UNIVERSITÉ DU QUÉBEC À RIMOUSKI

FACTEURS ENVIRONNEMENTAUX ET ANTHROPIQUES INFLUENÇANT LA VARIATION TEMPORELLE DANS LES ÉCHOUAGES DE MAMMIFÈRES MARINS DE L'ESTUAIRE ET DU GOLFE DU SAINT-LAURENT, QUÉBEC

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Composition du jury :

Véronique Lesage, présidente du jury, Institut Maurice-Lamontagne

Lena Measures, directrice de recherche, Institut Maurice-Lamontagne

Jean-Claude Brêthes, codirecteur de recherche, Université du Québec à Rimouski

Lyne Morissette, examinatrice externe, Arizona State University

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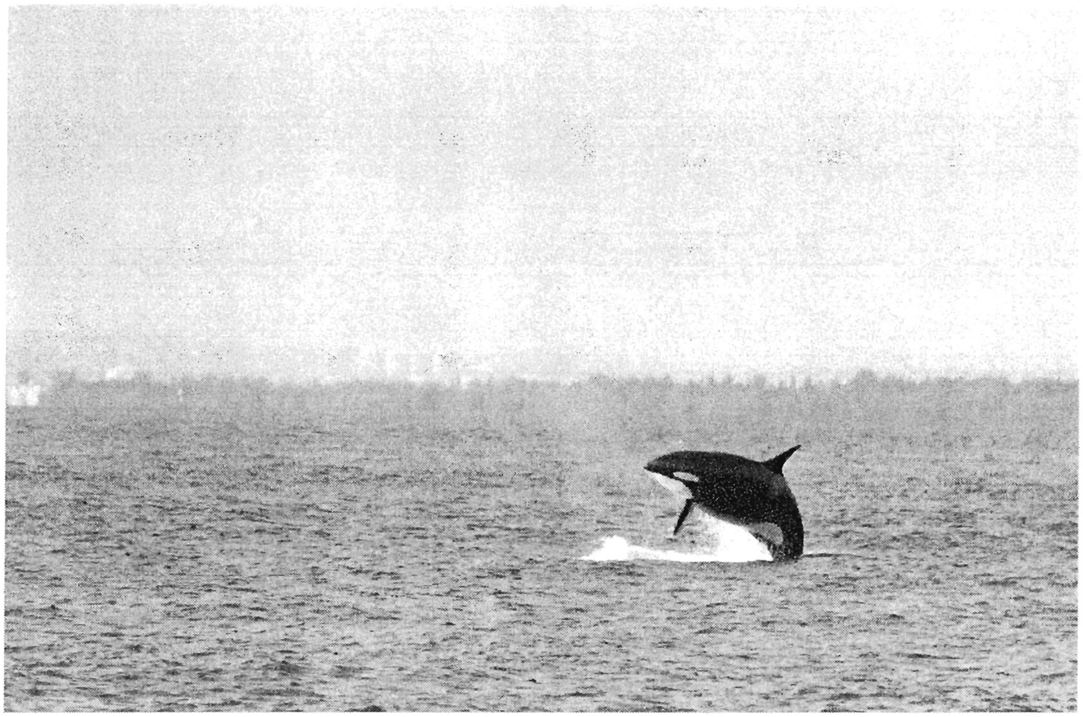

Nous n'héritons pas de la terre de nos parents, nous l'empruntons à nos enfants.

Antoine de Saint-Exupéry

Pour ceux que j'aime, ceux qui m'ont inspirée, ceux qui formeront les adultes de demain...

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RÉSUMÉ

L'estuaire et le golfe du Saint-Laurent sont des aires d'alimentation estivales importantes pour les mammifères marins et conséquemment, elles accueillent annuellement un grand nombre d'espèces. Toutefois, cet écosystème subit une forte pression anthropique par diverses activités humaines (*c.-à-d.* trafic maritime, pêche commerciale, tourisme, etc.). De plus, des suivis à long terme de l'écosystème ont démontré des changements importants des conditions environnementales. Afin d'identifier et de caractériser l'impact de ces changements sur la communauté de mammifères marins, nous avons analysé une banque de données d'échouage de 1994 à 2008. Généralement, le nombre d'événements d'échouage et d'interactions anthropiques augmente annuellement et est plus élevé en été, saison où les activités humaines sont particulièrement intenses et où la plupart des espèces sont présentes. Les modèles environnementaux montrent que les conditions de l'eau (volume de la couche intermédiaire froide, température de surface et débit d'eau douce) influencent les événements d'échouage de la plupart des espèces. Le couvert de glace influence négativement les espèces de pinnipèdes pagophiles et les mysticètes. L'abondance de krill influence spécifiquement les événements d'échouage du marsouin commun et du petit rorqual. Nous avons identifié en août 2008 un événement inhabituel qui s'est traduit par un nombre élevé d'échouages de plusieurs espèces (béluga, marsouin commun, phoque commun et phoque gris). Cet événement fut causé par une floraison d'algue toxique (*Alexandrium tamarense*) dans l'estuaire. Concernant l'analyse des facteurs anthropiques, nous avons identifié une augmentation inquiétante du nombre de prises accidentelles principalement de petits rorquals et de rorquals à bosse, excédant certaines années le prélèvement biologique potentiel (PBP) du « stock » de petits rorquals de l'estuaire et du golfe. Trois hypothèses ont été proposées afin d'expliquer cette tendance : i) un biais de l'effort, ii) des changements dans la distribution du petit rorqual et iii) des changements dans les pratiques des pêches. Nous avons également observé une augmentation des événements anthropiques impliquant le marsouin commun dans le parc Marin Saguenay-Saint-Laurent. La nature de ces événements suggère une chasse illégale. Ce projet a permis de valider l'utilisation de l'échouage comme un outil de suivi de l'influence des changements environnementaux et des activités anthropiques sur la communauté de mammifères marins de l'estuaire et du nord-ouest du golfe du Saint-Laurent.

Mots clés : mammifères marins, mortalité, changements environnementaux, glace, floraison d'algue toxique, prise accidentelle, aire marine protégée.

ABSTRACT

The Estuary and the Gulf of St. Lawrence are important feeding areas in summer for marine mammals and thus, support annually many species. However, this marine ecosystem is under a strong anthropogenic pressure by various human activities (*i.e.* maritime traffic, fisheries, tourism etc.). Additionally, long-term monitoring of the ecosystem demonstrates considerable changes of environmental conditions. To identify and characterize the impact of these changes on the marine mammal community, we analyzed the occurrence of stranding events from 1994 to 2008. Overall, the number of strandings and anthropogenic incidences increase annually and are higher in summer, season when human activities are particularly intense and when the majority of species are present. Environmental models show that water conditions (volume of the cold intermediate water layer, sea surface temperature, freshwater runoff) influenced stranding events in most species. Ice cover indeed influenced negatively the strandings of pagophilic seal species and mysticete. Krill abundance specifically influenced stranding events in harbour porpoise and minke whale. We identified in August 2008 an unusual event involving a high number of strandings of various species (beluga, harbour porpoise, harbour and grey seals). This event was caused by a bloom of toxic algae (*Alexandrium tamarense*) in the Estuary. Concerning the analysis of anthropogenic factors, we identified an increase of the number of entanglements mainly of minke and humpback whales, in some years exceeding the potential biological removal (PBR) of the minke whale stock of the Estuary and the Gulf of St. Lawrence. Three hypotheses were suggested to explain this tendency: i) bias in effort, ii) changes in the distribution of minke whales and iii) changes in fishery practices. We also observed an increase in anthropogenic events involving the harbour porpoise in the Saguenay-St. Lawrence Marine Park. The nature of these events suggests illegal hunting. This project allowed to valid the use of strandings as a monitoring tool to demonstrate the influence of environmental changes and anthropogenic activities on the marine mammal community of the Estuary and the northwestern Gulf of St. Lawrence.

Keywords: marine mammal, mortality, environmental changes, ice, harmful algal bloom, anthropogenic activities, entanglement, marine protected area.

