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Determination of flushing characteristics of the Irish Sea: a spatial approach

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Abstract

The Authors devised a novel generic approach to assessing the flushing of the Irish Sea through the determination of spatially distributed residence times and the development of flushing homogeneity curves. Results indicate that flushing of the Irish Sea is both spatially and temporally highly variable. Average residence times of the material introduced in winter may be up to 28% higher than the material introduced in summer, and the aerial flushing deviation index may reach up to 470 days. The spatial approach to flushing is an extremely useful complement to classical flushing analysis considering significant implications for management of water quality.

Keywords: numerical modelling, Irish Sea, residence time, flushing, shelf seas, thermohaline circulation

1. Introduction

Coastal waters remain under great threat from many aspects of human activity. Cohen et al. (1997) estimate that about 50% of global population lives within the coastal zone; much of the waste generated by these communities end in coastal waters. Local hydrodynamic regimes of coastal waters are responsible for such important issues as the distribution of effluents, transport of oil spills, sediments and other materials. Many natural chemical, physical and biological processes occurring within particular environments, including such important factors as low oxygen levels or eutrophication, are influenced by circulation patterns. The knowledge of hydrodynamic regimes in coastal waterbodies, being it ports and marinas, estuaries, bays and larger coastal embayments, shelf seas, but also ocean basins, is therefore desirable for engineers, scientists, managers and by policy makers.

An important physical attribute of each waterbody is the time scale characteristic that describes its ability to renew water contained in it. In literature, it is most often referred to as the flushing or residence time, (e.g. Bolin and Rodhe, 1973; Zimmerman, 1976; Takeoka, 1984; Dyer, 1997; Luketina, 1998). Water circulation in a given waterbody is a resultant of various forces, such as tide, wind and density structure; knowledge of water renewal times can significantly aid the assessment of the environmental state of waterbodies and their sustainable management.

The Irish Sea is a semi-enclosed shelf sea located between the islands of Ireland and Great Britain, see Figure 1. Water circulation and associated water quality issues concerning the Irish Sea have drawn the attention of more than a few researchers over the past few decades (Ramster and Hill, 1969; Simpson and Hunter, 1974; Proctor, 1981; Jefferies et al., 1982; Prandle, 1984; McKay and Baxter, 1985; McKay and Pattenden, 1993; Hill et al., 1997; Horsburgh et al., 2000; Dabrowski and Hartnett, 2008; Wang et al., 2008; Dabrowski et al., 2010). Being an area of important fishery activities (Hill et al., 1996) and simultaneously exposed to effluent discharges from multiple estuarine systems located on the Irish and British coasts as well as from offshore outfalls and subject to further development of the marine renewable energy sector, it is important that flow patterns and residence times within the Irish Sea are well understood.

Hydrographically, the Irish Sea, located between 52-55N and 3-6W, is a complex system where two tidal waves interact, and where wind and density-driven circulations also play an important role. Flushing and transport of pollutants are not well understood in the region. Previous efforts directed at estimation of the Irish Sea residence times did not include the complexity of circulation (Jefferies et al., 1982; Prandle, 1984; McKay and Baxter, 1985; McKay and Pattenden, 1993). Due to large variations in the published values of residence times, the authors concluded that the approach taking into account spatial variability of residence times is necessary. For a more detailed description of the oceanography of the Irish Sea the reader is referred to Bowden (1980).

In this paper, the objectives were to determine water renewal time scales in the Irish Sea and to analyze complex flushing in the region. The methodology used by the authors involves calculations of spatially distributed residence times and development of the flushing homogeneity curves (FHC); the approach is based on the application of a three-dimensional general ocean and coastal circulation and transport model. This model was applied previously to the region to investigate residence times in the eastern Irish Sea as well as travel times from the Sellafield's nuclear plant outfall site to various regions of the Irish Sea giving good agreement with previously reported estimates (Dabrowski and Hartnett, 2008). The model was also applied to examine the influence of the western Irish Sea gyre developing in spring and summer on net flows, turn-over and residence times in the region (Dabrowski et al., 2010). In this paper, the authors examine the complete Irish Sea and also its three hydrographically diverse subregions, therefore the analysis of spatial detail in residence times and development of FHC are required. The advantage of using a numerical model for the purpose of the flushing properties analysis is that it gives an additional insight into the impact of various physical processes upon the derived water renewal time scale characteristic. Impacts can be analyzed by excluding and including various forcing functions in the model.

The layout of the paper is as follows. Section 2 describes the methodology and model setup, Section 3 provides a brief model calibration report followed by the presentation and discussion of the results from the flushing simulations in Section 4, before drawing final conclusions in Section 5.

2. Method

2.1. Model description

In this study, a three-dimensional numerical model, ECOMSED, was applied to investigate water renewal time scales in the Irish Sea; the model is described in detail in Blumberg and Mellor (1987). Below, the main features of the model and details of its application to the Irish Sea are presented.

The bathymetry data of the Irish Sea was interpolated onto a 2 km rectangular finite difference grid developed for the purpose of this study. The model domain is delineated in Figure 1. Observations show that the density field in the Irish Sea is controlled primarily by temperature from early summer onwards (Horsburgh, 1999). For this reason, and due to the uncertainty in the salinity of inflowing oceanic water, salinity was held constant at the open boundaries and set to climatologies. Tides were imposed at the open sea boundaries as tidal constituents and the amplitudes and phases of M_2, S_2, N_2, K_1, P_1 and O_1 constituents were provided. Freshwater inputs along the British and Irish Coasts were included in the model and distributed according to values provided in ISSG (1991). Sea temperatures at the open ocean boundaries were specified at every computational time step, and the values were obtained by a linear interpolation of monthly data from Meteorological Service (1995) between the dates. A series of runs were performed to find an optimal surface heat flux model among those incorporated within ECOMSED, as well as appropriate parameter settings.

The bathymetry map is presented in Figure 1 along with the distribution of locations where tidal elevations (T1-T14) and tidal currents (C1-C14) were available for the model validation.

A full set of meteorological conditions was collated in order to perform seasonal simulations. The calendar year of 1995 was chosen for simulations, which was determined by data availability, and the fact that the existence of a well-established western Irish Sea gyre in that year was already reported (Horsburgh, 1999). Rationale for selecting this year for studying flushing properties of the Irish Sea is discussed in more details in Dabrowski et al. (2010). Forcing data was obtained from the US National Oceanic and Atmospheric Administration. This data originates from the reanalysis/forecast system performing data assimilation using past data from 1948 to the present.

