Simulating Harbour Porpoise Habitat Use in a 3D Tidal Environment

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***Abstract*—Assessing the environmental impacts of a project are often an important requirement of the planning and consenting process for a marine energy device deployment. Computer simulations are frequently used in other areas of marine energy development, and Individual Based Models (IBMs) provide one method for simulating marine life in order to investigate potential impacts of marine energy devices on the local ecosystem, including the possibility to simulate protected species such as Harbour Porpoise.**

This contribution will showcase initial results of a Harbour Porpoise IBM under development at Swansea University, which aims to combine fine scale temporal motion with tidal data from existing hydrodynamic models and other environmental properties in order to examine potential responses of Harbour Porpoise to marine energy developments.

***Keywords*—*Individual Based Model, Marine Energy, Environmental Impact, Harbour Porpoise,* Phocoena Phocoena**

I. Introduction

Assessing the environmental impacts of a project are often an important requirement of the planning and consenting process for a marine energy device deployment. In the UK and Europe, this is generally a legal obligation under the Habitats Directive [1] and other legislation [2], and can require a significant investment of time and money in order to obtain baseline data and determine the species present and the anticipated effects of any devices to be deployed.

The anticipated effects of a marine energy device are included in an Environmental Impact Assessment (EIA), including estimated effects on marine mammals and other parts of the local ecology. Individual Based Models can form part of the information included in these assessments, helping to inform decision makers about potential impacts of a marine energy device on the local wildlife [3], [4].

Individual Based Models can be used to investigate how different changes to the environment affect the use of an area, including potential cumulative impacts of multiple changes within the study area. Due to the small number of deployed devices, the environmental and ecological impacts of marine energy devices are, as yet, poorly understood. This limits the ability of developers and regulators to make confident predictions regarding the impact of devices on the local and wider environments. The use of behaviour based computer models offers a possible solution to this, by allowing the response of a population with a known set of behaviours to be investigated [5]–[7]

II. Individual Based Models (IBMs)

An IBM is a simple iterative model that independently calculates the movement and/or other properties of simulated individuals (also referred to as "boids") within an environment. Some of the early work using these models arose from the computer graphics industry [8], but has also been used in ecological models to investigate the interaction of animals of various shapes and sizes with the environment around them [7].

The movement and action of the simulated individuals is determined by the environment containing them and a set of behavioural rules. These rules determine the movement and internal state changes of the simulated individuals based on any combination of position, local environment, internal state and the position and behaviour of other individuals in the simulation. The exact combinations used vary depending on the species and level of detail being simulated [3].

IBMs have been applied to the problem of animal movement for a number of scenarios, including the possible effects of development and habitat loss on seabirds [9], and the potential effects of wind farm noise on Harbour Porpoise [5]. These studies, among others, have shown that the technique can provide a useful way of comparing possible outcomes of a development, and that these models can compare favourably to observed data.

The basic algorithm for an IBM can be outlined as follows:

1) For each boid in the population:
    a) Get information about the local environment
    b) Apply behavioural rules and decision on movement
    c) Update velocity and other properties
2) Record positions
3) Advance simulation clock
4) Repeat from 1 for next time step

This basic framework has been used to develop the Harbour Porpoise model described below.

III. Defining an Environment

In order to simulate the movement of virtual creatures in an environment, it is first necessary to define that environment and establish how it will be implemented. There are a number of different ways to define an environment for an IBM, broadly split into mesh based (or cell based) representations and discrete object representations [7]. Mesh based representations are more common, and typically closer to the format of available data. In this instance, the environment is defined by the results of an TELEMAC model. TELEMAC is a "suite of environmental simulation software" [10], allowing for the simulation of water flows, water quality and sediment transport.

A typical TELEMAC model can calculate the tidal flows through an area, based on provided bathymetry and boundary conditions. This sort of model is also used for tidal resource assessment, an important part of the site selection process for a marine energy devices as it allows the available power at a location to be predicted. Using this type of fluid dynamics model to define the environment within the simulation allows us to take advantage of models which a developer may have already developed as part of their site selection process, reducing the overheads required to make use of an IBM.