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1. ÉCOLOGIE DES MAMMIFÈRES MARINS

Les écosystèmes marins sont caractérisés par un réseau trophique particulièrement complexe en termes de structure et de fonctionnement puisqu'ils renferment un très grand nombre d'espèces qui interagissent entre elles de multiples façons (Stenseth *et al.* 2004). Ces écosystèmes sont généralement vastes et sans barrières géographiques définies (Stenseth *et al.* 2004) où les ressources se distribuent inégalement (phénomène de « *patchiness* ») à de grandes échelles spatiales et temporelles (Mackas and Boyd 1979). Dans ces milieux, la base des réseaux trophiques, le phytoplancton, est limitée par la disponibilité des nutriments (*p. ex.* le fer, le nitrate et le phosphore) et l'intensité lumineuse, tous deux contrôlés par des processus océanographiques physiques (*p. ex.* courants océaniques, stratification, vent et action tidale) et biochimiques (*p. ex.* décomposition de la matière organique) (Steele 1985). À l'opposé, les organismes de haut niveau trophique (*c.-à-d.* les prédateurs) exercent davantage un rôle de régulation particulièrement crucial pour contrôler les populations des autres espèces et maintenir la structure des communautés. Ils s'alimentent d'un large éventail de groupes trophiques, contribuant à augmenter les liens entre les espèces et favorisant la stabilité de l'écosystème (Morissette *et al.* 2006). Les mammifères marins sont un exemple typique de grands prédateurs pouvant structurer la composition en espèces et réguler les écosystèmes marins. De par leur stature imposante (*p. ex.*, le rorqual bleu peut mesurer jusqu'à 28 mètres de longueur et peser jusqu'à 150 tonnes) ces prédateurs consomment des quantités phénoménales (*p. ex.*, le rorqual bleu peut engloutir environ 4 tonnes par jour d'euphausidés) de ressources afin de satisfaire leurs exigences métaboliques (Croll and Tershy 2002, Heithaus and Dill 2002). Ainsi, leur alimentation peut représenter une forte pression de régulation pour les espèces de proies qu'ils consomment. Dans certains cas, l'importance du rôle régulateur des mammifères marins est telle que sa perturbation peut entraîner des modifications profondes de l'écosystème jusqu'à la base des réseaux trophiques par le biais de cascades trophiques. À titre d'exemple, autour des îles Aléoutiennes au large de la côte Pacifique en Alaska, le déclin de la population de loutres de mer par la chasse commerciale a entrainé une prolifération des oursins et, conséquemment, une augmentation de la pression de broutage sur les plantes macrophytes menant à un déclin de la communauté végétale ainsi que des espèces animales associées (Estes & Palmisano, 1974). De par leurs comportements migratoires, les mammifères marins peuvent aussi agir comme vecteur liant différents écosystèmes en transférant notamment de l'énergie sous forme de subsides allochtones. Pour certains écosystèmes moins productifs (*p. ex.* les zones océaniques oligotrophiques), ces apports allochtones peuvent représenter une source additionnelle d'énergie pouvant soutenir la productivité primaire. À titre d'exemple, dans le nord du golfe du Saint-Laurent, les mammifères marins contribuent à l'apport de nutriments dans l'écosystème par des processus comme la minéralisation des nutriments et le retour de la biomasse en ressources sous forme de détritus (Brown *et al.* 2001). De plus, puisqu'ils sont situés au sommet des réseaux trophiques et ont une durée de vie relativement longue, les mammifères marins peuvent agir comme espèces baromètre témoignant de la qualité des écosystèmes (*p. ex.* floraisons d'algues toxiques : (Landsberg 2002, Flewelling *et al.* 2005). De manière générale donc, l'étude des mammifères marins et de leur démographie est un incontournable dans une optique de compréhension globale des interactions trophiques et du fonctionnement des écosystèmes marins (Reddy *et al.* 2001, Aguirre and Tabor 2004, Moore 2008).

Chez les vertébrés supérieurs, et en particulier chez les mammifères marins, l'étude des populations représente un défi de taille pour les écologistes puisque ces organismes sont typiquement peu abondants, largement distribués, et occupent souvent des environnements inaccessibles à l'homme (Gulland and Hall 2007). Les mammifères marins sont au nombre des ces espèces pour qui les suivis écologiques représentent un travail soutenu, tant pour des raisons logistiques que monétaires (Fowler and Smith 1981). En effet, ces organismes passent la majorité de leur vie immergés et effectuent de longues migrations pour compléter leur cycle vital, certaines espèces vont même occuper plusieurs habitats à travers divers écosystèmes (Forcada 2002). En plus de ces contraintes écologiques, l'étude des mammifères marins peut souvent se heurter à diverses subtilités politiques et légales étant donné le statut de plusieurs espèces protégées (Gulland and Hall 2007).

Malgré ces nombreuses limitations, il est néanmoins possible d'étudier les populations de mammifères marins en examinant les échouages d'individus retrouvés sur le littoral (Wilkinson and Worthy 1991, Byrd *et al.* 2008). De par sa logistique relativement simpliste et ses faibles coûts de mise en place (comparativement à des études comportant de la capture ou du marquage), l'étude des échouages représente un outil méthodologique efficace puisqu'il offre une opportunité unique d'acquérir des connaissances sur la biologie des mammifères marins (Odell 1987, Wilkinson and Worthy 1991, Geraci and Lounsbury 2005b). Un échouage est communément défini comme tout animal aquatique retrouvé sur le rivage vivant (en mauvaise santé) ou mort (Geraci and Lounsbury 2005b). On distingue deux catégories d'échouages : l'échouage en masse qui implique deux individus ou plus (excluant une mère et son petit) de la même espèce au même moment et au même endroit (Walsh *et al.* 2001, Geraci and Lounsbury 2005b), et l'échouage individuel. La fréquence des événements d'échouage et l'emplacement des individus retrouvés peuvent varier en fonction de la distribution (un individu ne peut s'échouer dans un environnement qu'il ne fréquente pas) et de la mortalité (à la suite d'une mortalité, l'individu dérive et est retrouvé échoué) des individus. Dans certains cas cependant, l'échouage peut représenter la cause de la mort lorsque les individus viennent frapper le littoral aux suites d'erreurs de navigation et d'écholocalisation (Dudok Van Heel 1962), de la rencontre de conditions topographiques complexes (Brabyn and McLean 1992) ou de la poursuite d'une proie près du rivage (Geraci and Lounsbury 2005b). Toutefois, ce phénomène serait surtout observé chez les odontocètes et plus particulièrement chez la famille des delphinidés, où les individus très grégaires peuvent parfois venir s'échouer et mourir en grand nombre (Walsh *et al.* 2001, Geraci and Lounsbury 2005a). Ainsi, pour la majorité des espèces de mammifères marins, l'échouage survient à la suite de la mortalité et représente donc un outil important pour l'étude de la mortalité individuelle (Wilkinson and Worthy 1991, Geraci and Lounsbury

2005b). En étudiant par exemple la distribution spatiale des échouages, la variabilité temporelle, les causes de mortalités individuelles à l'aide de nécropsies, ou encore les liens qui rallient les événements d'échouages à des phénomènes environnementaux et anthropiques, il est notamment possible de mieux comprendre les facteurs critiques qui peuvent affecter la démographie et la dynamique des populations de mammifères marins (McLellan *et al.* 2002, Silva and Sequeira 2003, Evans *et al.* 2005).

2. DISTRIBUTION DES MAMMIFÈRES MARINS

Au sein des mammifères marins existe une grande diversité d'origine évolutive, qui influence la biologie et l'écologie des espèces. On distingue deux grands ordres : les cétacés et les carnivores (sous-ordre pinnipèdes), eux-mêmes subdivisés en sous-ordre mysticète (baleine à fanons) et odontocète (baleine à dents), et en familles phocidé (phoque) et otariidé (otarie), respectivement. De ces différences d'origine évolutive ont émergé des adaptations morphologiques, physiologiques et comportementales qui distinguent les espèces dans les modes de locomotion, les types d'habitats fréquentés, les types d'alimentation et modes d'approvisionnement (certaines espèces sont spécialistes comme le rorqual bleu et d'autres sont généralistes comme le petit rorqual), les stratégies de reproduction (certaines espèces ont un jeune à chaque quatre ans comme la baleine franche alors que d'autres ont un jeune annuellement comme les pinnipèdes), la thermorégulation, la grégarité (certaines espèces sont solitaires comme le petit rorqual et certaines sont grégaires comme le béluga), etc. (Würsig 2002).

À leur tour, ces différences influencent directement la sélection de l'habitat et la distribution des individus au sein des populations. À titre d'exemple, chez certains pinnipèdes pagophiliques (phoque du Groendland, phoque à capuchon et phoque annelé), le substrat de glace représente une composante essentielle de l'habitat, particulièrement lors de la période de mise bas ou de la mue, et influence ainsi la distribution des organismes dans le milieu marin (Bartholomew 1970, Boyd 1998, Kelly 2001b, Laidre *et al.* 2008). Pour les cétacés cependant, la présence de glace dans l'habitat peut représenter une contrainte plutôt qu'une ressource, pouvant même agir comme une barrière limitant l'accès des individus à un autre habitat (Bowen and Siniff 1999). Par exemple, un couvert de glace extensif et persistant dans l'aire d'alimentation de la baleine grise, en mers de Bering et Chukchi, fut associé à une diminution du recrutement et à une augmentation de la mortalité dans cette population (Le Boeuf *et al.* 2000, Perryman *et al.* 2002).

