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Influence of seasonal circulation on flushing of the Irish Sea.

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Abstract

We applied a three-dimensional general ocean and coastal circulation model to the Irish Sea in order to determine water renewal time scales in the region. The model was forced with meteorological data for 1995, a year with relatively warm summer and when extensive hydrographic surveys were conducted in the Irish Sea. We investigated intra-annual variability in the rates of net flow through the Irish Sea and carried out several flushing simulations based on conservative tracer transport. Obtained annually averaged net flow through the Irish Sea equals 2.50 km3/d; the results indicate that this flow is seasonally highly variable and under certain conditions is reversed to southward. We calculated residence times of the entire Irish Sea and the western Irish Sea, which is subject to strong thermal stratification every year. The difference in obtained residence times is as high as five-fold with baroclinic effects responsible for a two-fold increase in the value of residence time. Obtained results point at the importance of spatial and temporal consideration for transport of pollutants in the shelf seas where similar thermal structures develop. Implications for management are numerous and involve activities such as transport, fishing, use of resources, nature conservation, monitoring, tourism and recreation.

Keywords: numerical modelling, Irish Sea, residence time, flushing

1. Introduction

The Irish Sea is commonly defined as the semi-enclosed body of water, being a part of the Northwest European continental shelf extending northwards from St. David's Head and Carnsore Pt. on the Welsh and Irish coasts to the North Channel between Larne and the Mull of Galloway, Gaffney (2001). The Irish Sea is characterized by concurrent action of tides entering it from the north and the south, which results in the establishment of unique features affecting the overall circulation in the region. Since it is an area of increased fishery activities, and simultaneously exposed to effluent discharges from multiple estuarine systems and outfalls located offshore, such as Sellafield's nuclear plant outfall, the flow pattern within the Irish Sea needs to be well understood. Also, trawling and engineering activities carried out in the Irish Sea can adversely affect its aquatic environment, if improperly managed due to a lack of knowledge on the circulation of water and its consequences.

Despite all the research efforts into understanding the Irish Sea hydrodynamics, including extensive modelling approaches, strongly seasonal character of water circulation in the region had not been thoroughly examined and described until mid 1990s (Hill et al., 1994). In summer, thermal stratification develops in several regions, most notably in the western Irish Sea and in the north-eastern Celtic Sea, both characterised by weak tidal currents, and where cold, dense water, left over from the previous winter is entrapped in topographic depressions. The boundaries between stratified and mixed waters are also well defined and presence of strong baroclinic currents persisting over the heating season have been previously described in both the western Irish Sea (Hill et al., 1994) and at the southern entrance to the St. George's Channel (Brown et al., 2003).

The modelling effort of the region dates back around 30 years, when Heaps and Jones (1977) developed a numerical model to predict density-driven flows in the western Irish Sea. Predicted currents were too weak (1-2 cm/s), which most likely resulted from too coarse resolution (14 km). Barotropic, finer resolution models developed in the following years (Proctor, 1981; Davies and Aldridge, 1993; Davies and Lawrence, 1994), although successful in predicting tidal circulation, they failed to represent the residual currents that make up the density-driven western Irish Sea cyclonic gyre, which additionally supports a baroclinic interpretation of the feature. High resolution, three-dimensional curvilinear models have been also used to examine the wind induced flows, particularly in the North Channel region, showing that strong wind events are responsible for the occurrence of seasonal southward flow through the channel (Young et al., 2000; Davies et al., 2001). The first reproduction of the western Irish Sea gyre was obtained by the application of a three-dimensional diagnostic model, giving good agreement with previous observations, Hill et al. (1996), Hill et al. (1997). Horsburgh (1999), Xing and Davies (2001) and Horsburgh and Hill (2003) applied a three-dimensional density-resolving model and succeeded to predict the gyre in a prognostic manner. Good agreement was achieved, and the accuracy of temperature field prediction depended on the advection scheme implemented and the choice of turbulent model parameters. Young et al. (2004) also successfully modelled thermal stratification in the Irish Sea and the Celtic Sea and predicted previously observed westward geostrophic flow along the front of the latter.

Baroclinic circulation associated with the aforementioned thermal fronts can significantly affect water exchange processes in the Irish Sea. For example, the marine plankton can be retained and the primary production enhanced, which supports a valuable fishery of *Nephrops norvegicus* and other species in the western Irish Sea, Hill et al. (1997). The retentive properties of the gyre sustain also higher levels of contaminants, which bring a particular risk for inhabiting populations in the event of spring or summer oil and chemical spills (Hill et al., 1996). Significant influence of the seasonal circulation on travel times from Sellafield nuclear reprocessing plant outfall to various regions of the Irish Sea has already been shown (Dabrowski and Hartnett, 2008). Hartnett et al. (2007) concluded that thermal front at the southern entrance to the St. George's Channel affects the transport and pathways of scallop larvae in the investigation based on a hydrodynamic and transport model. Van der Molen et al. (2007) also concluded that dispersion of fish eggs and larvae are affected by release time and location presenting a major challenge for the design of effective spatial management strategies. The above studies used 1995 meteorological data for model forcing due to the availability of hydrographic data for that year originating from numerous surveys (Horsburgh, 1999; Horsburgh et al., 2000; Horsburgh and Hill, 2003; Young et al., 2004). It was also a relatively warm year, which allows determining the potential impact of strong thermal stratification and density-driven flows.

In this research, the authors developed a three-dimensional barotropic and baroclinic model of the Irish Sea and the north-eastern Celtic Sea based on Estuarine Coastal Ocean Model and Sediment Transport, ECOMSED, (Hydroqual, 2002) to study the influence of seasonal circulation on water residence times in the region, with primary focus on the western Irish Sea. Following sections outline physical environment of the study area, basis of numerical model and its application, methodology adopted to calculate flushing characteristics and brief model calibration report. The results from the flushing simulations are then presented and discussed before final conclusions are drawn.

2. Study Area

The extent of the study area and its geographic location are presented in Figure 1. The modelled area consists of the Irish Sea, including the St. George's Channel and the North Channel, the Bristol Channel and the north-eastern part of the Celtic Sea. A deep channel running from the Celtic Sea to the North Channel may be distinguished, with the minimum depth of 80m, and the maximum depth of 275m in the North Channel (Figure 1).

The tides dominate the dynamics of the Irish Sea, with the chief constituents being the M_2 and the S_2 tides, Gaffney (2001). They enter the region through both the St. George's and North Channels, with the two paths meeting along a line running westward from the south of the Isle of Man (location T15 in Figure 1) (McKay & Pattenden, 1993), where tidal currents are exceptionally weak (< 0.3 m/s) (Hill et al., 1996). Currents of 1-1.5 m/s are usually observed during mid-ebbs and mid-floods in the North and St. George's Channels, where most of the tidal energy is dissipated (MacDowell, 1997). Due to the above and in spite of deep water featuring in both channels they are generally well mixed in the vertical. The nodal point for velocity corresponds to the area where two tides meet forming a region of permanent slack water to the west and south of the Isle of Man. The degree of stratification can be described as a function of the amount of tidal energy available to mix the water column. Simpson and Hunter (1974) suggested that a measure of this energy is given by a log of a ratio of water depth to the cube of the maximum tidal surface current, and a limiting value for front formation being $\log[H/v_s^3] = 2$. A number of locations susceptible to development of such fronts separating vertically well-mixed regions from the stratified ones can be shown in the study area. The main front, recognised to have a major restriction to water circulation was observed to the west and south of the Isle of Man, which corresponds to the strong velocity gradient (Simpson and Hunter, 1974). Another front is located at the southern entrance to the St. George's Channel, where it meets with the Celtic Sea.