The model solves the advection-diffusion equation to predict spatial distribution of active (temperature and salinity) and passive tracers; MPDATA advection algorithm developed by Smolarkiewicz (1984) has been applied. Horizontal diffusion is calculated according to the formula developed by Smagorinsky (1963), which adjusts the scale of mixing to the grid size. Horizontal Prandtl number, being the ratio of horizontal viscosity to horizontal diffusivity, was held constant and set equal to the recommended value of 1.0 (Hydroqual, 2002). The value of the Smagorinsky coefficient was fixed at 0.1 as suggested by Mellor (2003). Small-scale mixing not directly resolved by the model is parameterized in terms of horizontal mixing coefficients. Turbulence closure scheme is based on the 2.5 level algebraic stress equations developed by Mellor and Yamada (1982) with recent corrections presented in Mellor (2001). Vertical Prandtl number, being the ratio of vertical viscosity to vertical diffusivity, and the background mixing parameter were set equal to the recommended values of 1.0 and 10^{-6} m^2/s (Hydroqual, 2002), respectively. The above settings proved to be successful in the reconstruction of the distribution of Tc-99 (Olbert et al., 2010a, 2010b) and water temperatures in the Irish Sea (Dabrowski et al., 2010; Olbert et al., 2011).

Further details on collated data can be found in Dabrowski (2005).

2.2. Water renewal time scale calculations

A concept of residence time derived in Takeoka (1984) was utilised in this study as being the most suitable characteristic for describing exchange processes, when the total material in a reservoir is considered. Takeoka (1984) introduced the remnant function, *r(t)*, as the ratio of the mass of material within a reservoir at a given time to the initial mass of this material, and defined the average residence time, τ_r, as follows:

$$\tau_r = \int_0^\infty r(t)dt \qquad (1)$$

Amongst the researchers who have utilised the above definition of the average residence time was Murakami (1991), who developed a universal formula for the remnant function, capable of representing the dye decay curves for basically any reservoir with the tidal exchange:

$$r(t) = \exp(-A_1 t^{B_1}) = \frac{c(t)}{c_0} \qquad (2)$$

The empirical constants A_1 and B_1 depend on the shape of the decay curve and must be determined for each case. An additional advantage of Murakami's expression is the fact that it can be easily integrated numerically giving the value of the residence time of a studied reservoir.

It can be easily shown that under the assumption of complete mixing, the residence time of a reservoir equals the time required to reduce the initial concentration of a tracer by an exponential factor *e*, see for example van de Kreeke (1983) and Asselin and Spaulding (1993). In this study, we treat individual numerical model's cells as completely mixed reactors, therefore we calculate the e-folding time, τ_e, of each cell to compute the spatial distribution of residence time.

2.3. Summary of methodology

The three-dimensional ocean and coastal circulation and transport model was applied to develop a barotropic and baroclinic model of the Irish Sea. Following its calibration, passive tracer simulations were carried out to track spatial and temporal distribution of the conservative tracer following its initial uniform distribution throughout four regions presented in Figure 2. The tracer was introduced in the model in the form of an instantaneous release and was uniformly dispersed throughout the regions of interest. Four selected regions are distinct with regards to the topographical features as well as the circulation patterns. Region A consists of the entire Irish Sea. Region B is northern Irish Sea; this is a region of enhanced fishery activity and its western section is subject to strong thermal stratification. Region C covers the area of the St. George's Channel only. It is the region of highly energetic tidal circulation; it is vertically well mixed and is also bounded by strong baroclinic features developing seasonally. Region D, the eastern Irish Sea, is separated from the main channel running south-north; it is considerably shallower and receives high input of contaminants from several major estuaries.

Dye decay curves, $c(t)/c_0 = f(t)$, obtained from the simulations were approximated by the remnant function, $r(t)$, equation (2), using the least squares method. Integration of $r(t)$, equation (1), yields the average residence times of the examined regions. Calculated average residence times are representative of the entire regions, i.e. tracer concentrations were averaged horizontally and vertically. Influence of thermal stratification and associated baroclinic features developing in the Irish Sea, such as the western Irish Sea gyre, which affects water exchange processes in the region, has been a subject of a separate research presented in Dabrowski et al. (2010).

Five flushing simulations for each region were carried out in this study; the simulations differed in the tracer release date and forcing functions applied. Two release dates were considered, summer (1st of June, runs F1 – F4) and winter (1st of December, run F5), and four versions of the model comprised following forcing functions: tides only (run F1), tides and wind stress (run F2), tides and heat fluxes (run F3), tides, wind stress and heat fluxes (runs F4 and F5). A characterisation of the simulations is presented in Table 1.

Finally, the *e*-folding times for each computational cell were computed and presented as contour plots, showing the distribution of residence time with flushing pathways clearly marked. On the basis of the spatial distribution of residence time, FHC were developed summarising percentage area distribution of residence times throughout the regions. The authors also proposed the aerial flushing deviation index, FDI, as a useful measure of the spread in the values of distributed residence times. FDI is the difference between the values of τ_e, $\tau_{e90\%}$ and $\tau_{e10\%}$, for which 10% of the area are characterised by greater and lower distributed residence times, respectively. Therefore, FDI also represents the average slope of FHC.

