Sources and sinks of scallops (*Pecten maximus*) in the waters of the Isle of Man as predicted from particle tracking models

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Introduction

Marine Protected Areas (MPAs) are advocated to perform two functions: i) conservation: protecting biodiversity within the reserve and ii) fisheries enhancement: improvement of fisheries yields and sustainability through spillover of adults and larvae from reserves to fished areas and the prevention of overexploitation (Hilborn et al., 2004; Kaiser, 2005). Whereas the first function is non-controversial, the second remains open to debate for temperate systems and there is currently insufficient empirical scientific evidence for spillover effects of MPAs, with good examples so far only demonstrated for tropical marine ecosystems such as coral reefs (Russ and Alcala, 1996; Roberts et al., 2001; Sweeting and Polunin, 2005). Siting marine reserves at locations that maximise potential spillover from the MPAs to adjacent fishing grounds, and at the same time enable the establishment of a network of reserves linked by larval dispersal, is a crucial step towards sustainability. However, research on practical methods for achieving this is in its infancy. Furthermore, setting aside a marine reserve initially reduces the area that can be fished, thus reducing initial yield. The question then is whether the yield in the area that remains open will increase enough to compensate for losses from the closed area (Hilborn et al., 2004). Displacement of existing fishing effort will lead to an increase in fishing pressure outside the MPA and an associated decline in stocks that would have been similar or worse than the situation without the marine reserve. It is critical to have scientific evidence to improve the implementation of MPAs and to engage stakeholders in this management approach. The location of MPAs in inappropriate locations will reduce their credibility with the fishing industry if they do not achieve their intended goals.

Unlike fish, scallops (*Pecten maximus*) are sessile species that are restricted to specific seabed types that enable the scallop to recess into the sediment. Scallops release eggs and sperm into the water and the resulting larvae are transported on tidal currents for a period of 3 – 5 weeks. Given the considerable tidal energy in the Irish Sea, the dispersal distance from the point of source of larvae could be considerable. Therefore it is important to study the potential sources and sinks of scallops if we are to provide evidence to inform the location of possible areas closed to scallop fishing (designed to increase scallop biomass and hence generate more larvae). To do this, particle tracking models (PTMs) are useful tools that enable us to model and predict the movement of particles (larvae) transported on tidal currents. Such models simulate larval trajectories in three-dimensional flow fields (Tremblay et al., 1994; Proctor et al., 1998; Mullon et al., 2003; Pedersen et al., 2003; Miller et al., 2006). Developing accurate PTMs requires information on hydrodynamic conditions (tidal flows, currents, gyres, meteorological forcing e.g. wind) and on larval biology (time of spawning, vertical migration, duration and depth of planktonic drift, growth and mortality rates).

The present study was undertaken to provide initial insights into the dispersal dynamics of particles released from six sites in the coastal waters of the Isle of Man. Three sites were pre-determined as possible source locations (Port Erin, Douglas and Laxey Bay). These sites were chosen because they are either existing or were proposed closed areas). Each of the other sites was chosen in an iterative process advised by the outcome of each successive modelling exercise (i.e. the outcome of modelling site 1 informed the choice of location of site 2…). Models were run for 3 and 5 weeks which encompasses published estimates of the time scallop larvae spend in the water column prior to settlement.

Methodology

In shelf seas, astronomical tides are the dominant cause of water movements. However, since tidal currents are oscillatory, they do not significantly affect the long-term transport of larvae relative to residual currents. This residual flow is primarily due to local wind stress on the sea surface and horizontal density gradients (baroclinic flows). For a numerical model of the Irish Sea applied to Lagrangian transport, it is essential to account for this residual flow. The 3D baroclinic/barotropic POLCOMS model was applied in this project at a horizontal resolution of approximately 1 km with 20 vertical (sigma) layers to the northern Irish Sea (Fig. 1). Lateral boundaries of the POLCOMS model were driven by astronomical tides and baroclinic flow provided from an outer nested model of the northwest European continental shelf at a resolution of approximately 12 km (Fig. 2). Both outer and inner nests were coupled with high resolution (hourly) meteorological data of wind speed, wind direction, atmospheric pressure, air temperature, cloud cover and relative humidity.

For the purposes of developing realistic baroclinic flows, the model simulation was started on the 1st March since at that time, stratification throughout the Irish Sea will be minimal as a result of the preceding autumn/winter climate. Hence, the assumption was made that a single temperature value (8°C) was applied throughout the domain as the initial condition. Since realistic model output was not required until August (i.e. 5 months later), the exact nature of this artificial initial condition is not critical. For both outer and inner nested models, the temperature and velocity fields were evolved from this initial condition until August at which point the depth-averaged velocity field for the high-resolution inner nest was written to file every 15 minutes for a period of 35 days. Since larval density does not affect hydrodynamics, the particle tracking model (PTM) was used offline (in conjunction with POLCOMS-generated flow fields) using advective (deterministic) and diffusive (stochastic) steps in order to track the larval positions forwards (and backwards) in time, using the six proposed marine reserve positions as initial conditions.

Using a high performance (12 processor) Silicon Graphics machine at Bangor University, 1×10^{6} particles were simulated for each release scenario using a model time step of 5 minutes. Bi-linear interpolation was applied to each particle position to determine the components of velocity at sub-grid cell scales. Since the time step of the PTM (5 minutes) does not match the time step of the POLCOMS model output (15 minutes) it was also necessary to make a temporal linear interpolation of the velocity field for every time step of the PTM. The time step of 5 minutes was chosen according to the Courant-Friedrichs-Lewy condition which states that for stability and accuracy, model information must not propagate more than one grid cell in one time step, i.e.

$$\delta t \leq \frac{\delta x}{u} \qquad \text{and} \qquad \delta t \leq \frac{\delta y}{v}$$

where δt is the time step, δx and δy are the eastwards and northwards cell size (respectively) and u and v are the eastwards and northwards velocity (respectively).

Since wind forcing and baroclinic currents are stochastic, the model was run for 10 different release events (at a spacing of 48 hours) throughout August and the results combined to give a more robust prediction of dispersal than a single release would achieve. On each release, the advection and (turbulent) diffusion of 1×10^{6} particles was simulated. Therefore, with 10 releases, this resulted in 10×10^{6} particles used to derive probability density plots. These quantify on a cell-by-cell basis the percentage probability that a particle which has originated from a proposed marine reserve will be located at this new location over the prescribed time period. The model was also run backwards to give the probability that particles terminating at a marine reserve have originated from different source locations.

Results

By way of example, the particle positions for each release scenario (i.e. staggered in 48 hour intervals) are plotted after 21 days in Fig. 3 for the Ramsey Bay case. In most of the outputs, the particles have been entrained by the western Irish Sea gyre (a cyclonic, i.e. anticlockwise, system). The particles for all ten of these simulations were combined and the number of particles present at each model grid cell (approximately 1 km × 1 km) were summed and divided by the total number of particles released to produce the probability density plot

(Fig. 4). Hence, this is the 21 days forwards dispersal kernel for a theoretical Ramsey Bay marine reserve.

Considering all simulations together provides useful insights into the potential connectivity around the waters of the Isle of Man. Ramsey Bay is of note as it appears to transport particles to the Northeastern Irish Sea towards the Solway Firth/Cumbrian coast with some larvae transported to the northwestern coastline of the Isle of Man, and many retained at the northerly end of Ramsay Bay. However the supply of larvae to Ramsey Bay would appear to be from a semi-circular array of offshore seabed that perhaps indicates some form of gyre system in that region. Offshore regions to the east of the Isle of Man appear to supply larvae to inshore grounds such as Laxey and Douglas. These two sites disperse larvae that are advected to the North (Ramsey Bay), but primarily to the south and southwest of the Isle of Man which is the location of some of the most important fishing grounds. Larvae dispersed from Derbyhaven and Port Erin are advected to the south west grounds but in the case of Port Erin largely to the northwest offshore area known as 'The Targets'.

Discussion

The use of a particle tracking model has provided useful preliminary insights into the connectivity of the scallop grounds around the Isle of Man. There is considerable connectivity around the Island among the different known scallop grounds. This would suggest that a network of areas would increase the resilience of the scallop population from over-exploitation. However, some source areas were located beyond those waters under the jurisdiction of the Isle of Man Government. These source areas are therefore 'at risk' from scallop fishing activity by other fleets that controlled by UK and EU regulations.

Isle of Man fishing industry observations indicate that the scallops in Douglas and Laxey Bays are poor quality in terms of their meat condition and yield. However, the predictions generated by the PTM suggest that these scallops may have a disproportionate importance in terms of supply of larvae to commercially fished areas to the south and west of the Isle of Man. Based on these predictions, recommendations were made that the stock enhancement programme that occurred in 2008 was focussed on the introduction of scallops into Douglas Bay and the area closed to scallop fishing.

The modelling work undertaken is a preliminary attempt at understanding the issue of connectivity around the Isle of Man. Further model runs that incorporate larval behaviour (diurnal vertical migration between the surface and the seabed or pycnocline) and a wider range of wind forcing events. It would be highly desirable to take a forward look at climate change scenarios by running the PTM with wind and temperature parameters forecast under climate change scenarios.

Recommendations

Undertake further runs using the PTM to test its sensitivity to larval behaviour and a wider range of climate forcing events.

Undertake further runs using the PTM to test climate change scenarios to evaluate the resilience of the scallop fisheries around the Isle of Man to climate forcing events.

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Table 1. The six proposed reserve positions are plotted in Fig. 5 and the results for the simulations are given in Figures 6-11, as listed in the following table.