The combination of persistent slack water and depths exceeding 100 m in the western region of the Irish Sea encourages stratification, since insufficient tidal energy is produced to overcome the input of surface buoyancy due to solar heating. A two-layer system develops between April and October, the surface layer being 20-40 m thick and up to 7°C warmer than the bottom layer (Horsburgh, 1999). A dome of cold, dense water, composed of water left over from the previous winter, can be found beneath the thermocline. The boundary of this region is marked as a front with strong horizontal temperature gradients, with the clearest boundary observed on its southern and eastern sides where there is a temperature change of about 2°C in less than 2 km (Gaffney, 2001). Location of the front corresponds to the location of the front based on the $\log[H/v_s^3] = 2$ line, as suggested by Simpson and Hunter (1974).

Since the dome of cold water is static, the sloping density surfaces bounding it can only be maintained in geostrophic balance by cyclonic surface layer flow (Hill et al., 1997). Mean speeds calculated on the basis of the recorded drifter trajectories were equal to about 5 cm/s (Horsburgh et al., 2000). Further surveys carried out in 1993 and 1994, showed the existence of cyclonic residual flows of up to 20 cm/s, concentrated in jet-like cores at the base of the pycnocline and immediately above the flanks of a well-defined dome of dense water (Hill et al., 1996). Since the bottom density gradients have been recognised as the significant factor driving the baroclinic near-surface flow, the gyre becomes progressively faster due to persistent sharpening of the bottom fronts with proceeding heating season. The dome develops quickly, over a matter of days, in late spring, and breaks down equally quickly in early autumn, as a result of cooling and strong wind events (Hill et al., 1997).

The summer frontal system in the Celtic Sea strongly limits exchange of momentum and mass between the Irish and Celtic Sea, although eddy-like intrusions of colder water from the Irish Sea penetrating southward into the Celtic Sea have been reported (Horsburgh et al. 1998; Brown et al., 2003). Geostrophic, cyclonic flows along the Celtic Sea margins are estimated to be around 10 cm/s, extending to 30 cm/s in the St. George's Channel (Brown et al., 2003).

3. Method

3.1 Description and setup of the model

The equations that form the basis of the circulation model describe velocity and surface elevation fields, and the temperature and salinity fields. Two simplifying approximations are used in the model: first, it is assumed that the weight of the fluid identically balances the pressure (hydrostatic assumption), and second, density differences are neglected unless the differences are multiplied by gravity (Boussinesq approximation). Complete details of the model's governing equations can be found in Blumberg and Mellor (1987) and Hydroqual (2002).

The bathymetry data of the Irish Sea was interpolated onto a 2 km rectangular finite difference grid developed for the purpose of this study. Locations of the model's four corners are: bottom left 51°41'N and 10°02'W, bottom right 49°42'N and 04°21'W, top right 54°06’N and 01°09’W, top left 56°03’N and 05°50’W. As a result, 220 and 294 cells have been obtained in the I- and J- directions, respectively, giving 64,680 computational grids. In the vertical we specified ten sigma terrain-following layers.

Data from the tide gauges were obtained from the British Oceanographic Data Centre (BODC). Hourly values of sea surface elevations at locations T1-T15 presented in Figure 1 have been acquired and used for the model calibration and forcing at the open sea boundaries in the North Channel and the Celtic Sea. Rates and directions of the tidal streams at 14 locations (C1-C14) across the area under investigation have been extracted from the Admiralty Chart N^{o} 1824A, and consisted of the hourly estimated values of the magnitudes and directions of mean spring and mean neap depth averaged tidal flows. Additional data on current speeds recorded over one tidal cycle at four locations (B1–B4) were obtained from BODC.

Salinity was held constant at the open boundaries in all model runs at the value of 35 psu, being an average recorded in this part of the North Atlantic Ocean. Freshwater inputs along the British and Irish Coasts were included in the model and distributed according to values provided in ISSG (1990). Sea temperatures at the open ocean boundaries were specified at every computational timestep, and the values were obtained by a linear interpolation of monthly data from Meteorological Service (1995).

A full set of meteorological conditions was collated in order to perform seasonal simulations. These parameters comprised of wind speed and direction, air temperature, barometric pressure, cloud cover, precipitation and evaporation rates, relative humidity and shortwave solar radiation. The year 1995 was chosen for simulations, which was determined by data availability from numerous hydrographic surveys (Horsburgh, 1999; Horsburgh et al., 2000; Horsburgh and Hill, 2003; Young et al., 2004) and the fact that relatively warm summer was experienced that year and thus a strong thermal stratification in the western Irish Sea and the Celtic Sea is expected. Indeed, the existence of a well-established stratification and the gyre in the western Irish Sea in that year was reported (Horsburgh et al., 2000). This stratification occurs in the above regions every year due to limited tidal mixing as determined by the parameter $\log[H/v_s^3]$; see Simpson and Hunter (1974) for more details. The majority of data were provided by the US National Oceanic and Atmospheric Administration (NOAA) from their NCEP Reanalysis 2 model. Data on 2m air temperatures and precipitation and evaporation rates was obtained from Monthly Weather Bulletin published by Met Eireann, the Irish meteorological office (Meteorological

Service, 1995). Daily averages of the aforementioned parameters were utilised. Figure 2 presents summer (June-August) mean temperatures and wind speeds at position 52°30'N and 05°00'W, located close to the centre of the modelled region, for years 1991-2009 provided by NOAA/NCEP. As can be seen in Figure 2, year 1995 experienced the warmest summer in the period 1991-2009. Also, in the period 1991-2002, the long term mean temperature was only exceeded on two occasions, in 1995 and 1997, whereas in the period 2003-2009 on five occasions, indicating that relatively warm summers, such as that of 1995, are becoming a more common occurrence. Figure 2 shows that the mean summer wind speed in year 1995 was also lower than 1991-2009 summers mean, indicating weaker than usual wind stirring, which further aids the development of thermal stratification. Due to the above factors, thermal stratifications and associated density-induced circulation were well developed in the studied region in year 1995, which allows for the assessment of their potential impact on transport phenomena. As the result, year 1995 became a preferred year amongst the researchers to study seasonal fluxes (Horburgh et al., 1998; Horsburgh, 1999; Horsburgh et al., 2000; Horsburgh and Hill, 2003; Xing and Davies, 2001; Young et al., 2004; Dabrowski and Hartnett, 2008) and movement of fish larvae (Hartnett et al., 2007; van der Molen et al., 2007) in the region.

We carried out several model runs featuring surface heat flux models by Large and Pond (1982), Rosati and Miyakoda (1988) and Ahsan and Blumberg (1999) in order to determine the most suitable model for the study area as well as the most appropriate parameters setting. We obtained best calibration results as regards predicted sea temperatures when using the model by Ahsan and Blumberg (1999) with fraction of shortwave radiation absorbed in surface layer and attenuation coefficient at 0.2 and 0.3, respectively.