The results of this sort of model provide a three dimensional, temporally variable meshed environment which includes the water depth and velocities throughout the simulation domain. This provides the basis of a simulated environment within which we can define and simulate virtual animals, such as Harbour Porpoise.

A. Meshes and mesh movement

A mesh is an approximate representation of a space or object, constructed of nodes and edges which form a set of connected elements. In the case of TELEMAC, these elements are linear (variables are assumed to vary in a linear fashion between the nodes of each element [11]) and represent the wet areas of the simulation. Discretising space using a mesh allows the value of variables to be approximated by calculating their values at a finite number of positions - the nodes that form the mesh. In this instance, the equations of the model are solved at each node for each timestep in the simulation.

The mesh used in this model is three dimensional, formed by stacking layers of a two dimensional triangular mesh. This creates prismatic elements between the layers, as shown in figure 1. The vertical (z) coordinates of each node are time dependent, and are updated at the start of each simulation timestep. The vertical movement of the nodes causes the elements to grow, shrink and move over the course of the simulation, representing the rise and fall of the tide. The movement and changing size of elements has to be taken into account when tracking the movement of the virtual porpoise.

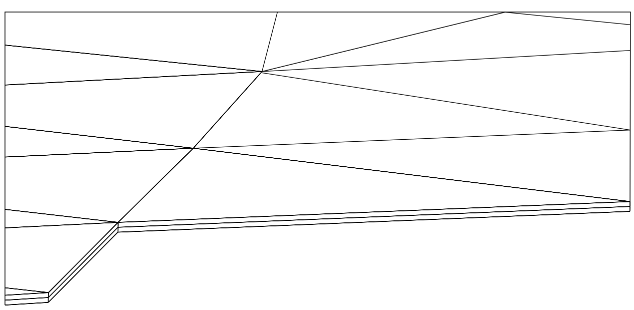


Fig. 1. Example mesh, showing the triangular faces of the 2D mesh and the prismatic elements formed between the layers

B. Variable interpolation

The value of simulation variables is calculated and stored at the location of each node within the simulation, either as part of the TELEMAC model or when additional data is imported. The elements in the TELEMAC models used have edge lengths in the x,y plane ranging from 50m to 1700m depending on the model and the location within that model. The lengths of edges in the z (vertical) axis range from 0m to 40m. Given the comparatively large distances between nodes and the virtual porpoise, it is necessary to interpolate the values stored at each node to calculate a suitable value at the location of each virtual porpoise - this is done using mean value coordinate interpolation. This allows variables to be interpolated in a smooth, continuous and linear manner at any point within the elements used [12].

The timesteps provided by the TELEMAC results (mesh timesteps) can be at relatively coarse intervals, as determined by the `GRAPHICS PRINTOUT PERIOD` option in TELEMAC - in practical terms this is often due to the amount of storage space required to store data at more frequent intervals. In the models used in this simulation, values are provided at 1 hour intervals for the overall duration of the input data (60 days). These values are then interpolated linearly to obtain intermediate values at each simulation timestep (typically between 5 and 10 second intervals). These intermediate values are used as the basis for the spatial interpolation described above.

C. Incorporating Additional Data

In addition to the variables calculated by TELEMAC (water velocity, vertical position), it is necessary to incorporate additional information to drive the behaviour of the virtual porpoise. This additional data falls into two categories in this simulation: gradients and scalars. Both variable types are stored as values at each node at each mesh timestep.

Additional scalar data is incorporated by providing values at each node at each mesh timestep. The example sets of food and noise data used in this simulation have been generated by seeding a number of point sources within the bounds of the simulation and calculating values for each node. Each source is assumed to be independent, which allows the value V at point $\vec{x}$ to be calculated as:

$$V_{\vec{x}} = \sum_{i=1}^{N} \frac{v_i}{r_i^n}$$

where v_i is the value of point source i and r_i is the distance from position $\vec{x}$ to node i. The value of n can vary depending on the characteristics of the data being generated - this simulation has used $n = 1$ for both food and noise [13].

Both scalars and gradients are calculated as a preprocessing step, and are stored as part of the input data for the simulation, allowing them to be used for multiple runs of the simulation. Gradients can be calculated for both original and additional variables, and are primarily used to provide a directional input for behavioural rules based on the parent variable.

