3MTSim: An agent-based model of marine mammals and maritime traffic to assist management of human activities in the Saint Lawrence Estuary, Canada.

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Abstract

The agent-based model, 3MTSim, simulates the spatiotemporal movement of marine mammals and maritime traffic in a portion of the St. Lawrence Estuary in Canada (covering the Saguenay-Saint Lawrence Marine Park and the proposed Saint Lawrence Estuary marine protected area). The model has been developed as a decision-support tool to inform management and planning in the Estuary. 3MTSim allows users to test different zoning scenarios for maritime traffic (e.g., area closures, speed limits, regulations concerning the observation of marine mammals) in order to assess their effects both on navigation dynamics and on marine mammal exposure to vessels. 3MTSim includes an individual-based model of marine mammal movement patterns that has been elaborated based on existing telemetry data on fin, blue and beluga whales as well as on land based theodolite tracking of humpback and minke whales. Observations recorded aboard research and whale-watching vessels have provided the spatial data necessary to estimate species' abundances and distribution maps that are used to initialize the whale model. Different types of vessels, including cargo ships, commercial whale-watching and tour boats, pleasure craft and ferries are also modelled individually. The model represents the decision-making process of boat captains as a function of environmental conditions, the contextual setting and their respective goals. An extensive database of real-time tracking data available for the different types of vessels, coupled with observations and interviews, has served in the elaboration of the boat captain model. In this paper, an overview of the entire system is presented, with a description of the 3MTSim architecture and the approaches used to represent the different model components. The effectiveness of 3MTSim as a decision support tool is demonstrated via the results from a sample of scenario-based simulations.

Keywords: agent-based modelling; individual-based modelling; decision support systems; integrated management; coupled social-ecological systems; marine protected areas

1. Introduction

The Saint Lawrence Estuary in Québec, Canada (Figure 1) is the world's largest estuary and is an area of exceptional oceanographic phenomena and marine biodiversity. The region has resident populations of beluga whales and harbour seals as well as migratory populations of humpback, minke, blue, and fin whales that use the estuary as a summer feeding ground due to its high concentrations of forage species. In total, up to 13 cetacean and pinniped species may visit the estuary in a given season. Nearly half of these species are listed as endangered (Ministère des ressources naturelles et faune 2010, Fisheries and Oceans Canada 2004). The area is also subject to intense pressure by human uses, including commercial shipping, ferries, and tourism, which pose cumulative threats to the marine wildlife, including risks of collision, disruption of feeding and reproductive activities, habitat loss, risks of exposure to toxic chemical spills and to noise (Fisheries and Oceans Canada 2004). Over 5000 cargo ships pass through the estuary each year and approximately 13,000 commercial tourism excursions (mostly whale-watching) visit the main foraging ground each summer (Chion et al. 2009).

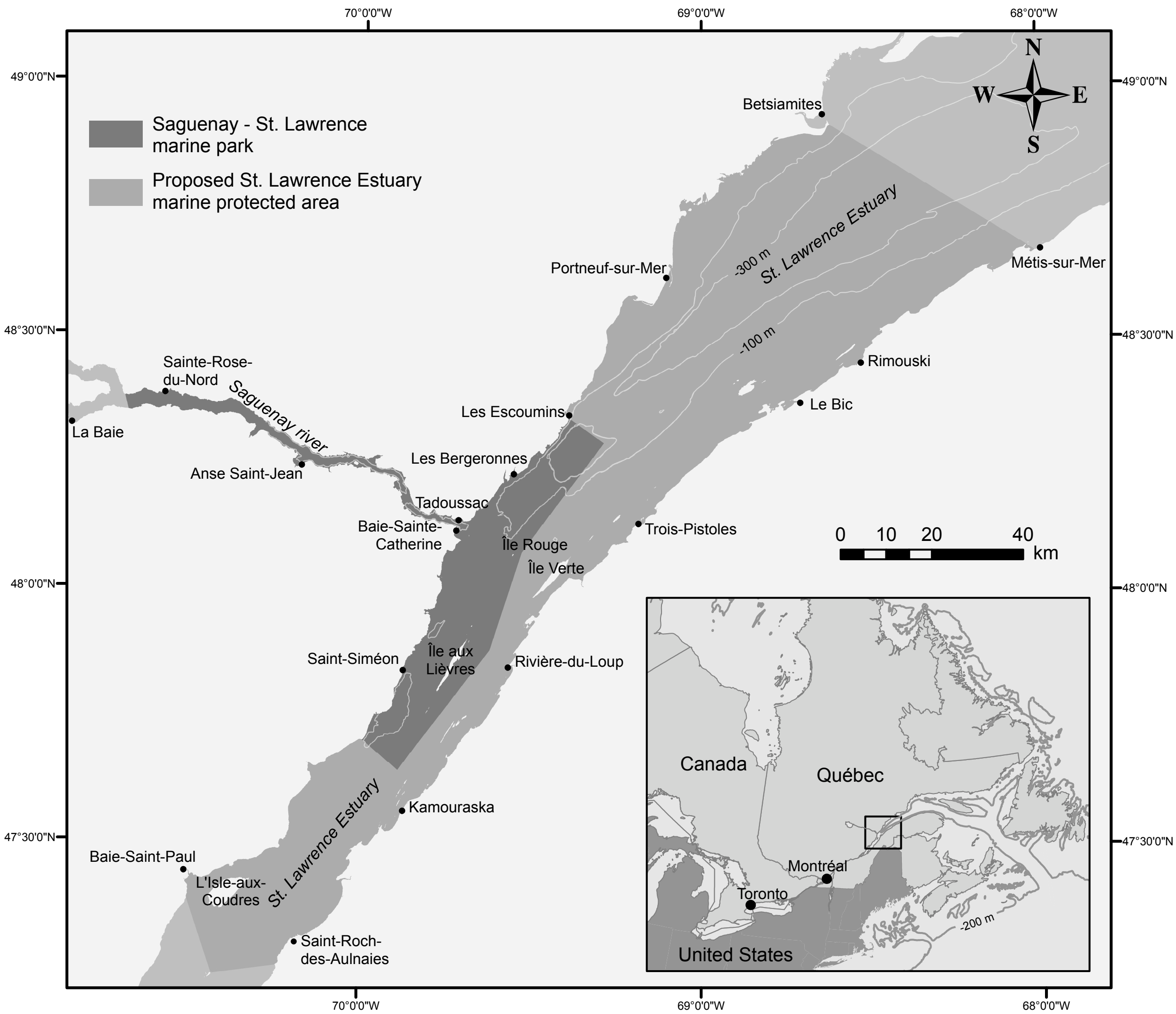


Figure 1: The study area in Québec, Canada, showing the limits of the Saguenay-Saint Lawrence Marine Park and the proposed Marine Protected Area.

Two protected areas have been proposed by the Canadian government in recognition of the need to implement an integrated management plan across the estuary. The Saguenay–Saint-Lawrence Marine Park (SSLMP) was created in 1998 by Parks Canada. The park preserves a representative portion of the Saguenay River and the Saint Lawrence estuary for conservation purposes, while encouraging its use for educational, recreational and scientific purposes (Ménard 2009). The proposed Saint Lawrence Marine Protected Area (MPA) will cover an area of ca. 6 000 km^2 of the Saint Lawrence Estuary adjacent to the SSLMP and will be managed by Fisheries and Oceans Canada (DFO). This MPA aims to ensure the conservation and long-term protection of marine mammals and of their habitats and food resources.

Managers of the park and proposed MPA are faced with the challenge of developing an integrated management plan that protects and conserves the marine biodiversity of the region, while at the same time ensuring the economic viability of regional tourism relying heavily on whale-watching activities.

They must also operate within the constraints imposed by the maritime shipping industry, which, in economic terms, is considerably more important to the national economy than the regional tourism industry. Commercial shipping lanes for cargo ships heading to and from the Atlantic Ocean and the major industrial centres of the Great Lakes region pass directly through the park and MPA. The seasonal whale-watching industry has been regulated since 2002 within the limits of the park, and the park overseas approximately 50 permits to operate whale-watching vessels each year. Tourism is a major driver of the local economies of several small coastal communities. Park and MPA managers must, therefore, manage human activities in the region so as to meet the multiple objectives of the local tourist economy, commercial shipping and conservation of ecosystem health and resilience.

