Numerical simulations of the spread of floating passive tracer released at the Old Harry prospect

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Abstract
The Gulf of St Lawrence is under immediate pressure for oil and gas exploration, particularly at the Old Harry prospect. A synthesis of the regulatory process that has taken place over the last few years indicates that important societal decisions soon to be made by various ministries and environmental groups are going to be based on numerous disagreements between the private sector and government agencies. The review also shows that the regulatory process has taken place with a complete lack of independent oceanographic research. Yet, the Gulf of St Lawrence is a complex environment that has never been specifically studied for oil and gas exploitation. Motivated by this knowledge gap, preliminary numerical experiments are carried out where the spreading of a passive floating tracer released at Old Harry is examined. Results indicate that the tracer released at Old Harry may follow preferentially two main paths. The first path is northward along the French Shore of Newfoundland, and the second path is along the main axis of the Laurentian Channel. The most probable coastlines to be touched by water flowing through Old Harry are Cape Breton and the southern portion of the French Shore, especially Cape Anguille and the Port au Port Peninsula. The Magdalen Islands are less susceptible to being affected than those regions but the probability is not negligible. These preliminary results provide guidance for future more in-depth and complete multidisciplinary studies from which informed decision-making scenarios could eventually be made regarding the exploration and development of oil and gas at the Old Harry prospect in particular and, more generally, in the Gulf of St Lawrence.

Keywords: spill, Old Harry, Gulf of St. Lawrence, surface currents, dispersion, policy and law

1. Introduction
1.1. Political and regulatory context

The Gulf of St Lawrence (or simply the Gulf hereafter, figure 1) is a unique and sensitive ecosystem (DFO 2005, Benoit et al 2012) that is politically divided into five separate regions regulated by multiple bodies. The Gulf is currently under serious pressure for oil and gas exploration and development (AMEC 2013, Genivar 2013). This is actually a pressing public issue that is frequently making headlines in eastern Canada.

The first exploration well may be drilled by the end of 2014 at the Old Harry prospect by Corridor Resources Inc. (2011). This prospect is situated within Newfoundland and Labrador’s boundaries where federal authority for leasing as well as environmental assessment, monitoring, and protection have been delegated to a unique federal-provincial board, the Canada-Newfoundland and Labrador Offshore Petroleum Board (hereafter referred to as the C-NLOPB or Board). The regulatory process surrounding Corridor’s Old Harry exploratory well project involves a project-level environmental assessment that prompted the updating of a broader strategic environmental assessment review. Both processes are discussed below.
In 2008, Corridor Resources acquired an exploratory licence from the Board to conduct geophysical and seismic surveys at the Old Harry site. Surveys were completed in 2010, then Corridor applied for an exploratory drilling licence. In February 2011, the Board released a draft scoping document for the environmental assessment for government and public comments. However, public concern expressed in response to the project was so unprecedented that the Board Chairman, Max Ruelokke, wrote to the federal Minister of the Environment, Peter Kent, recommending the most stringent level of environmental assessment and public consultation on the Old Harry project. Ruelokke (2011) stated that ‘the public commentary received to date is of a level and nature greater than any the C-NLOPB has received respecting environmental aspects of a proposed exploration or production project in its 26-year history. The Board believes this warrants reference to a mediator or review panel.’

However, Minister Kent’s decision was to proceed with a ‘screening’ environmental assessment—the lowest level of environmental assessment and one typically not requiring public consultation. But he suggested this screening could include ‘extensive’ public consultation. In addition, he committed to updating the 2005 ‘Western Newfoundland and Labrador Offshore Area Strategic Environmental Assessment’ (WNL-SEA) and the 2007 ‘Western Newfoundland and Labrador Offshore Area Strategic Environmental Assessment Amendment’, a process that should include ‘thorough public consultation’ to better examine the broader environmental effects of oil and gas activities (Kent 2011).