3.2 Calculation of flushing characteristics

In the model, we calculate transport components in y-direction in the St' George's Channel and in x-direction in the North Channel at every computational time step according to the following equation (written for the x-component):

$$TC = \sum_{n=1}^{\sigma}[U(i, j,\sigma) \cdot 0.5 \cdot (D(i, j) + D(i-1, j)) \cdot \Delta z_{\sigma n}] \quad (1)$$

where TC is the transport component in x-direction in m^2/s, U is the velocity component in x-direction, D the local depth being a sum of the mean water depth and current water elevation, and $\Delta z_{\sigma n}$ the relative thickness of the n-th sigma level. Since the numerical grid is of 'Arakawa C' type, the local depths used to calculate transport components are the average of two water depths computed by the model at the centres of grids, adjacent to the point of U-velocity calculations. Volumetric transport is then obtained when TC is multiplied by the local channel width. Time averaging over duration of a spring-neap cycle (14 days) yields net flows through the Irish Sea, and two identical values should be obtained for the two channels if freshwater inputs are neglected.

The average residence time, τ_r, is defined as an expected time during which the material exists in the area under consideration; see Dabrowski (2005) for an extensive review of various flushing concepts. A concept of the remnant function proposed by Takeoka (1984) is utilised in this study. Takeoka (1984) defined the remnant function, r(t), as the ratio of the mass of material within a reservoir at a given time, M(t) to the initial mass of this material, M_0. Providing that the reservoir is at steady state and its volume does not change in a long term, r(t) equals also to the ratio of the material concentration at time t, c(t), and its initial concentration, c_0

$$r(t) = \frac{M(t)}{M_0} = \frac{c(t)}{c_0} \quad (2)$$

Takeoka (1984) proved that the average residence time of a reservoir is an integral of the remnant function:

$$\tau_r = \int_0^\infty r(t)dt \quad (3)$$

Murakami (1991) utilised the above definition of τ_r and showed that in most cases r(t) can be well approximated by the following exponential function:

$$r(t) = \exp(-At^B) \quad (4)$$

where A and B depend on the shape of the tracer decay curve and have to be determined for each case. Formula (3) can be easily integrated giving an accurate value of τ_r.

3.3 Summary of the methodology

Initially, the tidal model was developed and calibrated against available data at locations T1–T15, C1–C14 and B1-B4. Subsequently, meteorological forcing and freshwater inputs have been implemented and several configurations of the model were executed to determine the most suitable heat flux model, as described in section 3.1. Predicted sea temperatures were compared against data available for locations E1-E3 presented in Figure

3 and the model parameters tuned until good agreement was achieved. Particular emphasis was put on proper representation of thermal structure in the western Irish Sea region. Subsequently, we carried out passive tracer simulations and tracked spatial and temporal distribution of the tracer predicted by the model. The tracer was assumed to be initially uniformly dispersed throughout the regions of interest presented in Figure 3. We considered two separate regions, namely the entire Irish Sea with the exclusion of the North Channel (region A) and the western Irish Sea (region B). Surrounding waters were assumed to be initially free of tracer as well as waters entering the modelled domain through the open boundaries. The solute transport models were run for a simulation time of 20,000 hrs; this simulation duration was sufficiently long to ensure low concentrations of tracer throughout the Irish Sea at the end of the period. Average tracer concentrations in the areas of interest were then tracked with time and dye decay curves constructed, $c(t)/c_0 = f(t)$; these were subsequently approximated by the remnant function, r(t), given by equation (4). Average residence times were then obtained from equation (3). On the basis of the model simulations we also calculated the net flows through the Irish Sea according to equation (1).
We carried out a number of simulations characterised by different tracer release dates as well as exclusion of baroclinic flows and wind forcing in order to determine the contribution of various effects into the values of the average residence times.

4. Results

4.1 Hydrodynamic model

Depth-averaged currents predicted by the model at a mid-ebb stage of a tide are presented in Figure 4. These are consistent with the currents predicted by the Hydrographic Office (MacDowell, 1997). The strongest currents of the magnitude 1-1.5 m/s are predicted in the St. George’s Channel and the North Channel. The areas of slack water in the western Irish Sea and the north-eastern Celtic Sea are clearly visible. Figure 4 also presents spatial pattern of temperature differences between surface and nearbed layers as predicted by the model on the 10th of August 1995. Stratification in the western Irish Sea and the Celtic Sea is well developed and its spatial extent corresponds closely to those presented in Horsburgh et al. (2000) and Young et al. (2004) and also those determined by the tidal mixing ratio ($\log[H/v_s^3]$) in Simpson et al. (1977).

Figure 5 presents a comparison of model predictions of currents speeds and surface and nearbed sea temperatures in the region of western Irish Sea with data. The data is for point

B3 in Figure 1 and point E3 in Figure 3. The comparisons presented in Figure 5 are typical of the good correlation obtained between model predictions and data for many locations throughout the Irish Sea; full details of these comparisons may be found in Dabrowski (2005) and Dabrowski et al. (2003). The validation of the model results against temperature in a stratified region of the Irish Sea is particularly significant due to the importance of thermal fronts on water circulation in the region, which has been described in previous sections.

4.2 Flushing simulations

The annually averaged net flow produced by the model is equal to 28 920 m^3/s = 2.50 km^3/day. Hence, the resulting sectionally-averaged northward drift is equivalent to 1.01 cm/s = 0.87 km/day and 0.42 cm/s = 0.37 km/day in the North Channel and the St. George's Channel, respectively. For comparison, the net flow produced by the tidally only forced model reaches almost 90 000 m^3/s of the volume flux. If wind shear stress is excluded from the model forcing then the net flow rises to 46 980 m^3/s, but it is a two-fold drop when compared to the tidally only forced model. However, it should be noted that since wind shear stress also plays a significant role in the development and maintenance of density structure, this value cannot be considered as a fully reliable reflection of the contribution of baroclinic flows to the overall circulation.

Figure 6 presents the seasonal variability in the values of net northward flow through the Irish Sea, averaged over individual spring-neap cycles for the complete year of simulations. In the case of the barotropic and baroclinic model, during the first three months of the year the flow is southward. During spring and summer the flow is variable, but relatively weak with the average value of 22 972 m^3/s over the months of April until September. It is followed by a sudden increase in the northward flux leading to as much as 180 000 m^3/s volume flow at the end of December. Exclusion of wind forcing from the model gives a better insight to the contribution of density-driven circulation to water exchange processes in the Irish Sea. Gradual decrease of the northward drift is observed commencing around the 1st of June and finishing in mid September, when the flow drops down to less than 18 000 m^3/s from nearly 55 000 m^3/s in the beginning of June. Subsequently, the northward flow increases more than four times over the period of two months.

Figure 7 presents the dye decay curves, $c(t)/c_0 = f(t)$, for the two regions examined. In the case of region B, which stratifies in summer, two decay curves are presented separately; one for average dye concentration in surface layer and one for nearbed layer. Also, in region A the tracer was released on the 1st of June and the 1st of December, whereas in region B on the 1st of February. Eleven simulations in total have been carried out for region B with tracer release dates taking place on the 1st day of each month between February and December in order to examine the influence of the western Irish Sea gyre on the retention of the material within the region. Three additional runs with the release dates on the 1st of February, 1st of June and 1st of October have been carried out with baroclinic flows excluded. Remnant functions, r(t), have been fitted using the least squares method and integrated according to equation (3) to obtain average residence times. These are summarized in Table 1 for region B. The average residence times in the entire water column and only the surface layer have been considered separately. Figure 8 illustrates temporal variability of depth-averaged residence time in region B. Also shown are the values obtained from the model with baroclinic flows excluded. Water contained within the region on the 1st of October is characterized by the lowest value of τ_r equal 45 days, whereas τ_r reach maximum for winter releases up to 241 days for the 1st of December release. The values are similar for all summer releases and vary between 105 and 127 days. Two simulations have been considered for region A, namely summer (1st of June) and winter (1st of December) tracer releases. The value of depth-averaged τ_r obtained for summer release equals 386 days, whereas for winter release is approximately two months greater and equals 444 days. For the surface layer, 381 and 448 days were obtained for the summer and winter releases, respectively.

