform 1 (LF1) and lifeform 2 (LF2) into the state space plot. The plot can be considered as a map created by co-ordinates as LF1 and LF2 are independent from each other. An elliptical shape like a `doughnut' appears due to the natural succession of lifeforms (see Fig. 9.2).

A geometric method known as Convex Hull (Sunday, 2004; Weisstein, 2006) is applied to the cloud of the data points with a certain data exclusion (here 90% of the data were considered), drawing an outer envelope. According to Tett and Mills (2009) limitation theory suggests that the bundle of microplankton data points should have a hollow centre. To create this hollow centre, an inner envelope is established by applying the Convex Hull method to the centre points turning them inside-out and once the envelope is also drawn around them, they are re-inverted again. The procedure is illustrated in Fig. 9.2.

9.3 Assigning species to lifeforms

The selection of lifeform pairs relevant to the planktonic component of MSFD descriptors D1 (Biological diversity), D4 (Food web), D5 (Eutrophication), and D6 (Sea floor integrity) was discussed by Gowen et al. (2011) and lifeform combinations for each of the above descriptors were presented by Gowen et al. (2013) and are shown in Table 9.1.

At present there are insufficient data from the seasonally stratifying region of the western Irish Sea to prepare reference envelopes for all of the lifeform pairs in Table 9.1. However, there are sufficient data to allow reference envelops to be created for the following:

- Biological diversity: Diatoms and dinoflagellates were chosen as lifeforms because they are evolutionary distinct groups with different attributes and general biology.
- Food webs: Large (<20μm) and small (>20μm) phytoplankton were chosen because the size of different phytoplankters reflect different pathways of energy flow through the food web. Eutrophication: Three reference envelopes have been created for this descriptor.
    - Diatoms and auto/mixotrophic dinoflagellates: a shift in community composition could appear towards potentially harmful groups.
    - Microflagellates and ciliates: indicative for a shift from an autotrophic to a more heterotrophic system.
    - *Pseudo-nitzschia* spp. and potentially toxin producing dinoflagellates: indicative of a shift in algal community towards harmful dinoflagellates.
- Sea floor integrity: Pelagic and tychopelagic diatoms were chosen because they can be indicative for seabed disturbance.