3. Model Validation

The general tidal circulation in the Irish Sea predicted by the model follows the pattern described in the literature (Bowden, 1980; ISSG, 1991). Contours of the model-predicted depth-averaged tidal currents on a spring tide are presented in Figure 3(a). The model reflects all features of the tidal circulation within the region properly, for example strong currents in St.George's and North Channels as well as the area of persistent slack water to the east of the Isle of Man. The extents of the regions of fast flow, exceeding 1.2 m/s, in the St. George's, the North and the Bristol Channels as well as the slack water in the Western Irish Sea are in close agreement with the observations; see ISSG (1991). Magnification of tidal currents near headlands was observed, as predicted by previous models (Horsburgh, 1999; Proctor, 1981). An important feature from the point of view of this research work is the model's ability to predict locations of thermal fronts, with particular emphasis placed on the western Irish Sea region, which stratifies during late spring and summer each year. Simpson and Hunter (1974) proposed that the spatial pattern of seasonal stratification is controlled by the distribution of tidal mixing as summarized by the parameter H / v_s^3, where H is the water depth, and v_s is the maximum tidal surface current. Figure 3(b) presents the spatial distribution of the $\log[H / v_s^3]$ parameter predicted by the model; contours of $\log[H / v_s^3] = 2$, which according to Simpson et al. (1977) determine the locations of thermal fronts, are labelled. The spatial distribution of this parameter predicted by our model corresponds closely to that observed by Simpson et al. (1977) in: the western Irish Sea, the southern reaches of the St. George's Channel as well as in Cardigan Bay to the east of the St. George's Channel. Comparisons of model-predicted and recorded tidal elevations at selected coastal location (T14) and predicted and recorded currents over a tidal cycle at location B3 in the western Irish Sea are also presented in Figure 3(c) and 3(d), respectively. As can be seen, very good agreement with the observations has been achieved for the barotropic component of the hydrodynamic model. The presented comparisons are typical of the good correlation obtained between model predictions and data for many locations throughout the Irish Sea.

Application of the heat flux model by Ahsan and Blumberg (1999) resulted in the best correlation between the model-predicted temperatures and data used for comparison. Sea surface temperatures at locations E_1 and E_2 were obtained from the NOAA-CIRES CDC analysis/forecast system, whereas surface and nearbed temperatures at location E_3 were measured in-situ (Horsburgh, 1999); for locations of E_1 – E_3 see Figure 4(a).

The model revealed particularly good capabilities to simulate proper values of temperatures in the western Irish Sea region (E_3) as presented in Figure 4(c), with R^2 values of 95.6% and 96.0% for surface and nearbed temperatures, respectively (see also Dabrowski et al. (2010) for more details). With regards to locations E_1 and E_2, the R^2 values averaged at 93.4% and 87.2%, respectively. The validation of the model results against temperature in a stratified region of the Irish Sea is particularly important due to the influence of thermal fronts on water circulation in the region.

Two other heat flux bulk formulae were tested as part of this study resulting in slightly worse predictions when compared to data; for detailed intercomparison of the performance of various heat flux models see Dabrowski (2005).

In the western Irish Sea cold relict water is preserved in a dome-like shape throughout summer, as shown in Figure 4(b). The location of transect is shown in Figure 4(a). Strong thermocline and horizontal thermal fronts are clearly visible; the upper boundary of the dome is located approximately at 20 m depth below surface. This temperature structure strictly corresponds to density structure; this result is consistent with observations reporting the presence of colder, denser water lying below 20 – 40 m water depth (Hill et al., 1997).

Since the dome is static, the sloping density surfaces bounding it can only be maintained in geostrophic balance by cyclonic surface layer flow (Hill et al., 1997). Recorded flows are typically between 5-10 cm/s and locally exceed 10 cm/s, and are approximately front-parallel (Horsburgh et al., 2000). Figure 5(a) presents the residual circulation reproduced by the model for mid-summer, when stratification is well developed. As can be seen in Figure 5(a) the model successfully reproduces this anticlockwise seasonal circulation and the magnitudes of the predicted baroclinic currents are similar to those reported in Horsburgh et al. (2000). As can also be seen in Figure 5(b), the barotropic only model does not predict such circulation in the western Irish Sea region.

The reader is referred to Dabrowski (2005), Dabrowski et al. (2010), Olbert et al. (2010a), Olbert et al. (2010b) and Olbert et al. (2011) for further details on the model validation including validation of the advection-diffusion model (Olbert et al., 2010b).

4. Results and discussion of flushing analysis

Net flows through the Irish Sea have been discussed in Dabrowski et al. (2010) and in more details in Dabrowski (2005). In this paper we concentrate on the calculations of residence times and quantification of their spatial variabilities.

4.1. Residence times

The average residence times obtained for simulations F1-F5 carried out for regions A-D are summarized in Table 1.

The results from the passive tracer transport simulations reveal a significant variability in the values of the average residence time depending on the forcing functions applied. Both baroclinic and wind induced currents proved to be largely responsible for increased retention of water within the Irish Sea. The average residence time of region A obtained in run F4 is greater by as much as 37% when compared to the tidally only forced model (F1) and equals 386 days; thermohaline circulation alone increases τ_r of region A by 24%, see Table 1 run F3. This shows the retentive character of baroclinic circulation developing in the Irish Sea. Further contribution towards increased retention of water in the Irish Sea is due to wind driven circulation. Similar percentage increases apply also to regions B and C. Region D, in turn, does not exhibit any significant variability in flushing rates, and, as can be seen in Table 1, baroclinic circulation does not affect the residence time of the region (run F3), whereas wind-induced circulation tends to reduce the residence time only slightly. Region D is shallower than the remaining regions of the Irish Sea, does not stratify in summer, and is located away from the main channel running south-north through the Irish Sea, as indicated in Figure 1. Flushing of region D as well as travel times from the Sellafield's nuclear power plant outfall site located within this region to various parts of the Irish Sea have been the subject of separate research presented in Dabrowski and Hartnett (2008).

Also, as shown in Table 1, water contained within regions A-C on the 1st of December, will have a greater residence time by about two months than that contained there on the 1st of June. This is not surprising when the annual variation in net flows through the Irish Sea is considered. Dabrowski et al. (2010) conclude that the material contained within the Irish Sea in December will be initially transported northward at high rates; however it will be returned to the regions over the next three months as the flow reverses southward. In contrast, for the summer release the northward transport is predicted for the first three months; the rates are significantly lower when compared to those in December. It is followed by c.1.5 months of southward transport, however the rates are low. The flow then reverses to northward and the magnitude progresses quickly to high values in December. The above pattern results in higher values of the residence time of water in regions A-C in the case of winter release (F5) when compared to the summer release (F4). Since region D is located beyond the main channel, it is not subject to the above variability and thus the summer and winter residence times are virtually identical.

Previous estimates of residence times in the Irish Sea include those by Jefferies et al. (1982), who used observed distributions of ^{137}Cs and obtained the value 530 days for region B. He also considered region D separately and calculated the residence time of 290 days for this region. Further studies, carried out by McKay and Baxter (1985) and McKay and Pattenden (1993), delivered significantly lower residence times of region B of approximately 360 days. Values obtained by the authors of this research are closer to the latter estimate and equal 263 and 338 days, for the summer and winter tracer releases, respectively. Due to high spatial resolution in which transport processes have been addressed in this study, the authors believe the proposed estimates are more reliable.