In December 2011, Corridor submitted its draft assessment reports to the Board for comment by relevant federal and provincial agencies. As part of this submission, Corridor contracted Stantec Consulting Ltd (2011) to provide an oil spill scenario analysis (carried out by SL Ross Environmental Research Ltd (2011)). A conclusion of this assessment was that oil spills originating at the Old Harry well could be expected to affect at most an area of dimension 22 km × 40 km before reaching concentration below 0.1 ppm of total petroleum hydrocarbon (TPH), a threshold they considered safe for the marine ecosystem. The report concluded that nearby coastlines of Newfoundland, Nova Scotia and Québec (Magdalen Islands) would be saved from any contamination if there were to be an incident associated with any conceivable worst-case scenarios of surface spillage.

Environment Canada and Fisheries and Oceans Canada critiqued Stantec’s environmental assessment and spill

![Figure 1. A map of the Gulf of St Lawrence and its bathymetry. The red triangle is the location of the Old Harry prospect site.](image-url)
modelling report. Environment Canada attempted to reproduce the consultant’s oil spill results and arrived at a different conclusion: the department determined that ‘the probability of oiling is very high for Newfoundland ... and Cape Breton’ (pp 40–41 Environment Canada 2012). Corridor responded by asserting that Environment Canada’s results were based on a corrupted database that provided incorrect oil parameters (SL Ross Environmental Research Ltd 2012a) and proceeded to submit the final environmental assessment report in February 2013. In response, Environment Canada still expressed concern about the use of ‘best case conditions’ in the consultant’s oil spill modelling which, given uncertainties in the exact oil type that may be found at Old Harry, may underestimate spill impact since only the fate of a very light and highly volatile surrogate for an unknown reservoir has been examined (Mercer 2013). Although Environment Canada recognized that assuming the existence of such a light surrogate was based on reasonable assumptions, the department nevertheless recommended that the ‘best practice dictate the application of worst case scenario analysis’ by also examining the fate of heavier oil type (Mercer 2013; Corkum 2013). Environment Canada ended up asking the Board, twice, to put an end to the exchanges, given that their recommendations were not being followed (Mercer 2013, Corkum 2013).

Fisheries and Oceans Canada also critiqued the proponent’s oil spill modelling and noted gaps in the environmental assessment that could hinder oil spill preparedness (Kelly 2013). Corridor defended its spill modelling and maintained that the company can safely drill this exploratory well (Corridor Resources Inc., 2013).

In October 2013, Fisheries and Oceans Canada’s Canadian Science Advisory Secretariat released its science review of the revised environmental assessment and oil spill modelling report. This review repeated concerns about the adequacy of the oil spill modelling, stressing the report has ‘important information gaps’. Further, the department challenged the proponent’s conclusion that there would be no significant or cumulative environmental effects from the exploratory well. The department’s science team found that this conclusion was ‘not supported’ with regard to oil spills and blowouts (DFO 2013, p 5) as the proponent’s oil spill predictions were incomplete or ‘unrealistic’ (pp 40–41).

The final stages of the Old Harry review are now on hold due to the ongoing Strategic Environmental Assessment (WNL-SEA). In February 2012, the Board terminated the work of the independent reviewer tasked with conducting public consultations on this project until the Environmental Assessment update was completed. The WNL-SEA update aims to provide a regional analysis of the environmental impacts of oil and gas exploration and development. More specifically, the process will inform the Board’s decision on issuing the Old Harry exploration drilling licence.

In 2012, AMEC Environmental & Infrastructure began preparing the WNL-SEA update which included public consultations primarily on the west coast of Newfoundland, as well as in the other four Gulf provinces. The draft WNL-SEA update was released for public review in June 2013 (AMEC 2013) and comments were accepted until late September 2013. The finalized SEA Update Report will soon follow. The Board has indicated it would then ‘evaluate all options for public review’ on Old Harry, including ‘the possible resumption of an independent review’ (C-NLOPB 2013).

Decisions made by the Board over the next months on the Old Harry project, in light of the ongoing WNL-SEA update, will determine the future of oil development in the Gulf. Yet to date there is limited independent scientific research available on the environmental risks of oil activities to inform this process. This means that, at the current time, Board decisions are not being informed by science.