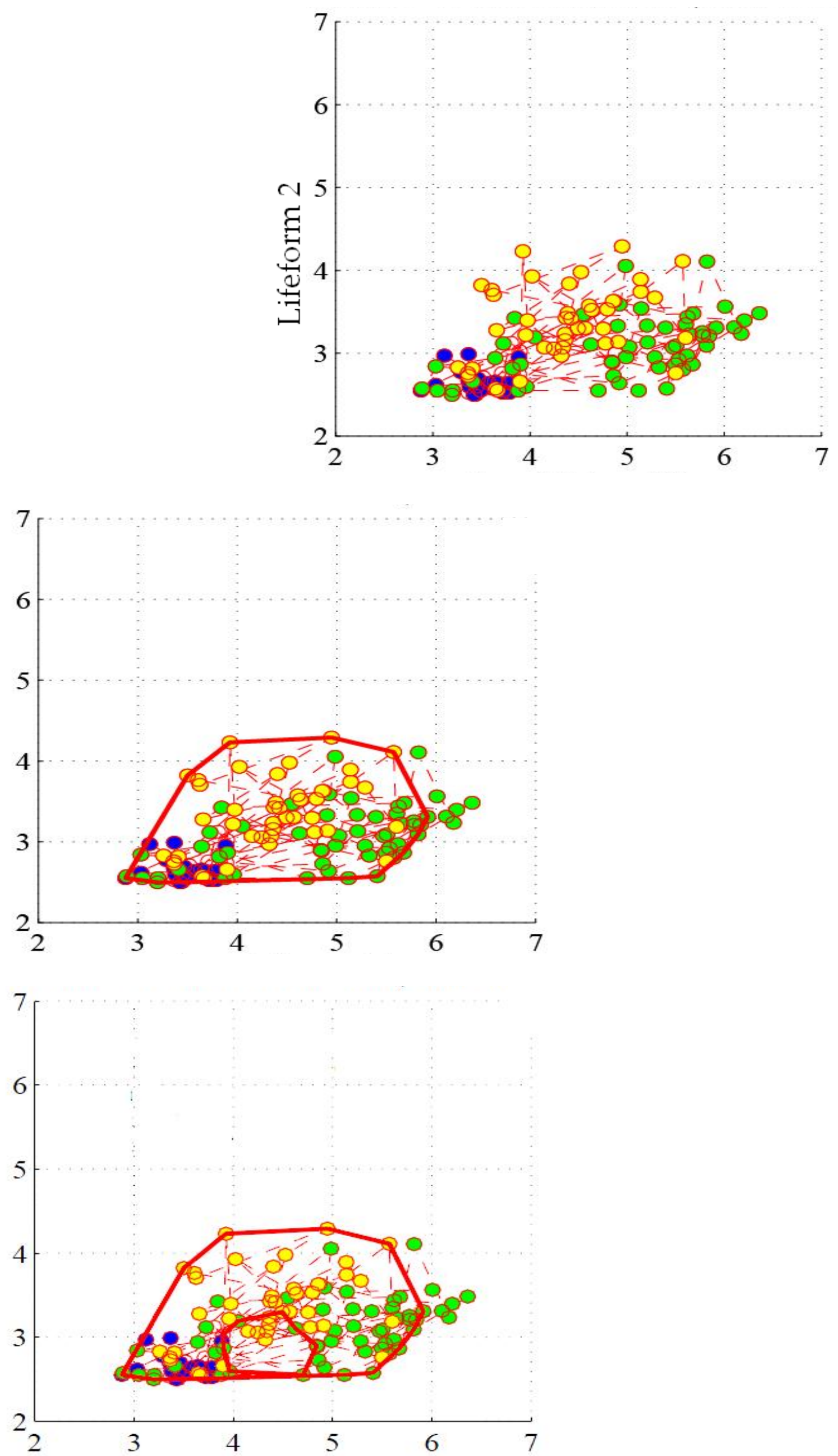


Figure 9.2: An illustration of the development of the state variable space plot in three steps fitting an outer and inner envelope around the data points of the state variables (lifeform 1 and 2).

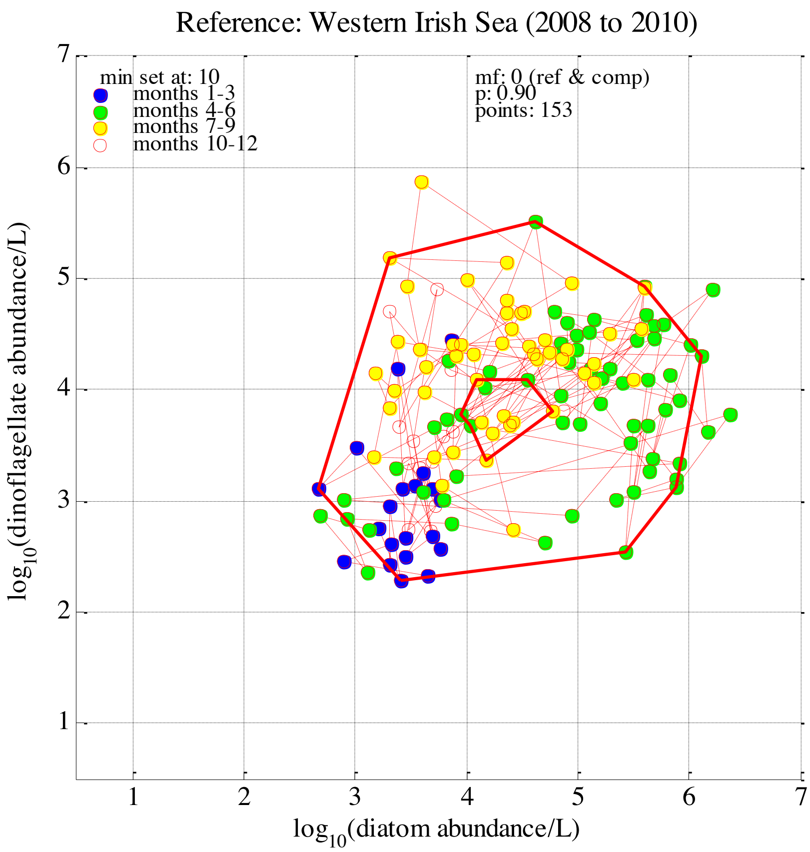
Table 9.1: A revised set of lifeform pairs for the MSFD Biodiversity, Food web, Eutrophication and Seabed integrity descriptors

