Relative Risk of Contamination by Region during Hydrocarbon Spills in the Gulf of St. Lawrence

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by

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ABSTRACT

Lefaivre, D., St-Onge Drouin, S., D'Astous, A., and Senneville, S. 2020. Relative risk of contamination by region during hydrocarbon spills in the Gulf of St. Lawrence. Can. Tech. Rep. Hydrogr. Ocean Sci. 330: v + 11 p.

The potential risk associated with hydrocarbon spills is not spatially uniform for all coastlines but can be quantified with modeling. Using annual hindcasts of the oceanographic conditions of the Estuary and Gulf of St. Lawrence, the trajectory of particles that mimic a Gulf-wide uniform hydrocarbon spill was computed for the period 2001-2010. The particles were released in the surface layer of a three-dimension circulation model on each grid cell of the model during the ice-free period. The particles drifted from the action of currents and winds for 8 days. The main conclusions are: a) Most of the particles (94%) are still in the Estuary and Gulf of St. Lawrence. b) The coastlines are at risk because 41% of the particles ground. c) All coastline of the Estuary and Gulf of St. Lawrence are at risk. However, the islands in the Gulf are more exposed as well as the regions to the south and to the east. d) Half of the particles (52%) are still in the water. e) The results are similar from one year to another. Now that the risk for all regions has been assessed, it will be possible to plan ship deployment to aid recovery of spilled hydrocarbons and to design protection schemes for coastlines with higher vulnerabilities.

RÉSUMÉ

Lefaivre, D., St-Onge Drouin, S., D'Astous, A., and Senneville, S. 2020. Relative risk of contamination by region during hydrocarbon spills in the Gulf of St. Lawrence. Can. Tech. Rep. Hydrogr. Ocean Sci. 330: v + 11 p.

Le risque potentiel en cas de déversement d'hydrocarbures n'est pas uniformément distribué pour toutes les côtes mais ce risque peut être évalué en modélisation. À l'aide de reproductions annuelles des conditions océanographiques de l'estuaire et du golfe du Saint-Laurent, la trajectoire des particules représentant un déversement d'hydrocarbures sur l'ensemble du golfe a été calculée pour la période 2001-2010. Les particules ont été relâchées dans la couche de surface d'un modèle de circulation à trois dimensions, sur chaque cellule de la grille du modèle pendant la période libre de glace. Les particules ont dérivé sous l'action des courants et des vents pendant 8 jours. Les principales conclusions sont : a) En majorité, les particules (94%) sont encore dans l'estuaire et le golfe du Saint-Laurent; b) Les côtes sont à risque puisque 41% des particules s'échouent; c) Toutes les côtes de l'estuaire et du golfe du Saint-Laurent sont à risque. Cependant, les îles du golfe sont plus exposées ainsi que les régions au sud et à l'est; d) La moitié des particules (52%) sont encore à l'eau; e) Il y a peu de variations dans l'analyse des résultats d'une année à l'autre. Maintenant que le risque pour chacune des régions est identifié, il sera possible de planifier le déploiement des navires pour récupérer un déversement d'hydrocarbures, mais également de concevoir des systèmes de protection pour les côtes présentant des vulnérabilités plus élevées.

PREFACE

This report is dedicated to the individuals from the federal departments of Environment and Climate Change Canada, Transport Canada, and Fisheries and Oceans Canada (Canadian Coast Guard and Science Branch), who contributed to the preparation and salvage of the barge *Irving Whale*.

CONTEXT AND OBJECT OF THE STUDY

This study was produced as part of an initiative by the Government of Canada to establish a world-class safety system for tankers (WCTSS). This initiative is oriented around three axes:

1- Preventing Spills from Happening;
2- Responding and Cleaning in Case of a Spill;
3- Holding Polluters Liable.

This study is part of the second element, specifically under the following sub-element: Response capacity in risk management and response time in the event of an incident. Results are to be used at the planning stage and as a tool for decision making in the course of action for hydrocarbon recovery after a spill. Moreover, Fisheries and Oceans Canada also has the mandate to identify vulnerable coastal environments in order to protect species and habitats in the event of an oil spill. The object of this study is to identify the regions most likely to receive spilled oil in order to plan the deployment of ships to recover an oil spill, but also to design protection systems for coasts with higher vulnerabilities in the Estuary and Gulf of St. Lawrence.