En plus des différences écologiques et biologiques intrinsèques à l'espèce, les facteurs environnementaux (*p. ex.* la température de l'eau), écologiques (*p. ex.* compétition inter et intraspécifique), démographiques (*p. ex.* la taille de la population, l'âge, le sexe et le statut reproducteur) et anthropiques (*p. ex.* trafic maritime) exercent une influence significative sur la distribution des populations de mammifères marins (Bowen and Siniff 1999, Forcada 2002). Parmi les facteurs environnementaux, on distingue les composantes biotiques (*p. ex.* abondance des ressources, présence de prédateurs) des composantes abiotiques (*p. ex.* la température de la couche de surface, l'étendue du couvert de glace, etc.) (Begond *et al.* 2006). En plus d'influencer de manière directe la distribution spatio-temporelle des mammifères marins (*p. ex.* tolérance physiologique à des degrés de températures ou des salinités particulières (Gaskin 1968, Fullard *et al.* 2000, Elwen and Best 2004). Les composantes abiotiques affectent la distribution par des répercussions indirectes influençant à priori les composantes biotiques, dont la disponibilité des ressources alimentaires (Selzer and Payne 1988, Jaquet and Whitehead 1996, Baugmgartner *et al.* 2003, Friendlaender *et al.* 2006, Bluhm and Gradinger 2008). Cette dernière interaction est particulièrement importante puisque la disponibilité des ressources alimentaires est l'un des paramètres exerçant le plus d'influence sur la distribution des mammifères marins (Harwood 2001, Forcada 2002). En effet, en milieu marin, les ressources alimentaires, particulièrement celles qui sont pélagiques, sont distribuées de manière très hétérogène à travers le temps et l'espace (Mackas and Boyd 1979) et cette distribution est principalement modulée par la dynamique des processus océanographiques physiques tels que les phénomènes de front thermiques, de ruptures de pente topographique et de convergences (Olson and Backus

1985, Ballance 2002, Genin 2004). Une rupture de pente, par exemple, peut conduire à une résurgence marine et conséquemment à de grandes agrégations d'organismes suivant la montée d'eau froide riche en sels nutritifs qui favorisent le développement de floraisons phytoplanctoniques (Fiedler and Bernard 1987, Podestá *et al.* 1993, Griffin 1999). De tels processus océanographiques conduisent donc à une forte productivité biologique locale (Walford 1958) et augmentent la disponibilité locale et la prédictibilité de la dispersion des proies pour les mammifères marins (Fiedler and Bernard 1987, Croll *et al.* 1998, Doniol-Valcroze *et al.* 2007). Lorsque ces phénomènes surviennent en milieux tempérés (*p. ex.* dans l'estuaire du Saint-Laurent (Cotté and Simard 2005), la disponibilité locale des proies peut fluctuer entre les saisons (influencée par les composantes abiotiques de l'écosystème) et, subséquemment, peut affecter la distribution des mammifères marins. Pour certaines espèces, l'hétérogénéité temporelle dans la distribution des ressources force les individus à effectuer de longues migrations entre ces aires d'alimentation et les aires de mise bas (Stern 2002). Pour les espèces résidentes d'un écosystème, les patrons de distribution seront tout aussi variables entre les saisons en fonction de la disponibilité des ressources, bien que moins remarquables que chez les espèces migratrices (Forcada 2002, Goetz *et al.* 2007). À titre d'exemple, le phoque commun de l'estuaire du Saint-Laurent quitte ses aires d'échoueries estivales lorsqu'une couverture de glace se consolide sur les baies de l'estuaire et entreprend une migration de 65 à 520 kilomètres vers des zones d'hivernage de faible couverture de glace ou d'eau libre pour s'alimenter (Lesage *et al.* 2004).

3. LES CAUSES DE MORTALITÉ DES MAMMIFÈRES MARINS

En conservation, la connaissance des composantes biodémographiques des populations animales est essentielle pour comprendre la dynamique des populations (Fowler and Smith 1981) et pour anticiper ses réponses aux changements des conditions environnementales (Proffitt *et al.* 2007). L'estimation des taux de mortalité des individus et la compréhension des facteurs sous-jacents influençant la survie sont l'une des plus importantes cibles des écologistes de la conservation. Chez la majorité des populations de grands mammifères, l'âge est l'un des principaux traits biodémographiques individuels pouvant influencer les taux de mortalité, où les taux sont typiquement plus importants chez les juvéniles et les individus âgés, et plus faibles chez les classes d'âge intermédiaires (courbe en « U » (Caughley 1966, Eberhardt 1981, Neal 2004)). Les mammifères marins suivent aussi cette tendance puisque la probabilité de survie des jeunes au cours de la première année est souvent très faible (de l'ordre de 50 % chez plusieurs espèces de pinnipèdes et de cétacés (Sumich and Harvey 1986, Barlow and Boveng 1991, Berta and Sumich 1999). Par ailleurs, chez la plupart des grands cétacés, les taux de mortalité des vieux individus sont en général mal compris comparativement aux juvéniles (Berta and Sumich 1999). Cette lacune est attribuable à la forte pression de la chasse commerciale historique qui, en décimant les effectifs, a profondément modifié la structure d'âge des populations qui, pour certaines, n'ont toujours pas recouvré leur état initial (Sumich and Harvey 1986, Reeves 1986, Berta and Sumich 1999).

3.1 Les causes de mortalité naturelle

Les causes de mortalité naturelle au sein des populations de mammifères sont nombreuses et diffèrent en fonction de la classe d'âge. Si les jeunes sont principalement affectés par l'inanition et la prédation, les individus plus âgés y sont souvent moins vulnérables et vont davantage mourir à la suite de maladies ou de parasitisme (Burton 1973, Evans 1987, Berta and Sumich 1999). Toutefois, ces causes de mortalité naturelle (écologiques) agissent souvent de manière synergique (Henry 2001). Chez les jeunes pinnipèdes, la mort par inanition en raison d'une diminution de la disponibilité de nourriture dans l'aire d'alimentation des femelles est la cause de mortalité, à la naissance, la plus souvent mentionnée (Chambellant *et al.* 2003, Reid and Forcada 2005). La femelle, forcée à effectuer de longs déplacements entre les aires d'alimentation et l'aire d'allaitement, subit une augmentation des coûts liés à l'approvisionnement, réduisant ainsi l'apport nutritionnel pour le jeune qui doit accumuler les réserves lipidiques nécessaires à sa survie et sa croissance (Bryden 1968, Trillmich 1985, Beauplet *et al.* 2005, Reid and Forcada 2005). Les réserves lipidiques procurent une isolation thermique au froid (Bryden 1964) et des nutriments essentiels à la survie post-sevrage (Bryden 1968, Hindell *et al.* 1994). Cette période est particulièrement critique puisque le jeune sevré devra faire face à de nombreux défis, dont la prédation et l'apprentissage de la capture de proies (Hindell *et al.* 1999, Beauplet *et al.* 2005).

La prédation par des espèces terrestres, aviaires ou aquatiques est une source de mortalité naturelle importante pour les mammifères marins (Weller 2002). Les pinnipèdes sont probablement les mammifères marins les plus sujets à la prédation, et plus particulièrement chez les jeunes individus (Lavigne and Kovacs 1988, Berta and Sumich 1999, Weller 2002). À titre d'exemple, la prédation des jeunes phoques annelés par l'ours polaire peut comprendre de 8 à 44 % de la production annuelle de jeunes (Smith 1991). La prédation par l'orque épaulard peut aussi être une source non négligeable de mortalité pour les populations de cétacés (Lowry *et al.* 1987b, Jefferson *et al.* 1991, Pitman *et al.* 2001) .

La maladie est également une cause considérable de mortalité naturelle au sein des populations animales et peut aussi entrainer des épisodes de mortalité massive d'un grand nombre d'individus en cas d'épizootie. Historiquement, des épizooties de morbillivirus ont causé des mortalités massives chez plusieurs espèces de cétacés et de pinnipèdes, notamment des milliers de phoques communs (*Phoca vitulina*) et des centaines de phoques gris (*Halichoerus grypus*) dans la mer du Nord en 1988 (Osterhaus and Vedder 1988, Harwood and Grenfell 1990), des centaines de grands dauphins (*Tursiop truncatus*) sur la côte Atlantique des États-Unis entre 1987-1988 (Lipscomb *et al.* 1994, Duignan *et al.* 1996, Taubenberger *et al.* 1996), d'une dizaine de marsouins communs (*Phocoena phocoena*) sur la côte nord de l'Irlande en 1988 (Kennedy *et al.* 1988, Mc Cullough *et al.* 1991) et d'une centaine de dauphins bleu et blanc (*Stenella coeruleoalba*) le long de la côte espagnole (Raga *et al.* 2008). Les changements environnementaux (*p. ex.* la température de surface de l'eau et la disponibilité des proies) peuvent jouer un rôle prépondérant dans l'émergence et la virulence de certaines épidémies (Lavigne and Schmitz 1990, Van Bressem *et al.* 2009). Aussi, les espèces estuariennes et côtières auraient un risque supérieur de développer une maladie comparativement à celles qui vivent en milieu océanique en raison de l'altération de leur habitat par les facteurs anthropiques comme la contamination chimique (Taylor 2003, Gulland and Hall 2007, Van Bressem *et al.* 2009) et biologique (Measures and Olsen 1999). Par exemple, les bélugas de l'estuaire du Saint-Laurent retrouvés échoués comportent des taux élevés de concentration de plusieurs contaminants (*p. ex.* les BPCs, le DDT et le Mirex) susceptibles de causer une immunovulnérabilité et une baisse de la fertilité (Béland *et al.* 1993, Martineau *et al.* 1994, Lebeuf *et al.* 2007). Certains individus démontrent également des maladies chroniques comme des cancers gastro-intestinaux et mammaires (Martineau *et al.* 1994, Martineau *et al.* 2003, Measures 2008).

Le parasitisme conduit moins fréquemment à la mort d'un individu. Cependant dans des cas sévères, l'infection peut provoquer l'échouage et la mort (Geraci and St. Aubin 1986, Gulland *et al.* 1997, Measures 2008). Le parasitisme surgit souvent en simultanéité avec la malnutrition, les autres maladies, la contamination chimique et les conditions environnementales anormales. En effet, la contamination chimique ou la malnutrition affecte la réponse immunitaire de l'individu, réduisant ainsi sa capacité à résister à sa charge parasitaire, augmentant les risques d'infection parasitaire (Ross *et al.* 1996, Henry 2001).