1.2. Motivation for independent oceanographic research

Assessing the environmental impacts of oil spills in the Gulf of St Lawrence is an outstanding problem. The problem is difficult to tackle partly because the fate of oil spills in coastal seas largely depends on complex physical processes that are not fundamentally well-understood nor easily observable, such as surface waves, Langmuir circulation, internal tides and high-frequency internal waves, turbulent mixing, meso- and submeso-scale eddies, fronts, sea-ice physics, wave-ice interactions, etc. This subarctic seasonally ice-infested and harsh sea shares many characteristics with the coastal Arctic where, according to Short and Murray (2011), no-one is prepared to contain or mitigate large spills. The problem is further complicated by the fact that oil is not passive and interacts biologically and chemically in a complex and not well-understood manner with the marine environment with sometimes unexpected and indirect consequences. For example, while oil may be broken down or consumed by marine microbes this comes at an environmental cost: microbial degradation of organic matter consumes oxygen (see for example Adcroft et al 2010, for the case of the Gulf of Mexico). Therefore, an oil spill at the bottom of the Laurentian Channel, in 460 m depth, may lead to reduced dissolved oxygen due to microbial oxygen consumption, which may in turn impact higher trophic levels of the marine ecosystem that are already under low-oxygen stress in this environment (e.g. Bourgault et al 2012). Such processes are generally absent from standard oil spill models and require much broader, interdisciplinary and specialized studies to be assessed.

Given these considerations, it may be premature to pretend having the capacity to make realistic oil spill scenarios and to produce at this point informed environmental assessments for the Gulf. Here, we propose to take a large step back in order to approach the problem from a much simpler and broader perspective. Our approach is inspired by Maltrud et al (2010) who conducted a similar modelling study during the Deep Horizon oil spill in the Gulf of

3 Referenced reports, comments and responses are available on-line through the C-NLOPB website at http://www.cnlopb.nl.ca/environment/corridorresinc.shtml
Mexico. Essentially, rather than attempting to realistically simulate oil dispersion processes in all their complexity, the strategy adopted here to examine more simply the horizontal spreading of a passive floating tracer released at Old Harry. In their oil spill model SL Ross Environmental Research Ltd (2012b) assumed that light oil resulting from a surface spillage would be instantaneously diluted within the top 30 m of the water column (p 19), therefore considerably reducing the initial concentration. This appears to us unlikely given the strong summer stratification that exist in both temperature and salinity over the gulf (e.g. Galbraith 2006, his figure 2). It is difficult to conceive a mechanism that could rapidly vertically mix very light, and therefore highly buoyant oil, while maintaining the temperature and salinity stratification. This partly motivates the reason for only examining here the spreading of a floating tracer assuming it would not significantly mix vertically given the stratification. The fact that the tracer is passive means that there is no possible decay from, or interaction with, biological, chemical or physical processes. In other words, we are conducting a numerical experiment in order to provide a better understanding of surface water circulation and spreading around the Old Harry site. This is a step we feel necessary to accomplish before proceeding with more complex biogeochemical simulations of oil and contaminant dispersion. This approach can be considered to provide upper bounds on the spread of oil or, equivalently, to provide worst case scenarios, as recommended by Environment Canada (see also Short and Murray 2011, for similar recommendations in terms of exploration in the Arctic).

2. Methods

2.1. Numerical model

We work in an Eulerian frame of reference where tracer concentration is calculated given known advective and diffusive horizontal fluxes from currents and eddies. This approach is analogous to that largely used for simulating sea-ice as a 2-dimensional viscous-plastic continuum floating over a three-dimensional ocean (e.g. Tremblay and Mysak 1997). Floating tracer concentration $C(x, y, t)$ is determined by numerically approximating the solution of the
conservative advection-diffusion equation,
\[
\frac{\partial C}{\partial t} + \frac{\partial (uC)}{\partial x} + \frac{\partial (vC)}{\partial y} = \frac{\partial}{\partial x} \left( K \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left( K \frac{\partial C}{\partial y} \right) + S,
\]
(1)

where \(x\) and \(y\) are, respectively, the eastward and northward axis, \(u(x, y, t)\) and \(v(x, y, t)\) are the known surface velocity components and \(K(x, y, t)\) is the horizontal diffusivity induced by unresolved subgrid-scale eddies, a coefficient to be detailed below, and \(S(x, y, t)\) is the imposed source term. This term is set to zero everywhere except at Old Harry, as will be detailed below. In order to make this study as general as possible, the concentration \(C\) is normalized relative to the concentration at the source site.