IV. Implemented behaviours and rules

Once a suitable environment has been defined, it is necessary to define the behavioural rules that the simulated animals will follow.

A. Correlated Random Walks

Correlated Random Walks (CRWs) are a well established method for analysing animal movement, and have also been implemented in other examples of IBMs [5]. To implement a CRW, a small amount of noise is added to the heading and/or velocity at each timestep. In this instance, a small amount of noise is added to both heading and velocity using a pseudo-random number generator that yields a Gaussian distribution centred around zero, with a standard deviation of 1. This distribution ensures that movements remain correlated to the original direction and velocity. In the absence of other behaviours, the virtual porpoise first orient themselves to minimise drag relative to the local water flow and this orientation and velocity becomes the input to the CRW.

B. Depth Dependent Behaviour

The first obstacle for the simulated harbour porpoise is remaining in sufficiently deep water. As discussed above, elements change in height over the course of the simulation, changing the column depth at those locations. Additionally, there are elements along the edge of the domain that have zero height at some points during the simulation. This raises two problems - firstly, the interpolation method implemented assumes that all elements are 3D and would generate invalid data for a 2D element and secondly, porpoise both occupy a finite volume and exhibit a preference for particular water depths. The solution is to add a behavioural rule that causes the porpoise to swim towards deeper water when the local depth decreases below a given threshold value.

An examination of available literature suggests that Harbour Porpoise are likely to be found in depths ranging from around 20m to 200m, with one study showing a preference for depths greater than 60m, and an avoidance of areas with depths less than 10m [14]. On this basis, any simulated harbour porpoise that finds itself in less than 10m of water will reorient itself and swim towards deeper water. The direction is taken from the precomputed gradient of the depth, with the porpoise yawing about its axis to face the direction of the gradient. This behaviour takes precedence over all other behaviours implemented at this point, and the threshold applies equally to all simulated individuals.

C. Simulated Noise Response

One of the potential impacts of renewable energy devices in the marine environment comes in the form of noise emissions [15] - both during construction and when devices are in operation. These noises are likely to be of different intensities, durations and have different frequency spectra, and detailed modelling of porpoise response to these factors is non-trivial. A simplification is to consider only the additional noise due to the device as a single pressure level, using a threshold value to govern the behavioural response of the virtual porpoise.

To demonstrate potential response to noise, a number of point noise sources were added to the model. The value of these sources is intended to represent the sound pressure level at the source, and is held constant throughout the simulation. When the local noise level rises above the threshold value given, the virtual porpoise will then orient themselves against the gradient and swim away in a similar manner to the depth response rule described above. For the examples shown, this rule takes precedence over food and drag response, but is subordinate to the depth response behaviours.

D. Food as an influence

In addition to device noise, the location of food within an area is likely to be an important driving factor in the movement of porpoise throughout an environment. Food is defined in a similar manner to noise sources as above, with a number of point sources seeded into the environment. These point sources are currently static for the duration of the simulation. The orientation of the porpoise at each step is determined by a balance between the minimum drag orientation and the direction of the nearest food source. This balance is dependent on the value of the field at that point.

V. Examples

To demonstrate the rules described above and the interactions between them, a number of example scenarios have been run. These scenarios have been run using different combinations of the rules described, as laid out in table I, but using the same background data.

Two different initial distributions have been used in the scenarios, as indicated in table I labelled HP2 and HP4. Distribution HP2 contains 40 porpoise randomly seeded within a 1000m × 1000m × 1m box. Distribution HP4 contains 40 porpoise within an 8000m × 8000m × 1m box, approximately centred in the same location as distribution HP2.

