Development of a 2D horizontal biogeochemical model for the Irish Sea DYMONIS

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DYMONIS is a numerical model designed to test the interaction of processes linking increased inputs of nutrients to possible increases in phytoplankton production (eutrophication). Originally developed for the North Sea, it has been applied to the Irish Sea. A basic process, which must be modelled before more complex ones, is represented by the salinity field, which passively traces the mixing of river and sea water. To fit the observed data, this requires a 1.5-fold increase in the current estimate of rain inputs. This is reasonable, given the uncertainty in estimates of such inputs. Comparison with model output of observed salinities from the long-term data series from the Isle of Man “Cypris” station shows that real weather effects on circulation have a greater effect on salinity than probable changes in river discharges. Nutrient concentrations are determined by the mixing of river and ocean waters, removal by autotrophic organisms and return from detrital phases. The model shows that the minimum nitrate concentration in winter in the southern Irish Sea is a consequence of the varying balance of these processes with time. It can be demonstrated that long-term increases in the concentration of nitrate off the Isle of Man could be a simple artefact of the increase in river and atmospheric inputs and of the essentially estuarine nature of the Irish Sea.

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Introduction

The Irish Sea is a relatively small (2430 km³) and landlocked marine area. Exchange with adjacent shelf waters is restricted and the residence time of water is about one year. It is bounded by the land masses of the UK and Ireland and receives a significant input of fresh water. Short-term studies have shown that both Irish (Dundalk Bay and near shore) and UK (Liverpool Bay) coastal waters are enriched with nitrogen and phosphate (Foster, 1984; Gillooly et al., 1992) and a recent UK study (Jonus, 1999) concluded that enrichment had increased phytoplankton production and standing stock in Liverpool Bay. Nutrient data collected since 1954 by the University of Liverpool, Port Erin Marine Laboratory (PEML) in the more open sea waters off the Isle of Man, show an increase in winter (January and February) of concentrations of nitrogen (nitrate and nitrite) and phosphate (Allen et al., 1998). The work reported here was carried out to gain insight into the possible nutrient enrichment of the Irish Sea by using a numerical model which was relatively simple, but which has been well established with respect to its ability to model long-term features of the distribution of point source inputs from land into the North West European shelf sea system (Prandle, 1984; Jones and Howarth, 1995; Hydes et al., 1996). The model developed by Tappin et al. (1997) was also based on the same hydrological and biogeochemical models (Jones and Howarth, 1995; Tett and Walne, 1995). It has successfully been used to simulate the winter concentrations and distributions of trace metals in the North Sea.
We have adapted the Dynamic Model of Nutrients for the North Sea, DYMONNS (Hydes et al., 1996) to the Irish Sea, hence DYMONIS (Dynamic Model of Nutrients in the Irish Sea). The modular nature of the DYMONIS FORTRAN code meant that the model was adapted in a step-wise process. Firstly, the components of the physical model were modified, and this part of the model was run separately until the results for the salinity fields were satisfactory. Secondly, data relevant to the biogeochemical processes modelled by DYMONIS were introduced. This yielded a model which can be used to reproduce seasonal cycles of phytoplankton dynamics. However, this will not be discussed further in this paper.

The lack of a comprehensive data set for the Irish Sea meant that the data required for both boundary and initial conditions and forcing were initially derived from the data set used for DYMONNS. These data come from the Natural Environment Research Council North Sea Project (NSP) data base. For boundary conditions, the NSP boundary data for the northern most and southern most latitudes covered in DYMONNS were spatially averaged and applied in DYMONIS. This latitudinal mean for the north and south boundaries yielded one value applied in each boundary cell of DYMONIS. However, time variations (in model timestep interpolated increments) exist because 12 monthly measurements are available from the NSP data. Initial conditions were provided as area-wide averaged NSP data. Thus, each model gridpoint starts with the same value per variable. One exception is the salinity, which was derived from an hydrodynamic model of the Irish Sea (see below). The forcing functions are grazing pressure, irradiance and solute exchange across the sediment. The grazing pressure is derived from western Irish Sea data provided by R. Gowen (Department of Agriculture Northern Ireland, DANI) for the year 1996 and varies monthly. Daily irradiance for 1996 is derived from the Bidston meteorological station and solute (oxygen, nitrate, ammonium) exchange is the NSP spatial average for each month. This gross approximation of parameters and conditions for the Irish Sea was necessary to show that the model could run and produce reasonable output. Data have been gathered in the Irish Sea in the past few decades by different agencies and organizations, and the data sets that exist tend to be spatially and temporally patchy (Radach et al., 1995; Simpson and Rippeth, 1998). Among them, an exceptional data set is the “Cypris” data set collected off the Isle of Man (location shown on Fig. 1) by the Port Erin Marine laboratory (PEML) of the University of Liverpool. This contains hydrographic and nutrient data from 1954 and data are still being collected (Allen et al., 1998). These data and the observed changes within it provide an interesting test data set against which to examine the output from the DYMONIS model.