Eddy diffusivity is parameterized as in Saucier et al. (2003), i.e.
\[
K = \gamma L^2 \left[ \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial y} \right)^2 + \frac{1}{2} \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 \right]^{1/2},
\]
(2)

where \(\gamma = 0.1\) is the Smagorinsky coefficient and \(L = \sqrt{\Delta x \Delta y}\) is a characteristic lengthscale of the largest energy-containing unresolved subgrid-scale eddies, where \(\Delta x\) and \(\Delta y\) are the grid size dimensions.

In order for the advection-diffusion equation above to be useful, surface current fields \((u, v)\) must be known. Observed fields of surface currents are difficult to obtain and are not available for the Gulf of St Lawrence. Results from circulation models represent to date the best available information on the spatio-temporal evolution of surface currents over the entire Gulf. Until recently, such surface currents were not easily or publicly available and were used only by a few expert modelling groups. However, since January 2012, the Department of Fisheries and Oceans Canada has started the public dissemination of 48 h surface current forecasts over the Gulf of St Lawrence through the St Lawrence Global Observatory (SLGO) portal (St Lawrence Global Observatory 2013). Each 48 h forecast is reinitialized daily with updated forcing. The archived data contains the collection of the first 24 hours of each 48 h forecast (K Ratté, SLGO, pers. comm.). The skill of these forecasts is unknown.

Those currents come from the 5 km horizontal resolution operational model used by the Canadian Meteorological Centre (Smith et al. 2012). It is a coupled ice-ocean three-dimensional baroclinic primitive equation model, forced with tides, winds, river runoffs and atmosphere-ocean heat fluxes. Although the model is three-dimensional, the SLGO portal only dissemination surface currents, i.e. currents of the 5 m thick surface cells.

This is therefore the dataset we used that dictated the choice of our numerical domain and grid. We have downloaded all hourly data available for the year 2012. Year 2012 was anomalously warm with annual mean air temperature being the third warmest since 1945, sea surface-temperature during ice-free months being the second warmest since 2006 and sea ice volume being the 4th lowest since 1969 (Galbraith et al 2013). However, the wind speed was close to normal throughout the year with an annual mean and standard deviation at Magdalen Islands of 6.2 ± 3.0 m s\(^{-1}\) comparable to the climatological annual mean (1994–2012) of 6.3 ± 3.3 m s\(^{-1}\) (DFO 2013).

Note importantly that in their oil spill model SL Ross Environmental Research Ltd (2012b) used seasonal mean currents from Tang et al. (2008) rather than hourly currents as used here. They have argued that ‘Tidal currents were not considered in the assessment since their oscillatory movement results in little long-term net movement of surface oil.’ (p 16 and p 24). This is an aspect we have tested. It will be shown below that given the large tidal and inertial variability of the surface currents relative to the mean state, the use of hourly currents has important impacts on spreading patterns in comparison to using seasonal mean currents.

Equation (1) is discretized on a structured grid with finite differences. The time discretization is fully explicit with the Adams–Bashforth scheme used for the advective terms and the Euler scheme used for the diffusion terms. The advective terms are spatially discretized with a total variation diminishing (TVD) second-order upwind scheme with the van Leer flux limiter (Pietrzak 1998). The diffusion terms are discretized with centered differences. The grid has \(M = 250\) by \(N = 175\) cells. The model time step is set to \(\Delta t = 900\) s. The hourly current data are cubically interpolated at the model time step.