Figure 9 presents four snapshots of depth-averaged tracer concentrations at different times that have elapsed since its release in region A on the 1st of June. Particularly apparent is the southward, clockwise flow along the Irish coast towards the open ocean boundary during the heating season, and a jet-like intrusion of water into the St. George's Channel; see Figure 9(a). Following the breakdown of stratification in autumn strong northward flushing in the St. George's Channel, with water exiting the Irish Sea through the North Channel, is predicted; see Figure 9(b). After 250 days the St. George's Channel is well flushed and southward flow along the British coast can be noted; see Figure 9(c). Distribution of tracer presented in Figure 9(d) corresponds to the situation observed in early May, when temporary southward flow has reversed back to the north only a short time earlier, and elevated tracer concentration levels existing in the western Irish Sea will likely remain there over the next few months due to slackening effects of the geostrophic cyclonic circulation. The greatest tracer concentrations after one year into simulations exist in the eastern Irish Sea to the south-east of the Isle of Man; this area is outside of the main channel running through the Irish Sea and has previously been subject of a separate research presented in Dabrowski and Hartnett (2008).

5. Discussion

Annually averaged net flow of 2.50 km^3/d (28920 m^3/d) is identical with previous estimates (Dickson et al., 1987; Horsburgh et al.,1998). However, seasonal circulation patterns developing in the region due to both thermal stratification and wind action significantly affect water exchange in the region. Baroclinic effects cause a two-fold drop in the value of the annually averaged net flow through the Irish Sea when compared to only tidally forced model. This drop increases to three-fold due to wind action. The importance of both thermohaline and wind induced circulation on the net flow through the Irish Sea is even more apparent when intra-annual variations in net flow are considered; see Figure 6. Other reports also claim that peak flows in either direction may be up to 50 times greater than the yearly average (ISSG, 1990). Since southward net flow, predicted by the model for the first three months of the year, does not occur at any time when the wind is excluded from the model forcing, it supports the fact that this southward flow is due to prevailing winds. An inhibiting effect of baroclinic currents is also clearly manifested since gradual decrease of the northward drift is observed commencing around the 1st of June and finishing in mid September. This is caused by both the developing gyre with progressing speeds and also by thermal front located at the entrance to the St. George's Channel. Following the breakdown of stratification, the northward flow increases dramatically; this confirms the importance of density driven circulation within the Irish Sea.

Knight and Howarth (1999) have shown that under certain conditions water could be forced southward through the North Channel. This southward flow is supported by tracer studies (Jefferies et al., 1982). Extensive numerical modelling studies performed by Davies et al. (2001) and Davies and Xing (2003) revealed that it is northerly and westerly winds that produce inflow current through the North Channel. Bowden (1980) reports that in the western side of the North Channel there is a persistent strong southward flow which at times penetrates down the Irish coast as far as Dublin and is part of a general clockwise flow around Ireland. Existence of the above flows is confirmed in this study, see Figure 9.

However, our simulations suggest that, as opposed to the North Channel, this flow along the eastern and southern Irish coast is not a persistent feature and can be observed only during spring and summer months. Due to a lack of strong wind events between the months of May and September, coinciding with the developing stratification, the authors believe that this flow is a baroclinic feature and along the southern coast is part of a geostrophic flow presented in Brown et al. (2003) and Young et al. (2004). The movement of a tracer front helps to assess the magnitude of this flow along the southern Irish coast, which lies within the range 2.9 – 7.1 cm/s (2.5 – 6.1 km/d).

One of the first estimates of mean water residence time of about 18 months was proposed by Bowden (1955). Further studies carried out by Jefferies et al. (1982), McKay and Baxter (1985) and McKay and Pattenden (1993) delivered estimates of between 12-18 months. Figures obtained by the authors in this research fall into previously proposed range. As regards region A, water contained within it on the 1st of December, will have a greater residence time by about two months than that contained there on the 1st of June, due to the combined effects of winds and density gradients. Although over the first 160 days the relative dye concentration within the region is lower in the case of winter release than in the case of summer release, see Figure 7(b), the rate of dye removal in the former run is markedly lower from approximately 30 days onwards due to the reversal southward net flow, immediately followed by the effects of the developing gyre. It can also be noted in the same Figure that tracer removal generally slackens off until the end of September due to developing thermal fronts. This is followed by a sudden increase in the exchange rate corresponding to breakdown of stratification and strong wind events (around day 120 in the case of summer release). Intensified northward transport lasts until the end of January (around day 220 in the case of summer release), when the reversal southward flow occurs. This pattern, showing inhibiting effects of thermal stratification as well as transitions from windy to calm year seasons is clearly marked in the case of both releases. The retentive character of the western Irish Sea gyre is also manifested in the shape of the tracer decay curve presented in Figure 7(a), where significant decrease in the rate of tracer removal is observed between the months of April to September.

The differences between the values of τ_r obtained for the surface layer and those calculated for the entire water column are negligible in all considered cases, thus uniform transport of the material throughout the water column appears to prevail on the long-term basis (the time scale of τ_r and longer) and when averaged throughout the examined area. The values of surface layer τ_r and the entire water column τ_r do not differ even in the case of stratified western Irish Sea. However, when temporal changes of the average tracer concentration in the surface and nearbed layers are analyzed, see Figure 7(a), we discover different material content in the above layers persisting over the course of stratification (1 April – 1 October). At other times the water column is well mixed, which is also manifested by the uniform vertical distribution of the tracer. Nevertheless, the curve shapes are very similar and so are r(t) functions, which results in comparable values of the flushing characteristics.

Figure 8 shows how the average residence time of the western Irish Sea (region B) differs depending on the time of the year when material has been introduced. It appears that τ_r of water contained within the region on the 1st of December is more than 5 times greater than the residence time of the same volume of water contained there on the 1st of October (τ_r = 241 days and τ_r = 45 days, respectively). Reasons for this phenomenon have been already discussed and are associated with the southward flow occurring in the beginning of the year followed by the development of thermal fronts in spring and summer, as opposed to strong northward drift taking place in autumn and early winter. Retentive and slackening effect of the gyre is apparent in Figure 8 and is manifested by stable residence time between the months of April and August, being within the range 105 – 127 days.

Three additional runs for region B with the baroclinic flows excluded and tracer release dates on the 1st of February, June and October reveal that flushing is largely inhibited by the baroclinic circulation not only when the material is injected during the summer, but also two months prior to the development of thermal stratification. The ratios of τ_r from these model runs to τ_r obtained from the model including both barotropic and baroclinic effects equal 0.54 and 0.52 for the February and June tracer releases, respectively. In contrast, there is virtually no difference in the values of τ_r between the two runs if the material is released in October, when the western Irish Sea region is already vertically well mixed.