A. Environmental description

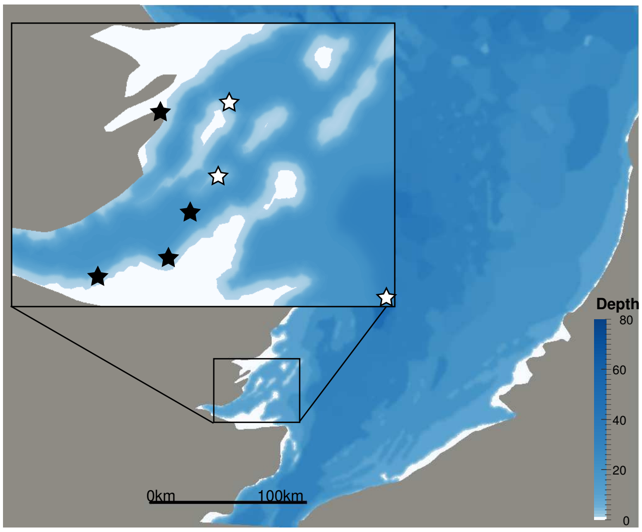
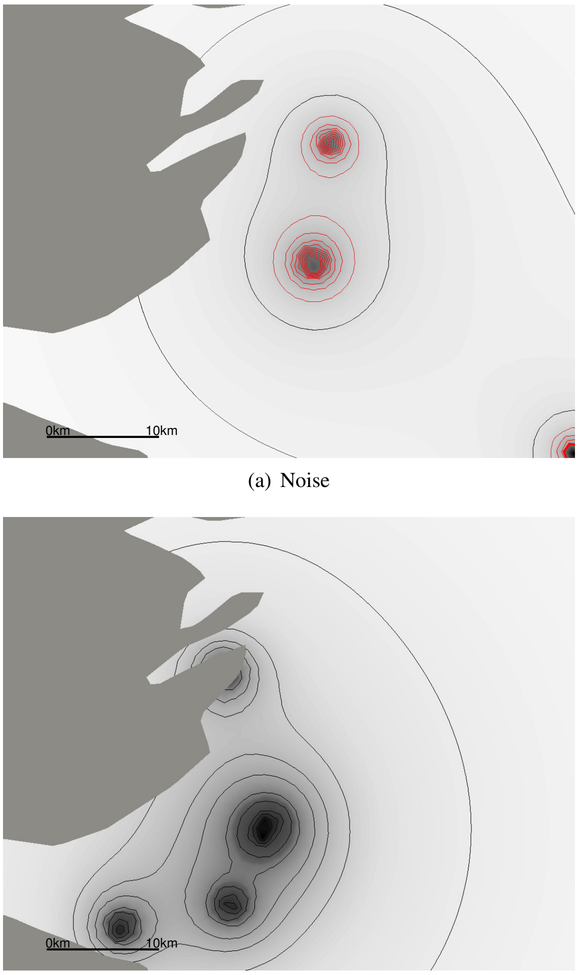


Fig. 2. Simulation Domain, showing noise sources (white stars) and food sources (black stars). The pale and white areas of the domain show shallow areas.

The tidal model used is a 60 day, 3 layer model of the North Sea with data recorded at one hour intervals. This is



(a) Noise

(b) Food density

Fig. 3. Food and noise data used in the simulation. Red lines in 3(a) show noise levels above the behaviour threshold

Scenario	Distribution	Food	Noise
A	HP2	Enabled	Enabled
B	HP2	Enabled	Disabled
C	HP2	Disabled	Enabled
D	HP2	Disabled	Disabled
I	HP4	Enabled	Enabled
J	HP4	Enabled	Disabled
K	HP4	Disabled	Enabled
L	HP4	Disabled	Disabled

TABLE I. COMBINATIONS OF MODEL RULES USED IN THE EXAMPLE SCENARIOS

interpolated linearly to give 4.5 second simulation timesteps and is shown in figure 2. The white stars in the figure mark the point noise sources and the black stars mark the point food sources. The value of the noise and food density fields is shown in more detail in figures 3(a) and 3(b).

VI. RESULTS

Each of the images shown in figures 4 and 5 shows the trails of each simulated porpoise in that scenario, starting at the open circles and ending at the filled circles. The colour of the trail reflects the behavioural state of the porpoise as it passed that point in the simulation and is explained further below.