Also a result of the WCTSS initiative, a companion publication to this one, is the State of Knowledge on Fate and Behaviour of Ship-Source Petroleum Product Spills, on the St. Lawrence Seaway, Montreal to Anticosti (Ryan et al., 2019). It provides a description of the bathymetry, the ocean circulation, the salinity and water temperature of the St. Lawrence River and Estuary and some background to what is presented here.

Finally, this work will be useful for the continuation of the WCTSS initiative within the Oceans Protection Plan (OPP). Two sub-components of the OPP could benefit from the results of this study, namely: 1- Characterization of coastal ecosystems and 2- Planning for an Integrated Environmental Intervention. For the characterization, six pilot areas have been identified in Canada. The Science Branch of Fisheries and Oceans Canada, Quebec Region, is responsible for the implementation of this initiative for the north shore of the St. Lawrence Estuary between the mouth of the Saguenay River and Pointe-des-Monts, region 3 of this work. For the Planning for an Integrated Environmental Intervention, the study area covers the entire Estuary and the Gulf of St. Lawrence for Quebec.

METHODOLOGY

RELEASE PATTERN AND SURFACE DRIFT

The first step was to choose the release pattern. Our intuition says that hydrocarbon spills should occur in the main navigational channels since that is where ships sail. On the other hand, experience tells us that ships experiencing troubles with seaworthiness will get away from these lanes and try to reach a port. Spills from grounding or burning ships often occur during their travel towards shore. In short, spills can occur anywhere. In order to avoid justifying of one scenario over another and to produce results that are scenario independent, the choice was made to make releases over the whole Gulf. Any difference in the amount of hydrocarbons beaching on a specific coastline will be the result of the forcings acting on the hydrocarbons at sea and not due to a specific release point.

The focus of the study is to calculate trajectories of hydrocarbons during their drift at the surface. The duration of each trajectory was set at 8 days, based on two factors. First of all, crude oil is mixed and weathered into the water column after 8 days. Secondly, the study by King et al. (2014) shows that over the same period of 8 days, diluted bitumen experience density change, becoming less buoyant, with density close to that of seawater, and gets more easily mixed in the water column. It is therefore appropriate to stop the calculation of surface drift after 8 days since the hydrocarbon is no longer at the surface. After this period, it is necessary to use the full three-dimensional modeling results to assess the mixing of the hydrocarbon in the water column according to its nature and to the ocean properties (temperature, salinity, currents, vertical mixing). This aspect, which includes the fate and behaviour of hydrocarbon, will be treated in a separate study. We have excluded from this study the winter period. The behavior of hydrocarbon in sea ice will also be part of another study.

THE OCEAN MODEL

The surface currents were calculated for the period 2001 to 2010 using a three-dimensional ocean circulation model of the Gulf of St-Lawrence (Saucier et al., 2003, 2009), hereafter the Ocean model. The Ocean model is driven by the observed freshwater flows from the St. Lawrence River and other tributaries, the tides, water temperature and salinity at Cabot and Belle-Isle straits, and by the atmospheric forcings (surface winds, air temperature, cloud cover, precipitation, and dew point temperature on a 24-km grid scale) provided by the Global Environmental Multiscale model of the Meteorological Service of Canada, Environment and Climate Change Canada. For the purpose of this study, the Ocean model was run in hindcast mode to provide the surface currents. A typical output of surface currents is shown in Figure 1. The hindcast consists of the hourly values of currents, water levels, temperature and salinity in three dimensions, on a 5 km horizontal grid with vertical layers of 5 to 20 meters from which the surface current is extracted.