Implications for management are numerous and involve activities such as transport, fishing, use of resources, nature conservation, monitoring, tourism and recreation and other. Studies aiming at the development of recommendations for a strategic policy framework for an administrative and regulatory process and operational guidelines under which dredging for marine aggregates in the Irish Sea can be sustainably managed has been carried out recently (Sutton et al., 2008). Research presented in this study adds to the discussion on devising relevant policies and operational procedures leading to minimisation of the environmental impact of such dredging. As regards transport-related issues, rerouting of ships carrying potentially environmentally hazardous materials may be considered. Since the western Irish Sea is an area of important fishery activity (Hill et al., 1996; Hill et al., 1997) there may be a need to divert certain part of sea-traffic from this area in spring and summer, since due to the retentive character of the western Irish Sea gyre any accidental spill may have disastrous consequences for the fishing industry. Since it has already been shown (Hartnett et al., 2007; van der Molen et al., 2007) that dispersion of fish eggs and larvae is affected by factors such as release time and location, the methodology for flushing analysis presented in this study may be adopted when devising management strategies to protect species. As regards the management of the monitoring programmes, responsible bodies should consider devising strategies focusing on regions subject to strong seasonal variations in flushing, taking also into account possible impact of climate change on the extents and strength of stratification and associated baroclinic circulation. In the coastal regions, where effluent discharges are taking place, flushing pathways and their seasonality should also be taken into consideration in the management of the marine leisure industry and specially protected areas. For example, as revealed in this study, effluents discharged into the Irish Sea from Dublin, located on the eastern Irish coast (Figure 1), will have different fate in spring and summer than during other times of the year due to the presence of seasonal southward flows along the coast, as discussed earlier in this section and illustrated in Figure 9.

The results presented in this study show that seasonal circulation may significantly influence water retention times even in tidally dominated shelf seas, therefore needs to be taken into consideration, particularly when occurring on regular basis, such as the baroclinic circulation resulting from the summer thermal structures developing in the western Irish Sea and the Celtic Sea. It is then desirable that similar studies are carried out in other shelf seas subject to stratification, such as the North Sea, where significant contribution of baroclinic currents to the overall circulation has been previously shown, although the summer stratification there is rather wind driven since tidal currents are weak throughout most of the region (Langenberg, 1997; Nielsen and John, 2001; van Haren, 2004), therefore patterns of seasonal circulation are expected to be less regular than that of the Irish Sea.

6. Conclusions

A three-dimensional numerical model was applied to the Irish Sea in this study, resulting in good prediction of the region's hydrodynamics, including both barotropic and baroclinic flows. Particular emphasis was put on the proper representation of thermal stratification developing in the western Irish Sea during spring and summer each year. Subsequently, the hydrodynamic model served as the basis for the Irish Sea flushing study assessment. The main conclusions that have emerged from this research are summarized below:

- This research has quantitatively shown that the net flow through the Irish Sea and associated flushing vary significantly during the course of a year. While the annually averaged flow is northward, southward flows are experienced under certain meteorological conditions. Both wind-induced and baroclinc circulations have significant slackening effects on water exchange in the Irish Sea
- It has been observed that average residence time of the Irish Sea exhibits distinct intra-annual variability. Calculated residence times vary depending on the flushing simulation starting date; for example, when simulations begin in December average residences times are significantly greater (444 days) than average residence times calculated when simulations begin in June (386 days).
- Detailed analysis of the stratified region of the western Irish Sea revealed that intra-annual variation in the values of residence times in this region is very significant; for example, the material introduced into the region in December is likely to remain there for the time period five times greater than the material that entered the region in October. The results also indicate that the cyclonic density-driven gyre developing in the western Irish Sea over the heating season causes a two-fold increase in the value of residence time of the region.
- It has been shown that, although in the stratified region tracer removal rates from the surface layer and nearbed layers vary on the short-term basis, vertically well-mixed transport prevails on the time-scale equal to the residence times of the analyzed regions or longer
- The importance of seasonal circulation on flushing of various regions of the Irish Sea presented in this paper indicates that it is worth carrying out more detailed analysis of spatial and temporal variations in flushing of other shelf seas experiencing similar thermal stratification. Baroclinic circulation induced by such features may prove to have very significant effects on retention times of all

pollutants and other constituents that are carried with water, indicating that careful management approach needs to be adopted.

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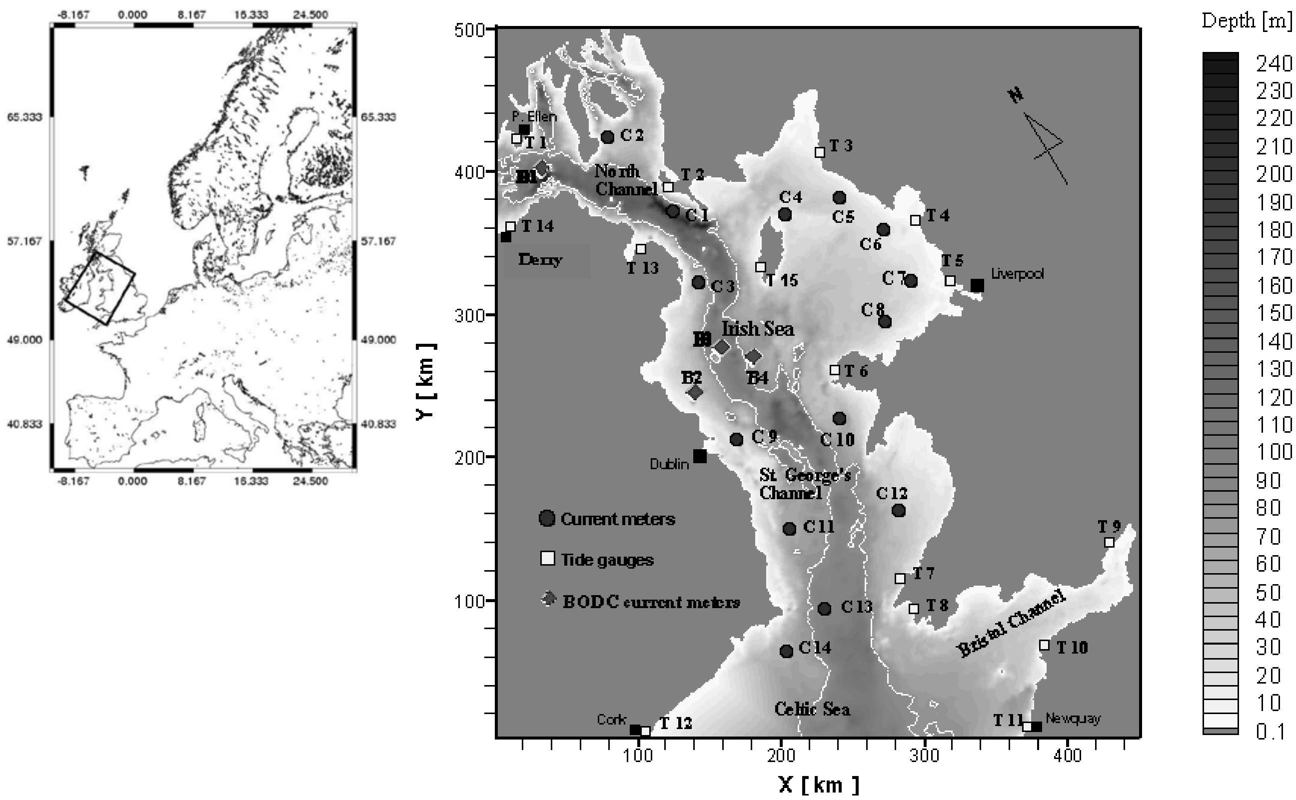

Figure 1. The Irish Sea bathymetry and model orientation. Contours of 80 m water depth are highlighted to show the extents of the main channel. Distribution of the field data collected for the model set-up and calibration is also presented.