En dehors des sources de mortalité écologiques, d'autres facteurs environnementaux peuvent avoir une influence importante sur la survie des individus. La présence et la dynamique des glaces sont un exemple de variable environnementale abiotique pouvant agir sur la survie d'un grand nombre d'espèces nordiques comme les phocidés pagophiles qui en dépendent pour leur reproduction (la mise bas), le repos et la mue (Kelly 2001b). Chez ces espèces par exemple, la survie du jeune durant les premières semaines de vie dépend de la disponibilité et la stabilité de cette ressource (Fay 1974, Bowen and Siniff 1999, Johnston *et al.* 2005). En effet, les animaux plus faibles ou âgés et les jeunes peuvent être directement écrasés par de la glace non consolidée en mouvement

(Lavigne and Kovacs 1988, Hammill *et al.* 1998). Contrairement aux pinnipèdes, la présence de glace peut représenter une source de mortalité pour les cétacés lorsque ces derniers s'y retrouvent emprisonnés après un épisode de formation accélérée de la banquise (Sergeant 1991, Johnston *et al.* 2005, Simmonds and Isaac 2007, Laidre *et al.* 2008). De plus, en modifiant le niveau d'exposition aux prédateurs (ours polaire sur le phoque annelé et le béluga) et en offrant des espaces de repos, le couvert de glace procure aussi d'autres avantages représentant un atout pour la survie (Lowry *et al.* 1987a, Kelly 2001a). Des anomalies promptes dans l'environnement peuvent également être cause de mortalité, parfois massive chez les mammifères marins (Harwood and Hall 1990, Clutton-Brock *et al.* 1991). Ces événements, s'ils entraînent la mort de plusieurs individus, peuvent être particulièrement marquants pour les populations de petite taille (Harwood 2002). Parmi les perturbations environnementales pouvant conduire à une mortalité massive de mammifères marins, notons les floraisons d'algues toxiques qui ont été documentées dans plusieurs épisodes de mortalité (Landsberg and Shumway 1998, Walsh *et al.* 2001, Landsberg 2002, Flewelling *et al.* 2005). À titre d'exemple, plus de 400 otaries de Californie (*Zalophus californianus*) sont mortes entre mai et juin 1998 à la suite d'une floraison d'une diatomée toxique (*Pseudo-nitzschia australi)* dans la baie de Monterey. Cette floraison fut associée à la production de l'acide domoïque, une neurotoxine, détectée dans tout le réseau trophique, confirmant son transfert via l'alimentation et comme cause de mortalité des otaries (Scholin *et al.* 2000).

3.2 Les causes anthropiques de mortalité

En 1982, les pays membres de la Commission Baleinière Internationale ont décrété un moratoire sur la chasse commerciale à la baleine. Néanmoins, la chasse scientifique et de subsistance persistent pour certaines espèces (*p. ex.* 1000 petits rorquals de l'Atlantique Nord tués par la chasse scientifique de la Norvège, en 2006 (Reeves 2009)) et s'ajoutent à un nombre croissant d'activités humaines pouvant causer la mort (Gulland and Hall 2007).

Parmi ces activités, notons la pêche commerciale qui, non seulement entre en compétition avec les mammifères marins pour les ressources marines, mais est également responsable de prises accidentelles dans divers engins de pêche à travers le monde (De Master *et al.* 2001, Read *et al.* 2006). La mortalité associée à ce type d'activité est particulièrement importante pour les petits cétacés comme le marsouin commun (*p. ex.* quelques milliers de prises fatales annuellement en mer du Nord (Vinther and Larsen 2004). La collision avec les navires est aussi une source de mortalité, notamment pour les grands cétacés (Laist *et al.* 2001). De plus, avec l'augmentation croissante de la population humaine, on assiste à une augmentation de la pollution chimique (Vos *et al.* 2003) et sonore (Frantzis 1998, Cox *et al.* 2006, Nowacek *et al.* 2007), du dérangement ainsi que de la dégradation et la perte d'habitats (Taylor 2003) pour les mammifères marins. Ces facteurs anthropiques s'ajoutent également aux changements environnementaux (*p. ex.* augmentation de la température de l'air et de l'eau et diminution du couvert de glace) qui sévissent dans plusieurs écosystèmes nordiques (Proffitt *et al.* 2007, Simmonds and Isaac 2007), amplifiant les menaces auxquelles les populations de mammifères marins font face aujourd'hui.

4. LES MAMMIFÈRES MARINS DE L'ESTUAIRE ET DU GOLFE DU SAINT-LAURENT

Dans l'est du Canada, l'estuaire et le golfe du Saint-Laurent (Fig. 1) constituent deux systèmes voisins extrêmement complexes et dynamiques où un apport d'eau douce en provenance des Grands Lacs s'oppose à une entrée d'eau salée en provenance de l'océan Atlantique (White and Johns 1997). Le golfe du Saint-Laurent rejoint l'Atlantique Nord par les détroits de Cabot et Belle-Isle, où le chenal Esquiman achemine l'eau de la mer du Labrador vers le golfe pour former la couche intermédiaire froide et où le chenal laurentien conduit l'eau de l'océan Atlantique vers la tête de l'estuaire pour former la couche d'eau profonde (Therriault 1991). L'entrée d'eau salée et d'eau douce, la couverture de glace saisonnière et les échanges avec l'atmosphère donnent lieu à une circulation cyclonique et une stratification permanente dans l'estuaire et la partie ouest du golfe. Toutefois, les forts vents (orientés vers le large), les cassures bathymétriques et l'action tidale entraînent des remontées d'eau froide (riche en sels nutritifs) locales dans certaines régions (*p. ex.* à l'embouchure du Saguenay et la Minganie) de l'estuaire et du golfe du Saint-Laurent qui viennent rompre la stratification de la colonne d'eau au cours de la période estivale (White and Johns 1997). Ces régions de résurgences sont associées à une grande productivité biologique et supportent une grande diversité de mammifères marins en été (Kingsley and Reeves 1998, Simard and Lavoie 1999).

L'estuaire du Saint-Laurent est divisé en deux régions, l'estuaire maritime et l'estuaire moyen (El-Sabh and Silverberg 1990). Une rupture de pente à la hauteur du fjord du Saguenay marque la limite entre ces deux systèmes, où le chenal laurentien très profond de l'estuaire maritime rejoint l'estuaire moyen de faible bathymétrie. La zone de front entre l'eau douce du fjord et l'eau salée, combinée à la rupture de pente qui force la remontée de l'eau intermédiaire froide vers la surface, provoque une résurgence marine (El-Sabh and Silverberg 1990). Conséquemment à la remontée accrue des sels nutritifs, la productivité primaire de cette zone est si élevée (El-Sabh & Silverberg 1990) qu'elle donne lieu aux plus riches agrégations de krill du nord-est Atlantique (Cotté and Simard 2005, Sourisseau *et al.* 2006) et à l'importante concentration d'espèces de poissons comme le capelan (Marchand *et al.* 1999, Simard *et al.* 2002). Ce phénomène d'agrégation régional confère des opportunités d'alimentation particulièrement attrayantes et prévisibles pour les mammifères marins en été (Simard 2008), d'où sa grande importance écologique (Lesage *et al.* 2007) et sa protection par la formation en 1996 du Parc Marin Saguenay-Saint-Laurent.

Une quinzaine d'espèces de mammifères marins fréquentent régulièrement l'écosystème de l'estuaire et du golfe Saint-Laurent dont cinq espèces de mysticètes, sept espèces d'odontocètes et quatre espèces de pinnipèdes (Tableau 1). L'ensemble de ces espèces peut être divisé en deux catégories en raison de la saisonnalité dans leur utilisation de l'écosystème. On distingue les espèces résidentes (*p. ex.* le phoque commun et le béluga) des espèces migratrices (*p. ex.* le rorqual bleu, le rorqual à bosse, le phoque à capuchon et le phoque du Groenland). La grande concentration et diversité de mammifères marins retrouvés en été dans l'écosystème du Saint-Laurent est toutefois menacée par l'industrie écotouristique florissante (Lesage *et al.* 1999, Henry and Hammill 2001), l'industrie halieutique (Fontaine *et al.* 1994a, Lesage *et al.* 2006), le trafic maritime et la contamination chimique (Béland *et al.* 1992, Hobbs *et al.* 2003, Measures 2008).