Descriptor	Lifeform pair 1		Lifeform pair 2		Lifeform pair 3	
D1: Biodiversity	Diatoms	Dinoflagellates	Gelatinous zooplankton	Fish larvae	Holoplanktonic crustaceans	Non gelatinous and non crustacean holoplankton
Lifeform feature(s)	All diatoms	All dinoflagellates	Ctenophores & Coelenterates	Excluding fish eggs	Excluding eggs	
Reasoning:	Evolutionary distinct groups		Indicators of alternative ecosystem states		Evolutionary distinct groupings that capture all holoplankton not included in Lifeform pair 2	
Pressure(s):	Nutrient enrichment; change in hydrographic conditions		Fishing		Fishing; Nutrient enrichment	
D4: Food-webs	Phytoplankton	Zooplankton	Large phytoplankton	Small phytoplankton	Large copepods	Small copepods
Lifeform feature(s)	Chlorophyll (mg m^{-3})	Abundance (m^{-3})	> 20 µm	< 19.9 µm	> 2 mm	<1.9mm
Reasoning:	Energy flow		Energy transfer from primary to secondary producers		Benthic-pelagic coupling	
Pressure(s):	Fishing		Fishing		Fishing; Nutrient enrichment	
D5: Eutrophication	Diatoms	Dinoflagellates	Ciliates	Microflagellates	Pseudo-nitzschia spp.	Toxin producing dinoflagellates
Lifeform feature(s)	All diatoms	Autotrophs and mixotrophs	Including tintinids	All species < 20 µm	Excluding P. delicatissima	All species on the Food Standards Agency list (Table 4)
Reasoning:	Shift in community composition towards harmful groups		Shift from autotrophic to heterotrophic system		Shift in algal community towards dinoflagellate HABs	
Pressure(s):	Nutrient enrichment		Nutrient enrichment		Nutrient enrichment	
D6: Sea floor integrity	Holoplankton	Meroplankton	Pelagic diatoms	tychopelagic diatoms		
Lifeform Feature(s)	Excluding fish larvae		All species			
Reasoning:	Benthic-pelagic coupling		Seabed disturbance			
D1.7: Biodiversity Ecosystem Structure				All lifeform pair combinations.		
Reasoning:	Changes in these lifeforms provide a comprehensive overview of the structure and functioning of the planktonic component of marine ecosystems.					
Pressure(s):	Fishing; nutrient enrichment; aquaculture, industrial spills (e.g. oil, contaminants); river damming; seabed disturbance (inc. contaminant re-suspension); renewable energy; warm water outflows; ocean acidification					

The reference envelopes for the seasonally stratifying region of the western Irish Sea are presented in Fig. 9.3, 9.4, 9.5, and 9.6.

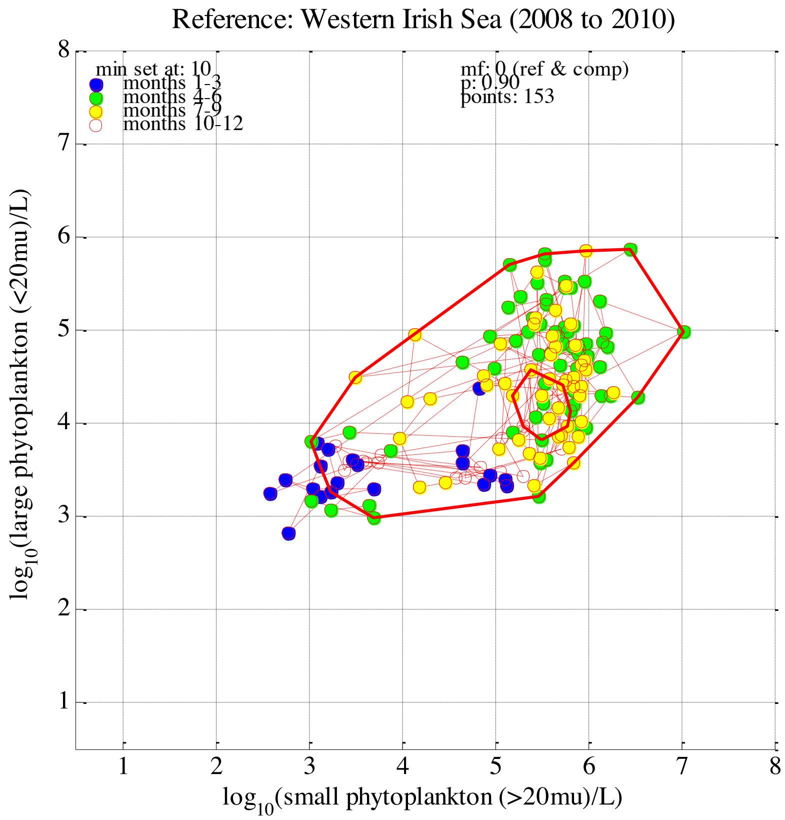
9.3.1 Biodiversity descriptor (D1)