4.2. Spatial distribution of residence time and flushing homogeneity curves

Spatial distributions of residence times in the domain, obtained using the methodology described in Section 2.2, are presented in Figure 6. Fully forced models were considered, therefore Figure 6 presents the results obtained from runs F4 (summer release) and run F5 (winter release) in regions A-D. As far as the entire region of the Irish Sea is concerned (region A), the St. George's Channel is flushed initially due to predominant northward flow in the case of both summer and winter tracer releases, and backwater is formed in the eastern Irish Sea with the maximum residence times predicted in the coastal waters near Liverpool. However, some significant differences in flushing pathways between runs F4 and F5 are also predicted. Waters adjacent to the Irish coast from c.50 km south of Dublin northward are renewed considerably quicker in the event of the winter release (F5). Tracer concentration in these waters drops below the *e*-fold value after about a year following its introduction. Hence, it coincides with the predicted strong northward drift, which is most likely responsible for faster tracer removal in this area. In the case of the summer release, after the time period of 7 months southward flow is predicted (see Dabrowski et al. (2010)), and also after one year the gyre in the western Irish Sea is developed. Therefore, water is retained in the area from c.50km south of Dublin northward for a longer time. Other differences in predicted residence times include locations near the Welsh coast in the St.George's Channel, where higher values are predicted in the case of the winter tracer release. The analysis of region B show that its western part is flushed significantly faster in both F4 and F5 runs. The areas characterised by the greatest values of residence times are in the south-east of the region, where backwater is formed. It can also be seen that the western part of region B is flushed faster in the case of summer release when compared to the winter release, due to a strong northward drift developing in the Irish Sea in autumn (see Dabrowski et al. (2010)). High variability in flushing of region C between the two runs is also apparent. Particularly interesting is also the strong gradient of the residence time values between the southern and northern parts of the region predicted by the model in run F5, including the Irish coastal areas As far as region D is concerned, areas surrounding the Isle of Man are well flushed, and introduced material stays for longer time mostly within south-east of the region in the case of both summer and winter releases. In contrast to other regions, similarity in the distribution of the residence time between the two runs is apparent. Only slightly increased retention in case of the summer release can be noted. This fact is also reflected in the values of the average residence times given in Table 1.

Flushing homogeneity curves for the examined region for the runs F4 and F5 are presented in Figure 7. In general, the steeper the flushing homogeneity curve the less variation in the values of residence times throughout the examined region. A hypothetical completely mixed basin would yield vertical flushing homogeneity curve. Figure 7 also confirms that there are significant differences in the spatial distribution of residence time depending on the time of the tracer release.

As can be seen in Figure 7, 60% of region A has the values of residence time greater than 500 days in the case of the summer release of tracer. Considering the winter release, this value drops to around 35%. On the other hand, c.150 days are required to renew water in the 10% of the area in the case of the summer release, whereas in the case of the winter release this time doubles. Similarly for regions B and C, it can be seen that the time required to flush the initial 10% of the area is significantly higher in the case of the winter release. Since gradients of the curves following the initial flushing of c.10% of the areas are similar, therefore it is concluded that this initial time is the major contributor towards increased average residence times in the case of winter releases. It can also be noted that region D differs in this regard: the time required to flush the initial 10% of the area is slightly lower in the case of winter release. Also, the curves are of similar shape and therefore the average residence times of the region are virtually the same, as presented in Table 1. The characteristic shapes of the curves indicate that although large parts of the regions are characterised by similar values of residence times, there are also places where sharp gradients in τ_e can be expected. This is represented by a characteristic ‘step’ on the FHC; the most pronounced being on the FHC for region A and summer release of tracer (see Figure 7(a)). Figure 7(a) shows that only a small percentage of the area features τ_e between c.300 and c.500 days, and for τ_e of more than 500 days the gradient of the curve is significantly greater. This characteristic 'step' indicates that the domain is divided into slow and fast flushing systems, in relative terms and that high gradient in the values of τ_e exist in the transition zone. This phenomenon can be noted in Figure 6, and is particularly apparent in the case of summer release in region A, where a sharp gradient is observed in the northern part of the St. George's Channel. It is worth noting that this divides energetic waters of the above channel from relatively slack waters of the Western Irish Sea.

Table 2 summarizes FDI for each FHC presented in Figure 7. The higher the value of the index the shallower the gradient of the curve and the greater the aerial deviation from mean. The highest value of FDI of 470 days is observed for region A and summer release (run F4), which is mainly due to the presence of sharp transition zone from quickly to slowly flushed regions, reflected by a characteristic step on the curve. FDI is significantly lower in the case of winter release indicating significant temporal difference in flushing pathways in the region. FDI values for other regions are lower (steeper curves) and less significant difference is observed for the two tracer releases considered. Region C is characterised by the lowest values of FDI and their summer and winter values are virtually the same, indicating similar average slope of FHC. Interestingly, as presented in Table 1, τ_r of this region in the case of winter tracer release is c.20% greater than in the case of summer release. It can be therefore concluded that this notable increase in the value of τ_r is attributed to the significant increase in the residence times of the quickest flushed areas. Indeed, as can be seen in Figure 7, $\tau_{e10\%}$ for this region increases from 105 days in the case of summer release to 160 days in the case of winter release.

5 Summary and Conclusions

This paper presents details of research into developing a better understanding of the assimilative capacity of the Irish Sea; a novel generic approach for flushing studies has been proposed as part of this research. With regards to the Irish Sea modelling, particular emphasis was put on the proper representation of thermal stratification developing in the western Irish Sea during spring and summer. Flushing characteristics considered include average residence time, spatially distributed residence times, flushing homogeneity curve and flushing deviation index.