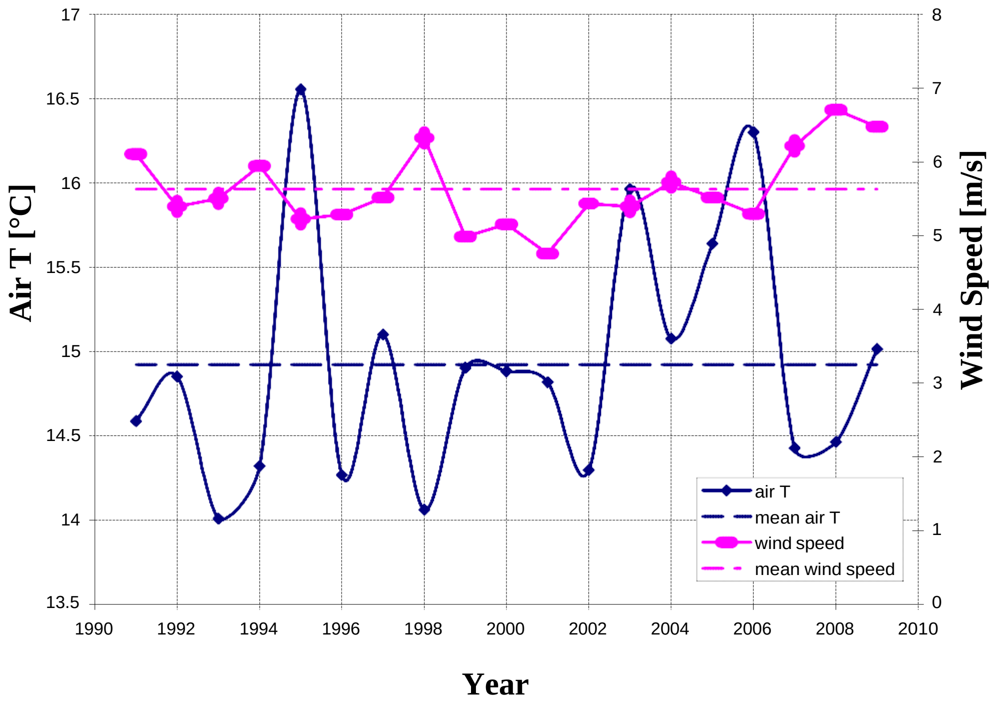

Figure 2. Summer (June-August) mean temperatures and wind speeds at position 52°30'N and 05°00'W for years 1991-2009 obtained from NOAA/NCEP.

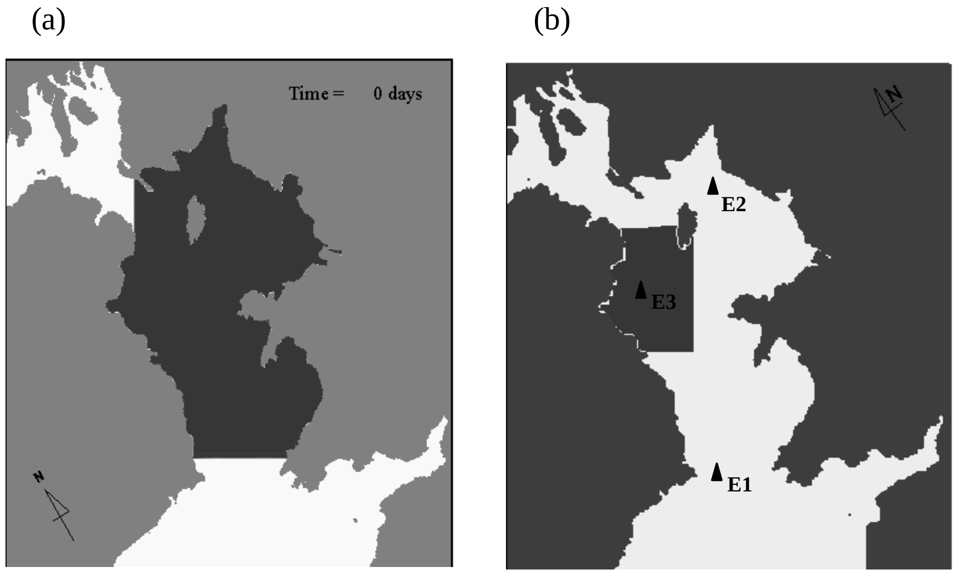

Figure 3. Extents of the regions of the Irish Sea selected for flushing studies: (a) region A and (b) region B. Darkened areas of the sea show the extents of each region, in which a conservative tracer was initially (simulation time = 0) uniformly dispersed in the numerical model. E1-E3 are the locations for which sea temperatures have been collated for model calibration.

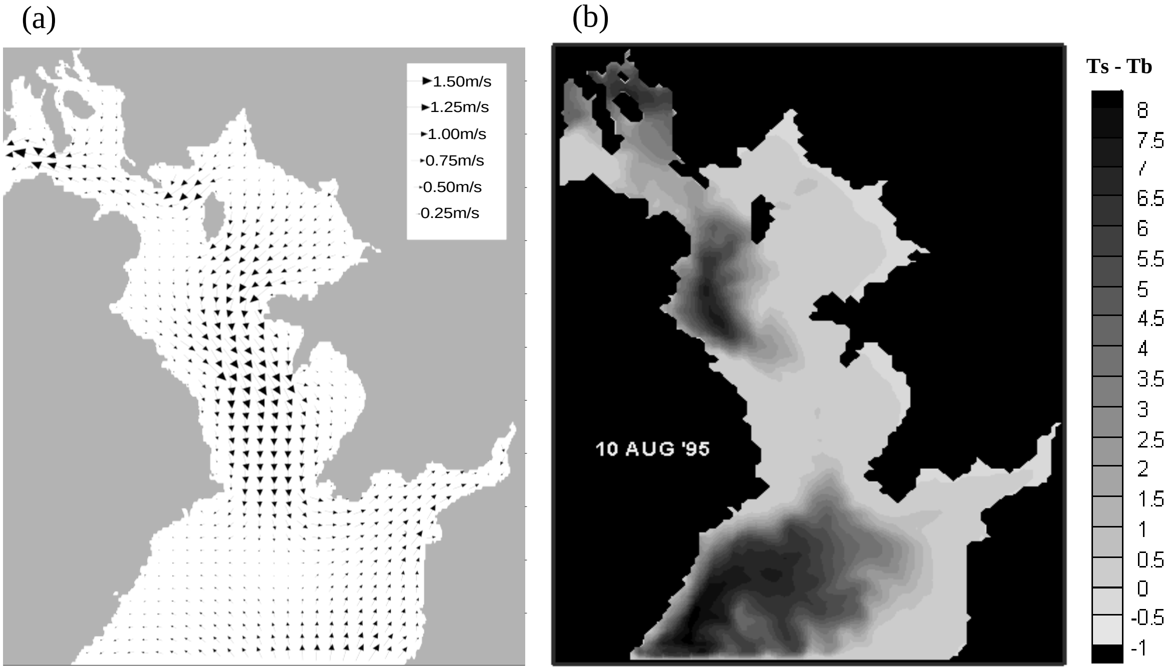

Figure 4. Model-predicted (a) hydrodynamic field on mid-ebb and (b) spatial pattern of thermal stratification.