The park and DFO managers work in concert with local stakeholders and industry players to develop zoning plans that are compatible with both conservation and industry objectives within this coupled social-ecological system. They are operating within the framework of an adaptive management plan, in which zoning and regulations are regularly adapted and updated based on new scientific knowledge and via public consultation with stakeholders. There is, however, a growing requirement to justify management decisions based on sound scientific arguments, which is where modelling may play an increasingly important role.

The objective of the project described here was to develop a model that could serve to inform and support management decisions by simulating the effects of different zoning and regulation scenarios (for example, spatial and temporal zoning of different activities in the estuary, off-limits zones, speed restrictions) on the system. This is an on-going collaborative project between researchers from three universities, Parks Canada, Fisheries and Oceans Canada, and the GREMM, a non-profit organization for marine mammal research and education. The model has been developed in close collaboration with the end users to ensure that it meets their decision-support requirements.

So as to permit the emergence of system responses to different simulated management scenarios, we have chosen a bottom-up, agent- and individual-based modelling approach (*sensu* (Parrott 2008)) in which individual boats and whales in the estuary are represented as distinct entities that interact in a spatially explicit environment. In our study we distinguish between goal-oriented *agents* whose behaviour is driven by cognitive heuristics and non-goal oriented *individuals* whose behaviour is driven by simple rules. Agent- and individual-based modelling is increasingly the tool of choice for simulating coupled social-ecological systems (Gimblett 2002). Such models have been applied in a wide variety of natural resource management contexts involving collective behaviour, including rangeland management in arid zones (Gross et al. 2006), management of water use and access in river basins (Schlüter and Pahl-Wostl 2007), control of irrigation channels (van Oel et al. 2010) and forest clearing for agriculture (Moreno et al. 2007). Agent-based modelling has also been applied to provide decision-support for national parks and recreation areas; typically to simulate visitor movements and to predict areas of over-crowding along vehicular or pedestrian routes (Roberts, Stallman and Bieri 2002, Itami et al. 2003).

Our model represents boat captain agents and individual marine mammals that move about and interact in a dynamic, spatially explicit environment representing a significant portion of the Saint Lawrence Estuary. A prototype of the multi-agent system was described in Anwar et al. (Anwar 2007). This prototype included whale-watching boat captains that navigated according to a simple rule set (i.e., attempt to follow whales while avoiding obstacles) and generic whale "agents" that moved randomly about the environment. Here, we report on substantial improvements to the system, which now includes multiple types of boat captains that navigate according to cognitive heuristic decision making modules and different species of marine mammals that move about the environment based on known patterns of movement and habitat selection. The model has been calibrated and validated with extensive field data. We show how the model can be applied to simulate several different zoning and regulation scenarios of current interest to managers seeking to reduce the impact of maritime traffic on marine mammals in the estuary.

2. Data

An extensive amount of data about whales and marine traffic in the region has been collected since 1994 by various researchers and agencies. The main sources of data used for model development, calibration and validation are listed in Table 1.

Description	Year	Source
ENVIRONMENTAL DATA		
Bathymetric and navigational charts	-	Canadian Hydrographic Service
MARINE MAMMAL DATA		
> 32,000 marine mammal sightings from whale watching boats	1994-2009	GREMM, Parks Canada, DFO
80 whales (fin, blue and beluga) tracked by VHF (> 380 hours)	1994- 2008	GREMM, Parks Canada, DFO
> 140 focal follows (fin, blue, minke & humpback whales) tracked from land based stations (~100 hours of tracking for individuals followed for more than 30 minutes)	2008-2009	C.C.A. Martins
547 baleen whales sightings from transect surveys	2006-2009	GREMM, Parks Canada, DFO
Marine mammal habitat limits (from the Fish Habitat Management Information System)	-	DFO
MARITIME TRAFFIC DATA		
> 2,100 whale-watching excursions tracked by GPS with contents sampling (nature of activities over time)	1994-2009	GREMM, Parks Canada, DFO
Predicted and real-time automatic information system (AIS) tracking of commercial traffic	2003-2007 (AIS 2007 only)	Canadian Coast Guard
Semi-structured interviews with whale watching captains	2008	C. Chion
Semi-structured interviews with St. Lawrence pilots (commercial shipping)	2008	C. Chion
> 15 hours of VHF radio monitoring	2008	C. Chion
180 questionnaires filled out by pleasure craft captains	2006	Parks Canada
30 track sticks (GPS coordinates) of pleasure craft excursions	2006	Parks Canada

Table 1: List of the major data sources used to build and validate the 3MTSim model. (GREMM = Group for Research and Education on Marine Mammals; DFO = Fisheries and Oceans Canada)

3. Model overview

The model combines a raster-based spatial environment (GIS) with an individual-based model (IBM) of whales and an agent-based model (ABM) of boats (Figure 2). During execution of the model, the movement of each individual whale and each boat is determined according to the rules and heuristics described in the sections below.

The model has been developed as a decision-support tool. The objective is thus to inform managers about the potential effects of alternative zoning and regulation plans (e.g., introducing speed limits, altering shipping routes, adding restricted access zones) on the patterns of traffic in the park and MPA and thus on the characteristics of whale-vessel encounters (rate, location, boat speed…). Simulations are run for short periods of time, based on existing environmental conditions and known scenarios of whale abundances and patterns of habitat selection, so as to assess how different management scenarios might affect the current situation. The model is not designed for performing population viability analysis for the whale species, nor to assess or predict long-term impacts of human activity on the marine ecosystem.