HYDROCARBON DRIFT SIMULATIONS

To calculate the advection of hydrocarbons, particles are added to the surface layer of the Ocean model. The particles are passive and transported using the 4^{th} order Runge-Kutta technique (Kloeden and Platen, 1992) through the surface current field, onto which is added the value of 3% of the local wind speed in the same direction. This intensification of the surface currents is necessary because the forcing of the wind is averaged over the first layer of the oceanic model which has a thickness of 5 m. The factor of 3% represents the influence of the wind at the top surface which acts upon the spilled hydrocarbons. It was validated by observations using a surface buoy fitted with a drogue set at depths of 0.5 m (2.1% of the wind) and 1.5 m (0.5% of the wind) (Gendron et al., 2018) and extrapolated to the surface according to theory (Ekman, 1905).

TRAJECTORIES

Using the calculation of the drift described above, the trajectories are calculated as follows. A particle is released at each point of the model grid (5 km mesh) every three hours during the ice-free period, April 1st to December 31st, from 2001 to 2010 (10 years), for a total of 22.7 million particles every year. The position of each particle is recorded at every hour during simulations. The choice of the 3-hour interval was made to save computing time because sensitivity tests showed that the difference in the results between a release every 3 hours and an hourly release was small enough to be neglected. A given individual trajectory ends after 8 days of computation, or when the particle either runs aground on a beach, or exits the Gulf (away from the model domain) by Cabot Strait or Strait of Belle-Isle.

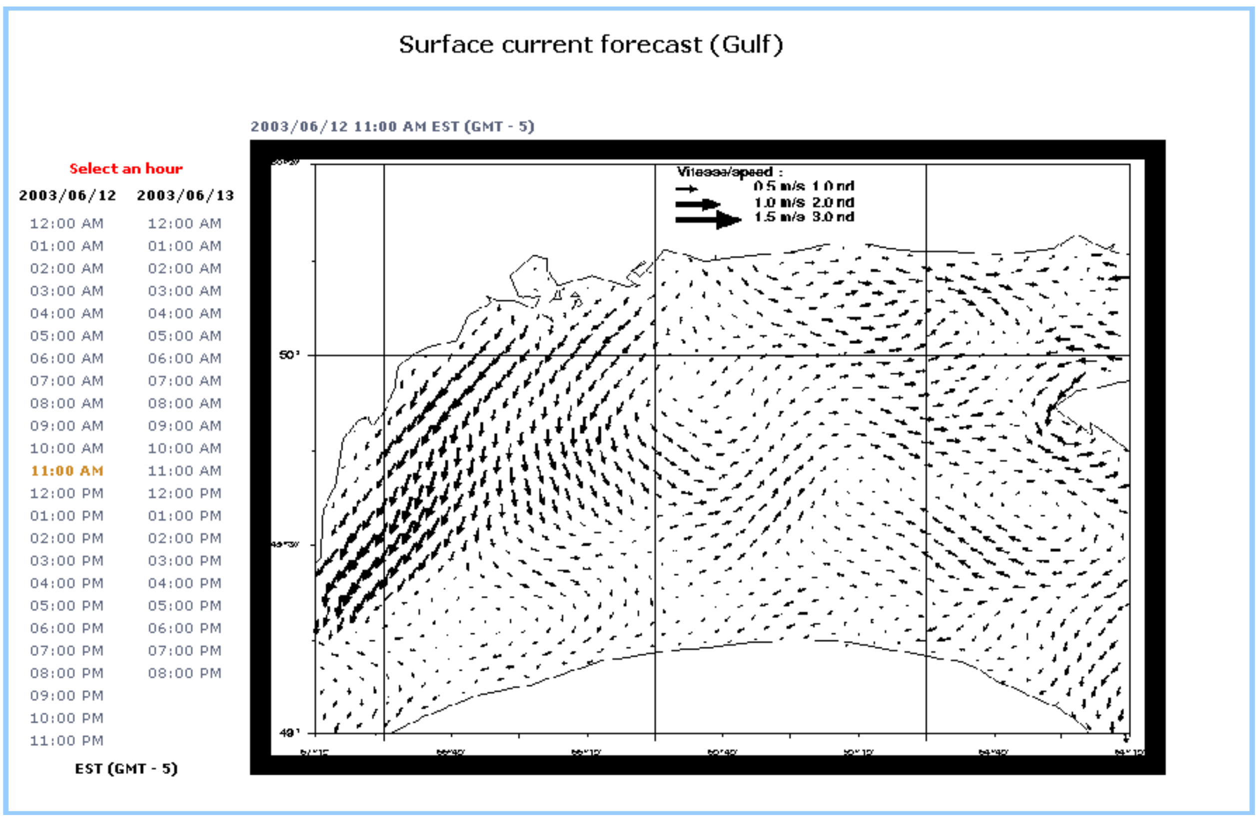

Figure 1. Example of surface currents on the grid of the Ocean model.