Figure 1. The model area of DYMONIS is made up of 36 rows and 29 columns, hence 1044 cells, of which 634 are non-land cells and 24 are boundary cells. The cells are 1/12° in latitude and 1/8° in longitude, i.e. approximately 8 x 8 km². The position of the PEML “Cypris” station is shown.
Three stages of the work are discussed here, concentrating on the distribution of nutrients during the winter and the implications of this work:

- Stage 1: Setting up DYMONIS (following the North Sea work) to run to a steady state from year to year with winter distributions of salinity and nutrients similar to those observed in the Irish Sea (e.g. Bowden, 1980).
- Stage 2: Assessing the possible causes for the observed lack of change in nitrate concentrations with salinity observed at higher salinities in the Irish Sea in winter (e.g. Foster, 1984; Gibson et al., 1997).
- Stage 3: Assessing the rate of change of nitrate concentrations in the “Cypris” long-term data set in relation to likely changes in anthropogenic inputs to the Irish Sea (Allen et al., 1998).

Models have to be developed with a clear task in mind. If the task is well defined, judgement becomes more objective. Output from models is often described as being “satisfactory” or as “accurately” reproducing an observed data set without providing a numerical measure of “satisfactory” or “accurately”. It is possible to judge the success of a model by measuring the deviation between the output of the model and suitable observations. This is only valid if account is taken of the degree to which the model contains “free parameters” which can be adjusted to minimize the deviation. The use we are making of the DYMONIS model is the visualization of the coupling of processes which control nutrient concentrations and which vary both in space and time. More detailed processes such as plankton patchiness and density-driven flows can be represented in some recently developed models, at some cost in terms of currently available computing power (Luyten et al., 1999). The aim here is not so much to reproduce precisely a particular feature occurring at certain points in time, as could be done with a more powerful and carefully parameterized model, but rather to rank the importance of the processes included in the model and to explore the interaction of processes which occur on different time and space-scales. This can be done with a relatively crude model such as DYMONIS, to a degree which is compatible with the currently sparse availability of data from the Irish Sea.

Description of the model

DYMONIS is an adaptation for the Irish Sea of a model initially developed for the North Sea (Hydes et al., 1996) that couples a 2D advection diffusion model to a 1D biogeochemical submodel. The driving forces for the physical framework developed by the Proudman Oceanographic Laboratory (POL, Jones, 1991; Jones and Howarth, 1995; Prandle, 1984) are tidal and time (monthly) varying meteorological residuals. Tidal and wind generated currents control advection, whilst diffusion is controlled only by tidal action. Salt and biogeochemical variables are treated as passive tracers by this advection–diffusion model. The DYMONIS domain covers the Irish Sea between 52.2°N and 55.2°N. Grid cells are 1/2° latitude by 1/8° longitude, ca 8 x 8 km² (Fig. 1). The time step is 6 h.