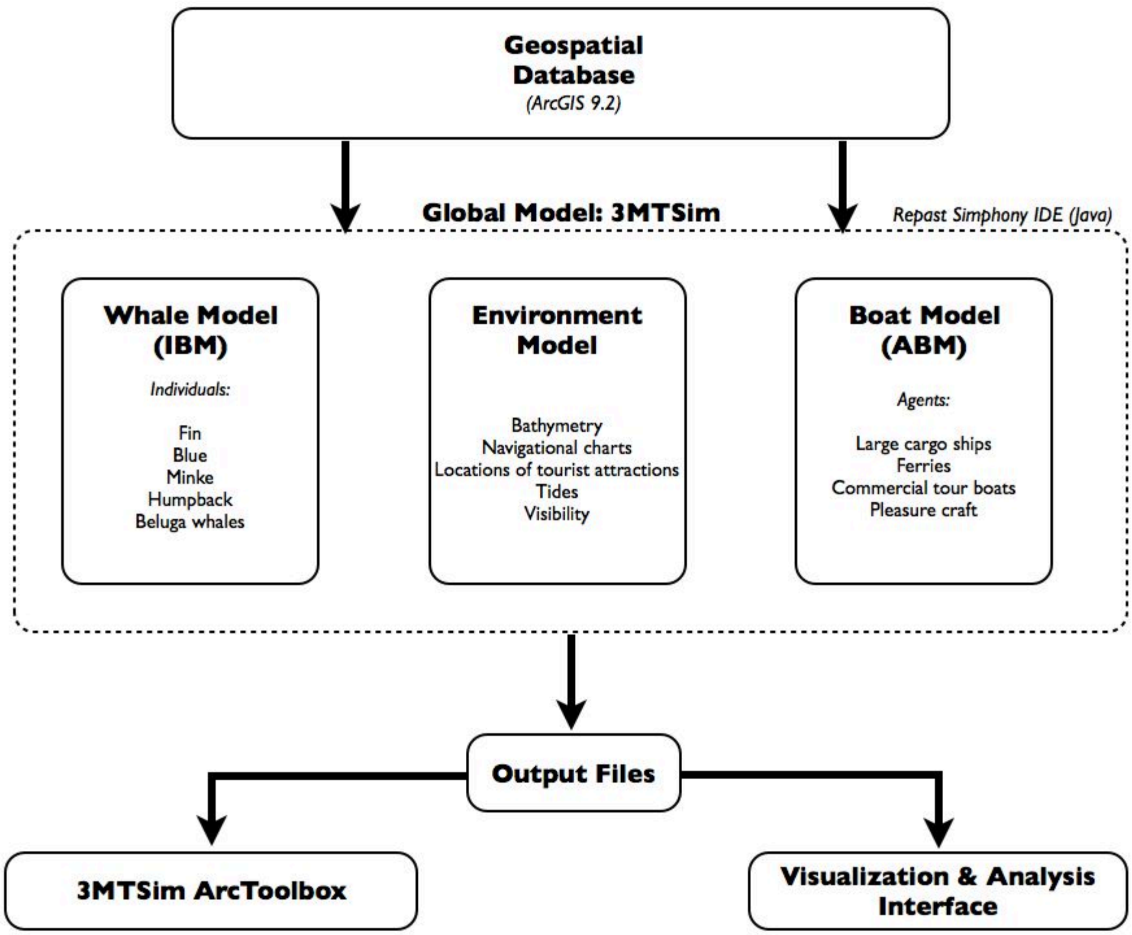


Figure 2: Overview of the 3MTSim system architecture.

3.1 Spatial environment

The spatial environment of the system is represented by raster files that were produced from marine charts provided by the Canadian Hydrographic Service. The bathymetry, shoreline, landmarks and navigational buoys are used in the model in order to identify navigable and non-navigable zones for the different types of ships represented in the model (according to ship draft). The bathymetry is also considered in the displacement and diving routines of whales. In the current model version, water depth is not adjusted according to the cycle of the tides. The state of the tide is modelled, however, according to a simple daily cycle that selects the tide condition (flood tide, high tide, ebb tide, low tide) according to the date and time of day. While weather conditions are not explicitly modelled, a single parameter is used to specify the visibility in the region. This value remains fixed for the duration of a simulation and mainly affects the ability of whale-watching boat captains to locate whales in their neighbourhood.

The raster charts defining the environment are imported during initialisation of a simulation.

3.2 Whale individuals

The model represents the five species of whales most commonly present in the estuary: beluga, fin, blue, minke and humpback whales. The overall objective was to adequately represent the movement patterns of the individual whales. Insufficient data was available on their food sources and on their individual comportment, so no attempt was made to devise a behavioural model. The current version of the model was thus developed using available tracking data (VHF) for beluga, fin and blue whales, land based theodolite tracks of humpback and minke whales as well as sightings made from research vessels and whale-watching boats (to determine spatial distribution and habitat use).

The whale model has been created using a pattern-oriented approach (Grimm 2005). Accordingly, the modelling process is based on inferring processes and parameters from field data that may serve to reproduce the patterns observed in that data. A number of hypotheses may be put forth regarding the processes that generate the observed patterns and a model is produced to test these hypotheses. Several models may thus be developed (one for each hypothesis) and the model which best reproduces the primary patterns in the data is selected.

For the whale model, a number of primary patterns were extracted from the field data. These included: trajectory patterns (turning angle, step length, speed, duration), social patterns (group size) and population-level patterns (spatial distribution). For the trajectory patterns, values of turning angles, step lengths, speeds and step durations were calculated from the available track data (VHF and land based). Distributions of each of these trajectory characteristics were computed for the five species. For the social patterns, sighting data was used to establish average group size (where "group" is defined as a number of whales of the same species within a radius of 400m from one another). For population-level patterns, data from whale-watching excursions was used to establish the spatial distribution of each species for each year. The spatial distribution for each species is represented as a raster map of relative frequencies at a 100x100m resolution. The state of the tide did not have a significant effect on trajectory patterns, but group size and spatial distributions do vary significantly with the tide for fin whales, and this effect is included in the model for this species' group sizes.

The individual-based whale model is described in detail by Lamontagne (Lamontagne 2009). The model combines a simple diving routine with a displacement algorithm to determine each individual whale's depth, direction and speed at each time step. Diving times and time at the surface are selected randomly from an empirically derived Weibell distribution computed for each species from tracking data. The diving routine uses a simple deterministic function to calculate the amount of oxygen available to a whale as a function of its depth and diving time, and serves to force the whales to surface regularly in order to breathe. Several different displacement algorithms were tested, starting from a simple uncorrelated random walk and increasing in complexity to include residence times and social interaction between whales (Lamontagne 2009). The ability of each algorithm to successfully match the (often conflicting) trajectory, social and population patterns for each species was tested. The algorithm that most successfully reproduced the desired patterns, and which is currently implemented in the model, is a modification of the correlated random walk (Turchin 1998). This algorithm (MNB for "mean normalised bias") randomly selects an individual's speed and trajectory duration from the known distribution functions and then adjusts the angle of movement so as to reduce the normalized mean difference between the real and simulated group size, turning angle and spatial distribution patterns for each species (Lamontagne 2009).

The MNB algorithm was developed and calibrated for fin and beluga whales (both trajectory and spatial patterns). Blue, humpback and minke whales were added after. Overall, the individual-based model of whale movement meets our current modelling requirements of having relatively realistic movement patterns that respect the known spatial distributions of the animals.

3.3 Boat captain agents

The objective in modelling the boat captain agents was to adequately reproduce their decision-making process so as to reproduce realistic traffic patterns given different environmental and marine mammal scenarios. Currently, three main types of boat agents are implemented, representing the most important marine traffic sectors in the study region: 1) commercial traffic in the shipping lanes (hereafter referred to as "cargo ships" although in reality this traffic sector includes many types of large tankers, cargo ships, cruise ships, etc.); 2) sightseeing excursion boats; 3) whale-watching boats. Pleasure craft and ferries will be added in the near future.

Sightseeing excursion boats, ferries and cargo ships are more easily modelled than the whale-watching boats: they have well monitored itineraries and routes with a predictable and well understood spatiotemporal variability in the study area. These ships are thus modelled using a path-planning algorithm (described in (Chion et al. 2010a)) that is implemented to get them from an origin to a destination via a series of known waypoints. For cargo ships, the number and frequency of ship passages is taken from historical real-time tracking data provided by the INNAV system of the Canadian Coast Guard. Ship characteristics (cargo type, length, draft, and maximum speed) are randomly generated as quadruplets according to real frequencies. The cargo ship agents then navigate by establishing waypoints between their origins and destinations and then selecting a sailing speed (as a fraction of their maximum speed) between each waypoint. Real cargo ships vary their speed in a predictable location-dependant way while crossing the study area. Accordingly, for each type of cargo (i.e. tanker, merchant, self-propelled barges, tugs, and cruise ships), the corresponding spatial variability is introduced as an input to the model, and ships update the fraction of their maximum speed according to the real distribution associated with the segment of their passage. Likewise, for ferries, the frequency and schedule of sailings will be taken from known schedules and their speeds will be selected randomly from known distributions calculated from the real data for each section of their route (between two waypoints). Finally, sightseeing companies offer well-defined tours with very low variability. Consequently, their spatiotemporal dynamics is predictable and straightforward to implement using known waypoints (typically touristic features and ports covered by companies).

Whale-watching boats are more challenging to model. These boat captains are goal-oriented and have to find a way to achieve their goal in a dynamic environment and subject to a number of constraints. Interviews with boat captains and park wardens conducted after excursions at sea, as well as VHF radio monitoring revealed a number of attributes of their decision-making while navigating to be included in the model. In particular, whale-watching boat captains: 1) take advantage of information on the most recent observations to explore space when no other information is available; 2) share information about whale locations (cooperation leading to a collective spatial memory); 3) give priority to certain "star" species such as the humpback whale; 4) try to adjust the content of their excursion according to that of their direct competitors; 5) should respect whale-watching regulations regarding speed limits, observation distances, and boat density around whales; and 5) must respect navigational limits related to currents and bathymetry.