Tableau 1. Espèces de mammifères marins communément rencontrées dans l'estuaire et le golfe du Saint-Laurent

Grands groupes	Familles	Espèces	Noms vernaculaires
Mysticètes	Balaenopteridae	*Balaenoptera musculus*	Rorqual bleu
		Balaenoptera physalus	Rorqual commun
		Balaenoptera acutorostrata	Petit rorqual
	Balaenidae	*Megaptera novaeangliae*	Rorqual à bosse
		Eubalaena glacialis	Baleine franche noire
Odontocètes	Monodontidae	*Delphinapterus leucas*	Béluga
	Physeteridae	*Physeter macrocephalus*	Cachalot
	Ziphiidae	*Hyperoodon ampullatus*	Baleine à bec commune
	Phocoenidae	*Phocoena phocoena*	Marsouin commun
	Delphinidae	*Globicephala melas*	Globicéphale noir
		Lagenorhynchus acutus	Dauphin à flancs blancs Atlantique
		Delphinus delphis	Dauphin commun
		Stenella coeruleoalba	Dauphin bleu et blanc
Pinnipèdes	Phocidae	*Phoca vitulina concolor*	Phoque commun
		Halichoerus grypus	Phoque gris
		Phoca groenlandica	Phoque du Groenland
		Cystophora cristata	Phoque à capuchon

5 PROBLÉMATIQUE, OBJECTIFS ET HYPOTHÈSES DE RECHERCHE

5.1 Problématique

L'estuaire et le golfe du Saint-Laurent accueillent chaque année un grand nombre d'espèces de pinnipèdes et de cétacés qui, pour la plupart, effectuent de grandes migrations pour venir s'alimenter dans ces eaux productives (Cotté and Simard 2005, Simard 2008). Le nord du golfe du Saint-Laurent a subi des changements profonds de sa structure trophique à la suite de l'effondrement des poissons de fond vers la fin des années 1980 (Savenkoff *et al.* 2004, Savenkoff *et al.* 2007, Morissette *et al.* 2009). De plus, en association possible avec les changements climatiques, des changements ont été notés dans l'épaisseur et l'étendue de la couverture de glace (déclin) et dans les moyennes de température (anomalies positives) (Galbraith *et al.* 2008). Toutefois, l'importance de ces facteurs environnementaux sur les populations de mammifères marins de l'estuaire et du golfe demeure énigmatique puisque les causes de mortalités sont très peu connues pour la majorité des espèces, hormis le béluga (Béland *et al.* 1987, Béland *et al.* 1992, Martineau *et al.* 2002, Measures 2008). De même, nous disposons de très peu de résultats de qualité concernant l'influence des diverses activités humaines sur les mammifères marins de l'estuaire du Saint-Laurent, à l'exception de quelques études concernant les prises accidentelles de marsouin commun (Fontaine *et al.* 1994a, Lesage *et al.* 2006) et la nuisance par le bruit (Blane and Jackson 1994, Michaud and Giard 1998, Lesage *et al.* 1999). Nous possédons une base de données sur les mentions d'individus échoués qui ont été systématiquement recueillies depuis 1994. En couvrant une période de plus de 15 ans, cette base de données peut nous permettre d'examiner les liens qui existent entre les événements d'échouages de diverses espèces et différents facteurs environnementaux et anthropiques provenant d'autres bases de données, pouvant ainsi nous renseigner sur les facteurs critiques influençant la mortalité individuelle. Jusqu'à maintenant dans l'estuaire, les données d'échouages de mammifères marins ont été principalement utilisées dans des études portant sur les taux de contamination (Béland *et al.* 1987, Lebeuf 2009) et l'état de santé des individus échoués (Béland *et al.* 1988, Béland *et al.* 1992), mais rarement en lien avec les changements environnementaux ou les activités anthropiques qui surviennent dans l'écosystème. Ainsi, il semble que ce type d'études cadre parfaitement dans une démarche scientifique visant i) une meilleure compréhension de l'écologie de la communauté de mammifères marins de l'estuaire et du golfe du St-Laurent et ii) l'identification des facteurs critiques pouvant être déterminants pour leur conservation.

5.2 Objectifs et hypothèses

Les objectifs généraux de ce projet sont 1) d'examiner la distribution spatiale des événements d'échouages et leur variation interannuelle et saisonnière, 2) de déterminer l'influence des facteurs environnementaux abiotiques (*c.-à-d.* température de surface de l'eau, volume de la couche intermédiaire froide, épaisseur et volume de la couverture de glace, débit d'eau douce et température de l'air) et biotiques[1] (*c.-à-d.* abondance de zooplancton et d'algue toxique) sur les variations interannuelles dans les événements d'échouages et 3) de quantifier l'impact des facteurs anthropiques (*c.-à-d.* prise accidentelle dans des engins de pêche, blessure sévère de causes anthropiques, blessure par balle d'une arme à feu, collision avec un navire et autres facteurs ne pouvant être classés dans une des catégories) sur les événements d'échouages.

Pour notre premier objectif de nature descriptive, nous n'avons défini aucune hypothèse.

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[1] À noter que la nature des facteurs biotiques testés se limite à l'abondance du krill dans l'estuaire et le golfe du Saint-Laurent puisqu'il représente le seul facteur pour lequel nous disposions d'une base de données pour notre aire d'étude. Aucune donnée n'est disponible, à ce jour, sur l'abondance du capelan, l'espèce clef de l'écosytème du nord-ouest du golfe du Saint-Laurent (Grégoire *et al.*, 2008).

Pour notre second objectif, nous avons posé deux différentes hypothèses en fonction de la nature des facteurs environnementaux considérés. Premièrement, nous posons l'hypothèse que la disponibilité des ressources alimentaires (le krill spécifiquement) influence la fréquence des événements d'échouages de mysticètes. En vertu de l'hétérogénéité spatiale et temporelle (interannuelle) dans la disponibilité du krill dans l'estuaire et le golfe du Saint-Laurent, nous prédisons une relation négative entre sa disponibilité et la fréquence des échouages de cétacés qui s'en nourrissent, où les années de raréfaction de krill correspondent aux années d'abondance des événements d'échouages de mysticètes. Deuxièmement, nous posons l'hypothèse que la nature des facteurs environnementaux qui influencent les événements d'échouages devrait varier en fonction de l'espèce considérée. Étant donné les différences importantes dans la biologie et l'écologie (*p. ex.* la sélection de l'habitat) des espèces à l'étude, nous prédisons i) que le couvert de glace devrait avoir une influence négative et positive sur la fréquence des échouages observés chez les pinnipèdes pagophiles et les cétacés, respectivement, ii) que le débit d'eau douce et l'abondance des algues toxiques devraient avoir une influence positive sur la fréquence des échouages des espèces résidentes (béluga et phoque commun) et iii) que la température de surface de l'eau devrait avoir une influence positive sur les échouages des phocidés pagophiles.

Pour notre troisième objectif, nous posons l'hypothèse que la fréquence des événements d'échouages est influencée par l'intensité des activités anthropiques (*p. ex.* halieutique, transport maritime). À la suite de la mise en place du Parc Marin Saguenay-Saint-Laurent (1998) et du Réseau québécois d'urgence pour les mammifères marins (2003), nous prédisons que l'occurrence des événements d'échouages avec évidence d'interactions anthropiques diminue dans le temps en réponse à la diminution des interactions avec les mammifères marins.

Le mémoire est divisé en deux principaux chapitres, chacun constituant un ouvrage destiné à la publication, ce qui donne lieu à l'utilisation de la langue anglaise et à une certaine répétition de l'information. Le premier de ceux-ci décrit quantitativement et qualitativement les tendances temporelles et spatiales du nombre d'échouages dans l'estuaire et le golfe du Saint-Laurent. Ces patrons sont examinés relativement à des variables environnementales. Le second chapitre se penche sur une description des variations temporelles des échouages pour lesquels il y a évidences d'interactions humaines (*c.-à-d.* prise accidentelle, arme à feu, collision avec des navires, blessures importantes et autres). Le mémoire se termine par une conclusion générale en français énonçant les points saillants de ces deux chapitres.

CHAPITRE 1

INFLUENCE DES CHANGEMENTS ENVIRONNEMENTAUX SUR LES ÉCHOUAGES DE MAMMIFÈRES MARINS D'UN ÉCOSYSTÈME ESTUARIEN

1.1 RÉSUMÉ EN FRANÇAIS DU PREMIER ARTICLE

Les échouages de mammifères marins sont observés le long de toutes les côtes du monde, cependant, nous en connaissons peu sur les facteurs qui influencent la fréquence de ce phénomène biologique. Comprendre ces mécanismes est particulièrement crucial pour la conservation des mammifères marins, puisque les observations d'échouage représentent un indice de la fréquence de la mortalité. Afin de mieux saisir les mécanismes environnementaux induisant les variations temporelles des échouages de mammifères marins, nous avons examiné des mentions d'échouages annuelles de l'écosystème du Saint-Laurent au Canada, une aire estivale importante pour plusieurs espèces de mammifères marins, et nous leur avons traité en perspective de relevés annuels de divers paramètres environnementaux biotiques et abiotiques récoltés dans la même région, pour la période de 1994-2008. Nos données montrent une augmentation significative de la fréquence des échouages à travers les années, avec un fort patron saisonnier (les organismes sont principalement trouvés échoués durant l'été). Les conditions de l'eau (*c.-à-d.*. le volume de la couche intermédiaire froide, débit d'eau douce et la température de surface) sont négativement corrélés à la fréquence des événements d'échouage de toutes les espèces (à l'exception des espèces pagophiliques pour lesquelles la relation est positive), alors que l'influence des autres facteurs est propre à l'espèce. Le volume de glace est négativement corrélé aux événements d'échouages de phocidés pagophiliques et de mysticètes, respectivement. L'abondance de krill est négativement corrélée à la fréquence des échouages de mysticètes (petit rorqual) et de marsouins communs. La température de

surface de l'eau est négativement et positivement corrélée à la fréquence des échouages de cétacés (incluant le phoque commun) et de phoques pagophiliques, respectivement. De plus, nos données suggèrent que la floraison d'algue toxique *Alexandrium tamarense* observée en août 2008 a probablement causé un nombre inhabituellement élevé d'événements d'échouage de béluga, de marsouin commun, de phoque commun et de phoque gris. Globalement, cette étude empirique souligne l'importance des relations partagées par les échouages de mammifères marins avec les variations interannuelles des facteurs environnementaux de l'écosystème du Saint-Laurent. Elle souligne également l'utilité des relevés d'échouage comme un indicateur biologique à long terme, fournissant des pistes sur les causes potentielles de mortalité des mammifères marins.