The main conclusions resulting from this research are summarized and discussed below:

- This research illustrates that the proposed new approach using spatial distribution of residence times and flushing homogeneity curves gives new insight into flushing of the Irish Sea and transport processes. Since the Irish Sea is a hydrographically complex system, a single value describing its flushing properties delivers a picture that is incomplete. It has been shown that even within hydrographically uniform subregions, further valuable information is obtained through the adaptation of the proposed approach, namely the compact visualisation of flushing pathways and quantification of the variation in flushing.
- The authors showed that not only the average residence times of various regions of the Irish Sea vary depending on the time of the year selected as the start date for the examination of the water renewal processes, but spatial distributions of residence times within these regions also differ. For example, sharp gradients in the values of residence times are predicted in the case of winter release that separate relatively quickly flushed St. George's Channel from the remaining relatively slowly flushed regions; the gradient is

significantly lower in the case of the summer release. Discrepancies within the St. George's Channel are also apparent when the region is considered separately. Relatively small variation in flushing pathways between summer and winter releases is observed in the eastern Irish Sea; this is consistent with the results on average residence times, which reveal region's stable flushing properties. Thus, plotting the distributed residence times for a region gives a second-order insight into the transport phenomena, and is therefore a useful complement to flow fields provided by the hydrodynamic model along with the general information provided by single values of average residence times.

- The concept of FHC was devised by the authors and then applied to summarize flushing properties. FHCs provide useful generic information about the degree of variation in flushing rates across the domain. In particular, the range of the values of residence time is delivered as well as the 'smoothness' of transition from quickly to slowly flushed regions. For example, curves of shallow gradients indicate higher spatial variability in residence times. Also, points of contraflexure and characteristic 'step' on the curve indicate the presence of sharp gradients in flushing rates when moving across the examined region, thus imposing careful management approach. The average slope of the curve is quantified by FDI. Apart from bringing in some more valuable information on the deviation in the values of residence time from mean, further important conclusions in relation to slowest and quickest flushed regions can be drawn when analysed in conjunction with τ_r. For example, an increase of τ_r without change of FDI indicates an increase in residence times of the quickest flushed regions. Therefore, FHC, FDI and τ_r may be utilised in determining the need of more detailed studies of transport and water renewal studies prior to making important management decisions.

- This research showed that average residence times of the Irish Sea and its subregions are functions of tidal action, meteorological conditions and density-driven currents, and thus also the time of the year considered. As far as the entire region of the Irish Sea and summer tracer release are concerned, tidal circulation alone flushes the domain in 282 days. When wind induced flows are included, the average residence time increases to 322 days. Finally, the average residence time of 386 days is computed when thermohaline circulation is also included; this is 37% increase when compared to tidal model. Regions B and C that were considered separately exhibit similar response to various forcing functions applied. In the case of a winter tracer release, further 15-28% increase in the values of average residence times is observed, depending on the region. In contrast, the eastern Irish Sea (region D) is characterised by relatively stable residence times. This significant variation in flushing properties was then investigated in more details using the new approach devised in this research. This is an extremely useful approach considering significant implications for management of water quality, particularly with regards to the discharge of persistent pollutants, such as radionuclides.

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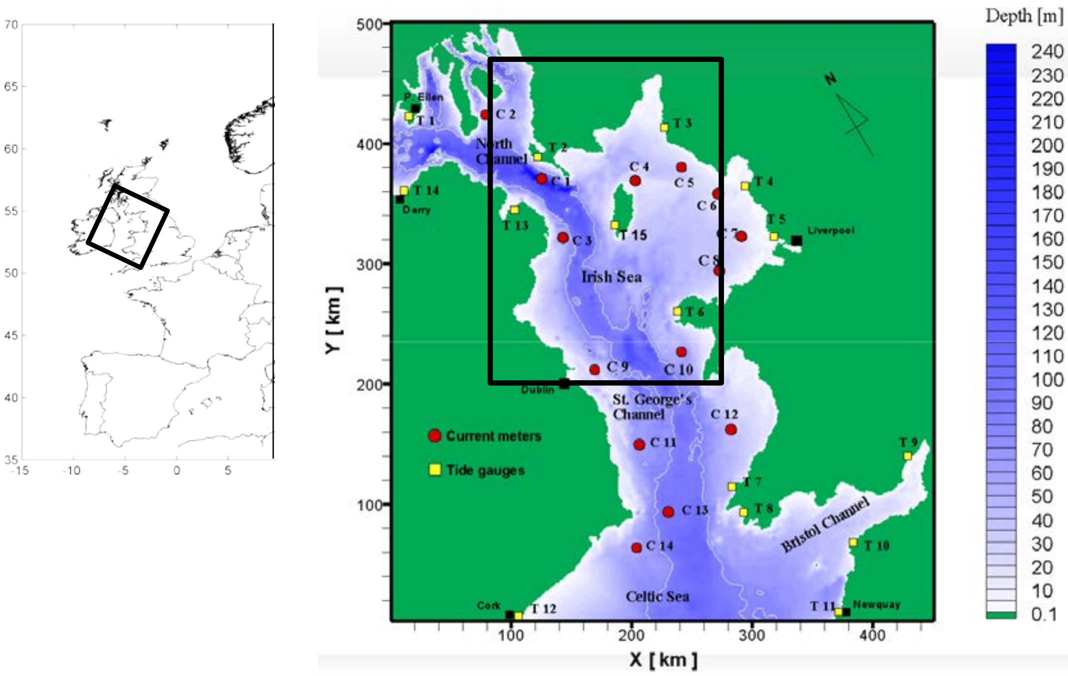

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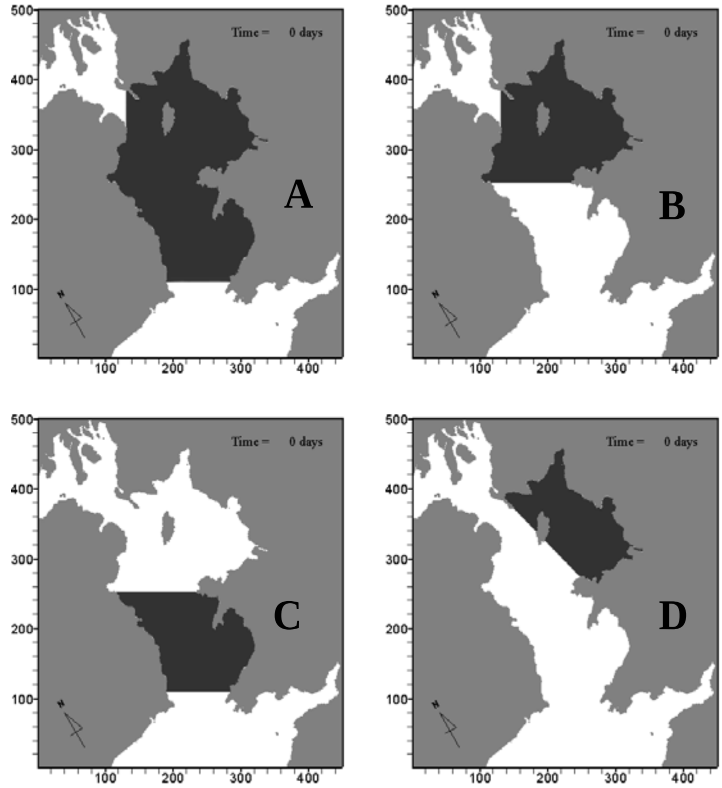