A. *Effects of initial porpoise distribution*

Comparing scenarios with the same rule combinations but different distributions (A/I, B/J, C/K, D/L) allows us to comment on the effect of initial position on the model results. Common to all the HP2 scenarios (figure 4) are a much tighter final position for the virtual porpoise when compared to the corresponding HP4 scenarios, with the simulated porpoise converging into the deeper water channel situated between the two noise sources. This location can also be seen in the final positions for the HP4 scenarios, but is supplemented by porpoise that have been able to venture further afield. The porpoise starting from HP4 experience more varied initial conditions due to the increased initial separations, which results in more divergent paths throughout the simulations, regardless of the rules combinations in effect.

B. *Depth response*

The effects of the depth response rules are included in all of the scenarios shown, with green markings on the trails shown in figures 4 and 5 indicating areas where this behaviour has been invoked. Figures 4(d) and 5(l) show scenarios D and L respectively, which include no other behavioural rules. It can be clearly seen in L that the porpoise that are seeded in shallow areas immediately move towards deeper water, with smaller green dots indicating porpoise reaching the edge of a shallow region. It should be noted that the depths shown in figures 4 and 5 are a snapshot of the depths at $t = 0$, and vary over the duration of the simulation.

C. *Food seeking*

Food seeking behaviour is present in scenarios A, B, I and J. Comparing scenario B and D (depth only) (Figs. 4(b) and 4(d)) shows only a wider dispersion in the final positions of the porpoise, caused by the additional attraction towards the food sources in the lower left area of the figures - given that the behaviour response is proportional to the amount of food in the surrounding area, it is likely that the porpoise are too far away from the food sources to detect it based on the values used in this example. Comparing the equivalent figures for the HP4 dispersion cases (Scenarios J and L, figs. 5(j) and 5(l)) show slightly more obvious changes, with extended porpoise presences in the lower left region of figure 5(j) in proximity to the food source.

D. *Noise avoidance*

Noise avoidance behaviour is present in scenarios A, C, I and K. Comparing scenarios C and D shows that porpoise movement is curtailed within the noise contour corresponding to the threshold value in C (fig. 4(c)), as is expected from the implementation described above. Sections of track where the noise avoidance behaviour is in effect are coloured red. The curtailed movement is also present in scenario A (fig. 4(a)).

The corresponding tracks in scenarios K and L are complicated by interactions between the depth rule (which takes precedence) and the noise avoidance rules. It can be seen in figure 5(k) that the noise source deflects porpoise movement away from the noise source (relative to scenario L, figure 5(l)), either away from the noise or into shallower water where depth avoidance behaviour takes effect (green sections of tracks). The combined effect of a noise threshold and depth requirements can make traversing particular areas difficult, and will have to be investigated further when simulating areas using more realistic data.

VII. Conclusions

The work completed to date has resulted in an individual based model framework which can be used to represent Harbour Porpoise movement in a tidal environment. The rules implemented exhibit plausible reactions to input data when tested with arbitrary values, but require further work in order to make them more accurately representative of the behaviours of real porpoise. In particular, it will be necessary to revisit the influence of water flow on porpoise movement when not responding to depth or noise. The current implementation of this behaviour tends to be dominated by local flow conditions, as evidenced by the zig-zag and corkscrew patterns seen in the results - particularly in figures 5(j) and 5(k).

Once further improvements have been made to the rules used in this simulation, it is planned to carry out a parametric study of the model, using the example area described above. The model will then be applied to a case study in Ramsey Sound - a consented tidal energy site in west Wales with an established Harbour Porpoise population [16]–[19]. The simulated Harbour Porpoise in this model will then be compared to existing site observation data in order to assess the fine scale performance of the model.