The 1D biogeochemical submodel is adapted from the model described by Tett (1990) and Tett and Walne (1995). The 2D physical framework used for DYMONIS implies that the water column is assumed to be well mixed and is represented in Tett’s model by a single layer. The assumption that the water column is well mixed throughout the year is a limitation of the model in the western Irish Sea, which is seasonally stratified (Gowen et al., 1995; Pingree and Griffiths, 1978). The biogeochemical processes are described through the cycles of seven state variables. These are: dissolved oxygen, nitrate and ammonium, microplankton and detrital nitrogen, and microplankton and detrital carbon. Microplankton is defined as organisms less than 200 µm in size and includes autotrophic (algae and bacteria) and heterotrophic (protozoa and bacteria) organisms. Detritus represents particulate organic material which is formed from dead microplankton and undigested material in zooplankton faecal pellets. Oxygen is produced by photosynthesis and consumed by respiration. The exchange of oxygen with the atmosphere is dependent on water temperature and wind speed. The simulation of the carbon cycle is limited to organic carbon. Microplankton carbon is produced by photosynthesis and converted to detrital carbon by grazing (messy feeding). Microplankton die and carbon is subsequently mineralized to CO₂ by heterotrophs and bacterial activity; CO₂ is a sink for carbon. Microplankton nitrogen is produced during growth by uptake of nitrate or ammonium and converted to detrital nitrogen at the death of organisms. Detrital nitrogen is mineralized to ammonium, which can be oxidized to nitrate or taken up during phytoplankton growth. Nitrogen:carbon ratios link organic nitrogen to organic carbon. Sediment processes are not modelled. Exchange of inorganic nitrogen and fluxes of oxygen across the sediment water interface is forced by functions derived from field measurements taken during the NSP programme. The resuspension of sedimented detritus is uncoupled from the deposition of water column detritus concentration and is derived from fixed, time invariant concentrations in the sediment (data taken from the NSP programme). All processes simulated by the biogeochemical model are schematized in Figure 2. Detailed description of the corresponding equations can be found in Tett (1990) and Tett and Walne (1995). Parameters values are taken from Hydes et al. (1996). The model is run to steady state when annual cycles for
each variable are identical in consecutive years. Steady state is generally reached within five model years.

Results and discussion

Stage 1: salinity fields

In the first stage of the model development, it was necessary to check that the physical framework of the model was performing adequately and that no numerical errors had been introduced when the code was adapted to fit the geographical boundaries of the Irish Sea and when the size of the grid cells was set to $8 \times 8$ km$^2$. The variable chosen to check the validity of DYMONIS results in the first instance was salinity. Salinity can be considered to be a passive tracer of riverine and atmospheric inputs of fresh water. The model results were compared to an output of the western European general purpose model from Proudman Oceanography Laboratories (POL, J. E. Jones, pers. comm.; Jones and Howarth, 1995) and observed distributions of salinity (Bowden, 1980; Allen et al., 1998), which are variable and dependent on prevailing wind patterns (Bowden, 1980).

DYMONIS model software code was considered to be running satisfactory once the model had reached steady state, when the salinity fields satisfied two conditions: first, that the DYMONIS salinity field corresponded to the POL salinity field (Fig. 3) to within 0.1 unit over most of the modelled area; second, that the modelled January salinity at the “Cypris” station must be equal to 34.2, the average winter salinity measured at “Cypris” between 1954 and 1996. The salinity output was initially too high over most of the modelled area (Fig. 4a), but was found to be acceptable if the rainfall parameter was increased by a factor of 1.5. In their model of salinity distribution in the North Sea, Jones and Howarth (1995) found that a similar adjustment of the NERC North Sea Programme rain estimate was required to get the best fit of model and observed distributions. This is equivalent to an average rainfall of 60 cm per year over the whole area of the Irish Sea. This modification of the rainfall data is reasonable as, on the one hand, the set up data used was from the NSP data set, and on the other hand, uncertainties in estimating the rainfall at sea are high. Figure 4b shows that DYMONIS winter salinity agrees with the output from the POL model over most of the model area, but DYMONIS results are lower near the river mouths. This reflects the fact that in DYMONIS river flows are varied monthly, with greatest values in winter, whereas the POL salinity field was calculated with constant river flow throughout the year. Consequently, the POL model had relatively less riverine inputs in winter compared to the situation described by DYMONIS.

The sensitivity of the modelled salinity distribution to changes in salinity at the boundaries was tested. The salinity was increased in all boundary cells by 0.5 units. This resulted in an increase in the DYMONIS January salinity field of about 0.5 units in the whole model domain except near the river mouths where freshwater influence dominated. When the salinity was increased by 0.5 units in the southern boundary cells only, the
DYMONIS January salinity field increased by more than 0.4 units, except north of 54.5°N. These results reflect the known hydrography of the Irish Sea, which is dominated by inputs of high salinity oceanic waters coming into the sea from the south through Saint Georges Channel. Inputs of oceanic water through the North Channel are known to occur but are more limited and infrequent (Dickson and Boelens, 1988; Knight and Howarth, 1999).