The trajectory of each particle is recorded hourly and the particles are listed in three categories:

1) Particles in the water.
2) Particles beached on a shore.
3) Particles outside of the Gulf.

When a particle reaches a coastline, the trajectory is stopped and its position is recorded. The number of beached particles for each cell on the shore (5 km by 5 km) is counted. The position of the particles still in the water after 8 days is recorded and counted by cell. The number of particles that exit the Gulf are simply counted.

RESULTS

After 8 days adrift, over the 10 years of simulation, the number of particles per category is shown in Table 1 and its variation per year in Figure 2. The Standard Deviation is calculated for the annual value over the mean. The Standard Deviation values are small showing little variation over the years.

Table 1. Yearly mean of the number of particles per category.

State of the particles	Number of particles (Million)	Standard Deviation (Million)	Proportion (%)
In the water	11.90	0.15	52.4
Beached on a shore	9.40	0.20	41.4
Outside of the Gulf	1.40	0.13	6.2
Total	22.70		

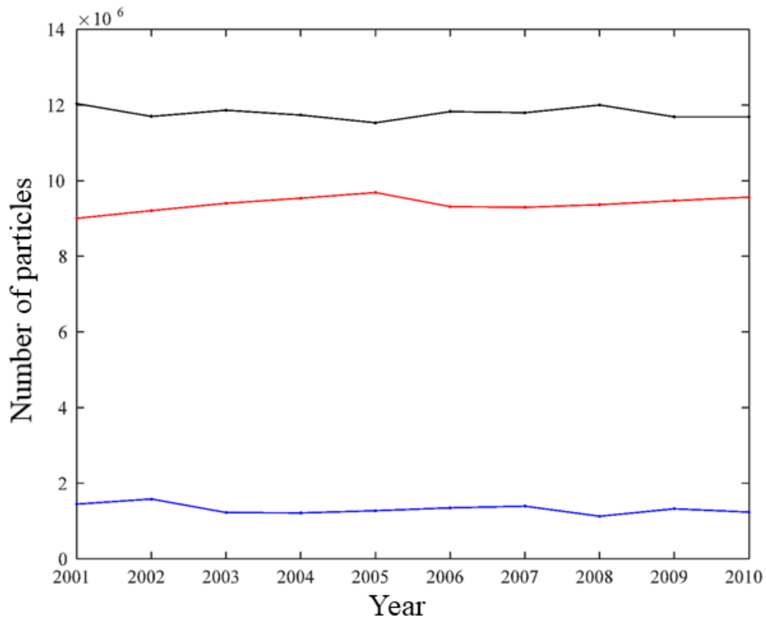

Figure 2. Number of particles per category by year. The number of particles still in the water is shown on the top curve in black, the particles beached on a shore, the middle curve in red, and the particles outside of the Gulf, the bottom curve in blue.

PARTICLES IN THE WATER AFTER 8 DAYS

The spatial variation of the concentration of the particles still in the water after 8 days is shown in Figure 3 as deviation from the mean. The number of particles in each cell is divided by the mean value of all the cells, over the 2001-2010 period. The color scheme is from blue (less than the mean) to yellow (higher than the mean). Above average values clearly stand out in the southern and eastern regions of the Gulf of St. Lawrence.