Reserve	Direction	Days	Figure
Derby Haven	Forwards	21	6a
		35	6b
	Backwards	21	6c
		35	6d
Douglas Bay	Forwards	21	7a
		35	7b
	Backwards	21	7c
		35	7d
Laxey Bay	Forwards	21	8a
		35	8b
	Backwards	21	8c
		35	8d
Port Erin	Forwards	21	9a
		35	9b
	Backwards	21	9c
		35	9d
Ramsey Bay	Forwards	21	10a
		35	10b
	Backwards	21	10c
		35	10d
Targets	Forwards	21	11a
		35	11b
	Backwards	21	11c
		35	11d

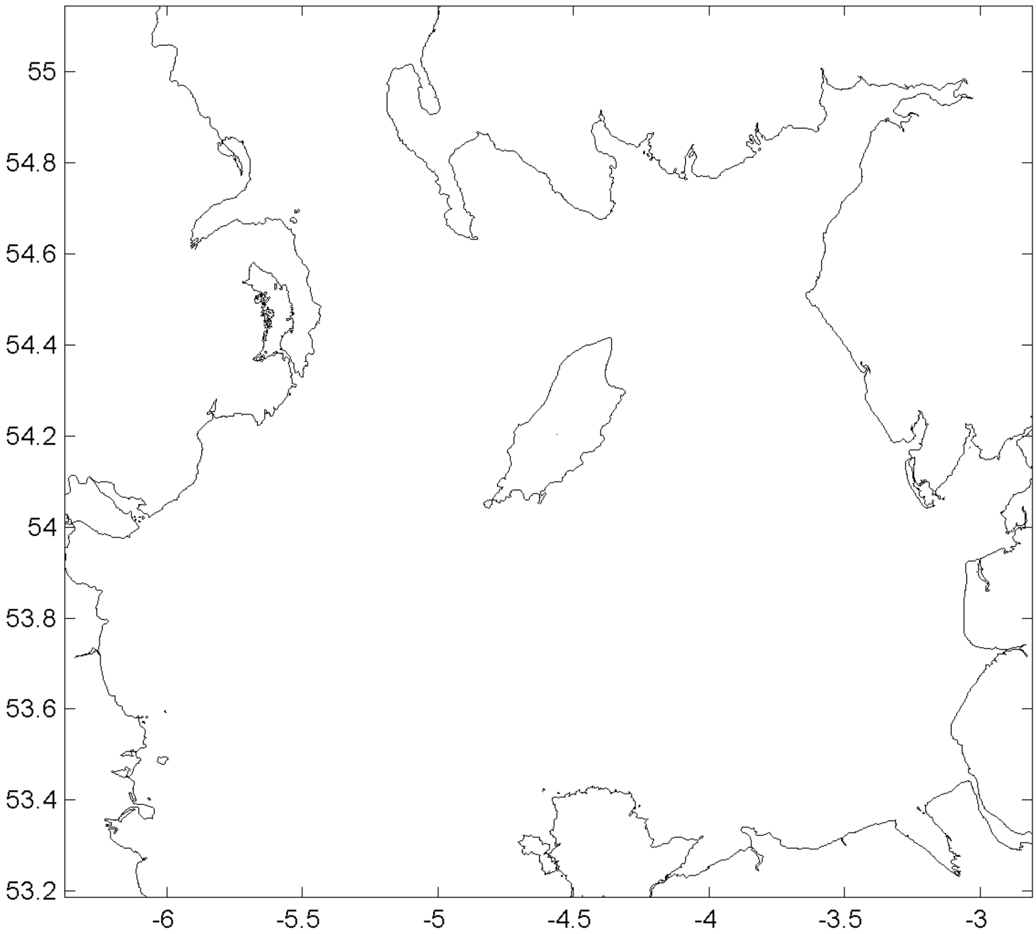


Figure 1. Model domain of northern Irish Sea.

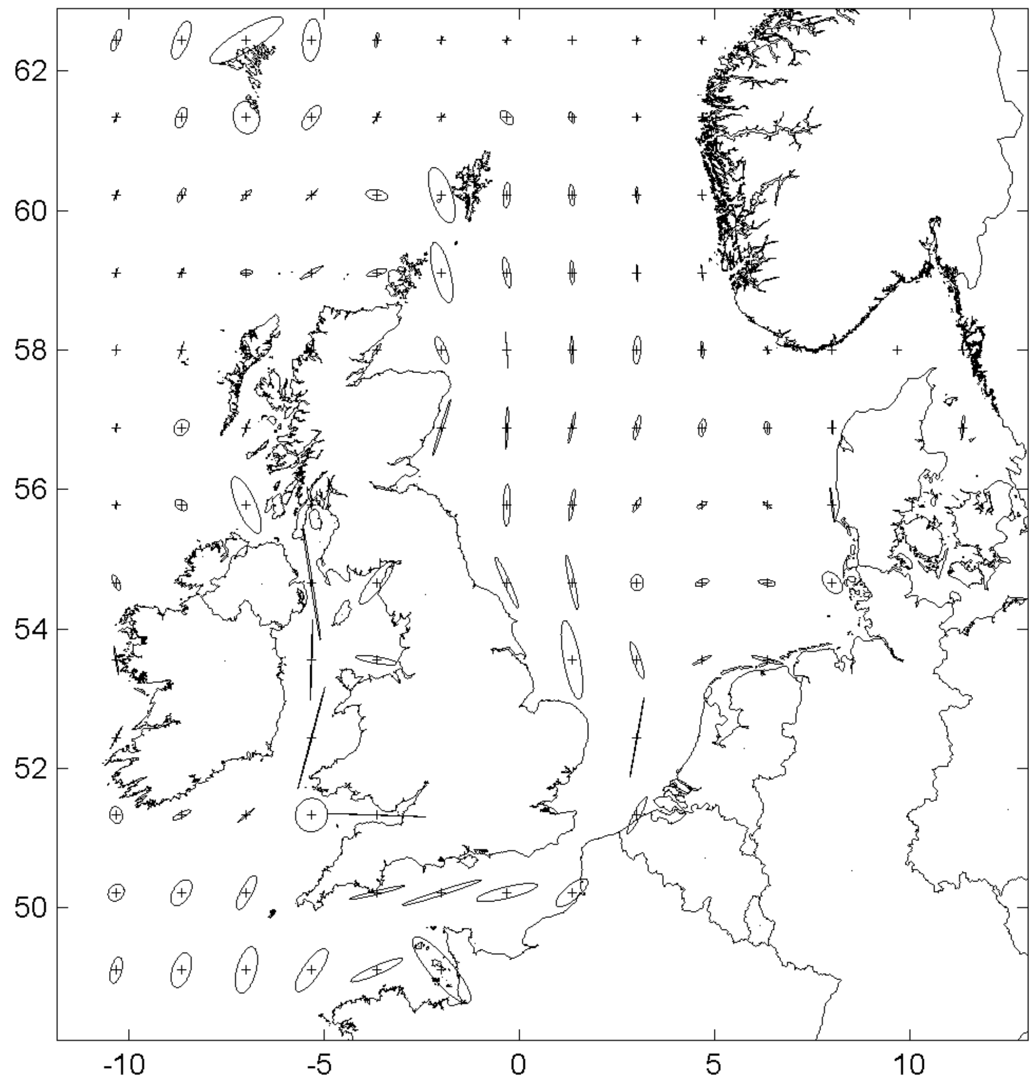


Figure 2. Domain of outer model nest: northwest European continental shelf. Also shown are the M_2 tidal current ellipses at every tenth modelled grid point.

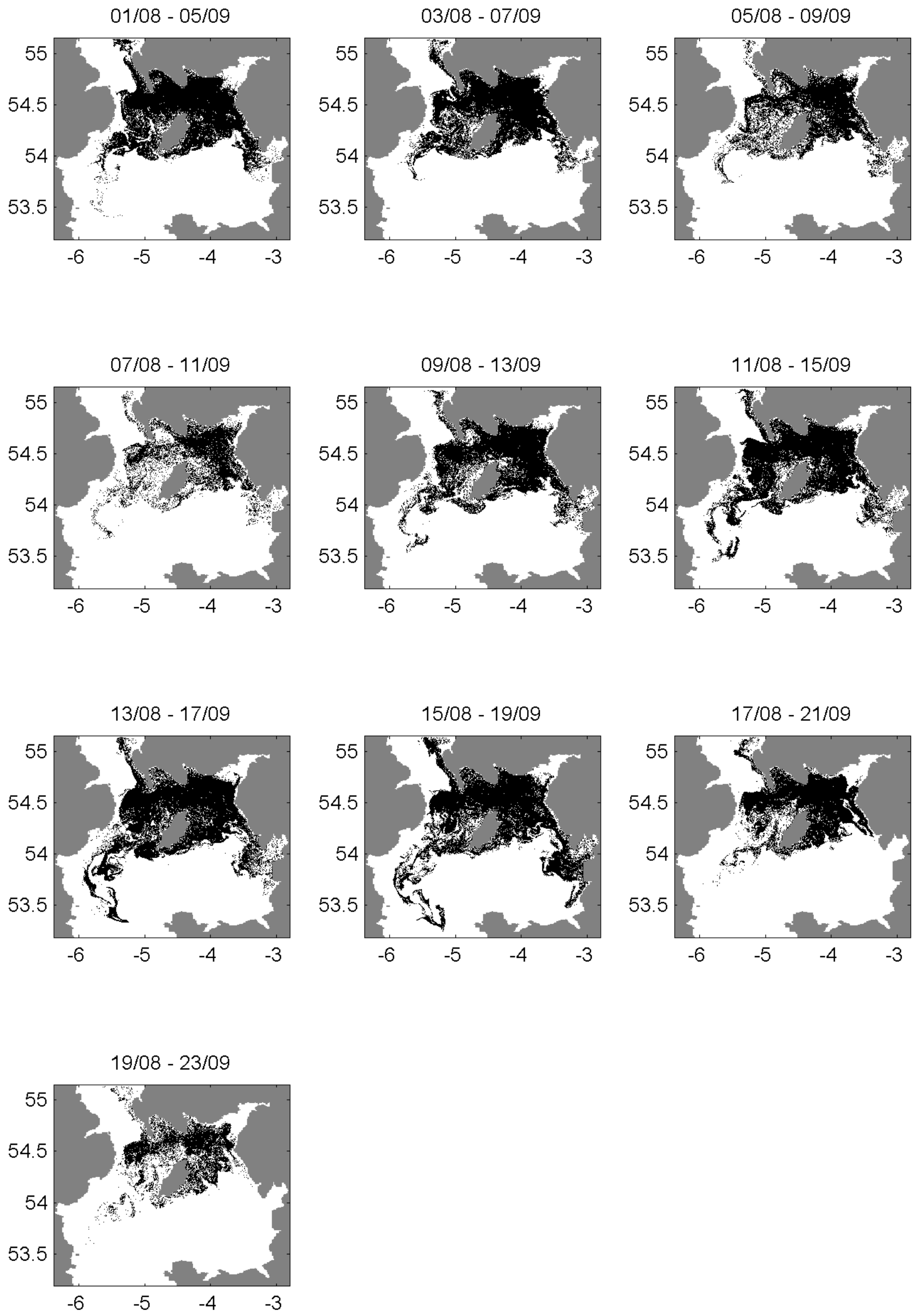


Figure 3. Example of individual release scenarios from Ramsey Bay after 21 days of simulation.