Sensitivity to riverine inputs was then evaluated. When the river flow was multiplied by 1.5, the salinity in the eastern and in the central part of the Irish Sea was significantly lowered (Fig. 4c). This is readily understood as these areas are away from oceanic influence and because the three main rivers that flow into the Irish Sea, the Eden, the Ribble and the Mersey, flow into the eastern part of the sea, which is shallower (average depth 10 m) than the western Irish Sea (average depth 42 m with a maximum at 171 m).

The output (Fig. 3) reproduces the general features of the salinity distribution in the Irish Sea. The gradient of salinity observed between the boundaries and the eastern Irish Sea is the result of the general circulation pattern: oceanic water enters the Irish Sea through St Georges Channel and flows northward, mixing with the fresh water riverine inputs, most of which are in the eastern Irish Sea. The salinity south west of the Isle of Man is close to 34.2, the average January value measured at station “Cypris” between 1960 and 1997. Overall, the POL salinity field compared reasonably well with the mean salinity field shown in Dickson and Boelens (1988), but because of the constant south west wind used to drive this version of the model, the tongue of relatively high salinity often seen in the western Irish Sea (Bowden, 1980; Dickson and Boelens, 1988) is not reproduced in the model. Varying the total volume of fresh water entering the Irish by a factor of two, to represent the likely range in flows between wet and dry years, only changes the salinity in the “Cypris Box” by 0.2 salinity units. This is true both when the model is run to steady state with different fresh water flows or when the fresh water flow is alternated from one year to the next in the model. The actual salinity at the “Cypris” site in winter varies by about 1.2 (Fig. 5), even though this station is far from major point sources of fresh water. These variations are probably caused by changes not only in rainfall and in riverine inputs, but also in winds, which force higher salinity water containing a large fraction of oceanic water to reach the centre of the Irish Sea. The model results and their variations discussed above fall well within, but are small compared to, the range of observations shown in Figure 5. A model which reproduces the observed range of salinity would need to include hydrographic flows driven by observed weather (wind) data as well as observed river flows and rainfall.
Stage 2: nitrate concentrations in winter

Having established a model which provides a stable representation of the salinity field, the biogeochemical model was implemented into DYMONIS. This used “North Sea average data” for concentrations of the initialization fields. River inputs are based on the known flows compiled from the Institute of Hydrology reports (Anon., 1996). Nitrate concentrations based on Environment Agency data (Peter Jones, pers. comm.) were used for all British rivers (300 μmol l⁻¹) and the nitrate concentrations in Irish rivers was set at 100 μmol l⁻¹ (Gibson et al., 1997). Sediment inputs were initially taken as the spatial average of North Sea observations (Nedwell et al., 1993). Both aerosol and wet inputs of nitrate and ammonium from the atmosphere are the temporal and spatial means of that used in DYMONNS and derived from Rendell et al. (1993). With this set up, the model ran to steady state in 5 years, but the winter nitrate concentration field was low (less than 4 μmol l⁻¹) in the central Irish Sea compared with observations (greater than 10 μmol l⁻¹, Gowen et al., 1995). The main cause of the deficit was identified as being high loss to sediments. Tests showed that the winter nitrate concentration was increased if the description of nitrogen flow from detritus was changed so that all nitrate deposited on to the sediment was returned to the water column within two months. This is a simple way to simulate recycling but is consistent with observations (Gibson et al., 1997). Gibson et al. (1997) concluded that as the water travels slowly northwards, some nitrogen is added from the land and the atmosphere, some is presumably lost by denitrification, but the bulk of nitrogen is regenerated and undergoes one or two cycles before flowing out via the North Channel.