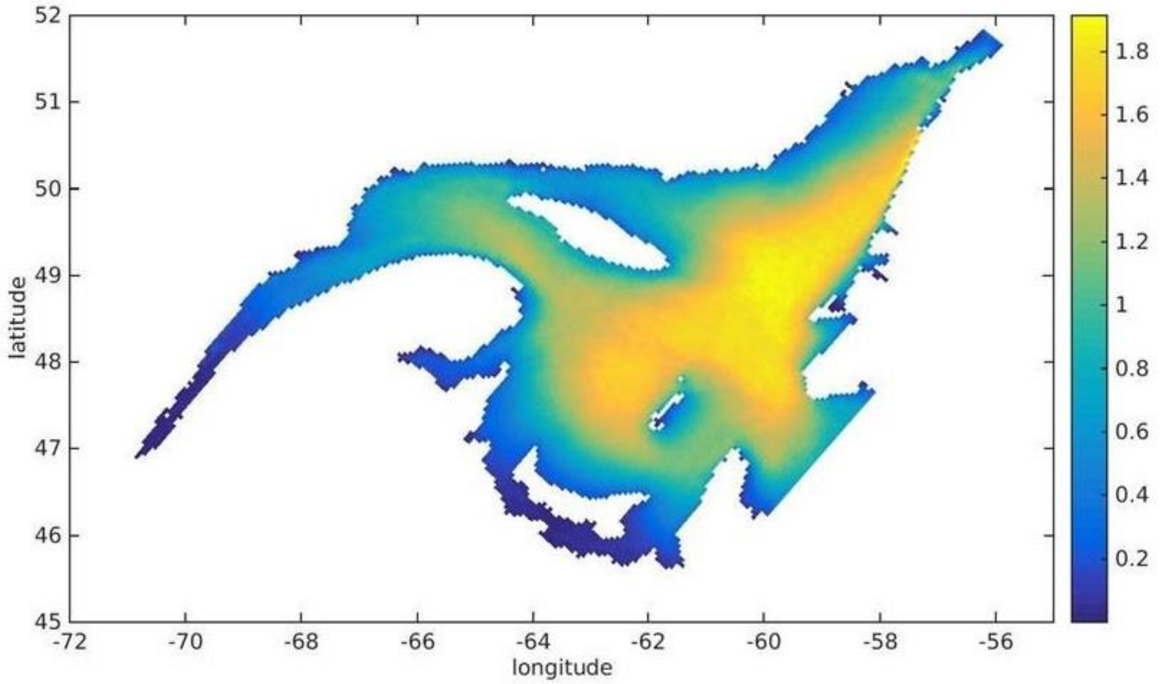

Figure 3. Spatial variation of the relative concentration of the particles still in the water after 8 days.

PARTICLES BEACHED ON A SHORE

The shorelines of the Gulf of St. Lawrence has been divided in regions as listed in Table 2. The total number of the particles beached by region over the 2001-2010 period is listed in column 4. With the number of cell for each region in column 3, the mean density of particles per region is calculated and shown in Column 5 along with its Standard Deviation in Column 6, which is the interannual variability. The relative risk in Column 7 is the ratio between the mean density of the region over the mean density for all regions. Finally, the rank of the relative risk for each region is shown in Column 8. In the case of region 20 and 21, the number of particles of one cell on the borderline has been divided between the two.

Table 2. Relative risk by region.