The main objective of the whale-watching boat captain agents is to observe whales as much as possible during an excursion (although they may also have sub-objectives related to sightseeing, for example). Thus, a model was developed in which whale-watching captains leave port according to known schedules, navigate using a path-planning algorithm to select the straightest path to a destination, and choose which whale to observe using a cognitive heuristic decision-making module (Chion et al. 2010b). The captains must make use of existing information (either from the previous day, if they are running one of the first excursions in the morning, or else from current data on whale locations) to select which whale to observe. This is a decision that is made rapidly, based on limited information, and several times during an excursion. We assume, therefore, that the captains are operating in a context of bounded rationality, where they will select what appears to be the best choice given currently available information and the contextual setting both in time (e.g., what species of whales they have already observed during the excursion will affect their choice of the next whale to target) and in space. Four candidate decision-making modules to reproduce this behaviour were tested, three of which imitate known models of cognitive heuristics and a fourth, a random choice, which serves as a null model for the basis of comparison. The three cognitive heuristics tested were: Take-The-Best (Gigerenzer and Goldstein 1996); Satisficing (Simon 1956) and Tallying (Payne, Bettman and Johnson 1993). The whale-watching ship captain model is described in further detail in Chion et al. (Chion et al. 2010b).

4. Model implementation

The model is written in Java using the Repast Simphony libraries version 1.2.0 (http://repast.sourceforge.net/index.html). Repast Simphony is a well-supported suite of libraries developed for agent-based modelling. The principal functions of the Repast platform used in the implementation of 3MTSim include those that facilitate event coordination, batch execution of simulations, data collection during a simulation and visualisation of agent movement during runtime. This is a significant upgrade from the previous version of Repast (v. 3) in which the prototype described in Anwar et al. (Anwar 2007) was developed. Repast Simphony provides substantial speed improvements and improved visualisation capabilities compared to previous versions.

The model's interface allows a user to select and specify parameters, initial conditions and management scenarios for a simulation. Two different types of display are available to visualise the movement of boats and whales in the environment during runtime (Figure 3a,b).

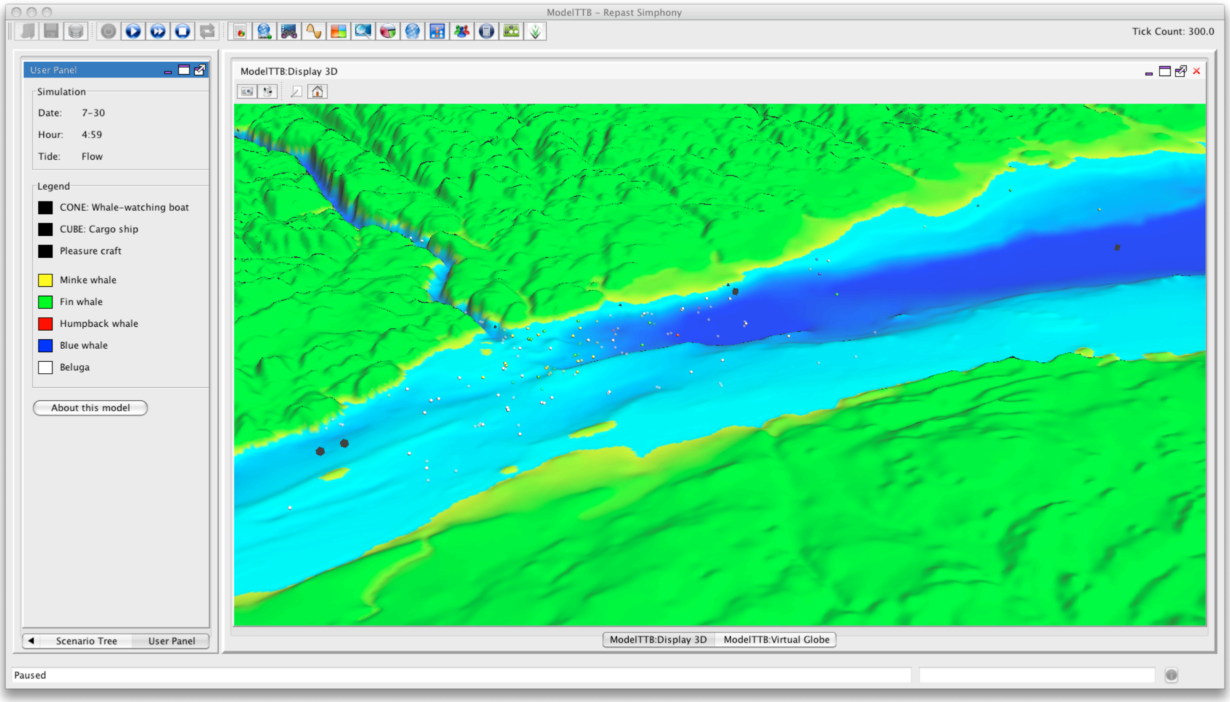
The temporal resolution of the model is 1 minute. Simulations are run for short periods of time, ranging from one day to a maximum of a whole season (early May to late October). The spatial extent of the environmental layers is approximately 43,700 square kilometres (the extent is slightly larger than the study area to allow for absorbing boundaries) and the spatial resolution is 100m x 100m for a total of 2205 x 1983 cells. Whales and boats move in continuous space. A fully configured simulation run may include up to 1500 whales and several hundred boats.

The model outputs the position, speed and other pertinent attribute values of each whale or boat object at each time step. The resulting space-time trajectories can then be post-processed to generate maps and statistics about a given simulation. See below for more information on data post-processing.

5. Model validation & scenario building

There is considerable inter-annual variability in the system in terms of which whales are present in the estuary, their abundances and spatial distribution. A number of hypotheses related to the distribution of krill have been proposed to explain these differences and there is ongoing work in the park to map and monitor prey abundance and distribution. Given this variability, to validate the whale-watching boat

(a)



(b)

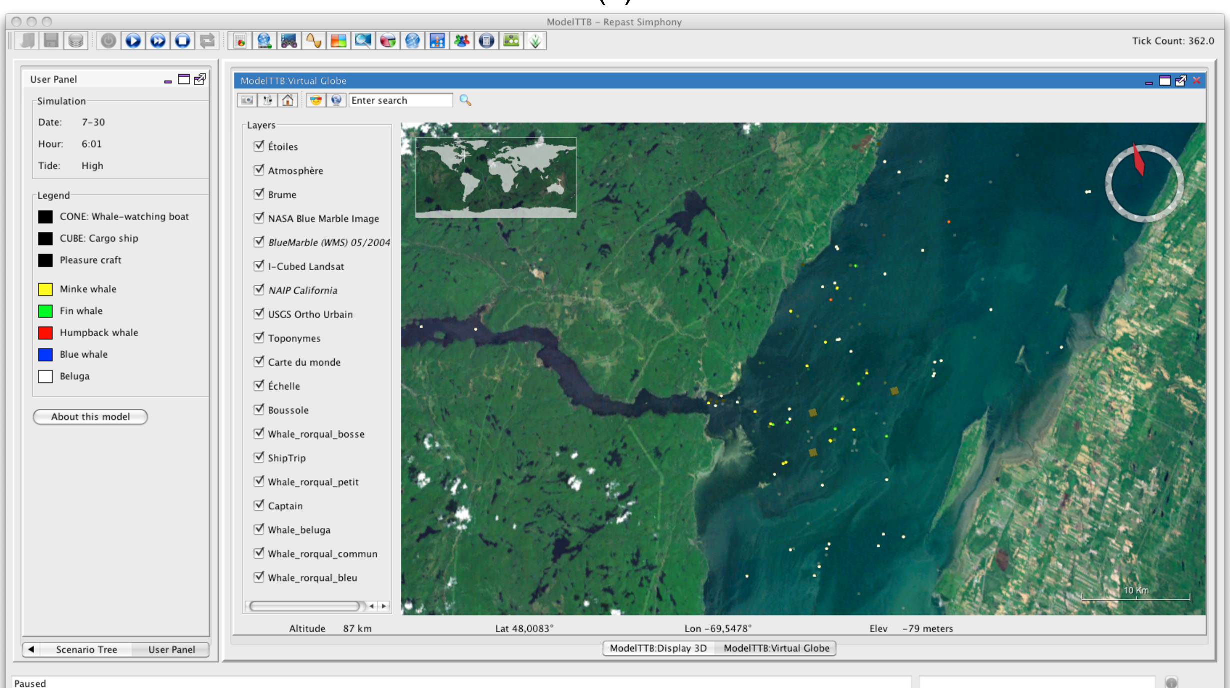


Figure 3: The 3MTSim interface (a) 3D view showing the bathymetry (b) 2D view using the WorldWind virtual globe. Coloured circles are individual whales; dark cones are whale-watching boats and black cubes are cargos. The size of boats and whales has been greatly exaggerated so as to facilitate visualisation.