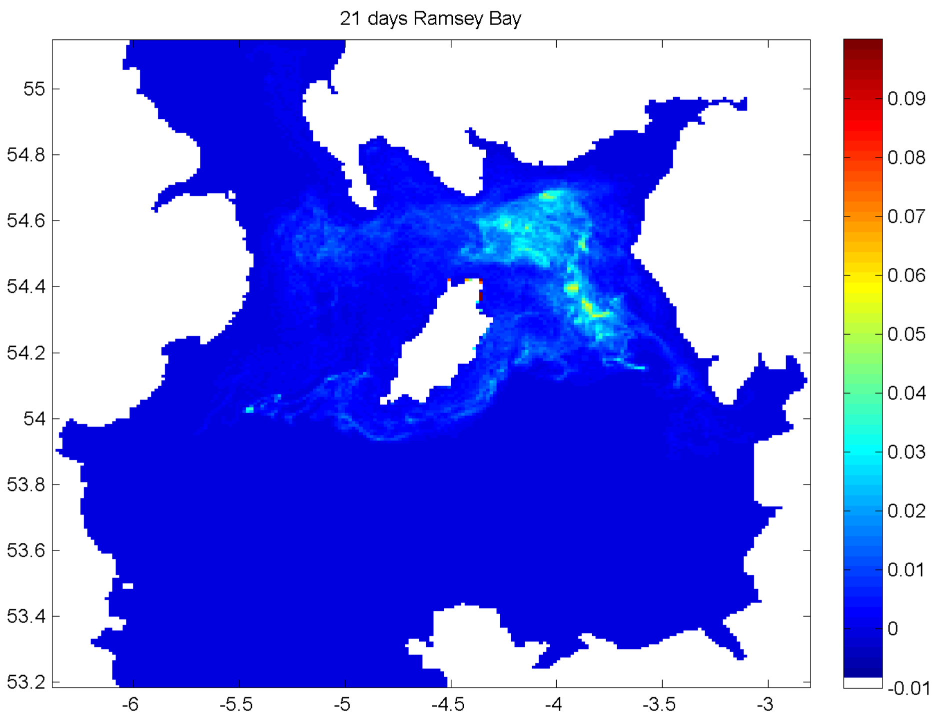


Figure 4. 21 day forwards Ramsey Bay probability density plot derived from the particle positions plotted in Fig. 3. Colour scale is percentage probability.

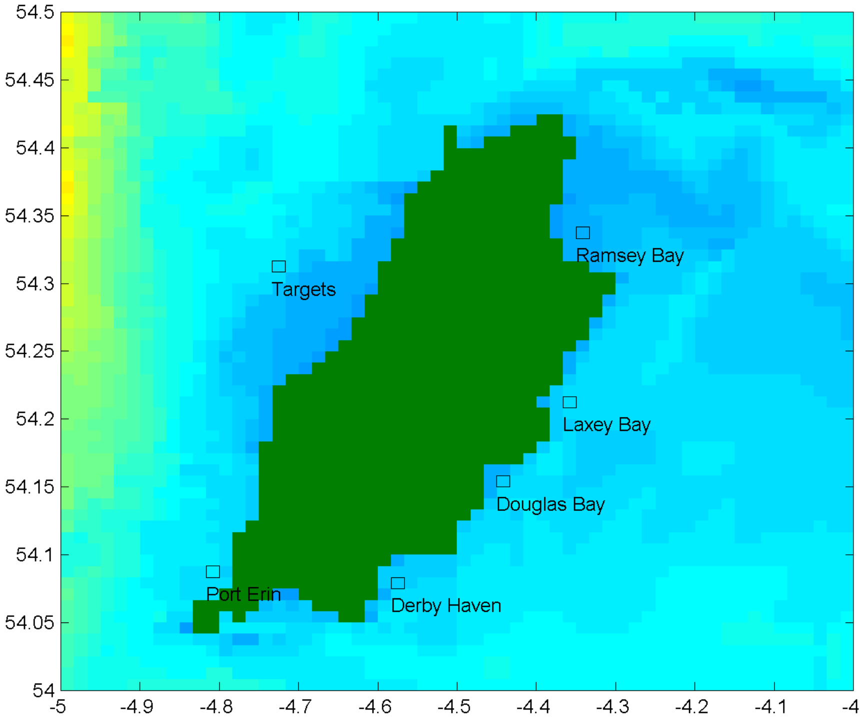


Figure 5. Proposed reserve positions used for PTM.

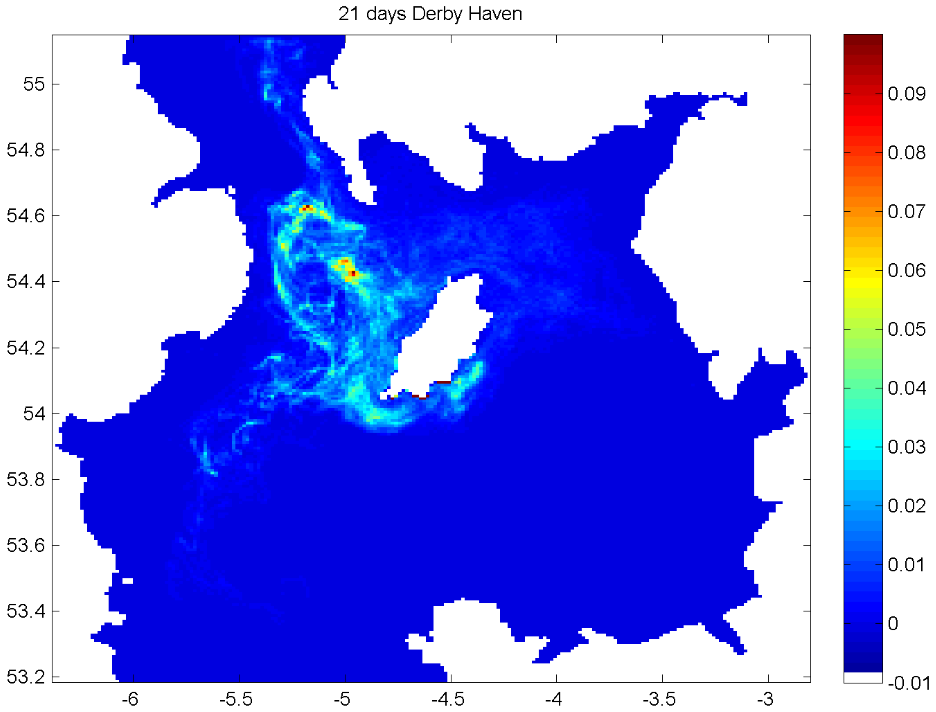


Figure 6a. 21 day forwards Derby Haven probability density plot. Colour scale is percentage probability.

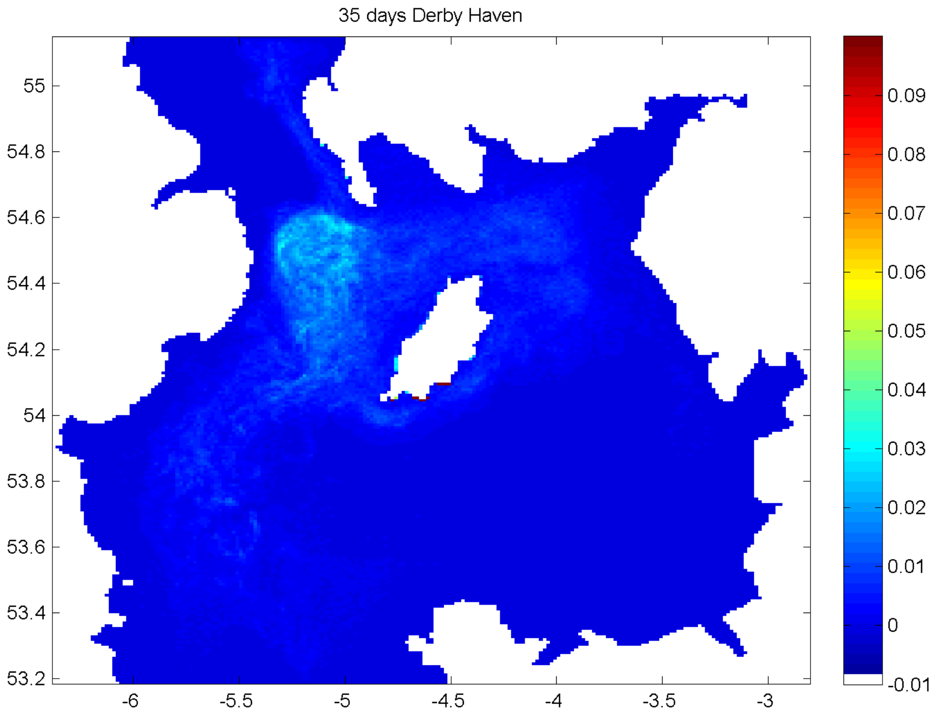


Figure 6b. 35 day forwards Derby Haven probability density plot. Colour scale is percentage probability.