Region Number	Region	Number of cells	Number of particles (Million)	Mean Density per cell (Thousand)	Standard Deviation (Thousand)	Relative Risk	Rank
1	Quebec City to the Saguenay	25	0.30	12.5	9.7	0.18	21
2	Quebec City to Île Verte	25	0.50	18.9	10.1	0.28	20
3	Saguenay to Pointe-des-Monts	82	2.00	24.3	11.8	0.35	17
4	Pointe-des-Monts to Sept-Îles	53	2.40	45.5	17.9	0.66	13
5	Île Verte to Rivière-au-Renard	117	8.20	70.3	24.1	1.02	8
6	Rivière-au-Renard to Percé	28	1.50	51.9	24.6	0.76	12
7	Campbelton to New Carlisle	19	0.40	22.5	10.9	0.33	18
8	Campbelton to Belledune	16	0.30	20.5	10.9	0.3	19
9	New Carlisle to Percé	28	1.20	44.5	19.2	0.65	14
10	Belledune to Miscou	54	3.10	57.5	29.4	0.84	10
11	Sept-Îles to Blanc Sablon	222	11.80	53.0	11.7	0.77	11
12	Anticosti Island, North coast	53	4.50	84.4	37.7	1.23	6
13	Anticosti Island, South coast	64	7.90	123.3	47.3	1.8	3
14	West coast of Newfoundland	228	24.50	107.5	32.9	1.57	4
15	Miscou to Strait of Canso	116	4.00	34.2	13.7	0.5	16
16	Cape Breton Island, West coast	48	5.90	123.4	54.8	1.8	2
17	Cape Breton Island, East coast	32	1.20	37.3	12.4	0.54	15
18	Prince Edward Island, South shore	59	3.50	60.0	32.4	0.87	9
19	Prince Edward Island, North shore	64	5.20	80.5	35.1	1.17	7
20	Magdalen Islands, Northwest shore	12.5	3.40	270.8	33.7	3.94	1
21	Magdalen Islands, Southeast shore	24.5	2.30	95.5	23.4	1.39	5
Mean			4.48	68.5	24.0		