module a selection of two different "whale scenarios" (species abundances and spatial distributions) was extracted for short (2 week) time frames in the data and the corresponding patterns (home ranges, spatial distributions, excursion contents and lengths) for these scenarios were extracted. The whale-watching boat agent model was then validated against these scenarios, to test its ability to generate similar patterns under these different conditions. This was done for each of the decision-making modules, and the "take the best" heuristic was found to be superior to the others in adequately reproducing the desired patterns, with excellent correspondence (greater than or equal to 83% match for each of five selected primary patterns describing excursion contents and distributions of boats across the territory in space and time) between real and simulated results (Chion et al. 2010b). For the ferries and cargo ships, since the model generates trajectories based on the statistics of historical data (waypoints, frequency of passages and speeds) model validation is more straightforward. For cargo ships, it was verified that the model generates realistic passages (e.g., no aberrant data or unrealistic boat behaviour), and reproduces both traffic density maps and spatial variability of speed patterns. For both patterns, correlation between the model and reality was found to range around 90%.

The whale model was validated using the pattern-oriented approach to compare the ability of different displacement patterns in accurately reproducing trajectory patterns and population-level spatial patterns. The MNB displacement algorithm that best produced the desired movement patterns for the whales was ultimately selected and was implemented in the overall model. Given that the whale model uses patterns as its input, it can easily be parameterized to reproduce known whale abundance and distribution scenarios, simply by introducing the appropriate maps of spatial distributions for each species. Currently, maps of the spatial distribution of each species for the years 1994-2009 are available as input and can be selected by a user at the beginning of a simulation.

6. Data analysis and geovisualisation

Both a stand-alone visualisation and analysis package and a geoprocessing Toolbox for ArcGIS desktop 9.2 were developed to manage the huge volume of data generated by the model and to reveal activity patterns of marine mammals and boat traffic. Both packages were written to post-process output from the simulations, which is typically in the form of CSV files in which the locations and other pertinent attributes of all of the boats and marine mammals are written for each time step of a simulation. The size of the output files can easily exceed several gigabytes for a single simulation.

By automating the analysis and cartography of the model's output, these two analysis and visualisation packages make scenario analysis with the model much more accessible to the end user and provide a visual spatial support to aid the decision-making process. They facilitate exploration of the data by integrating many interactive dimensions at the same time while avoiding the interpretative complexity of multivariate pattern generalization or recognition methods.

6.1 Stand-alone visualisation and analysis package

This stand-alone package consists of two main components, respectively called Database and Application. The database component was designed using a standard, general-purpose relational database management system: MySQL 5.0. It is a popular open-source database server with consistent fast performance, high reliability and ease of use that can run on more than 20 platforms, providing high flexibility for this project.

The application component was programmed using Java JDK 6 and delivered in an executable jar file with JRE6. Through an interactive visual interface, this component offers functionalities to dynamically query and visualise patterns of marine mammals and boats for specific periods of time or for the whole tourist season. These functionalities can be used for: 1) visualising the point and line density of locations of marine mammals and boats with zooming in and zooming out functions, 2) dynamically simulating the moving trajectories of boats and marine mammals by agent ID or by time point with zoom in and zoom out functions, 3) visualising the composition of marine mammals and boat types from different home ports in the study area using pie graphs, 4) visualising the distribution of boat activity types using bar graphs, and 5) visualising the total number of boats surrounding a marine mammal per minute.

The main advantage of this software package is its accessibility to any end user via open source licensing and its interactivity. Figure 4 provides an illustration of the graphical interface that was developed and the resulting output of a visualisation query.

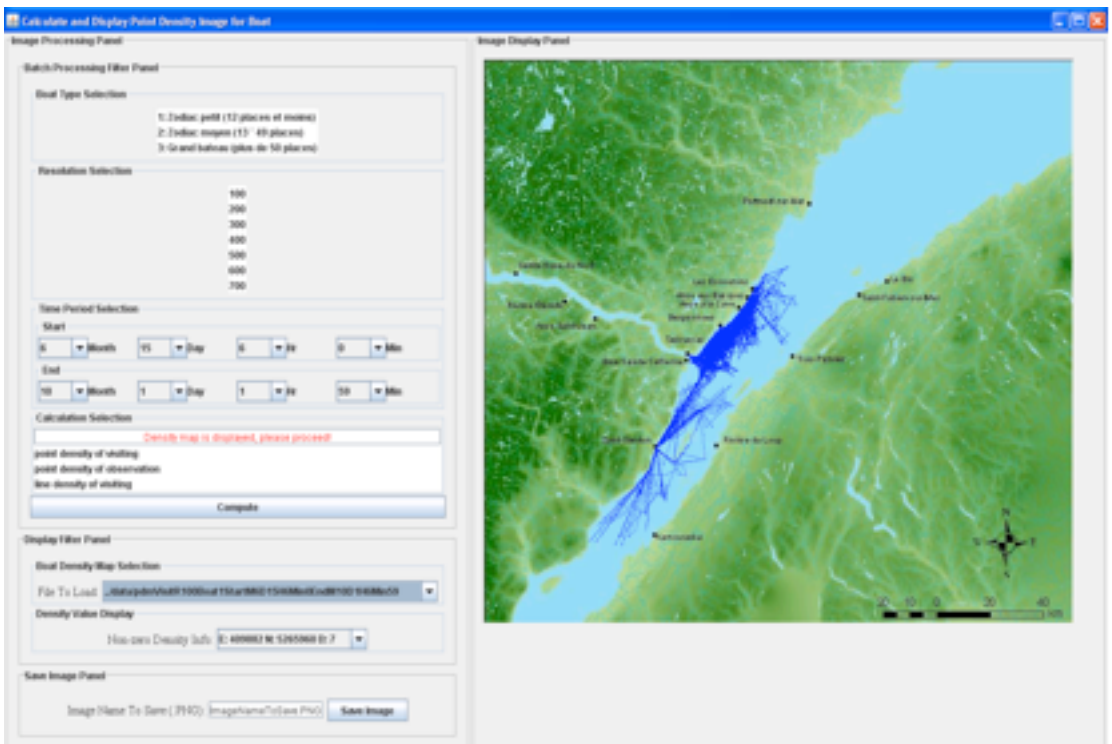


Figure 4: The post-processing software interface, showing a point density map of zodiacs at a spatial resolution of 100 m for a simulation covering the period of June 15 to October 1.

6.2 3MTSim Geoprocessing Toolbox

The ArcGIS desktop product is widely used and licensed by Canadian government agencies for their spatial analysis and cartographic needs and is the obvious tool of choice for Parks Canada or Fisheries and Oceans Canada end users wishing to generate high quality maps of simulation results. For this reason, an interactive Toolbox, specialized in the automated analysis of the model's output, was developed for ArcGIS desktop 9.2. The data analysis is performed in the background using Awk scripts, which are capable of parsing files many tens of gigabytes in size. The scripts are encapsulated in a Python program which is accessed via a visual interface to the geoprocessing Toolbox.

The interface allows a user to select from a number of analysis options. All of the analyses use the spatiotemporal trajectories of boat and whale movements to generate aggregate measures of boat or whale densities in space and time as well as co-occurrences between boats and whales. The user can choose to generate the cartographic results in raster or vectorial formats.