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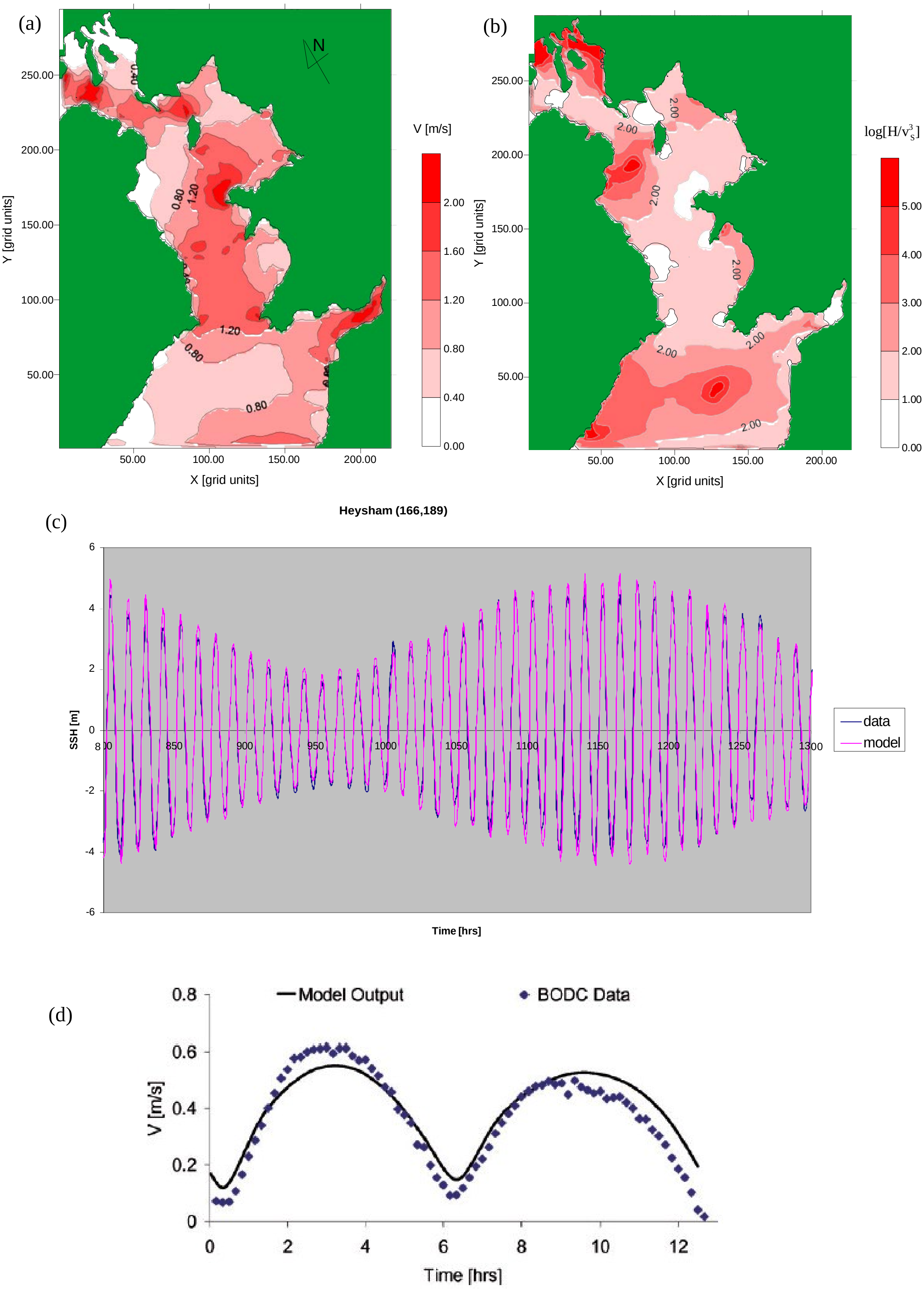