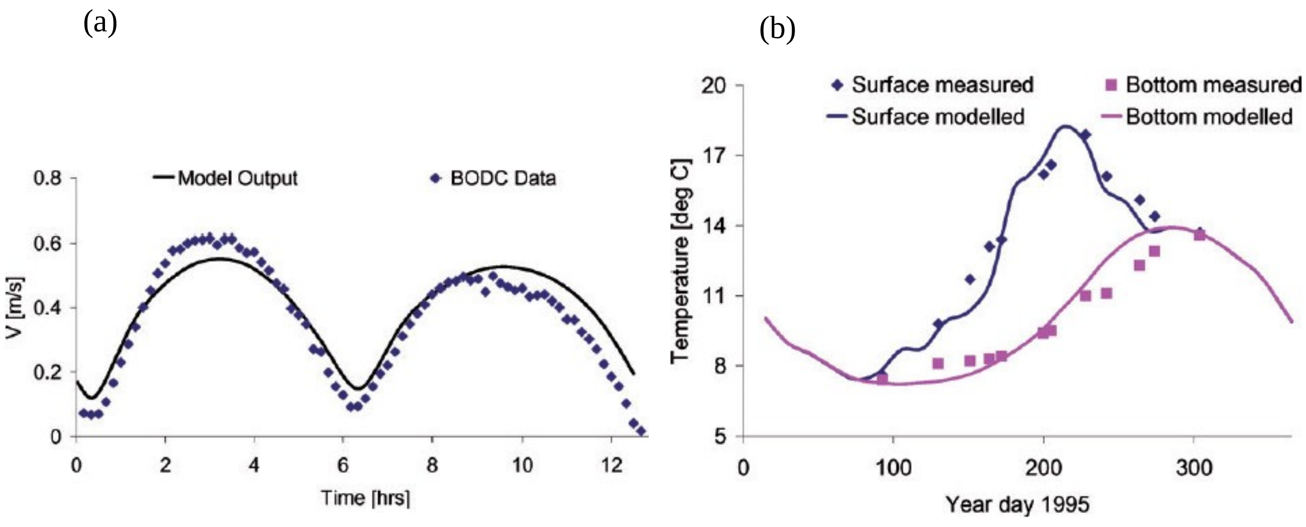

Figure 5. Comparison of measured and modelled (a) current speeds at location B3 and (b) water temperatures at location E3.

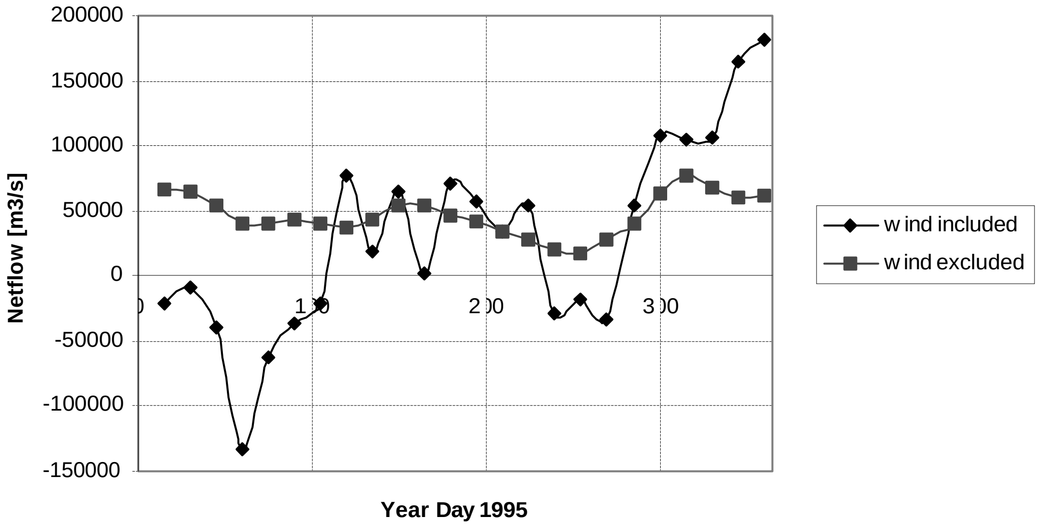

Figure 6. Spring-neap cycle and basin-averaged net flow through the Irish Sea over the course of the year 1995 produced by the model; positive values – northward, negative – southward.

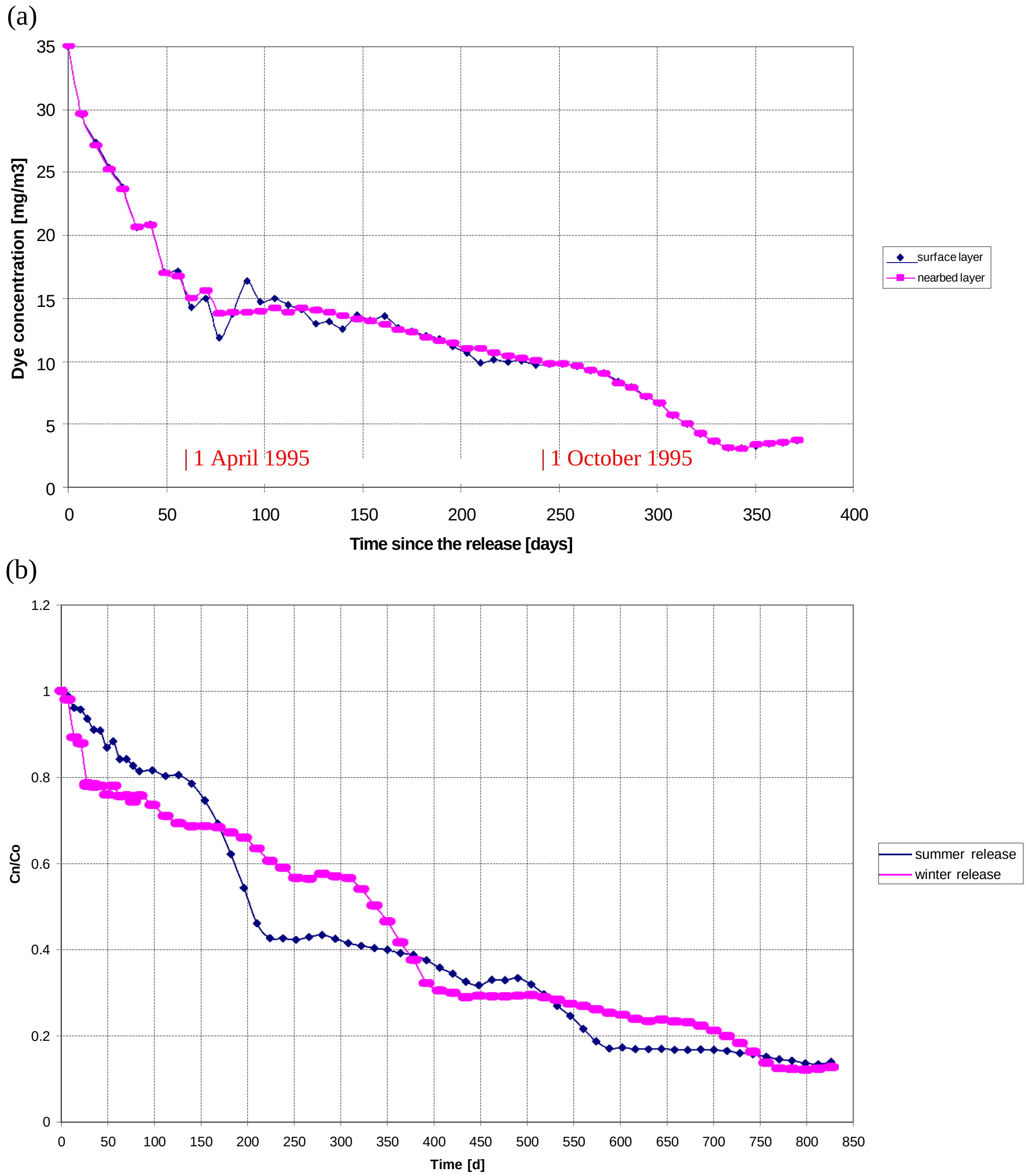

Figure 7. Decay curves of (a) tracer concentrations in the surface and nearbed layers of region B and (b) depth-averaged tracer concentrations in region A.