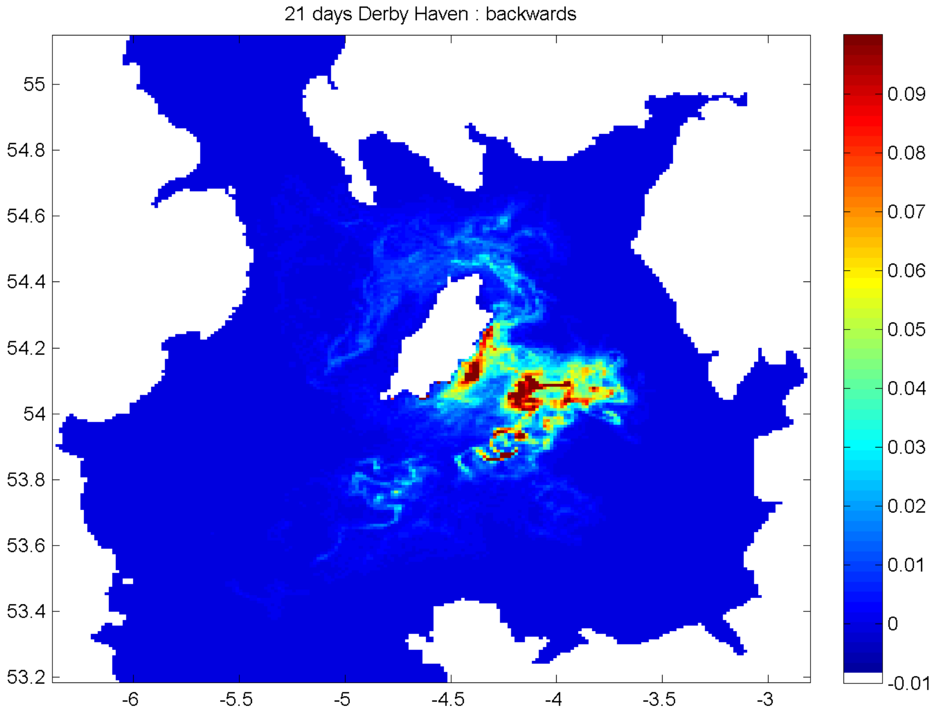


Figure 6c. 21 day backwards Derby Haven probability density plot. Colour scale is percentage probability.

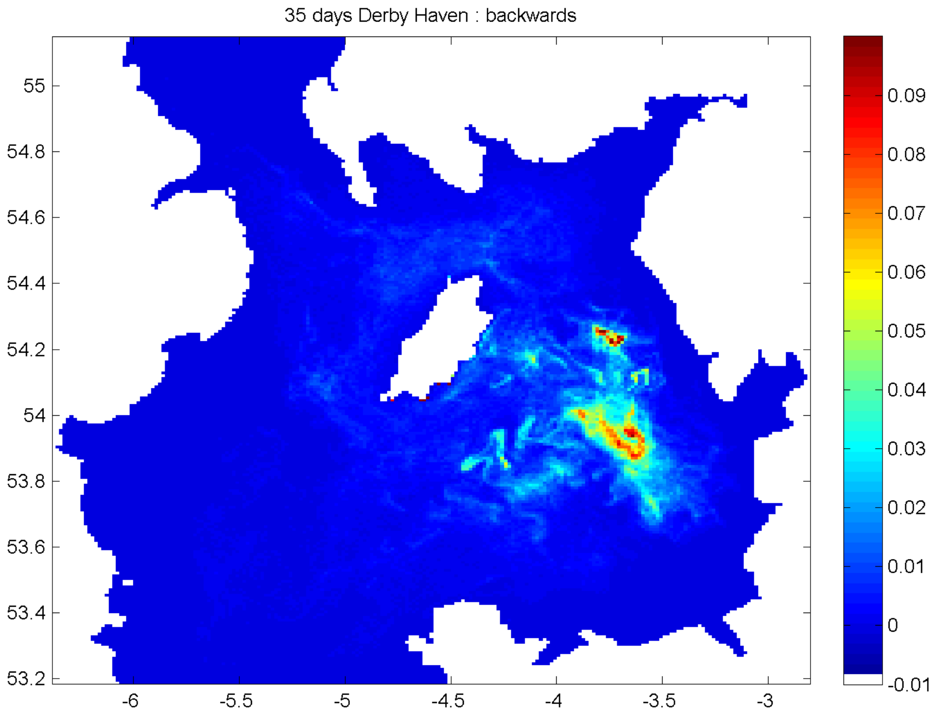


Figure 6d. 35 day backwards Derby Haven probability density plot. Colour scale is percentage probability.

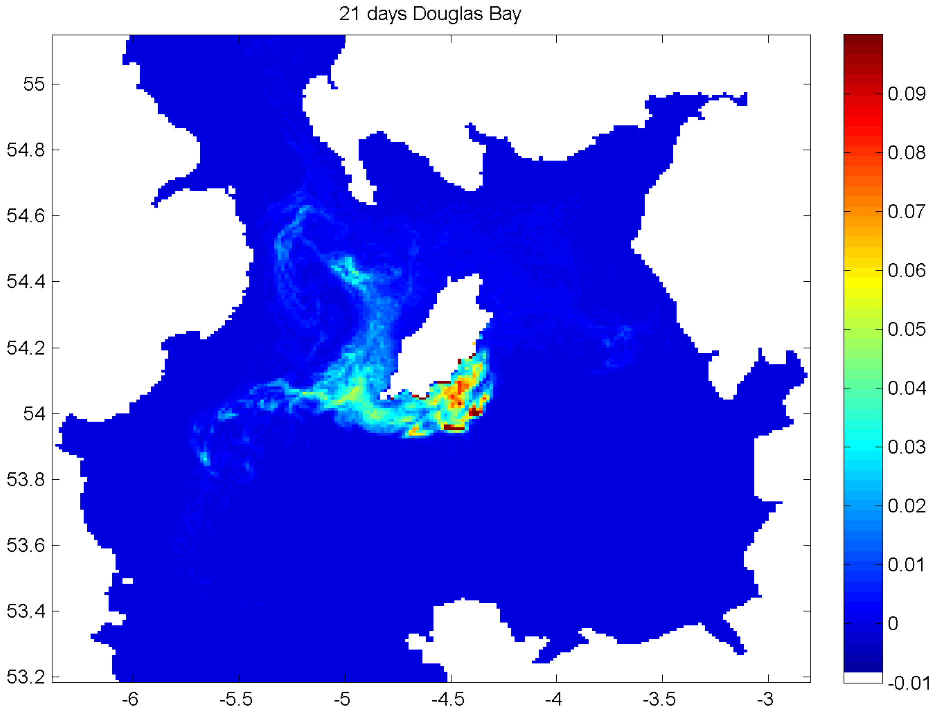


Figure 7a. 21 day forwards Douglas Bay probability density plot. Colour scale is percentage probability.

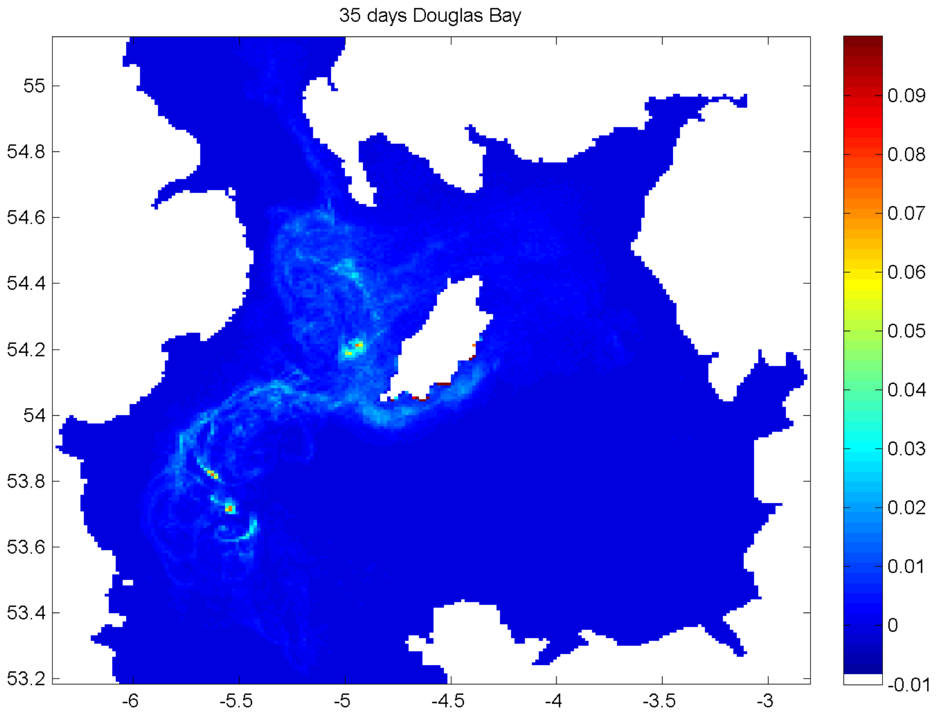


Figure 7b. 35 day forwards Douglas Bay probability density plot. Colour scale is percentage probability.