Ce premier article, intitulé *« Linking marine mammal strandings and environmental changes in an estuarine ecosystem»*, fut co-rédigé par moi-même ainsi que par la chercheuse Lena Measures et notre collaborateur Jean-Claude Brêthes. En tant que premier auteur, ma contribution à ce travail fut la récolte des données sur le terrain en 2008, la classification et la validation de la base de données, les analyses statistiques et la rédaction du mémoire. Lena Measures, la seconde auteure, a agi comme directrice de recherche en me guidant lors de la rédaction et la récolte de données. Jean-Claude Brêthes, le troisième auteur, m'a principalement aiguillée au cours du projet. Vincent L'Hérault, quatrième auteur, a contribué à la rédaction et Sylvie Lessard, la cinquième auteure, a fourni la base de données des algues toxiques, issue du programme de surveillance de Michel Starr à l'Institut Maurice-Lamontagne. Les données d'échouage à long terme ont été fournies par l'Institut Maurice-Lamontagne (1994-2002) et par le Réseau québécois d'urgence pour les mammifères marins (2003-2008). L'effort de terrain a été réalisé par plusieurs intervenants œuvrant au sein du Réseau québécois d'urgence pour les mammifères marins (RQUMM) : Station de recherche des Îles Mingan, Réseau d'observation des mammifères marins (ROMM), Centre québécois pour la santé des animaux sauvages (CQSAS), Institut national d'écotoxicologie du Saint-Laurent (INESL), Fondation Québec-Labrador, Amphibia Nature, Centre d'éducation et de recherche de Sept-Îles (CERSI), Exploramer et Zoo sauvage de Saint-Félicien. Une version abrégée des résultats de cet article a été présentée lors de la rencontre annuelle de la *Society for Marine Mammalogy* en 2009.

1.2 LINKING MARINE MAMMAL STRANDINGS AND ENVIRONMENTAL CHANGES IN AN ESTUARINE ECOSYSTEM

MARIE-HÉLÈNE TRUCHON†, MESURES, L.* BRÊTHES, J-C.†, L'HÉRAULT, V.‡, AND LESSARD S.*

*Institut Maurice-Lamontagne, Pêches et Océans Canada, 850 route de la Mer, Mont-Joli, Qc, Canada, G5H 3Z4, email marie-helene.truchon@uqar.qc.ca

†Institut des Sciences de la Mer, Université du Québec, 310 allée des Ursulines, Rimouski, Qc, Canada, G5L 3A1, Canada

‡ Département de Biologie, chimie et géographie, Université du Québec à Rimouski, Qc, Canada, G5L 3A1

Abstract

Marine mammal stranding events are reported all along the coasts of the world, yet very little is known about the factors which impact the occurrence of this biological phenomenon. Understanding these mechanisms is particularly crucial for marine mammal conservation as stranding observation represents a proxy for mortality occurrence. To better understand which environmental mechanisms generate variation in marine mammal strandings, we examined annual stranding records in Canada's St. Lawrence ecosystem, a major feeding ground for various marine mammals, and compared stranding rates with annual records of biotic and abiotic environmental parameters collected in the same area, for the 1994-2008 period. Our data showed a significant increase in the occurrence of strandings over time, and a strong seasonal pattern (organism were mostly found stranded during summer).Water conditions (*i.e.* volume of the cold intermediate layer, freshwater runoff and sea surface temperature) was negatively correlated to the occurrence of stranding events in all species (except pagophilic species for which the relation was positive), while influence of other factors was species-specific. Ice volume was negatively correlated to stranding events in pagophilic phocids and mysticetes, respectively. Krill abundance was negatively correlated to the occurrence of strandings in mysticetes and harbour porpoise. Sea surface temperature was negatively correlated to the occurrence of strandings in a few cetacean species, while it was positively correlated with pagophilic phocid strandings. Moreover, our data suggest that the toxic algal bloom of *Alexandrium tamarense* observed in August 2008 most likely caused an unusually high number of stranding events for beluga whale, harbour porpoise, harbour and grey seals. Overall, this empirical study highlights the important relationships marine mammals stranding events share with inter-annual variation of environmental factors in the St. Lawrence ecosystem. It also point out the importance of stranding records as a long-term biological indicator for potential mortality causes in marine mammal populations.

Key words: marine mammal mortality, environmental change, ice cover, harmful algal bloom, resource availability.

Introduction

Since recent years, there is a need to develop our understanding on how environmental changes may affect marine communities as many of them are threatened (Harwood 2001, Learmonth *et al.* 2006, Simmonds and Isaac 2007, Moore 2008). Marine mammals are species of particular interest from a conservation perspective as their high trophic level makes them most sensitive to perturbations in ecosystem and their charismatic status is commonly used to raise public awareness (Aguirre and Tabor 2004, Morissette *et al.* 2006, Moore 2008). Although numerous studies and dedicated conservation efforts were put forth, the ecology of marine mammals remains poorly understood as their marine and non-sedentary lifestyles, long generation times and protected status make them particularly difficult to study (Gulland and Hall 2007).

Stranding event records represent a long-term biological indicator that provides insights on the environmental factors influencing demographic processes in marine mammal populations, as well as their vulnerability to human-induced changes in their environment (Perrin and Geraci 2002, Byrd *et al.* 2008) (Bradshaw *et al.* 2006). For example, stranding observation networks play a major role in the detection of unusual mortality events (Wilkinson and Worthy 1991, Malakoff 2001). Stranding events are unpredictable, and depend on many factors which affect individual mortality (*e.g.*, human incidence, disease, intoxication, environmental conditions; (Geraci *et al.* 1989, Lipscomb *et al.* 1994, Fertl and Leatherwood 1997, Laist *et al.* 2001, Taylor 2003, Vos *et al.* 2003, Mac Leod *et al.* 2005)) and/or distribution of species (Leeney *et al.* 2008). Recently, some studies linked inter-annual variability in stranding events to changes in climate and thus highlighted the utility of stranding events to investigate the influence of environmental changes on marine mammal populations (Evans *et al.* 2005, Hart *et al.* 2006).

Marine mammal stranding reports were systematically recorded along the shores of the St. Lawrence ecosystem from 1994 to 2008. Recent changes reported in environmental conditions and in marine community structure (*i.e.*, more years with low ice conditions, changes in zooplankton composition and abundance) (Starr *et al.* 2002, Savenkoff *et al.* 2007, Harvey and Devine 2008, Galbraith *et al.* 2008) might have influenced marine mammal populations of the St. Lawrence ecosystem. Hence, analyzing the interaction between marine mammal stranding events and environmental parameters recorded in the St. Lawrence ecosystem might help better understand the critical oceanographic mechanisms impacting populations of these predators.

The objective of the present study was to investigate the existence of temporal variation in marine mammal stranding events with respect to changes reported in biotic and abiotic conditions in the Estuary and the northwestern Gulf of St. Lawrence for the 1994–2008 period. We hypothesized that the nature and direction of the environmental factors influencing marine mammal stranding events would vary among species. According to differences found in species' ecological and biological characteristics (*i.e.*, differences in sedentary vs nomadic distribution), we predict that i) water condition (cold intermediate layer volume, freshwater runoff and sea surface temperature) will negatively influence stranding events in all marine mammal species, ii) ice cover will negatively and positively influence pagophilic seal and cetacean stranding events, respectively and iii) krill abundance will negatively influence mysticete stranding events. These predictions follow the logic that these environmental parameters are mostly influencing marine mammal individual mortality (*e.g.*, in a good year of resource abundance, mortality per capita should be lower) rather than species distribution which might influence the occurrence of total mortality (*e.g.*, in a good year of resource abundance, more individuals may distribute themselves in the study area which might lead to a higher number of strandings).

Methods

Study area

Areas where stranded marine mammals were documented include the northwestern shore of the Gulf of St. Lawrence (GSL) and the St. Lawrence Estuary (SLE), Quebec, Canada (Northwest Atlantic Fisheries Organisation Divisions 4S and 4T) (Fig. 2.1). The SLE and the GSL are two complex and dynamic systems that receive great quantities of salt and fresh waters (White and Johns 1997). The SLE is characterised by a sill at the mouth of the Saguenay River that separates its upper and lower sections (El-Sabh and Silverberg 1990). This sill causes an important tidal upwelling of cold, saline and mineral-rich water associated with one of the richest krill aggregations of the North Atlantic (Cotté and Simard 2005) and high aggregations of fishes such as capelin (Marchand *et al.* 1999, Simard *et al.* 2002). The GSL is a semi-enclosed sea with a bathymetry dominated by the Laurentian Channel. The Esquiman and Laurentian Channels allow deep Atlantic waters into the Gulf through Cabot Strait and the Strait of Belle Isle. The combination of these inflows, tides, with atmosphere circulation and exchanges, seasonal ice cover and freshwater runoff result in an anti-cyclonic circulation with a wind-driven upwelling along the north shore (Therriault 1991). Persistent high density aggregations of krill make the SLE and the northwestern GSL important feeding grounds for a variety of marine mammal species in summer (Kingsley and Reeves 1998, Sourisseau *et al.* 2006, Simard 2008).