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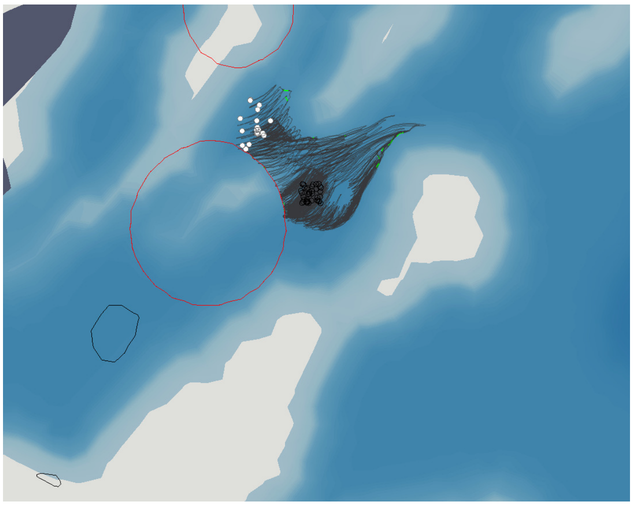
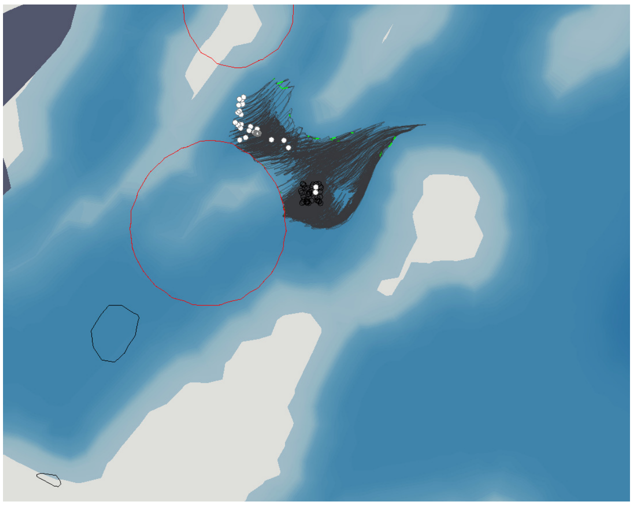
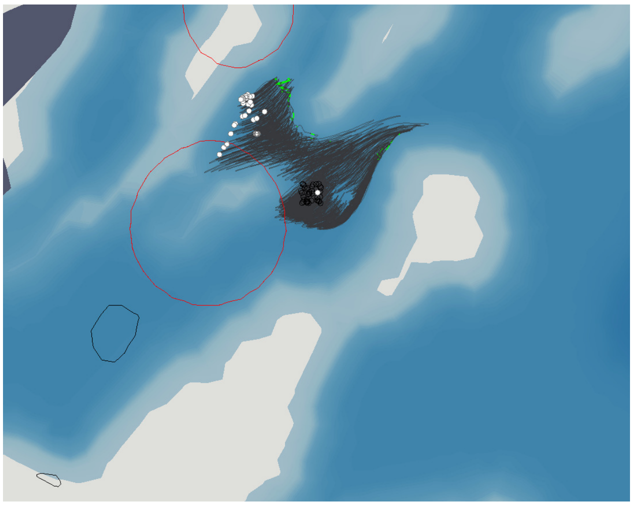


(a) Narrow start distribution, responding to food, depth and noise

(b) Narrow start distribution, responding to food and depth



(c) Narrow start distribution, responding to noise and depth



(d) Narrow start distribution, responding to depth only

Red lines indicate the noise threshold, black lines outline areas of high food concentration. See figures 3(a) and 3(b) for more detail.