The model reproduces a significant feature of the Irish Sea which is the non-conservative relationship between salinity and concentrations of nitrate at high salinities (Gibson et al., 1997; Foster, 1984). Measurements reported by Foster (1984) of samples collected in December 1975 show a clear discontinuity in the nitrate–salinity relationship at a salinity of 32.5, above which there was a small increase in the concentration of nitrate in the samples. More recent data from the western Irish Sea (Gibson et al., 1997) show the same tendency, as does the data from the UK Environment Agency’s survey in the eastern Irish Sea in January 1996 (Fig. 6).

In the model output this feature is reproduced as a minimum in the field of nitrate concentrations which occurs towards the southern boundary of the modelled area in winter (Fig. 7). The minimum occurs in that area because of its physical isolation from major sources of...
When a steady state is reached, line AEB will be and ocean sources, and are regenerated from detritus. Nutrient (E) will gradually disappear as nutrients are dispersed along the concentration gradients from river and ocean sources, and are regenerated from detritus. In summer in open waters on the shelf, concentrations of nutrients are reduced to near zero values (C). In winter in open waters on the shelf, concentrations in surface waters on the shelf will also be increased by the break down of stratification and mixing with bottom waters to give a concentration (E) at intermediate salinities. If there is no net removal process taking place in the system then with time through the autumn and winter, the minimum in concentration of nutrient (E) will gradually disappear as nutrients are dispersed along the concentration gradients from river and ocean sources, and are regenerated from detritus. When a steady state is reached, line AEB will be co-incident with the theoretical mixing line AB. If an active removal process is present then the minimum will remain throughout the winter period. This last scenario is what is observed in the Irish Sea and is illustrated by Figure 6.

Stage 3: rate of change of nitrate concentration at the “Cypris” station

The long-term series of measurements carried out at the “Cypris” station on the south west of the Isle of Man suggests that between 1960 and 1990 the nitrate concentration at this location nearly doubled (Allen et al., 1998, Fig. 8). There is no specific source of nitrogenous compounds around the “Cypris” station, which is likely to result in it being unrepresentative of waters of similar salinity in the eastern Irish Sea. The water depth at the station is 37 m, so an increase of 4 μmol l⁻¹, as recorded by PEML between 1954 and 1990 (Allen et al., 1998), in a model box of an area of 8 × 8 km² is equivalent to a change in nitrogen load of 132 t (N). The population of the Isle of Man was 54 000 in 1951 and 72 000 in 1996 (source: Department of Economic Affairs, Isle of Man). This corresponds to an increase of 18 000 inhabitants during a period concomitant to the increase in nitrate concentrations measured by PEML at “Cypris” station. Assuming that each new person discharges annually 3.3 kg of nitrogen (Meybeck et al., 1989), the maximum increase of raw sewage from the entire population of the Isle of Man between 1951 and 1996 is 59 t of nitrogen. Even if all this nitrogen was discharged at the “Cypris” station (which is obviously not the case) this is insufficient to explain an increase of 4 μmol l⁻¹ in nitrate.

Comparison of the limited amount of data available from other sources for the Irish Sea with observations at the “Cypris” station suggests that the range of concentrations and salinities observed there are in line with other observations in the central Irish Sea, taken on similar dates. Concentrations observed in December 1975 are similar to those reported by Foster (1984), and currently observed concentrations are similar to those observed elsewhere in the Irish Sea at similar salinities (Gibson et al., 1997).

In February 1998, the effective concentration of nitrate entering the eastern Irish Sea from UK west coast rivers was estimated to be about 400 μmol l⁻¹ (data from CEFAS, “Cirolana” Cruise 1/98). If inputs to the Irish Sea have changed in line with known changes elsewhere in Europe, the nitrogen concentration in some rivers may have been as low as 50 μmol l⁻¹ in the 1940s and 1950s (c.f. Bennekom and Salomons, 1981; Howarth et al., 1996). Over the same period, the ocean water concentration will have remained constant at a winter shelf break concentration at 8 μmol l⁻¹ at a salinity of 35.5 (Hydes et al., 1999). Assuming simple linear mixing (Boyle et al., 1974; Officer, 1979) then at
the mean salinity of 34.2 observed at the “Cypris” station, the steady state winter concentration of nitrate would be expected to have changed from 9.5 μmol l⁻¹ to 22.3 μmol l⁻¹, which is a greater change above an initially higher base line than has been observed. Both the initial value in the 1960s and subsequent increases are higher than observed.