The initial condition is set to \(C(x, y, 0) = 0\), i.e. water is initially free from any tracer. A no-flux condition is applied across solid boundaries. There is no possible deposits on shorelines. The tracer can freely circulate around and along coastlines. A clamped boundary condition is imposed at open boundaries (Cabot Strait and the Strait of Belle-Isle), i.e. \(\partial C/\partial t = 0\) (Jensen 1998). Given the initial condition \(C = 0\) everywhere, this means that the concentration within those open boundary cells never increases. In other words, the tracer instantaneously vanishes when reaching those boundary cells.

### 2.2. Release scenarios

A series of simulations was carried throughout year 2012 such that varying realistic forcing conditions were encountered. Three release scenarios are considered. In the first scenario, a tracer is continuously released at the Old Harry site \((x_0, y_0)\) every Monday and for one day at a rate of 1 unit per day, i.e.
\[
S(x_0, y_0, t) = \begin{cases} 
S_0 & \text{if } 0 \leq t \leq T \\
0 & \text{otherwise.}
\end{cases}
\]
(3)

where \(S_0 = 1\) d\(^{-1}\) is the release rate and \(T = 1\) d is the release duration. After one day, the simulation continues for an additional 30 days in order to examine the spreading within the gulf. Thirty days was chosen as the compromise between obtaining sufficiently long simulations within a
practical computational timeframe. The solution is saved every 6 hours. Once this first 31 day long simulation is completed, a new simulation is reinitialized one week later. Two consecutive simulations are therefore overlapped by roughly three weeks. This is repeated throughout the year. This produces 44 simulations covering all tidal, synoptic and seasonal variations in forcing conditions.

The other two scenarios are similar with the exception that the release duration is set to \( T = 10 \text{ d} \) for the second scenario (moderately long release) and to \( T = 100 \text{ d} \) for the third scenario (long release comparable to the Deep Horizon incident). The release rate is always set to \( S_0 = 1 \text{ d}^{-1} \) and simulations are re-initialized every Monday as in the first scenario.

We have emphasized just above that these scenarios are for continuous release. This is an important point to emphasize in this context because, in comparison, the ‘month-long’ simulations carried out by SL Ross Environmental Research Ltd (2012b) (section 5.2) are discontinuous, i.e. composed of a series (typically 120) of independent batch spills repeated every 6 hours. Each of these bath spills is tracked independently until its concentration reaches a value they considered safe for the ecosystem (< 0.1 ppm of TPH).

3. Results

3.1. Surface currents and variability

The annual mean circulation is principally characterized by the outflowing Gaspé Current and Gaspé Drift and by the inflowing West Newfoundland Current that flows northward along the French Shore of Newfoundland (figure 2). These currents are characterized by speed of order ~1 cm s\(^{-1}\). This annual mean circulation experiences seasonal variations (Saucier et al 2003) but the general mean pattern is consistent with this general view (see for example Galbraith et al 2013, for similar seasonally-averaged current patterns for year 2012 from another similar model).