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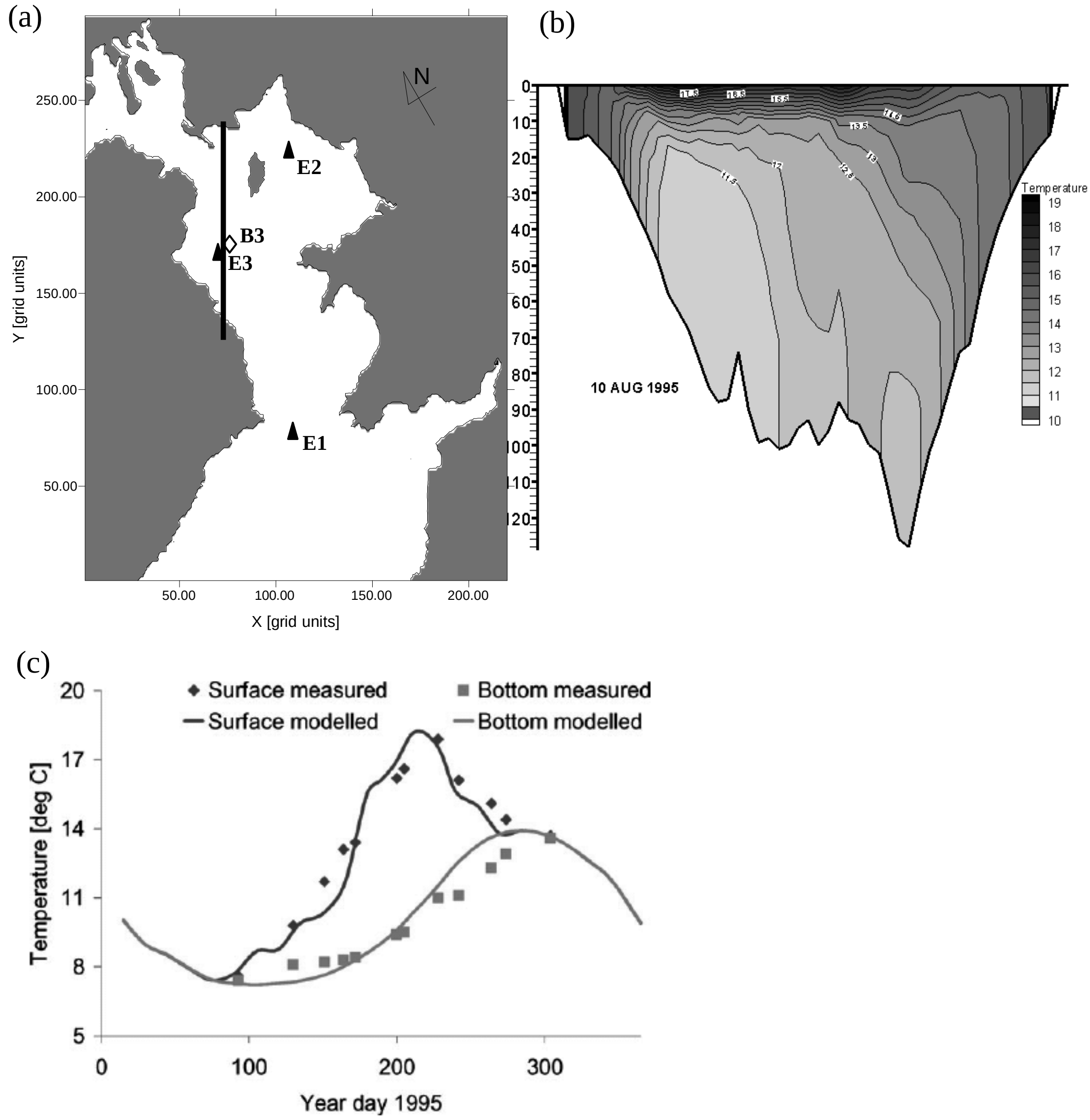

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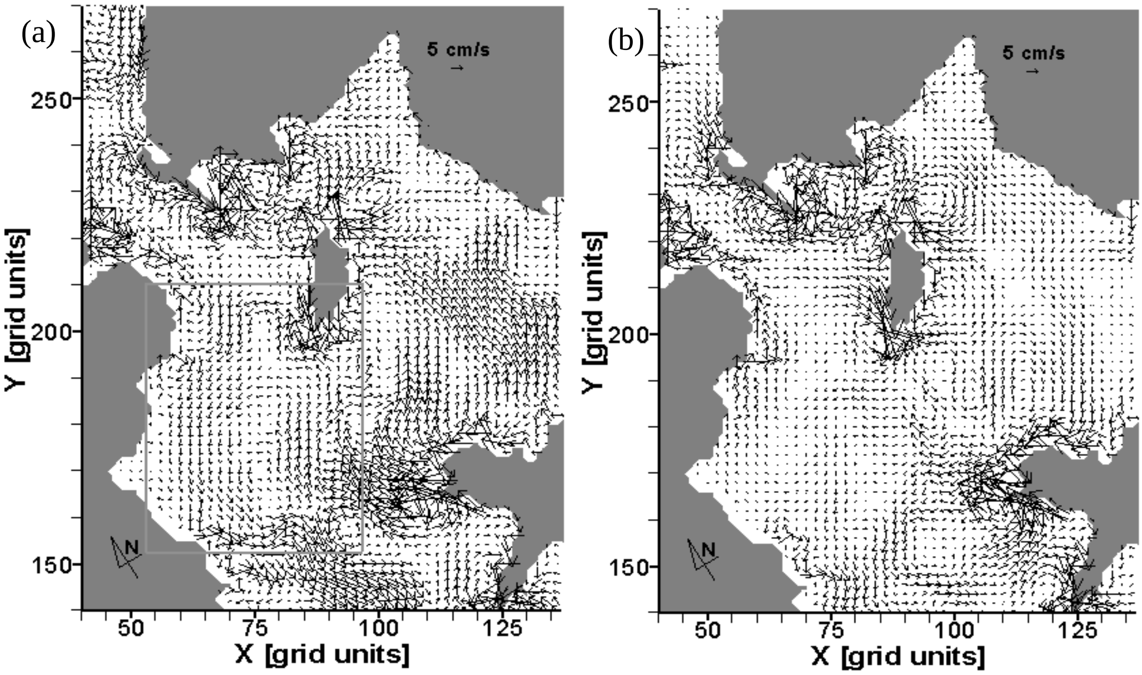