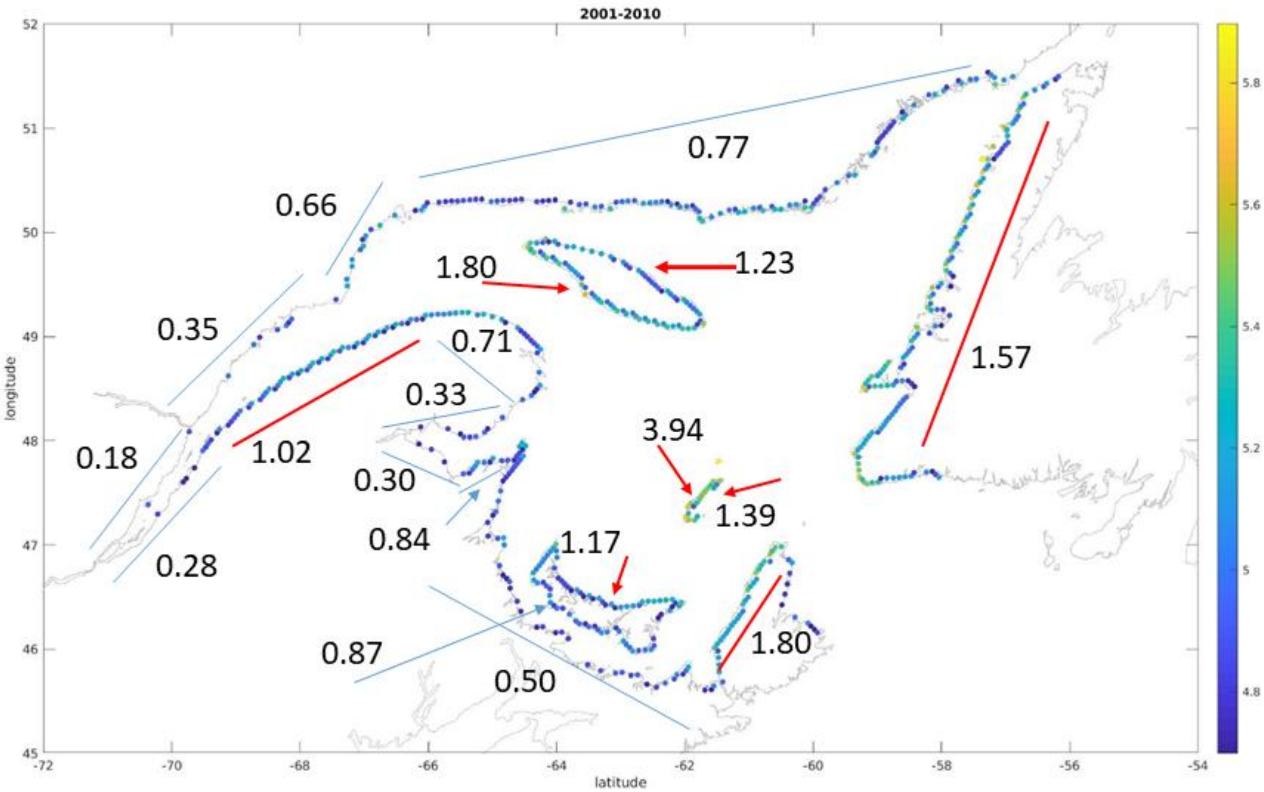

Figure 4. Relative risk by region. The color scheme on the coastline refers to the total number of particles that beached, on a log 10 scale. Numbers under 50 000 are blanked out to keep a proper color scale.

The relative risk per region, for the period 2001-2010, is shown in Figure 4. The thin lines delineate the regions listed in Table 2, with values of the relative risk less than one in blue and values higher than one in red. The figures in overlay represent the mean value over the region of the coastline identified by the thin lines. Above average values clearly stand out for the southern and eastern regions of the Gulf of St. Lawrence. For clarity purposes, differences with Table 2 occur on the figure. The value for Region 17 is not shown and the mean value (0.71) for regions 6 and 9, is printed on the figure. It is worthwhile to focus on a sub-region that does not show at this scale. It is the case of Brion Island, north of the Magdalen Islands. It stands out with a relative risk of 7.70, the highest value for all coastlines.

ANALYSIS AND DISCUSSION

The highest risks are in the southern and eastern regions of the Gulf of St. Lawrence. This applies both for particles in the water after 8 days and for beached particles. This pattern is consistent with the influence of the two main forcings, winds and fresh water flow, on the surface currents. The tides have limited residual effect at the Gulf scale. Firstly, the prevailing winds are westerly. Secondly, the freshwater flows from the St. Lawrence River and other rivers, follows the south shore from the east point of Île d'Orléans to the mouth of the Saguenay River, runs along the Gaspé Peninsula, and then flows to Cabot Strait by the Magdalen Shallows. The influence of these forcings on the surface currents is shown clearly in Figure 3 with particles in the water after 8 days.

To bring a hydrocarbon spill onto a coastline, one needs direct wind action because currents follow the constant bathymetry contour. The prevailing winds are from the West, (either northwest or southwest). However, winds from the northeast or the southeast are common and often of high intensity. The result of these events is that there is a risk for all coastlines to be impacted by a spill. However, given the pattern shown in Figure 3, with a greater number of particles in the southern and eastern Gulf of St. Lawrence, the end result is that the nearby shorelines are at greater risk. The coastlines exposed to the west show the higher risk: Anticosti Island, Gaspé peninsula (North shore), West coast of Newfoundland, Cape Breton Island (West coast), Prince Edward Island (North coast). The areas with the highest risk are both coasts of Magdalen Islands. The average standard deviation of the average density per cell is relatively low at 24 000, compared to the average density, which is 68 500. The ratio between the Standard Deviation and the Mean Density per cell (not shown) is relatively constant (35.0%) with non-significant variations from one region to another, except for regions 1 and 20. Region 1, Quebec City to the Saguenay River on the north shore, is the least at risk region (0.18) of a spill to reach its coastline but with the greatest relative variability (77.6%). At the other extreme, Region 20, Magdalen Islands, northwest shore, are the most at risk (3.94) of a spill to reach its coastline with the lowest relative variability (12.4%).

HISTORICAL SPILL CASES

How does the evaluation of risk regions in this document compare with a sample of historical cases presented in Table 3?

Table 3. List of spills

Vessel	Date	Spilled Amount (1000 l)	Product	Position	Impacted Region
Irving Whale	1970-09-07	4270	Bunker C, PCB	47° 22.15’ N 63° 19.77’ W	20, 19, and 16
Czantoria	1988-05-08	320	Light Crude Oil	46° 46.85’ N 71° 12.48’ W	1 and 2
Rio Orinoco	1990-10-16	200	Bunker C	49° 44.42’ N 64° 13.52’ W	13