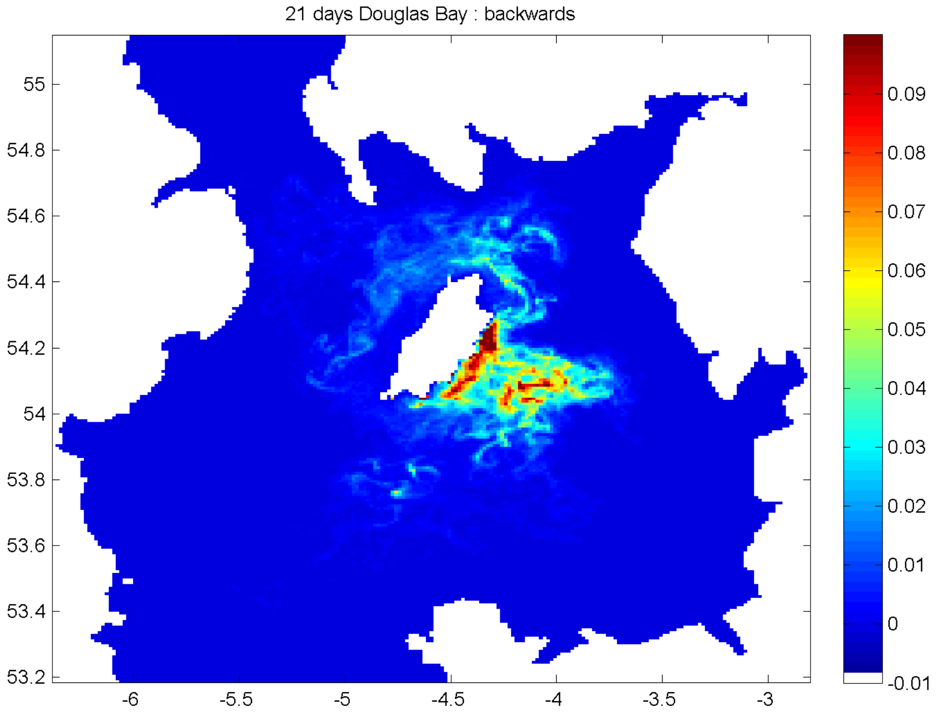


Figure 7c. 21 day backwards Douglas Bay probability density plot. Colour scale is percentage probability.

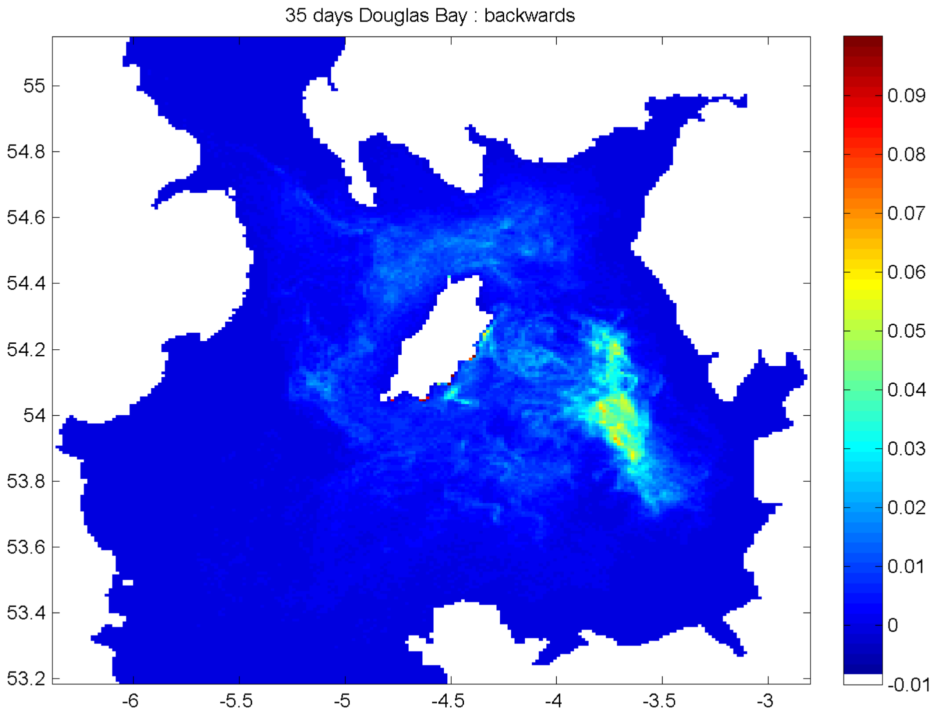


Figure 7d. 35 day backwards Douglas Bay probability density plot. Colour scale is percentage probability.

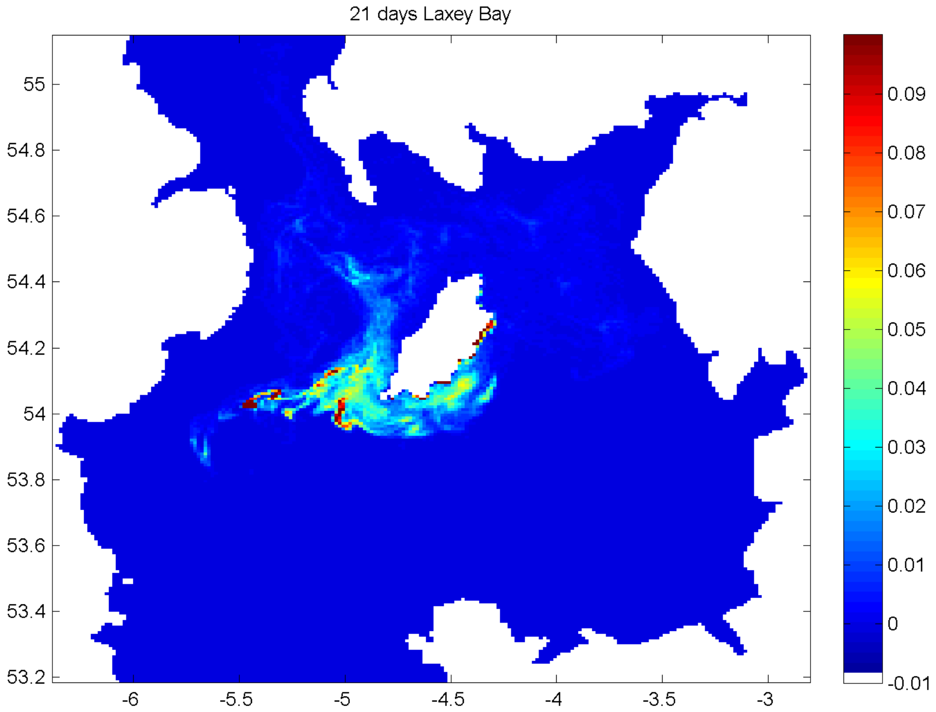


Figure 8a. 21 day forwards Laxey Bay probability density plot. Colour scale is percentage probability.

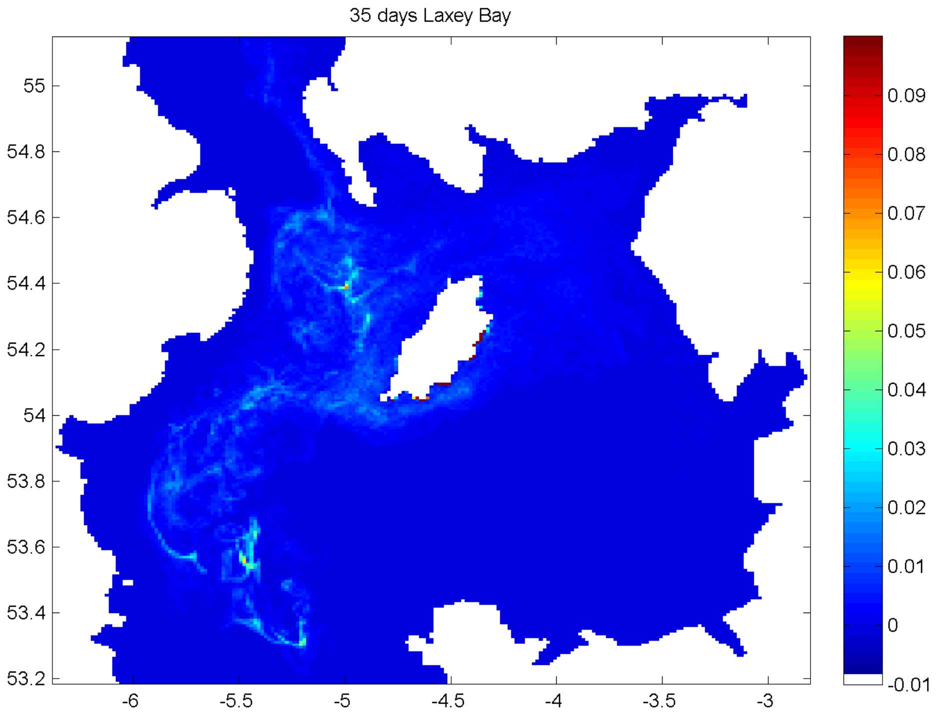


Figure 8b. 35 day forwards Laxey Bay probability density plot. Colour scale is percentage probability.

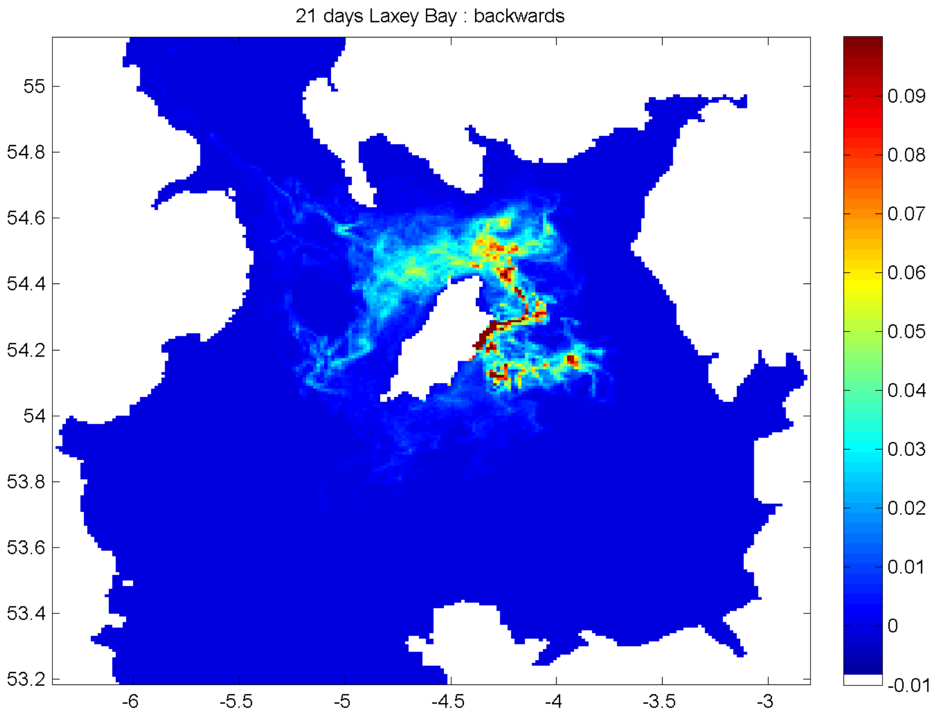


Figure 8c. 21 day backwards Laxey Bay probability density plot. Colour scale is percentage probability.