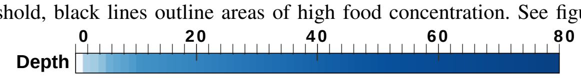
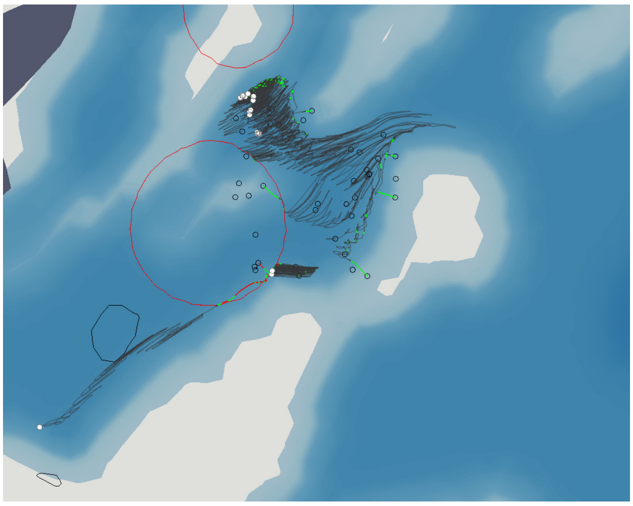
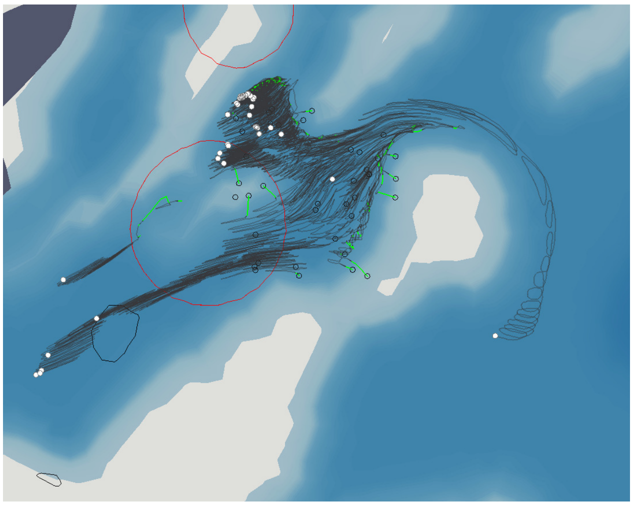


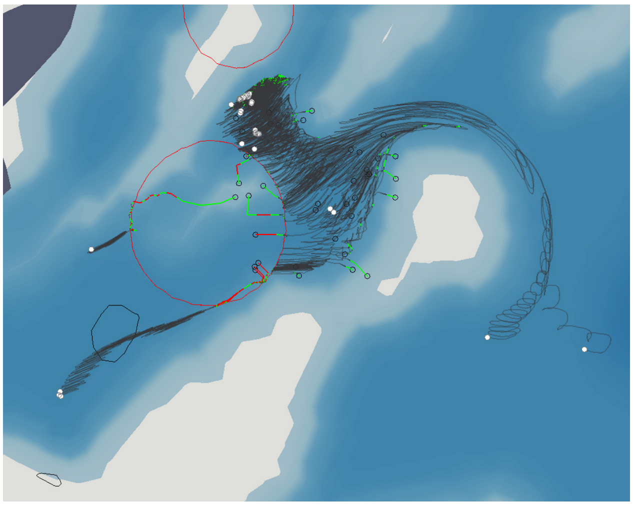
Fig. 4. Example results for different rules combinations, based on a narrow starting distribution



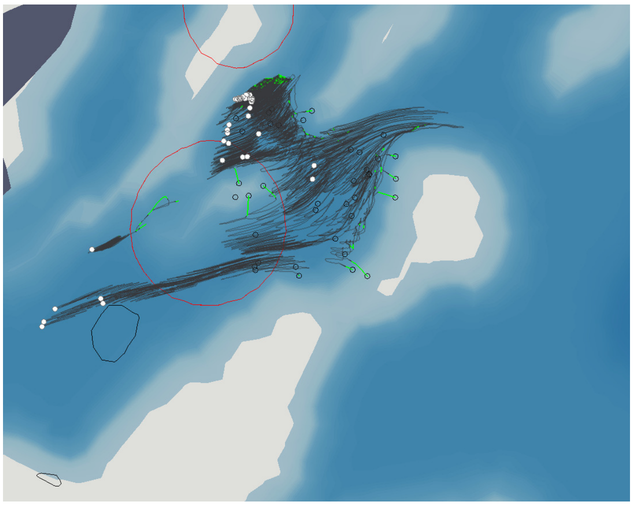
(i) Wider start distribution, responding to food, depth and noise



(j) Wider start distribution, responding to food and depth



(k) Wider start distribution, responding to noise and depth



(l) Wider start distribution, responding to depth only

Red lines indicate the noise threshold, black lines outline areas of high food concentration. See figures 3(a) and 3(b) for more detail.

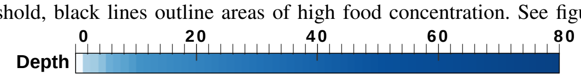


Fig. 5. Example results for different rules combinations, based on a wider starting distribution