As important, if not more important, for contaminant spreading than the mean circulation is the current variability that will be emphasized here. The spatial pattern of this variability is presented as the blue shade on figure 2 and specific examples are illustrated in figure 3 that shows instantaneous current fields for a region centered around Old Harry. Instantaneous flow speeds are much greater than the mean and currents could be oriented in any direction. At Old Harry, the modelled currents are normally-distributed with \( \pi = 3.0 \pm 39.8 \text{ cm s}^{-1} \) and \( \sigma = -3.5 \pm 37.8 \text{ cm s}^{-1} \), where the overbar indicates the annual mean and the \( \pm \) indicates the 95\% spread of the distribution (i.e. 1.96 the standard deviation). The current variability is therefore an order of magnitude higher than the mean. Instantaneous currents could be oriented in any direction with a slight preference for the northwest-southeast axis (not shown). A spectral analysis (not shown) indicates that the variability is principally caused by the semi-diurnal tide of frequency \( M_2 = 0.52 \) cycle per day (cpd) and the inertial current of frequency \( f = 1.49 \) cpd for this latitude. Second in importance is the diurnal tide of frequency \( K_1 = 1.00 \) cpd. Many other higher-frequency tidal constituents appear from this analysis (e.g. \( M_4 \), \( M_6 \), etc) but these have energies at least two orders of magnitude smaller. Year 2012 showed some seasonal variations with currents variability about twice as large during summer than winter as reflected in the following statistics for July–August-September (JAS) with \( \sigma_{\text{JAS}} = 7.7 \pm 50.2 \text{ cm s}^{-1} \) and \( \sigma_{\text{JFM}} = -4.5 \pm 48.6 \text{ cm s}^{-1} \) compared to \( \sigma_{\text{JFM}} = -1.1 \pm 27.2 \text{ cm s}^{-1} \) and \( \sigma_{\text{JAS}} = -7.3 \pm 25.6 \text{ cm s}^{-1} \) for the winter months (January–February–March). Whether this is indicative of a general seasonal trend or simply anecdotal of year 2012 would require more analyses that are beyond the scope of the present preliminary study but it could be that water mass spreading patterns exhibit seasonal changes, possibly caused by the presence of sea-ice. This is an aspect of the circulation that would need to be studied.

At Old Harry, away from the coast, the eddy diffusivity is log-normally distributed with \( \mathcal{K} = 15(4, 33) \text{ m}^2 \text{ s}^{-1} \), where the numbers in parentheses indicate the lower and upper 95\% interval of the distribution. Closer to shore, the diffusivity is typically an order of magnitude greater. These diffusivities are comparable to values determined numerically by Boufadel et al (2006, 2007) for the horizontal spreading coefficients of oil caused by non-breaking surface waves. Depending on wave and oil parameters (wave steepness, buoyancy velocity, etc) they determined horizontal diffusivity values of order 1 to 10 m\(^2\) s\(^{-1}\) (see for example figure 7 in Boufadel et al 2006).

3.2. Examples of spreading events

Six examples of concentration distributions at the end of the simulations are presented in figure 4. In most cases, the tracer patch ends up either within the northeastern region of the Gulf and along the French Shore of Newfoundland or ends up being stretched along the main channel axis. These two predominant distributions, i.e. along the French Shore or along-channel, can be partly understood in terms of the mean circulation of the area (figure 2). Old Harry is located at the boundary between the outflowing Gaspé Drift and the West Newfoundland Current. Therefore, it only requires that the instantaneous currents slightly push the tracer in one direction or another (e.g. figure 3) for it to be preferentially entrained either within the West Newfoundland Current or within the Gaspé Drift. These two distribution modes are not as clearly separated for the 100 day long release scenario because this period exceeds by far the synoptic time scale (few days) of current variability. Over the course of those long simulations the tracer may be entrained within the Gaspé Drift for a few days and then switched to be entrained within the West Newfoundland Current for a few more days and so on, such
that the final pattern is more evenly distributed within the gulf.

There are also evidences where the tracer is transported against the annual mean current. Examples of this are seen in panels b), d) and f) of figure 4 where the tracer released at Old Harry has moved a considerable distance (≈200 km) upstream against the mean Gaspé Drift.

3.3. Hourly versus seasonal mean currents and eddy diffusivity considerations

Results presented in the previous section highlight the importance of the current variability relative to the annual mean. Two questions arise from this observation: (1) what would the tracer distribution be like if the seasonal mean currents were used instead of the hourly currents, as done for example by SL Ross Environmental Research Ltd (2012b) and, (2) could the unresolved temporal variability be adequately parameterized with an eddy diffusivity?

To answer these questions, we have repeated two 10 day long release simulations with seasonal mean currents instead of using hourly currents. Simulations initialized on 7 May and 8 October were chosen for this exercise because they represent two typical cases where each mode, i.e. along the main channel or along the French Shore, of the resulting tracer distribution is clearly distinct (see panels c) and d) in figure 4). For the first run (7 May), the mean seasonal current for spring is used, i.e. averaged over the months of
April–June, while the averaged current for fall (October–December) is used for the second run (8 October). One important effect of such temporal averaging is to smooth out most eddies. Therefore, although the underlying numerical grid still uses a 5 km resolution, the effective diffusivity \( \tilde{K} \) required is expected to be larger in order capture the net effects of eddies that would otherwise exist at higher temporal resolution. The tilde is used here \( \tilde{K} \) to distinguish this effective diffusivity from the diffusivity \( (K) \) resulting from the Smagorinsky scheme when hourly currents are used.