Lifeform pair: diatoms and dinoflagellates



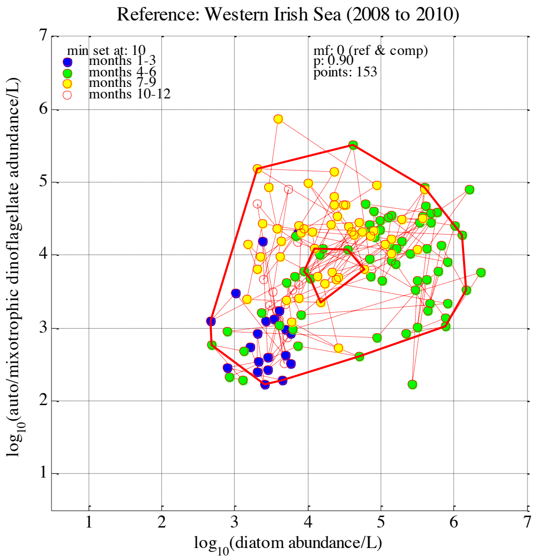
9.3.2 Food web descriptor (D4)

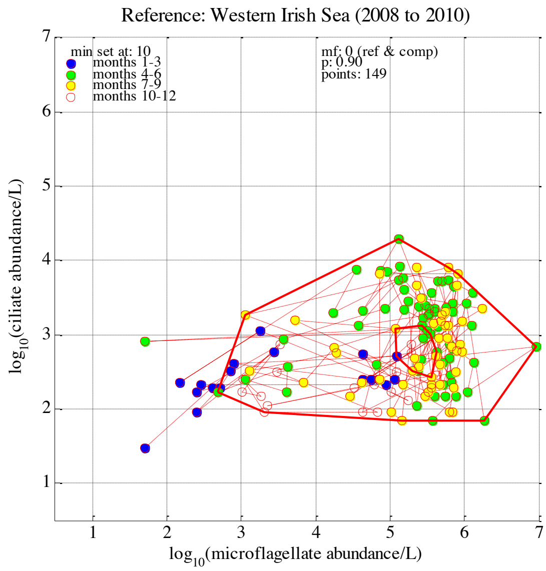
Lifeform pair: large (<20μm) and small (>20μm) phytoplankton.

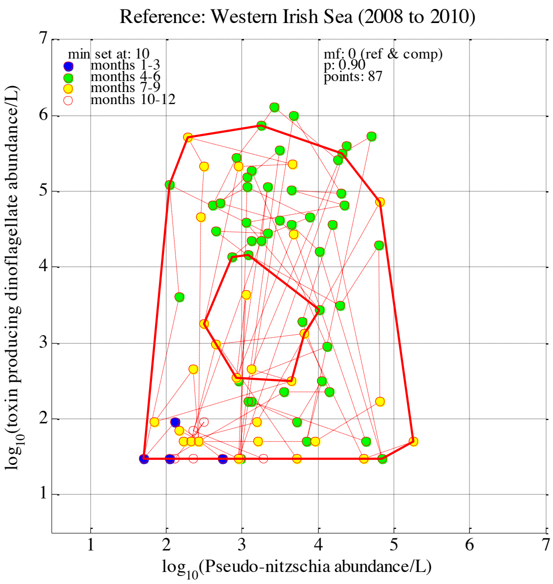


9.3.3 Eutrophication descriptor (D5)

Lifeform pairs: i) Diatoms and auto/mixotrophic dinoflagellates; ii) microflagellates and ciliates; iii) *Pseudo-nitzschia* spp. and potentially toxin producing dinoflagellates