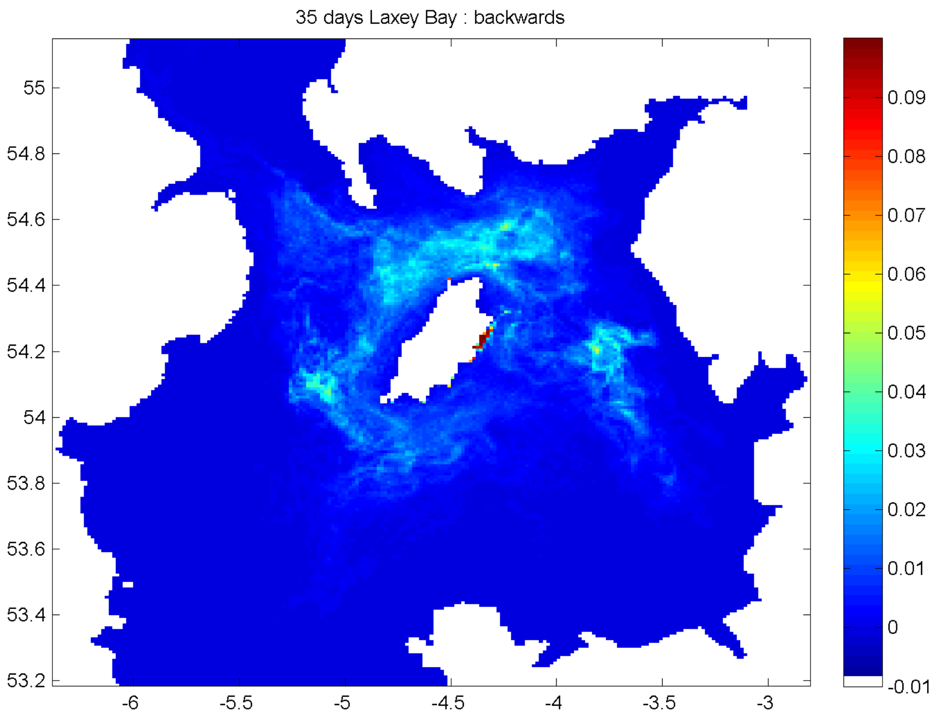


Figure 8d. 35 day backwards Laxey Bay probability density plot. Colour scale is percentage probability.

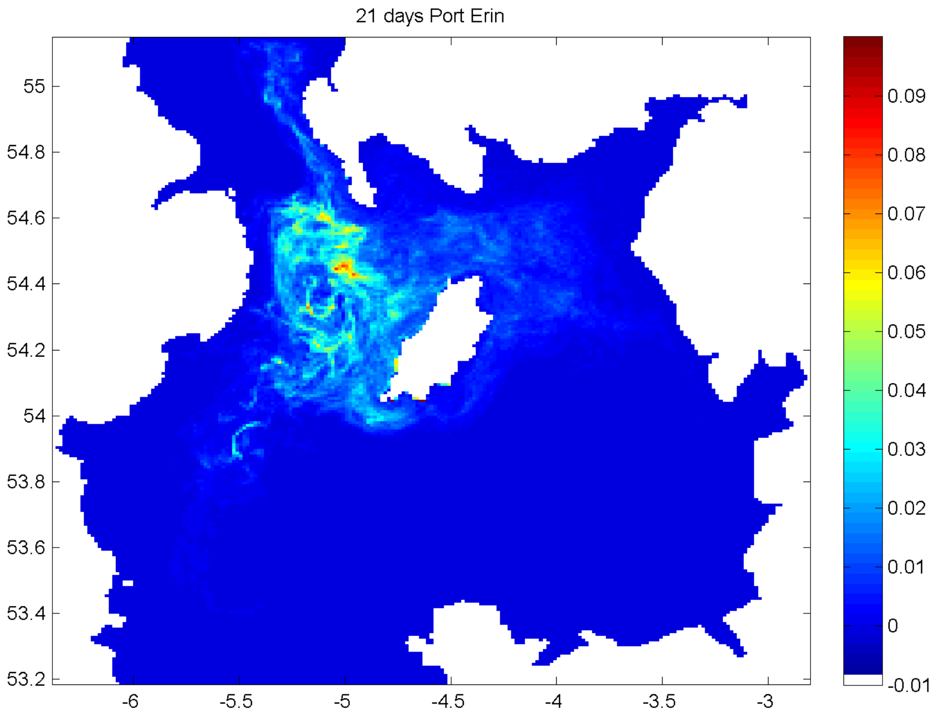


Figure 9a. 21 day forwards Port Erin probability density plot. Colour scale is percentage probability.

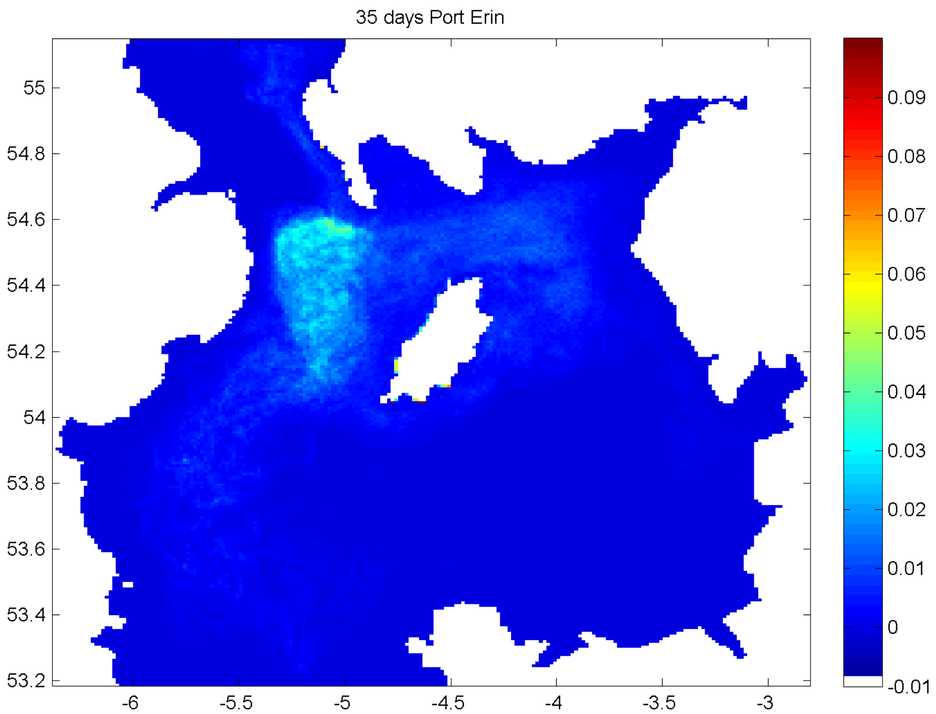


Figure 9b. 35 day forwards Port Erin probability density plot. Colour scale is percentage probability.

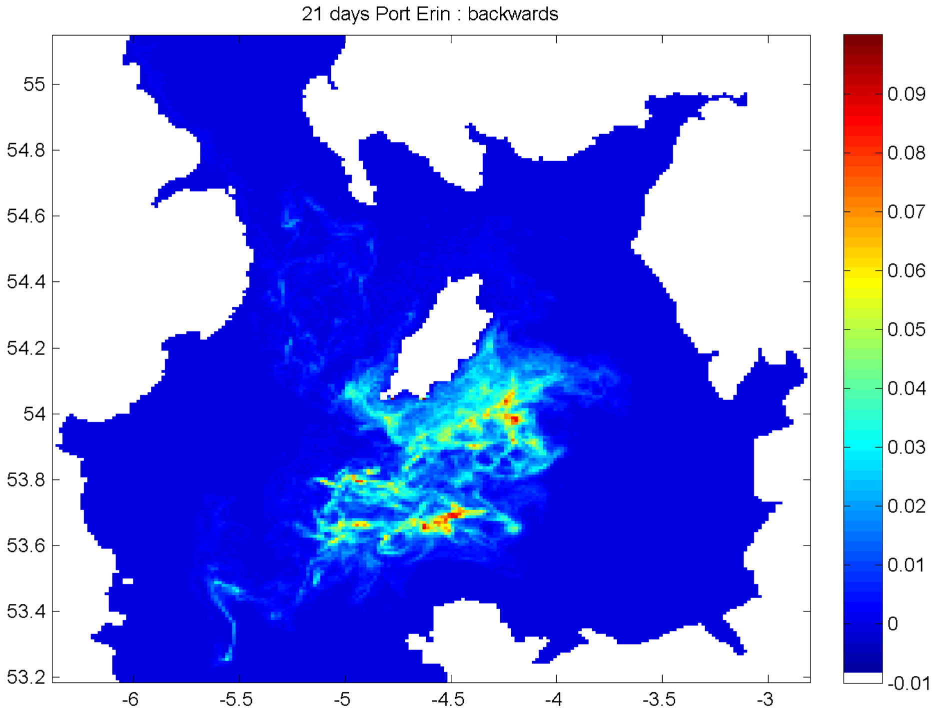


Figure 9c. 21 day backwards Port Erin probability density plot. Colour scale is percentage probability.