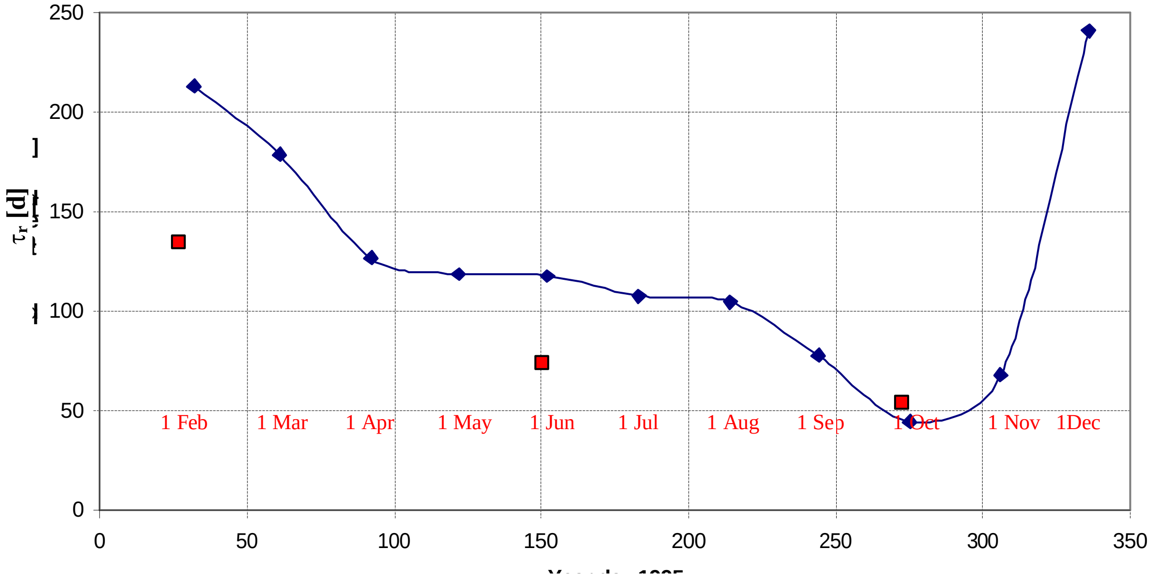

Figure 8. Temporal variability of the average residence time of region B. Squares represent the average residence times in the absence of baroclinic circulation.

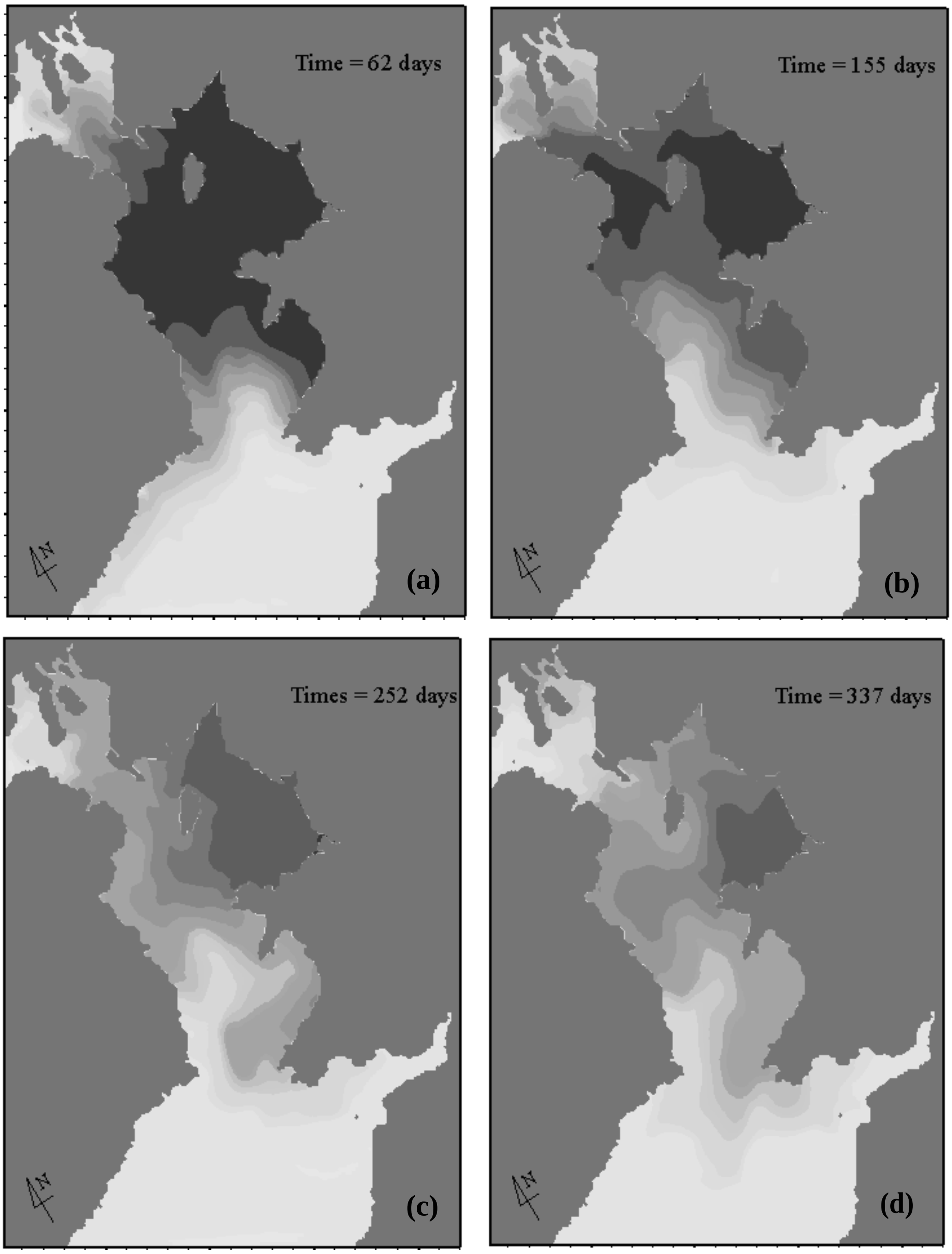

Figure 9. Spatial distribution of depth averaged tracer concentration predicted by the model following the summer release of tracer into region A. Individual snapshots correspond to the following dates: (a) 2 August, (b) 1 November, (c) 7 February and (d) 2 May of 1995.

Table 1. Residence times of region B obtained from tracer transport simulations for various tracer release dates in year 1995.

Time of release	**Depth averaged**			**Surface layer**		
	A	**B**	τ_r **[d]**	**A**	**B**	τ_r **[d]**
01 Feb	0.047	0.556	213	0.046	0.560	211
01 Mar	0.027	0.653	179	0.029	0.642	179
01 Apr	0.014	0.795	127	0.016	0.772	128
01 May	0.016	0.782	119	0.019	0.753	119
01 Jun	0.015	0.794	118	0.016	0.783	118
01 Jul	0.022	0.741	108	0.024	0.728	107
01 Aug	0.021	0.752	105	0.042	0.632	111
01 Sep	0.017	0.830	78	0.024	0.766	79
01 Oct	0.007	1.102	45	0.006	1.136	45
01 Nov	0.113	0.515	68	0.112	0.517	68
01 Dec	0.141	0.398	241	0.140	0.399	241