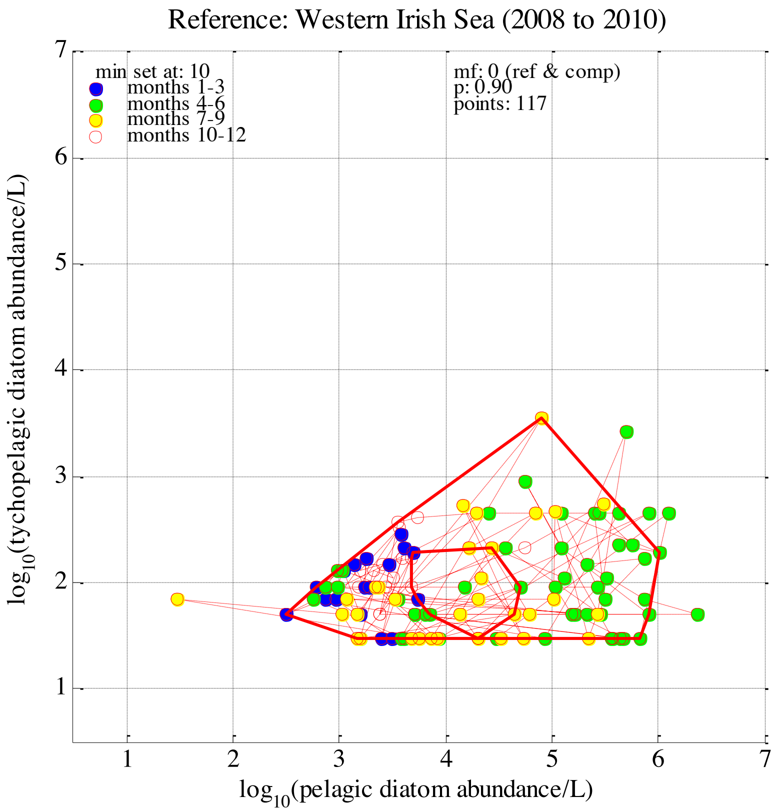






9.3.4 Sea floor integrity descriptor (D6)

Lifeform pair: Pelagic and tychopelagic diatoms



10. Conclusions

- The state of the microplankton in the seasonally stratifying region of the western Irish Sea was assessed using an ecohydrodynamic region approach.
- The physical and chemical oceanographic data show that the deeper offshore region of the western Irish Sea is a distinct ecohydrodynamic region (seasonally stratifying) which is subjected to a low level of anthropogenic nutrient enrichment.
- The start and duration of the microplankton production season is determined by the sub-surface light climate and the level of seasonal production is controlled by nutrient availability. The species that make up the microplankton community are typical for a seasonally stratifying water body and succession from diatoms and microflagellates in the spring to dinoflagellates in the summer to diatoms in autumn is a recurrent event in seasonally stratified regions in temperate shelf seas. We conclude that the condition (state) of the microplankton in the western Irish Sea is representative of GES. There has not been any obvious influence of top down or bottom up pressure driven change in microplankton structure over the last 20 years.
- Lifeform-state space reference envelopes have been created for the planktonic component of MSFD descriptors: Biodiversity (diatoms and dinoflagellates), Food webs (large (<20µm) and small (>20µm) phytoplankton), Eutrophication (diatoms and auto/mixotrophic dinoflagellates; microflagellates and ciliates; *Pseudo-nitzschia* spp. and potentially toxin producing dinoflagellates), and Sea floor integrity (pelagic and tychopelagic diatoms).
- These reference envelopes can be used to track future change in the microplankton in the seasonally stratifying region of the western Irish Sea and to provide reference conditions for other seasonally stratifying regions in UK coastal and shelf seas.

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