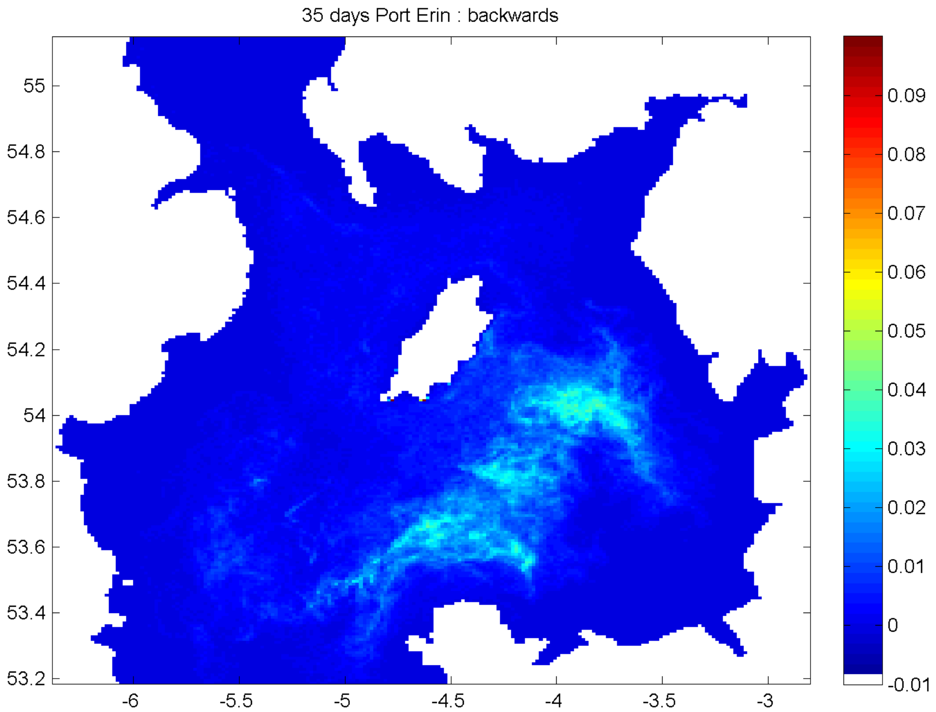


Figure 9d. 35 day backwards Port Erin probability density plot. Colour scale is percentage probability.

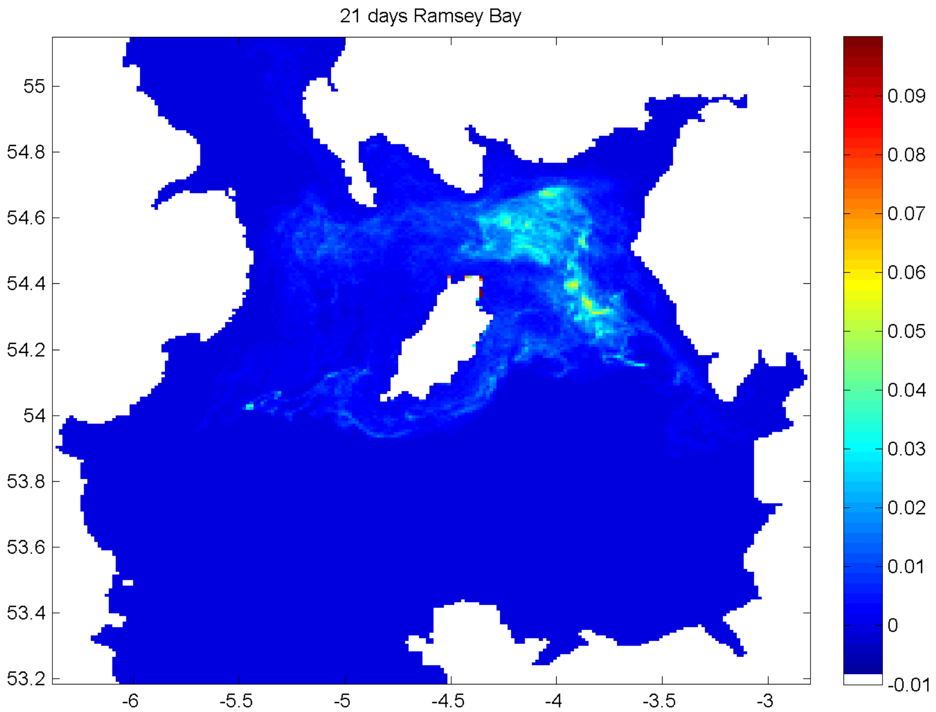
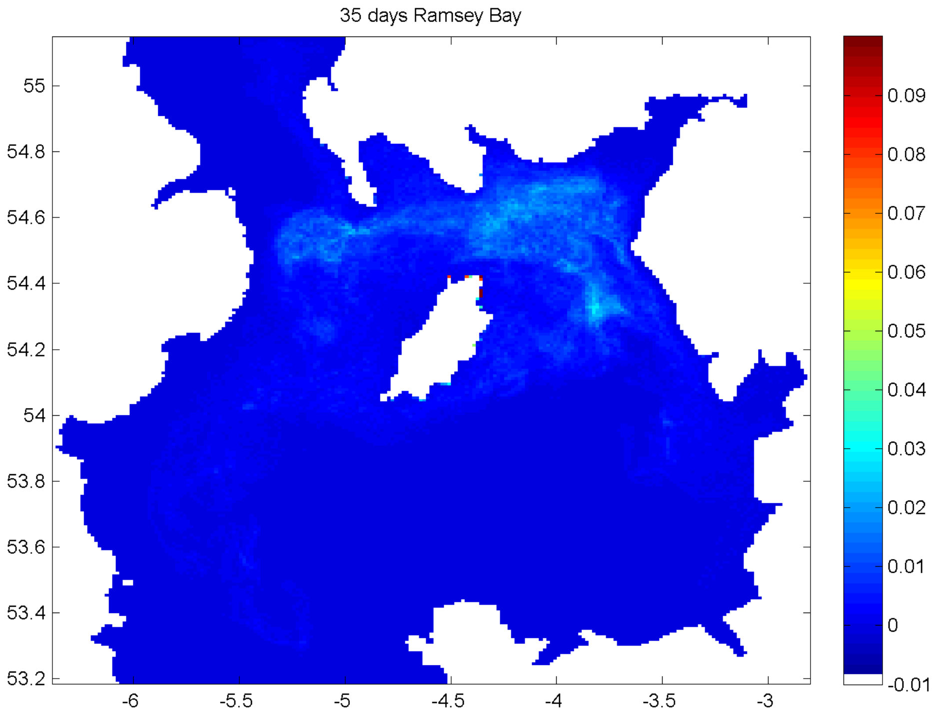


Figure 10a. 21 day forwards Ramsey Bay probability density plot. Colour scale is percentage probability.



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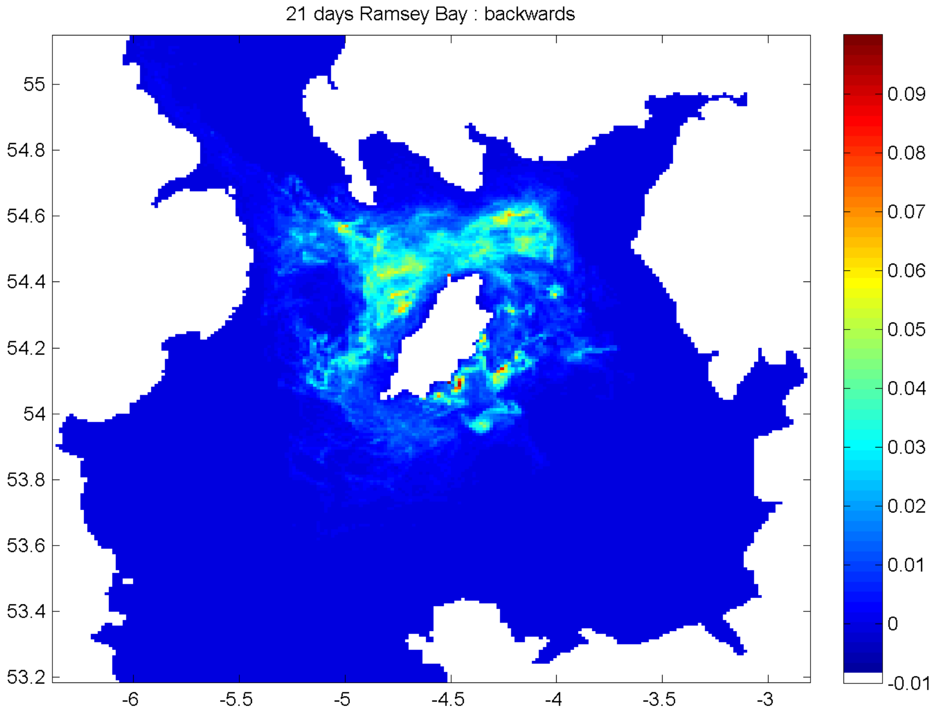

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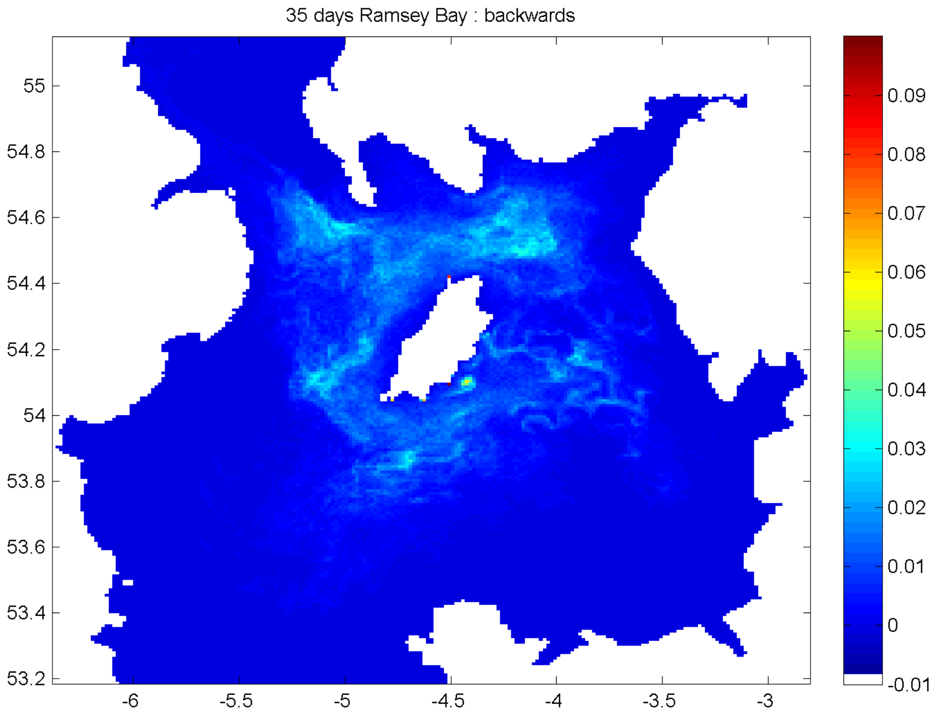

Figure 10d. 35 day backwards Ramsey Bay probability density plot. Colour scale is percentage probability.