After selecting the output format, the user can choose to generate a number of maps from a total of 11 categories. The first seven categories concern the distribution of marine mammals and whale-vessel interactions. The analyses include: marine mammal presence (spatial distribution); locations of marine mammals being actively observed by whale-watching boats; locations where marine mammals are exposed to boats (of any type) at a distance of 400, 1000 and 2000 metres; weighted index of co-occurrence between marine mammals and boats (using the method of Turgeon et al., (Turgeon, Parrott and Martins 2008)); and co-occurrences between marine mammals and boats filtered according to boat distance and boat speed. The latter analyses may aid park and marine protected area managers to assess collision risks between boats and whales. For each selected category, a map for each species as well as an overall map for all species together is generated.

The latter four categories of analysis concern only boats and generate the following maps for the study area: average vessel speed, maximum vessel speed, boat presence (spatial distribution) and boat presence according to homeport. One map is created for each type of boat (cargo ships, pleasure craft, ferries, and large, medium or small tour boats) as well as an overall map for all types of vessels together.

Lastly, the Toolbox also compiles certain data in the form of frequency histograms. For each marine mammal species, the total length of time an individual is observed by whale-watching boats per day is calculated as well as the length of time of continual (uninterrupted) observation per day. Information on the daily exposition of whales to boats at distances of 400, 1000 and 2000 metres is also compiled in histogram format. This information may help managers assess the impact of marine traffic on the marine mammal populations and to compare the effects of different zoning and regulation scenarios.

The 3MTSim geoprocessing toolbox has been used extensively in the model validation phase and was used to generate Figures 5-7 in this manuscript.

7. Results: Example scenarios & analyses

For a given whale abundance and distribution scenario and marine conditions (visibility), the model reproduces the behaviour of boat agents for different management scenarios. The user can select a known "whale scenario" extracted from the data, create his or her own scenario or use the default scenario (which is based on multi-year analysis of habitat selection for the different species). The user also specifies the number of whale-watching boat agents per port and their types (in terms of size and passenger capacity). Management scenarios are expressed by means of raster maps that define zones and speed limits. A number of pre-defined management scenarios are available to the user, or a new scenario can be developed with the aid of a geographical information system and subsequently loaded into the system.

To illustrate the functionality of the model and show examples of the kind of output that can be generated, a series of management scenarios were run. The first scenario, called the “baseline” is the *status quo*, with current whale-watching regulations in place and a maximum speed limit for all vessels circulating in the park and MPA of 25 knots. The second scenario explores the effect of implementing a 16-knot speed limit for the entire study area. All other parameters and initial conditions are the same as the baseline scenario. The third scenario explores the effect of moving a major shipping lane south of the marine park to avoid the passage of large numbers of transatlantic cargo ships through the baleen whale's main foraging ground. Each scenario simulates a two-week period (July 25 – August 7) during the peak tourist season. Whale abundances and spatial distributions were the same for each scenario and were based on data for 2007. The frequency of passage of cargo ships and the number of whale-watching excursions corresponded to known frequencies for the summer peak period. Twelve repetitions were run for each scenario. Repetitions of the same scenario used the same initial conditions and varied only in the seed provided to the random number generator.

Note that the results shown here are intended to demonstrate the functionality of the model and are for illustrative purposes only. They are not fully completed studies of each of the tested scenarios and thus should not be considered as definitive results for policy and management purposes. Simulations were done with 3MTSim version 2.0.

Figure 5 shows the output of the baseline scenario compared to corresponding data from the real system. Here, a visual inspection confirms that the model generates spatial distributions of boats and baleen whales that resemble those of the real system. The baleen whales tend to be aggregated at the head of the Saint Lawrence channel (an area of deep upwelling near the confluence of the Saint-Lawrence and Saguenay Rivers) which is their main foraging ground. Whale-watching and sightseeing excursions are generally aggregated around the highest concentrations of whales within the limits of the national marine park. Cargo ships follow the shipping lanes traversing the park and marine protected area. It is clear from this figure that the head of the channel is an area of intense activity, including potentially conflicting uses of the territory by different types of marine traffic and marine mammals.

Figure 6 shows the relative risk of lethal collision between vessels and all five whale species in the entire territory for the speed reduction (16-knot limit) scenario. We see that the relative risk of lethal collision is highest in and around the mouth of the Saguenay River and in some parts of the shipping lanes. These are regions where boats are typically navigating at higher speeds so as to reach a destination. In particular, excursion boats shuttling between the ports of Tadoussac and Baie-Sainte-Catherine (at opposite sides of the mouth of the Saguenay River) to pick up and drop off passengers are at risk of collision with the high concentration of belugas in the area. The average relative risk of lethal collision over the entire territory is reduced by 3% as the speed limit is decreased from 25 knots to 16 knots (2% reduction for the region covering the shipping lanes and 3% for the territory within the limits of the national park). The relative risk of lethal collision was calculated using the method described in Appendix A, that computes the probability that an encounter between a boat and whale will occur, and then uses ship speed to compute the probability that a collision is lethal, should one occur (Vanderlaan et al. 2008). The fairly minimal change in risk of lethal collisions between our two scenarios is not surprising for two reasons: 1) the calculations are based on historical data showing that the probability of lethal injury should a collision occur is 100% for ships navigating at 25-knots and is on average still greater than 80% for ships navigating at 16-knots (Vanderlaan and Taggart 2007), and 2) many of the cargo ships transiting in the area cannot reach 16 knots, making such a speed limitation scenario affect only a small proportion of ship trips. A greater speed reduction (12-knots or lower) will be necessary to attain a more substantial reduction in the relative risk of lethal collision.