In order to determine this effective eddy diffusivity for simulations based on seasonal mean currents, we carried out a series of twelve simulations by varying \( \tilde{K} \) between 0 and 500 m\(^2\) s\(^{-1}\) and performed a simple minimization. The minimization procedure is to examine the root-mean-square difference \( \epsilon \) between the reference field, i.e. the results from the simulation that uses hourly currents, and the simulation that uses the mean currents, and to pick the diffusivity that corresponds to the minimum value of \( \epsilon \). Mathematically, this means determining the diffusivity \( \tilde{K} \) that minimizes this function,

\[
\epsilon (\tilde{K}) = \left( \log (C) - \log (\tilde{C}) \right)^{1/2},
\]

where \( C \) is the reference tracer field at the end of the simulation and \( \tilde{C} \) is the resulting field with the mean currents and the effective diffusivity \( \tilde{K} \).

The minimization leads to \( \tilde{K} = 150 \text{ m}^2 \text{ s}^{-1} \) for the first run (spring) and \( \tilde{K} = 300 \text{ m}^2 \text{ s}^{-1} \) for the second run (fall) (figure 5). Figure 6 shows the tracer field at the end of the simulations for the reference run that uses hourly currents with Smagorinsky diffusivity compared with the run that uses the seasonal mean currents with the effective diffusivity \( \tilde{K} \) as determined by minimization. At first sight, the general patterns look qualitatively similar between these two approaches. There are however important differences in the details. For example, the first simulation with hourly currents shows that the tracer patch has approached very close to the Magdalen Islands and Cape Breton Island (figure 6, panel a). However, the companion simulation with seasonal mean currents and \( \tilde{K} = 150 \text{ m}^2 \text{ s}^{-1} \) does not show such threats for those islands (figure 6, panel b). Furthermore, the larger diffusivity \( \tilde{K} \) acts to smooth out the more filamentated structures seen when using the smaller Smagorinsky-based diffusivity.

The result of this exercise and previous considerations mentioned earlier about the large current variability suggest that hourly currents should be used whenever possible instead of the mean currents, especially since those currents are now easily available on-line. However, if for some practical reasons, perhaps due to computational limitation, only the mean currents can be used, our analysis suggests that the effective surface horizontal eddy diffusivity should be \( \tilde{K} \sim 10^2 \text{ m}^2 \text{ s}^{-1} \).

3.4. Statistical maps

Statistical maps that synthesize the main results of all simulations carried out for each of the three series of experiments are now presented. The first statistics gives the probability map that the concentration exceeds a certain threshold at any time during the course of the simulations. The pattern of these probability maps therefore depend on the specified threshold. In order to provide results as general as possible, two such maps for each scenario corresponding to two different thresholds are presented. The thresholds chosen are \( C \gtrsim 0.01 \) and \( C \gtrsim 0.001 \). These thresholds and corresponding maps must be interpreted by keeping in mind that in each scenario the release rate at Old Harry is set to 1 unit per day.
The second set of statistical maps gives the time, in days, it takes for tracer released at Old Harry to reach a concentration above a certain threshold. The same two thresholds as for the probability maps are used. These statistical maps are presented in figures 7–9. The results of this analysis suggest that, as anticipated from previous discussion, tracer released at Old Harry may follow two preferred routes. In the first path, the tracer is principally carried northeastward by the West Newfoundland Current along the French Shore of Newfoundland. In the second path, the tracer is carried southeastward by the main along-channel outflow current and may leave the gulf through Cabot Strait. What happens to the tracer after it has left the Gulf through Cabot Strait is uncertain but it would likely flow southwestward along the Nova Scotia coastline.