The largest spill occurred in 1970. The *Irving Whale* barge was being towed from Halifax (Nova Scotia) to Bathurst (New-Brunswick). She was carrying Bunker C oil which was kept in liquid state using a heated pipe filled with chlorobenzene (PCB) Aroclor 1242. She sank 60 km north of North Point (Prince Edward Island) and 100 km west of the Magdalen Islands. The spilled oil, Bunker C and PCBs, mainly affected the west coast of the Magdalen Islands at the time of the sinking. In the years that followed and until her salvage on July 30, 1996, small quantities of oil escaped to re-contaminate the Magdalen Islands (Region 20), but also the north shore of Prince Edward Island (Region 19) and west coast of Cap Breton Island (Region 16) (Gilbert et al., 1996, 1998; Riche, 2002). These three regions correspond to the coasts with the highest risks, with ranks 1, 2, and 7 respectively.

The second case occurred in 1988. The ship *Czantoria* missed her berthing at the Lévis Ultramar oil terminal, now known as the Jean-Gaulin refinery. She tore open two storage tanks and light crude oil spilled. The instruction to dock at high tide was respected and the oil did not flow back towards Quebec Bridge. It flowed downstream to Île d’Orléans. Hydrocarbons were spilled in relatively deep water, in greater than 10 meters depth, along a wharf that protrudes into the river. It was a windless day, so the spilled product followed the same deep water line and ran along the shore without beaching. The currents from tides and freshwater outflow carried it through the channel to the south of Île d’Orléans and then across the islands downstream. Over the following two days, the light winds pushed the oil to Île aux Ruaux and the north shore of Île aux Grues, and then to Île aux Coudres. On the night of the third day, strong southwesterly winds mixed the hydrocarbons into the water column (Division de l’habitat du poisson, 1988). After this spill, the transport of hydrocarbon on ships with no double hull was forbidden on the St. Lawrence River. This case validated two of our hypotheses. The first one is that in no-wind condition, spilled hydrocarbon does not beach a shore. Secondly, the islands are the most exposed. A light wind is enough to move a spill on their shores. Finally, it can be seen that Regions 1 and 2 have been affected only lightly by this spill, in line with our assessment which puts them in ranks 21 and 20 respectively, therefore with the lowest risk.

The third case occurred in 1990. The *Rio Orinoco* vessel experienced an engine failure while sailing into the Gulf. Westerly winds made her drift towards Anticosti Island. She ran aground and her hull was opened under the wave action. Bunker C hydrocarbons used as fuel for the engine spilled. The cargo of asphalt did not leak out the vessel due to its high viscosity. It took a year to salvage her because of the remoteness of the area and the winter season that had settled. Oil leaked throughout the year and spread over the coastline of the island. In this case, it was not the oil that was pushed by the wind, but the ship herself. She broke up on the coast. The results were the same. The south coast of Anticosti Island (Region 13) is a region that has a high risk of receiving hydrocarbons. This region ranks as the third of the highest risk, tied with the west coast of Cape Breton Island (Region 16).

In conclusion, although there have been only a limited number of historical cases, the spills that occurred have confirmed that the impacted shorelines are among the regions identified in this analysis as most at risk.

Now that the risk for all regions has been assessed, it will be possible to plan ship deployment to aid recovery of spilled hydrocarbons and to design protection schemes for coastlines with higher vulnerabilities.

HIGHLIGHTS

- After 8 days adrift, the majority of the particles (94%) were still in the Estuary and Gulf of St. Lawrence. Only 6% of them drifted out by one of two straits.
- The coastlines are at risk because 41% of the particles ground within 8 days.
- All coastlines of the Estuary and Gulf of St. Lawrence are at risk. However, the islands (Magdalen Islands, Anticosti Island, Prince Edward Island and Cape Breton) as well as the regions to the south (north shore of the Gaspé Peninsula) and to the east (west coast of Newfoundland) are most at risk.
- Half of the particles (52%) are still in the water after 8 days adrift. Marine resources in the water column and on the bottom are at risk since these hydrocarbons are entrained in the water column before they can reach any shoreline, with an increasing risk in the regions south and east of the Gulf of St. Lawrence.
- The results are similar from one year to another.

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