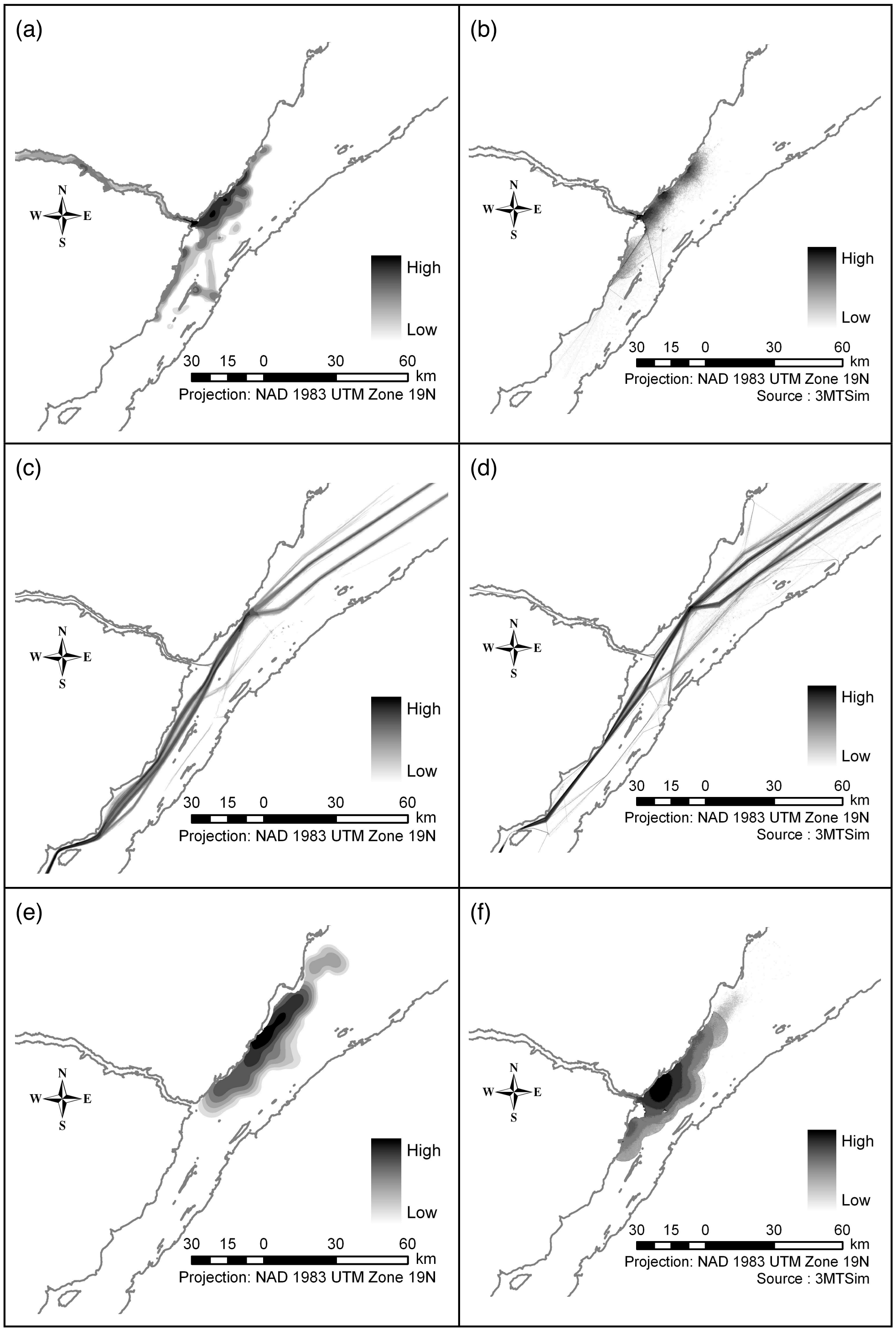


Figure 5: Reproduction of the present system's dynamics with 3MTSim. (a) Density of whale-watching boat excursions in the real system based on a sample taken during the 2007 peak season; (b) Density of simulated whale-watching boat excursions in the 3MTSim baseline scenario; (c) Density of all cargo ship passages in the real system for the 2007 season; (d) Density of simulated cargo ship passages in the 3MTSim baseline scenario; (e) Density of baleen whales (blue whale, fin whale,

humpback whale & minke whale) in the real system based on observations for the 2007 season; (f) Density of baleen whales in the 3MTSim baseline scenario.

Figure 7 shows the effects of closing the shipping lanes through the park and forcing cargos to take an alternative southern route. While this scenario may seem to be an appealing way of reducing the impact of commercial traffic on the baleen whales, it forces the cargos through a region that has a high number of belugas. This decision thus involves a trade-off in the impact on different species as well as potentially increasing the transit time through the region by large ships (the total trip length is increased by approximately 3km). The maps showing the total exposure of whales to all boats circulating within a 1000m distance show only minor differences between the two scenarios. This is not surprising given that there are very few cargo ships compared to the whale-watching excursion boats, which are not affected by this scenario. It is clear from the figure, however, that for this scenario baleen whale exposure to ships is reduced somewhat in the area of the feeding ground with a corresponding increase in exposure of the southern group of belugas to boat traffic.

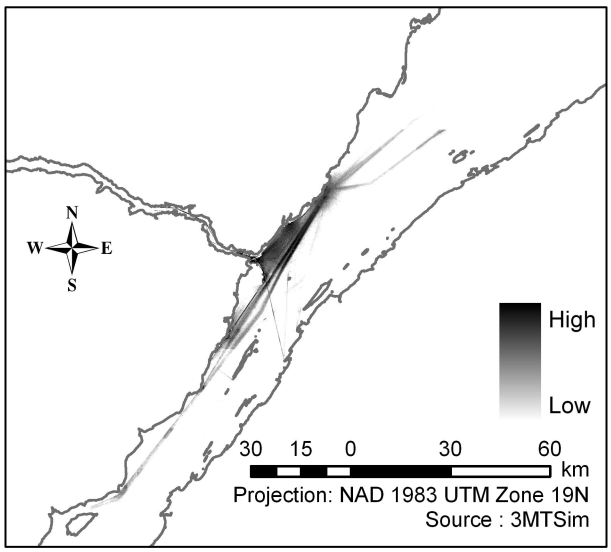


Figure 6: Relative risk of lethal collisions between whales and vessels for the 16-knot speed limit scenario.

Simulations of additional management scenarios of current interest to park and MPA managers are underway. The results of these scenarios may be communicated to boat captains and other stakeholders and decision-makers in multipartite meetings to provide a point of discussion of the potential effects of new regulations and zoning. It is expected that the model will help to contribute scientifically sound, quantitative arguments to support management efforts in the region.

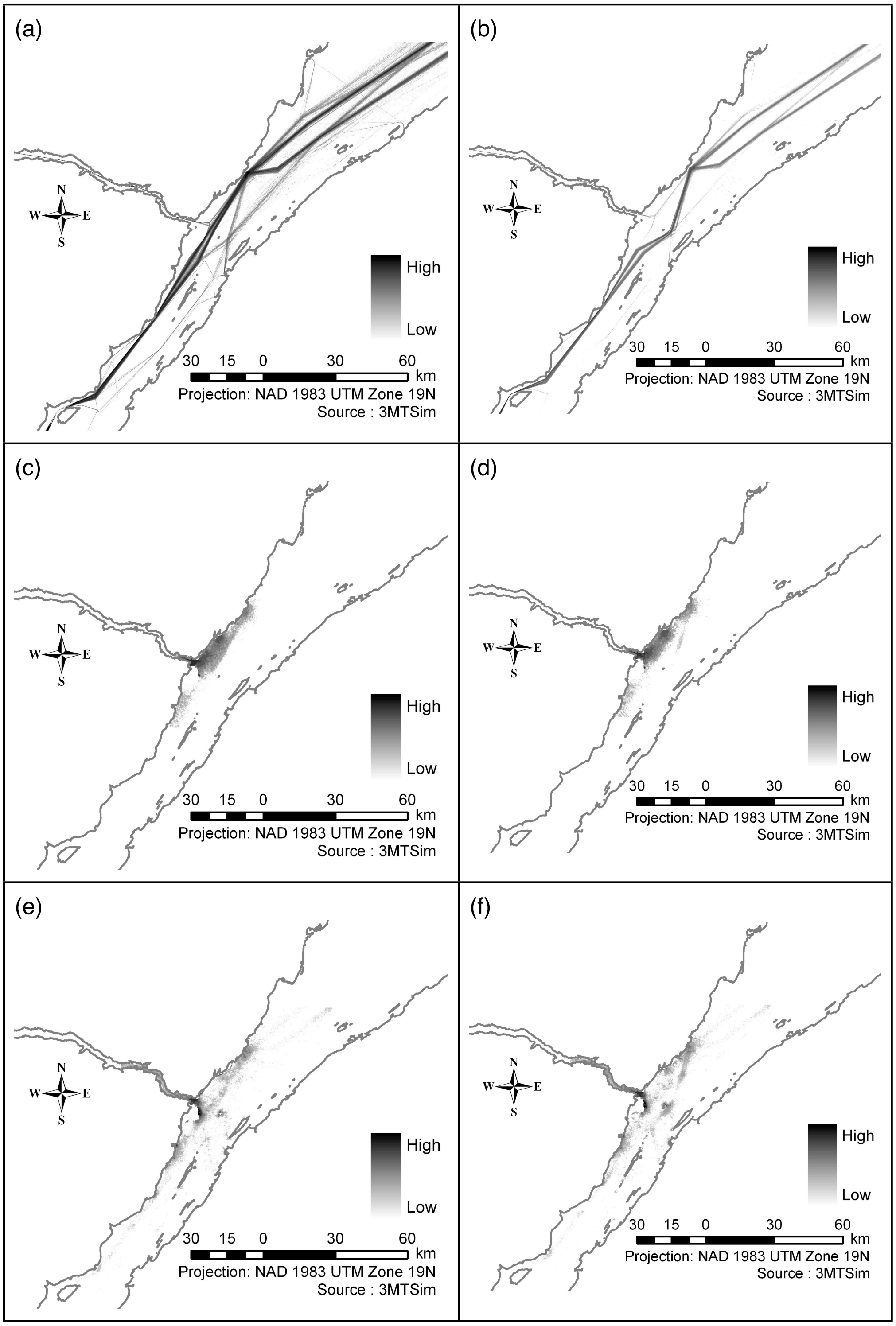


Figure 7: Effect of moving the commercial shipping lanes south of the main baleen whale feeding ground on whale - vessel encounters. (a) Density of cargo ships for the baseline scenario; (b) Density

of cargo ships for the shipping lane deviation scenario showing the route deviation south of Île Rouge; (c) Cumulative exposure of fin whales to boat traffic within a distance of 1000m, baseline scenario; (d) Cumulative exposure of fin whales to boat traffic within a distance of 1000m, shipping lane deviation scenario; (e) Cumulative exposure of belugas to boat traffic within a distance of 1000m, baseline scenario; (f) Cumulative exposure of belugas to boat traffic within a distance of 1000m, shipping lane deviation scenario.