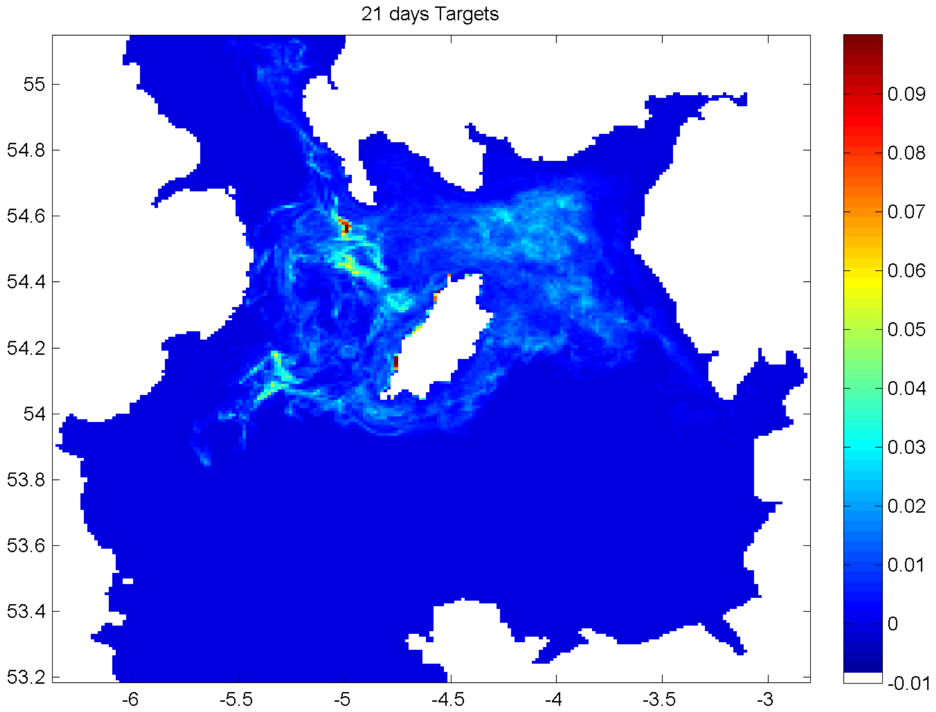

Figure 11a. 21 day forwards Targets probability density plot. Colour scale is percentage probability.

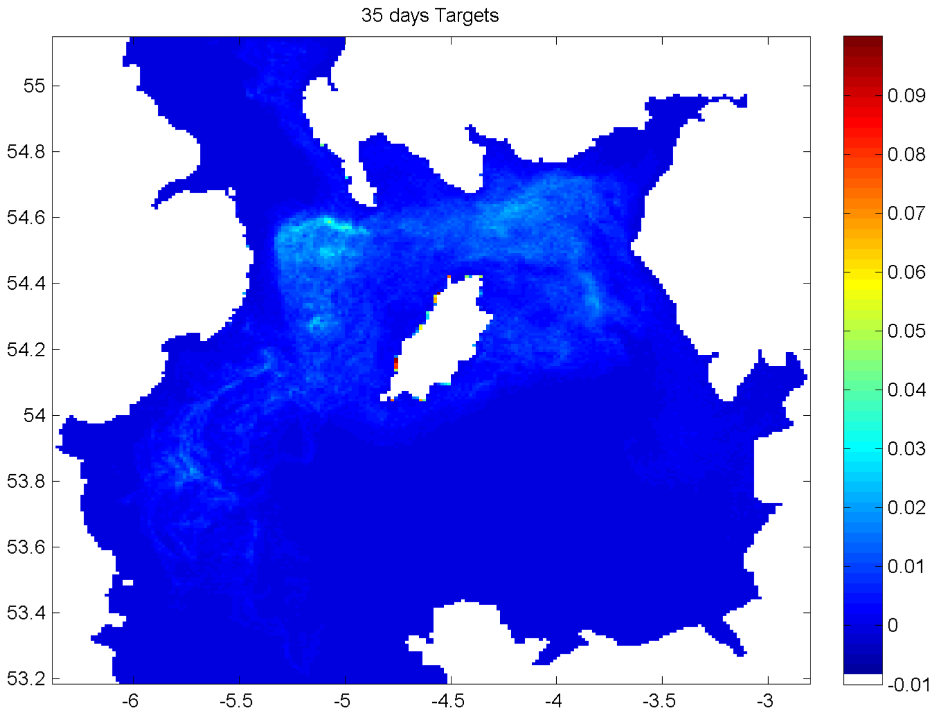

Figure 11b. 35 day forwards Targets probability density plot. Colour scale is percentage probability.

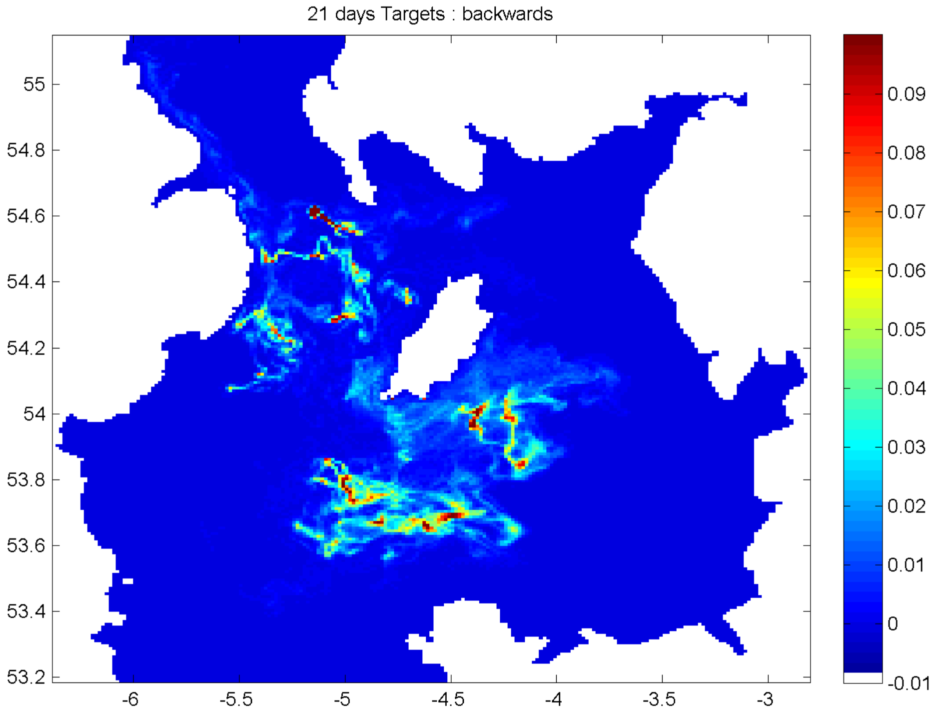

Figure 11c. 21 day backwards Targets probability density plot. Colour scale is percentage probability.

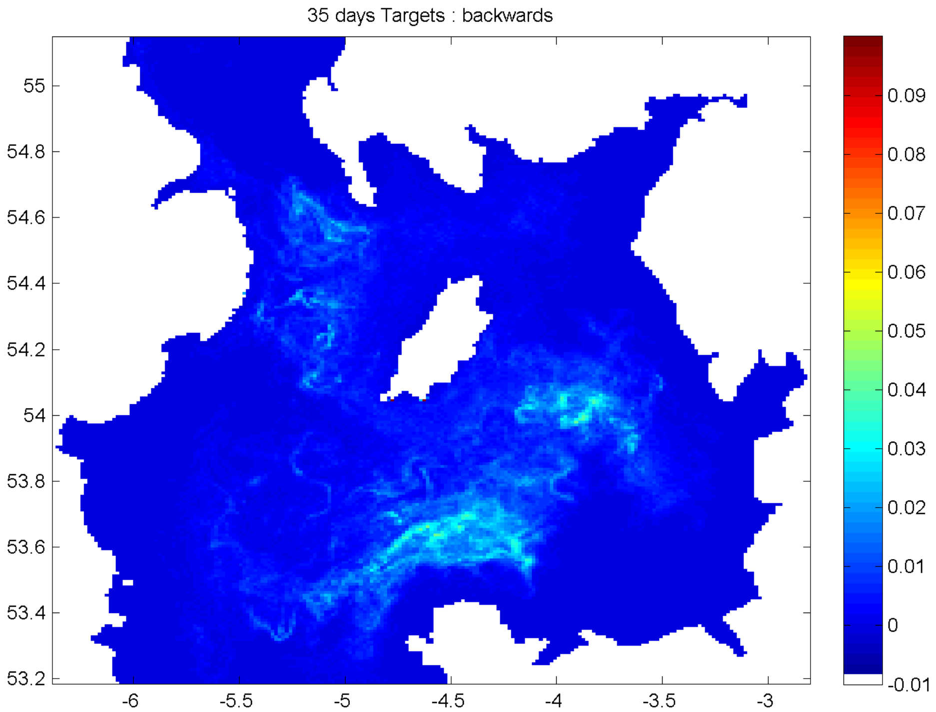

Figure 11d. 35 day backwards Targets probability density plot. Colour scale is percentage probability.