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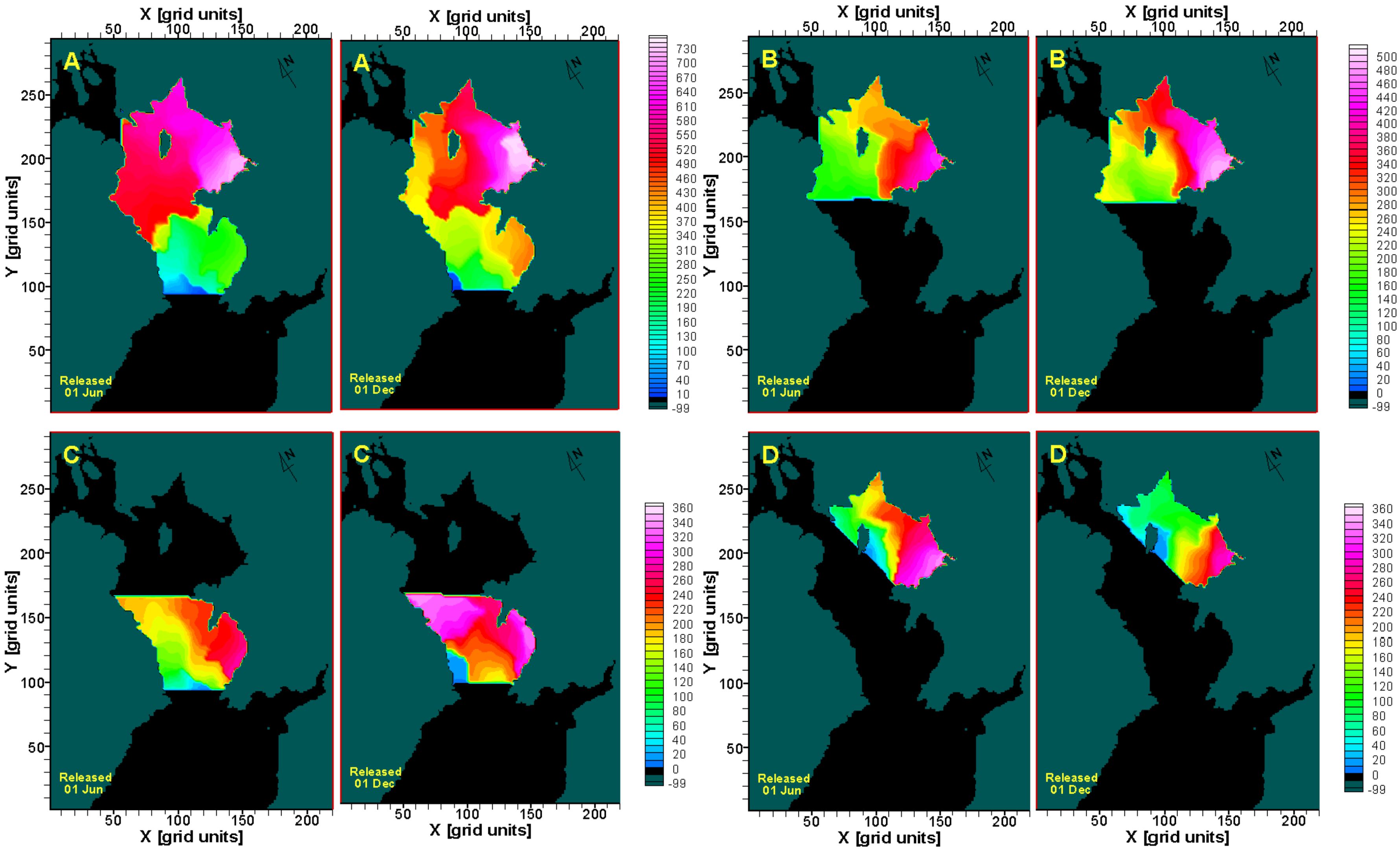

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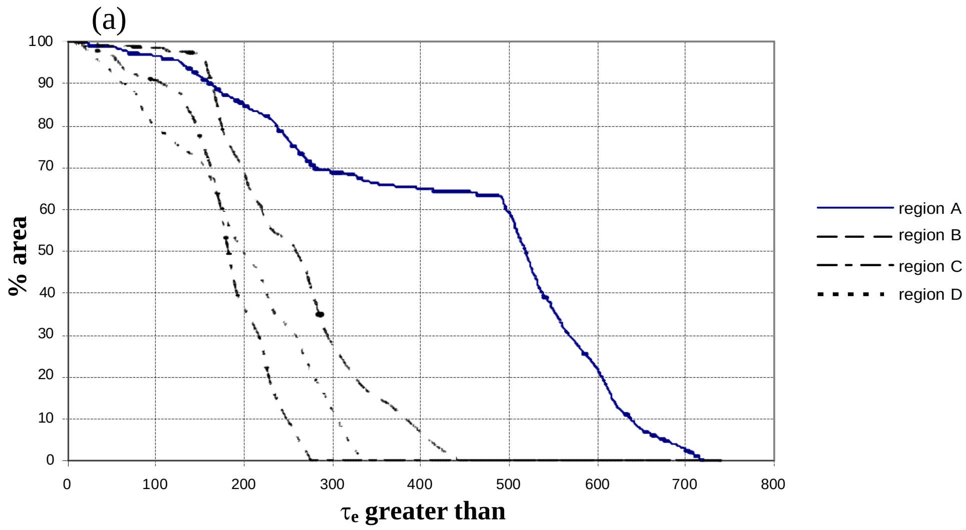

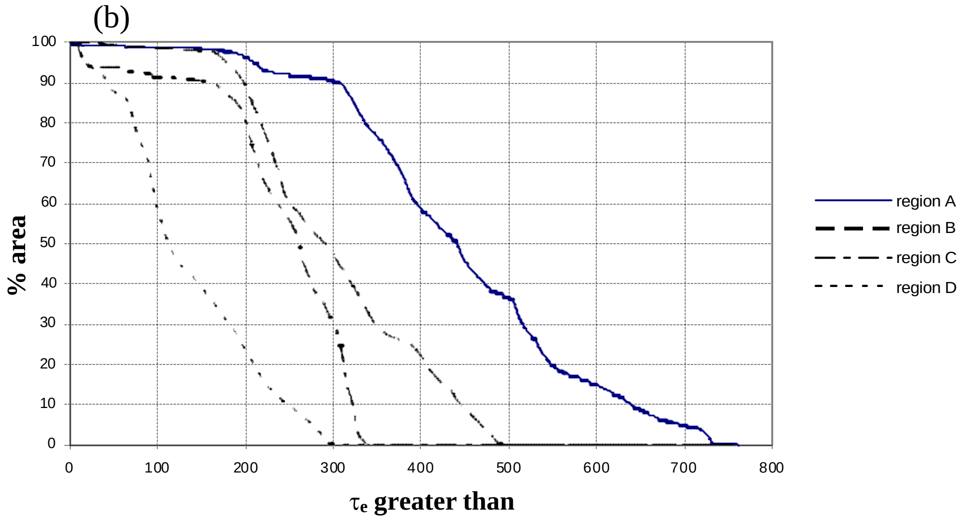

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Table 1. Characterisation of model runs and values of calculated residence times.

Model run	**Run characteristic**		**Residence times for regions A-D**			
	Dye release date	**Model version**	τ_{rA} **(d)**	τ_{rB} **(d)**	τ_{rC} **(d**	τ_{rD} **(d)**
F1	01 Jun	tides only	282	214	154	224
F2	01 Jun	tides + wind	322	219	179	209
F3	01 Jun	tides + heat flux	351	257	179	223
F4	01 Jun	tides + wind + heat flux	386	263	203	213
F5	01 Dec	tides + wind + heat flux	444	338	244	208

Table 2. Values of FDI for regions A-D and model runs F4 and F5.

Model run	FDI_A (d)	FDI_B (d)	FDI_C (d)	FDI_D (d)
F4	470	215	145	245
F5	330	245	155	205