9. Discussion and Conclusion

We have found that the agent-based approach is well suited for decision support applied to complex, multi-stakeholder management of coupled social-ecological systems. This type of model is easy to talk about and explain to users un-initiated to modelling, due to the fact that it is based on tangible, easily identifiable entities (in our case, boats and whales). Most people familiar with the real system can provide some insight into how the system works and about the important relationships between the key entities in the model. Also, while the approach is data intensive, the kind of data required is often available via monitoring programs. This is especially true for any areas that are of conservation interest, which have usually been the subject of at least some initial monitoring. Thus, there is often sufficient data to start such a project and to begin model conception. In this way, the model can be built up with existing cartographic information plus any monitoring information that exists, and can be complemented with information from interviews, questionnaires or role-playing games for targeted groups. This allows the model builders to seek out any key information related to agent decision-making or behaviour that may not have been previously documented. Model building can also provide insight into missing types of data and thus help to identify priorities for future data collection campaigns.

For the particular case of the Saint Lawrence Estuary, simulations based on current management conditions can be used to generate data and statistics that do not exist for the real system, and which can be used as a baseline with which to compare alternative management scenarios. The model can be used to respond to a multitude of questions, such as: What factors contribute to the aggregation of boats? How do the patterns of aggregation change with different whale abundances and distributions? How do the patterns of aggregation change with different zoning or speed regulation scenarios? How are whale-vessel encounters distributed in space and time? How does the distribution of encounters change with regulation or zoning changes? What is the average number of hours in a day that a whale is within a given distance of boats? Obviously, the number of questions that can be explored is large. The advantage of the agent-based approach is the ease with which data can be collected for individual vessels and whales, often for phenomena that cannot be fully monitored in the real system, permitting a multitude of meta-analyses regarding the dynamics of the system and the impact of marine traffic on marine mammals for present and future scenarios.

Management of the Saguenay-Saint Lawrence Marine Park and proposed Marine Protected Area involves the challenge of regulating widely different types of maritime traffic so as to avoid congestion, ensure safe passages and protect the marine ecosystem. The agent-based approach to modelling boats allowed for the representation of different types of collective and individual dynamics in a flexible manner and was thus well suited to this situation. In its current form, the model does not represent the physical system (oceanographic phenomena such as currents, mixing of fresh and salt water) that drives the spatiotemporal dynamics of the prey species at the bottom of the food chain, thus determining the presence and spatial distribution of whales. The model is thus restricted to simulating user-defined scenarios of whale abundances and spatial distributions, which is sufficient for current management purposes. Future versions of the model may, however, incorporate the dynamics of the physical environment, permitting a more mechanistic model of whale movement. Responses of whales to the presence of boats may also be included in future model versions, if sufficient data becomes available.

Often the model building process is equally important as the end result. Model building can incite people to think about the system in different ways, asking questions about how it works that they might not have asked before. Model building and subsequent discussions about the results can also bring together unusual combinations of people, contributing to discussion and idea sharing.

Prior to the start of this project, the data were distributed amongst different groups and researchers and much of it had not even been analysed to its full potential. One of the major contributions of this project has been the compilation of all of the available data into a single database and their subsequent cartography and analysis. The data has served not only for model building, but has also served to provide important insight on the current situation in the estuary, supplying on-going management actions and discussions with stakeholders (e.g., commercial tour companies, community groups, Saint Lawrence pilots) with quantitative support.

The 3MTSim model allows users to answer multiple questions that couldn't otherwise be addressed (via scenario building) or for which real data is unavailable (overlays of whale and boat distributions; cumulative exposure of whales to boats). As a decision-support tool, it effectively serves the purpose of informing management decisions, by providing data and results for different scenarios. The model may be used to provide insight into critical management issues and will serve to support multipartite meetings and discussions by providing new kinds of information that wasn't previously available. The modelling approach could be readily applied to other similar regions of the world where marine traffic and marine mammals are in close proximity generating management concerns. Lastly, due to the appealing virtual globe visualisation and ease of use, it may also be of interest to develop the interface further as an education tool that could be shared with the general public visiting park interpretation centres.

While many agent-based models and spatial simulation platforms have been developed for decision support, they have not all been successful in meeting these aims. There are many reasons for this, often related to the unavailability of data or the lack of participation by end users in all stages of model development. The development of 3MTSim has been a truly collaborative and multidisciplinary effort involving scientists from multiple sectors. We feel that the 3MTSim project is one of the rare examples of success, and are excited about the prospects of using the model to inform and eventually impact management decisions in the estuary. Projects such as this one may contribute to the overall goal of achieving the sustainable management of human activities in the Saint Lawrence estuary.

Software availability

Project documentation and a runtime version of 3MTSim can be downloaded from the following web page: http://www.geog.umontreal.ca/syscomplex/3MTSim/index.html

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Appendix A: Calculation of relative risks of lethal collisions

The relative risk of lethal collision is calculated for each 100m x 100m grid cell using the method described in Vanderlaan et al. (Vanderlaan et al. 2008). This method provides a probabilistic approach for estimating the risk of lethal collisions, based on the probability of encounters between boats and whales and average ship speeds in a region. Since our model does not simulate collisions per se, nor does it simulate whale reactions to approaching vessels, this probabilistic approach provides a good estimate of collision risk in our study area. Future versions of the model may simulate collisions and species-specific reactions to boats, allowing us to estimate collision risk in a more detailed manner.

From (Vanderlaan et al. 2008), the relative risk of lethal collision (RR_i) is calculated for each of *n* grid cells *i* as:

$$\mathrm{RR_i} = \mathrm{P_{rel}(Encounter)_i} \times \mathrm{P(Lethal} \mid \mathrm{Encounter)_i} \qquad (1)$$

where the probability of an encounter being lethal, $\mathrm{P(Lethal} \mid \mathrm{Encounter)_i}$ is calculated based on empirical data from 294 recorded vessel strikes on large whales using the following equation (Vanderlaan and Taggart 2007, Vanderlaan et al. 2008):

$$\mathrm{P(Lethal} \mid \mathrm{Encounter)_i} = \frac{1}{1+\exp^{-(-4.89+0.41\bar{x}_i)}} \qquad (2)$$

$\bar{x}_i$ is the average vessel speed in knots in grid cell *i*. This equation provides the probability of lethal injury based on aggregated data from reported strikes on multiple species of whales and for all types of ships combined.

The relative frequencies of all types of boats ($\mathrm{P_{rel}(Vessel)_i}$) and all species of whales ($\mathrm{P_{rel}(Whale)_i}$) for each grid cell *i* in the territory are used to calculate the relative probability of an encounter, $\mathrm{P_{rel}(Encounter)_i}$ using the following equation:

$$\mathrm{P_{rel}(Encounter)_i} = \frac{\mathrm{P_{rel}(Whale)_i} \times \mathrm{P_{rel}(Vessel)_i}}{\sum_{i=1}^{n}(\mathrm{P_{rel}(Whale)_i} \times \mathrm{P_{rel}(Vessel)_i})} \qquad (3)$$

The maps in figure 7 were generated with these equations using data from the 3MTSim scenarios. $P_{rel}(Vessel)_i$ and $P_{rel}(Whale)_i$ were computed for each scenario from the mean absolute frequencies (counts) of boats and whales for each grid cell over the 12 simulations. Similarly, the average vessel speed, $\bar{x}_i$, was computed as the mean of the average vessel speeds for each grid cell for the 12 simulations.

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