As we have also noted above, the model cannot reproduce day-to-day variations in concentration fields because these are highly dependent on short-term wind-driven events. But on longer time-scales, because the underlying hydrodynamics have been calibrated (Prandle, 1984) against the observed dispersion of ¹³⁷Cs, averaged conditions can be reproduced. On this basis it was decided to examine the output from the model running a hypothetical scenario in which the input of nitrogen to the Irish Sea was assumed to have changed progressively on the time scale of the nitrogen to the Irish Sea was assumed to have running a hypothetical scenario in which the input of nutrient inputs through dry deposition was shown to be negligible.

Table 1. The rate of increase of nutrients in the rivers and in the atmosphere corresponding to the model results shown in Figure 9. The effect of increasing ammonium in rivers and nutrient inputs through dry deposition was shown to be negligible.

<table>
<thead>
<tr>
<th></th>
<th>Rate of increase over 25 yr (μmol l⁻¹ yr⁻¹)</th>
<th>Starting concentration (μmol l⁻¹)</th>
<th>Final concentration (μmol l⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrate in river</td>
<td>14</td>
<td>50</td>
<td>400</td>
</tr>
<tr>
<td>In atmospheric wet deposition</td>
<td></td>
<td>1.60</td>
<td>5.7</td>
</tr>
<tr>
<td>Nitrate</td>
<td></td>
<td>0.93</td>
<td>3.3</td>
</tr>
<tr>
<td>Ammonia</td>
<td></td>
<td></td>
<td>26.6</td>
</tr>
</tbody>
</table>

Figure 9. Nitrate concentration at station “Cypris”: DYMOMIS results (■) when the river concentrations are increased from 50 to 400 μmol l⁻¹ over 25 years (see Table 1 for rates of increase) compared to the measured winter nitrate concentrations (●) at station “Cypris” since 1960 (Allen et al., 1998).
Conclusions

The aim so far with the development of the DYMONIS model has been not so much to precisely reproduce a particular data set but to rank the importance of the processes that are included in the model to explore the interaction of processes which occur on different time and space-scales and to determine any significant shortcomings in the model. DYMONIS runs to a steady state and reproduces winter distributions of salinity similar to those observed in the Irish Sea (Bowden, 1980) in terms of the overall gradients in salinity between rivers and the open sea boundaries of the model. DYMONIS output for salinity is sensitive to freshwater inputs from rivers and from rain, but the modifications of the input data which were imposed to obtain satisfactory results are well within the range of meteorological variations. However, the constant wind field used to drive this version of the model, does not reproduce the tongue of relatively high salinity water often seen in the western Irish Sea (Bowden, 1980; Dickson and Boelens, 1988). Similarly, although varying the total volume of fresh water entering the Irish Sea by a factor of 2 to represent the likely range in flows between wet and dry years does change the salinity in the “Cypris Box” by 0.2, the actual salinity at the “Cypris” site in winter varies by about 1.2 (Fig. 9). A variation of such amplitude is not reproduced. Flows in the Irish Sea are variable and are wind and density current driven (Bowden and Hughes, 1961; Knight and Howarth, 1999). A model which reproduced such a range of salinity would need to include hydrographic flows driven by observed weather (wind) data and also take into account density-driven flows which would give higher and more variable effective rates of advection.

On a longer time scale, DYMONIS reproduces the non-conservative behaviour of nitrate concentrations with respect to the salinity observed at high salinities in the Irish Sea in winter (e.g. Foster, 1984; Gibson et al., 1997). This reflects the balance implemented in the model between regeneration of nitrate from detrital material and fluxes through the boundaries. A more complete discussion would be possible if denitrification was simulated. The model provides an example of how observed distributions are determined by the balance of processes which are changing both in time and space.

The model results suggest that the increase of winter nitrate concentrations observed at the “Cypris” station on the south west of the Isle of Man (Allen et al., 1998) could be the result of increased loads of nitrogen in the rivers and in the atmosphere entering the Irish Sea from anthropogenic sources. The model shows that an increase in inputs of similar magnitude to that observed for other European river systems would result in the change observed at the “Cypris” station. The model appears to reproduce loss terms which result in the observed change being lower than if river and ocean water mixed conservatively in the Irish Sea.

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