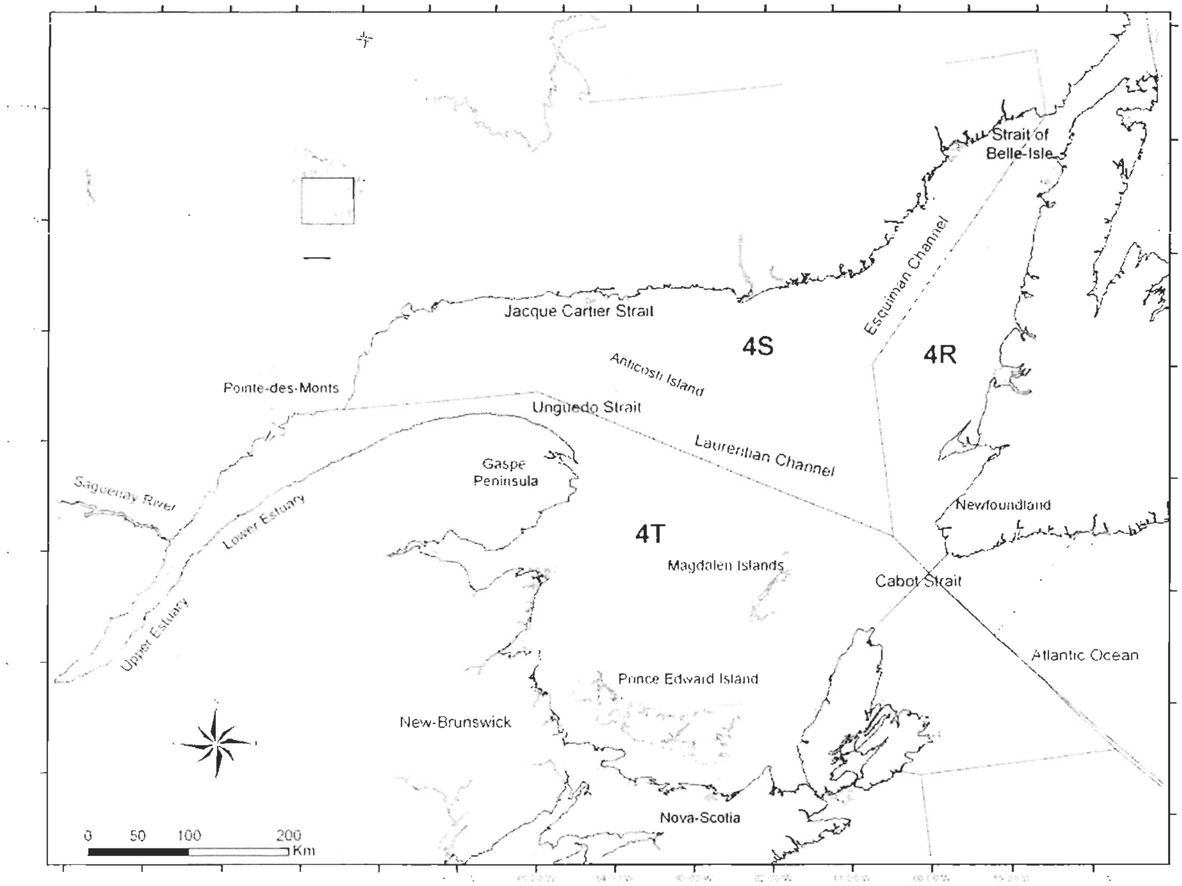

Figure 2.1 The study area covering the Estuary and the Gulf of St. Lawrence.

Data collection

Information on marine mammal strandings originated from phone calls made by the public, police, conservation officers, non-governmental organizations, municipal and provincial institutions. As a result, we could not control for variation in stranding sampling effort over the time period. Nevertheless, advertisements were done consistently over the years to make citizens aware of the network. From 1994 to 2002, stranding data were collected by Fisheries and Oceans Canada (DFO) at the Maurice Lamontagne Institute

(MLI, Mont-Joli, Qc, Canada). Beginning in 2003, stranding data were collected by RQUMM (Réseau québécois d'urgences pour les mammifères marins), a marine mammal response network co-ordinated by the non-governmental organization GREMM (Groupe de recherche et d'éducation sur les mammifères marins). We systematically examined stranding records, from these two databases. In this study, a stranding record corresponds to when a marine mammal comes ashore sick, weak or dead. A mass stranding event involves at least two animals ashore at the same place and time, except for cases involving a female and its young (Geraci and Lounsbury 2005a). Stranding events (either single or mass strandings), regardless of the number of animals in each event, were used as the sampling unit for analyses. Mass strandings were examined separately. Drifting carcasses and strandings suspected to have involved a human activity were excluded to minimize biases and over-estimation of events.

Analyses of stranding data included only those cases where identification of marine mammals was confirmed (pictures and/or a reliable observer). Thus, ambiguous cases of species identification were classified as "seal spp." or "cetacean spp." and were excluded from single-species analyses. Equivocal reports of stranding events were removed from subsequent analyses. Seasons were defined as Spring (Sp) - March to May, Summer (S) - June to August, Fall (F) - September to November and Winter (W) - December to February.

Environmental data were obtained from various monitoring programs of the DFO (MLI). Data included abundance of toxic algae (Michel Starr and Sylvie Lessard, unpublished data), krill abundance and biomass (Michel Harvey, unpublished data), sea surface temperature (SST), air temperature, freshwater runoff, volume and minimum temperature of the cold intermediate layer (CIL) and volume and extent of sea ice cover (Galbraith *et al.* 2008).

Abundance of toxic algae was recorded at eleven coastal stations where phytoplankton samples were taken every week from mid May to late October. Seven species, that have potential toxic effects, were considered: *Alexandrium* spp., *Dinophysis spp., Gymnodinium mikimotoi, Prorocentrum lima, Prorocentrum minimum, Pseudo-*

nitzschia pseudodelicatissima and *Pseudo-nitzschia seriata*. Krill abundance included three species (*Meganyctiphanes norvegica*, *Thysanoessa raschii* and *Thysanoessa inermis*) and was collected at four fixed stations (Anticosti Gyre, Rimouski, Gaspé Current and Shediac Valley) in mid-June and late fall (late October and early November). Zooplankton collections and standard measurements are outlined in Mitchell *et al.* (2002).

We chose dynamic abiotic variables (*i.e.,* sea surface temperature and ice volume) rather than static abiotic variables (*i.e.,* bottom topography) given that dynamic variables are known to have a stronger influence on habitat selection and spatial distribution of marine mammals in this and other regions (Friendlaender *et al.* 2006, Doniol-Valcroze *et al.* 2007, Skov *et al.* 2008). Dynamic oceanographic variables affect the abundance and aggregation of some marine mammal preys (Simard *et al.* 2002, Redfern *et al.* 2006, Simard *et al.* 2008) and thus may be a good predictor of marine mammal distribution (Doniol-Valcroze *et al.* 2007). Similarly, the presence of high zooplankton aggregations have been documented in the Estuary and NWGSL and are known to be associated with large whale distributions in other areas (Croll *et al.* 1998) and likely in the St. Lawrence as well (Simard and Lavoie 1999, Cotté and Simard 2005, Sourisseau *et al.* 2006). Abundance of toxic algae was, moreover, included as a variable that may cause mortality in marine mammal populations (Geraci *et al.* 1989, Flewelling *et al.* 2005, Doucette *et al.* 2006). In the Estuary, the development of harmful algal blooms (HABs) are promoted by freshwater runoff (Weise *et al.* 2002, Fauchot *et al.* 2005) which may also be an important factor acting on the distribution of beluga whale (Vladykov 1944, Goetz *et al.* 2007). Subsequently, we also incorporated freshwater runoff data in our modelling.

Data analyses

Species were selected for analyses using a minimal threshold of $n > 10$ stranding events for statistical reasons. At first, to detect differences between years and seasons in the species composition of the entire database, we used permutations with PERMANOVA v.1 (Anderson 2001a). Correct P-values were obtained through Monte Carlo random draws for the asymptotic permutation distribution (Anderson and Robinson 2003). Then, ANOVAs were performed to detect differences in the occurrence of strandings between years and seasons for each species. These analyses were followed by post-hoc t-tests for single factors (*i.e.* years and seasons). Although our data do not represent a sampling of a whole population and therefore we do not have replication of samples and thus variance, we used ANOVAs to test temporal variability of stranding occurrence. We believe that the use of ANOVA is acceptable because the parametric test of ANOVA is more severe to observed significant tendencies compared to simple observations of stranding occurrence by year and season. Kruskall-Wallis tests were used when large inter-annual differences existed in sample sizes and variance precluded use of parametric ANOVA as well as mathematic transformations (Zar 1999). As stranding events are sporadic and unpredictable, we assumed independence between years and seasons.