Given those thresholds, the most probable coastlines to be touched are the French Shore of Newfoundland, especially the region around Cape Anguille and the Port-au-Port Peninsula, and Cape Breton in Nova Scotia. For small (1 day) and intermediate (10 day) releases, the probability that the Magdalen Islands get affected is somewhere between 5% and 10% depending on the scenario and criteria considered. For the large release scenario (100 days) the entire eastern half of the Gulf is highly susceptible to being affected, including a high probability ($P > 50\%$) for the Magdalen islands. The time it takes for the tracer to reach the most sensitive regions of Cape Breton and Cape Anguille is between 10–20 days.

Figure 6. Comparisons between results from simulations that use the hourly currents and the Smagorinsky eddy diffusivity (left panels) with simulations that use the mean seasonal currents with an effective eddy diffusivity $\tilde{K}$ (right panels). Panels a) and c) are identical to panels c) and d) of figure 4. The simulations of panel b) and d) use, respectively, $\tilde{K} = 150 \text{ m}^2 \text{s}^{-1}$ and $\tilde{K} = 300 \text{ m}^2 \text{s}^{-1}$ as determined from the minimization procedure described in the text and shown on figure 5.
4. Discussion and conclusion

This study presents a synthesized overview of the politics and regulatory context within which oil exploration in the Gulf of St Lawrence is taking place. This synthesis highlights the disconcerting disagreements that exist between the private sector (i.e. Corridor and its consultants) and government scientists, and the problem faced by the Board as it attempts to make a decision on oil exploration without adequate scientific information. Our analysis of the situation strongly motivates independent oceanographic research.

This study is indeed the first independent scientific initiative to examine surface spreading around the Old Harry prospect in the Gulf of St Lawrence. The problem associated with oil dispersion in natural environments like the Gulf is complex and our results are really only preliminary. Nevertheless, the results presented here may be useful for identifying particularly sensitive regions where broader ecosystemic independent research efforts could be concentrated. For example, our results suggest that the French Shore of Newfoundland and Cape Breton have the highest likelihood of receiving water, within 10–20 days, that has transited through Old Harry. These results could motivate studying the ecosystems of those regions as a priority.

Given the criticisms of existing industry, government, and non-governmental studies on the impact of oil and gas exploration in the Gulf of St Lawrence, as well as the preliminary nature of current scientific studies, this study indicates that there is a clear need for comprehensive, independent, field-based scientific research on this project.

Figure 7. Statistical maps showing (left) the probability (in %) in the 1-day release scenario that a region receives at one time or another over the course of the simulation a concentration above (a) $C \geq 0.01$ or (c) $C \geq 0.001$. (right) The time it takes for the tracer to reach surrounding regions given the same thresholds $C \geq 0.01$ and $C \geq 0.001$. 
This recommendation follows the first guiding principle proposed by Short and Murray (2011) for the exploration and exploitation of oil in harsh, ice-infested, offshore environments; that is to invest seriously in multidisciplinary science programmes prior to issuing exploratory drilling licences. The ongoing strategic environmental assessments (AMEC 2013, Genivar 2013) provide opportunities to foster this research.

More broadly, this study raises questions about the current regulatory structure managing oil development in the Gulf. Currently, the Board has the authority over the decision on Corridor’s Old Harry exploratory drilling licence. Yet our analysis suggests that there is a lack of scientific evidence to assess the impact of oil spills at Old Harry. Given this, inter-provincial collaborative regulation with federal involvement would be more appropriate than isolated province-based decisions on oil and gas development in the Gulf.

With this study we hope we have provided oil spills experts, ecotoxicologists, oceanographers, environmentalists, policy-makers and the general public with an intelligible portrait of the policy and regulatory context within which oil and gas exploration is evolving in eastern Canada. With this interdisciplinary approach, we hope we have also provided a basic understanding of the surface circulation and spreading processes around Old Harry upon which more advanced studies could be developed.

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Figure 9. Same as figures 7 and 8 but for the 100 day release scenario.