Linear regression models were performed to determine associations between temporal changes of stranding and those of biotic and abiotic variables for each species, from 1994-2007. The year 2008 was not considered because we already identified the cause of the unusual high number of stranding events during this year. This high in 2008 may influence models obtained as an outlier, thus precluding the observation of annual tendencies from 1994-2007. In model selection, a theoretical information approach is recommended over stepwise significance testing because it usually yields better models and leads to a clearer understanding of predictor variables (Greaves *et al.* 2006). Thus, variables with ecologically significance or influence were initially selected (Anderson et al. 2000). Akaike's Information Criterion (AIC) was used to select the most parsimonious model based on the lowest value and those with differences of < 2 AIC units were considered well supported by data (Burnham and Anderson 2002). Model averaging was performed when models were relatively similar to obtain residuals of each variable selected by the most parsimonious model selected.

We have restricted our models to have no collinear variables by a Pearson's correlation coefficient > 0.6. To avoid problems in regression fitting caused by the strong correlation of ice cover with krill abundance (0.7) and CIL volume (0.6), we used the residuals of ice cover volume, indicating the deviation from the average of this variable (resICEV), as a predictor (Buisson *et al.* 2008). Thus, the seven predictors (air temperature, CIL volume, SST, freshwater runoff, resICEV, krill abundance and toxic algae abundance) chosen for analyses, were poorly correlated. Finally, the most parsimonious model was compared to a null model (*i.e.* without predictor variables) to evaluate the power of environmental variables selected by this model for each species. Logarithm transformations were applied to data when criteria of normality of distribution and homogeneity of variance were not met (Zar, 1999). ANOVAs and model selection analyses were performed using R v2.4 computer software (R Development Core 2009).

The locations of stranding events were recorded according to the closest city, town or village and were pooled by year into two groups, cetacean (small and large cetacean) and seals. Distribution maps, created using ArcMap 3.1 (ESRI, Redlands, CA, USA), were used to explore the spatial variation of stranding events and to identify potential geographic concentrations or "hotspots".

Results

From 1994 to 2008, 1193 stranding events were reported on the shores of the St. Lawrence, and included 549 cetaceans (405 odontocetes, 96 mysticetes and 48 cetacean spp.) and 644 pinnipeds (260 identified to species; Table 2.1). Cetacean stranding reports included 10 species of odontocetes and 5 species of mysticetes. Minke whales (*Balaenoptera acutorostrata*) (N=61) and beluga whales (*Delphinapterus leucas*) (N=205) were the most frequently reported mysticete and odontocete, respectively. Pinniped stranding reports included five species of phocids, where harbour seals (*Phoca vitulina*) (N=80) and grey seals (*Halichoerus grypus*) (N=80) were the most frequently reported. Stranding events mostly involved individual stranding, yet 22 mass stranding events were reported (*e.g.* mostly in the Magdalen Islands, where they represented 41% of reports). Mass strandings involved mostly harp seals (*Phoca groenlandica*) and Atlantic white-sided dolphins (*Lagenorhyncus acutus*). There was very few stranding observations concerning rare or less common species of the St. Lawrence Estuary (*i.e.*, pygmy sperm whale (*Kogia breviceps*), common (*Delphinus delphis*) and striped dolphins (*Stenella coeruleoalba*), northern bottlenose whales (*Hyperoodon ampullatus*), pilot whales (*Globicephala melas*), Sowerby's beaked whales (*Mesoplodon bidens*) and bearded seals (*Erignatus barbatus*) which precluded statistical investigations.

Distribution of stranding events

Stranding events generally occurred more frequently along the south shore of the St. Lawrence Estuary compared to the north shore (Fig. 2.2-2.3). Distribution patterns widely varied between the two groups (cetaceans and pinnipeds). While the majority of cetacean stranding events were reported near and opposite of the Saguenay fjord's mouth, in the lower St. Lawrence Estuary and on the islands shoreline, pinniped stranding reports came regularly from the upper Estuary and the St. Lawrence River.

Table 2.1 Species composition of marine mammal stranding reported (N = 1193) in the Estuary and the Gulf of St. Lawrence, Quebec, Canada, for the period 1994–2008.

Species	Years															Total
	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	
Mysticete																
Balaenoptera acutorostrata	1	2	4		4	5	6	9	6	2	7	1	6	5	3	61
Balaenoptera physalus	1	1		1	2	1	3	1	4	2	1	2	2	2	2	25
Balaenoptera musculus			1				1	1	1		1	1			1	7
Megaptera novaeangliae										1			1			2
Eubalaena glacialis								1								1
Subtotal	2	3	5	1	6	6	10	12	11	5	9	4	9	7	6	96
Odontocete																
Delphinapterus leucas	14	13	9	13	12	16	11	12	16	15	19	8	9	15	23	205
Phocoena phocoena	3	1		3	6	6	11	17	22	12	13	12	12	11	19	148
Lagenorhynchus acutus	3		1		1	6	3	1	5	1		1	2	7	2	33
Delphinus delphis												1	1			2
Stenella coeruleoalba															1	1
Globicephala melas				1					1				1	1	2	6
Hyperoodon ampullatus	2			1												3
Mesoplodon bidens													1			1
Physeter macrocephalus						1			1	1			1		1	5
Kogia breviceps								1								1
Subtotal	22	14	10	18	19	29	25	31	45	29	32	22	27	34	48	405
Cetacea sp.	1	2	2	2	5	5	8	5	2	2	2	5	3	2	2	48
Subtotal	25	19	17	21	30	40	43	48	58	36	43	31	39	43	56	549

Table 2.1 continued.

Species	Years															Total
	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	
Pinniped																
Phoca vitulina	2		1	5	1	6	5	6	10	7	8	6	6	3	14	80
Halichoerus grypus		1	3	3	2	3	3	1	7	4	1	6	5	3	38	80
Phoca groenlandica		2	2	2	2	4	4	5		4	1	2	3	2	2	35
Cystophora cristata	3		3	1		8	2	7	2			8	28		2	64
Erignathus barbatus															1	1
Seal spp.	8	11	33	14	8	17	11	21	22	18	18	13	84	34	72	384
subtotal	13	14	42	25	13	38	25	40	41	33	28	35	126	42	129	644
Total	38	33	59	46	43	78	68	88	99	69	71	66	165	85	185	1193

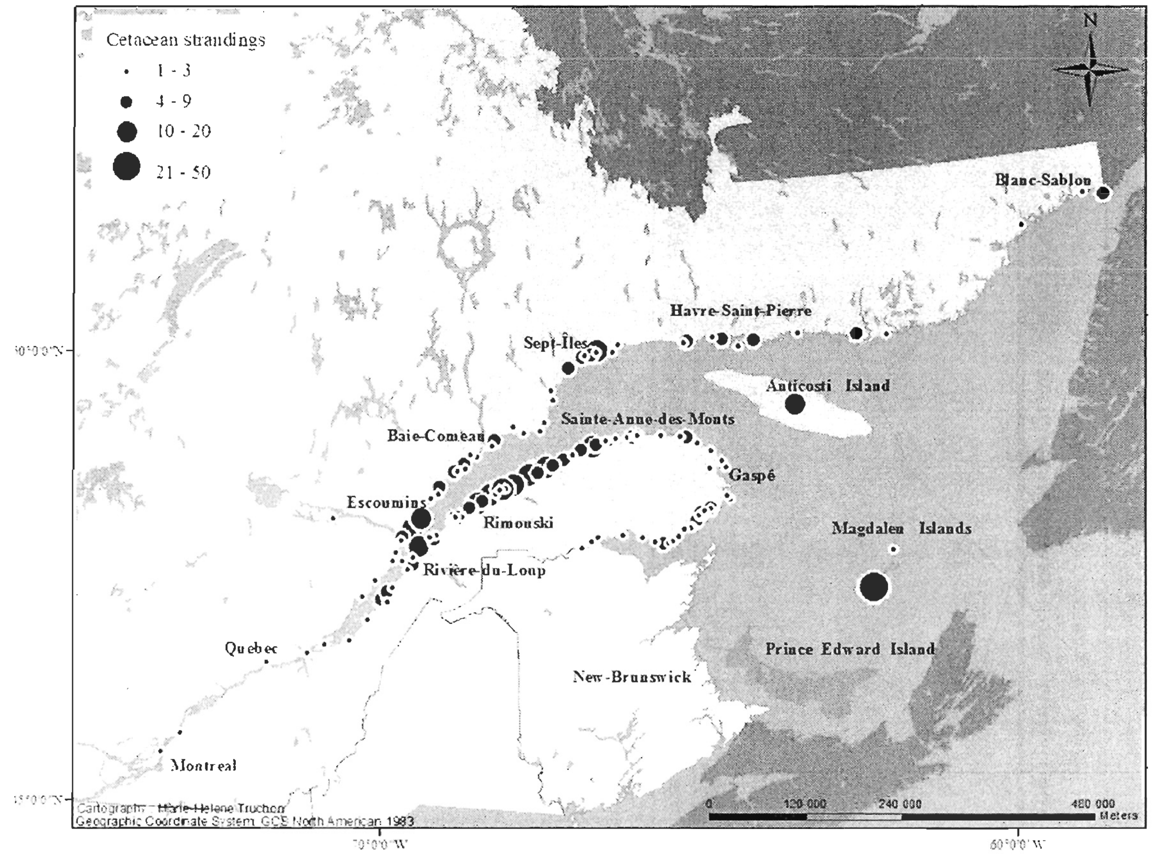

Figure 2.2 Distribution of cetacean's stranding events in the Estuary and the Gulf of St. Lawrence, Quebec, Canada, from 1994 to 2008.

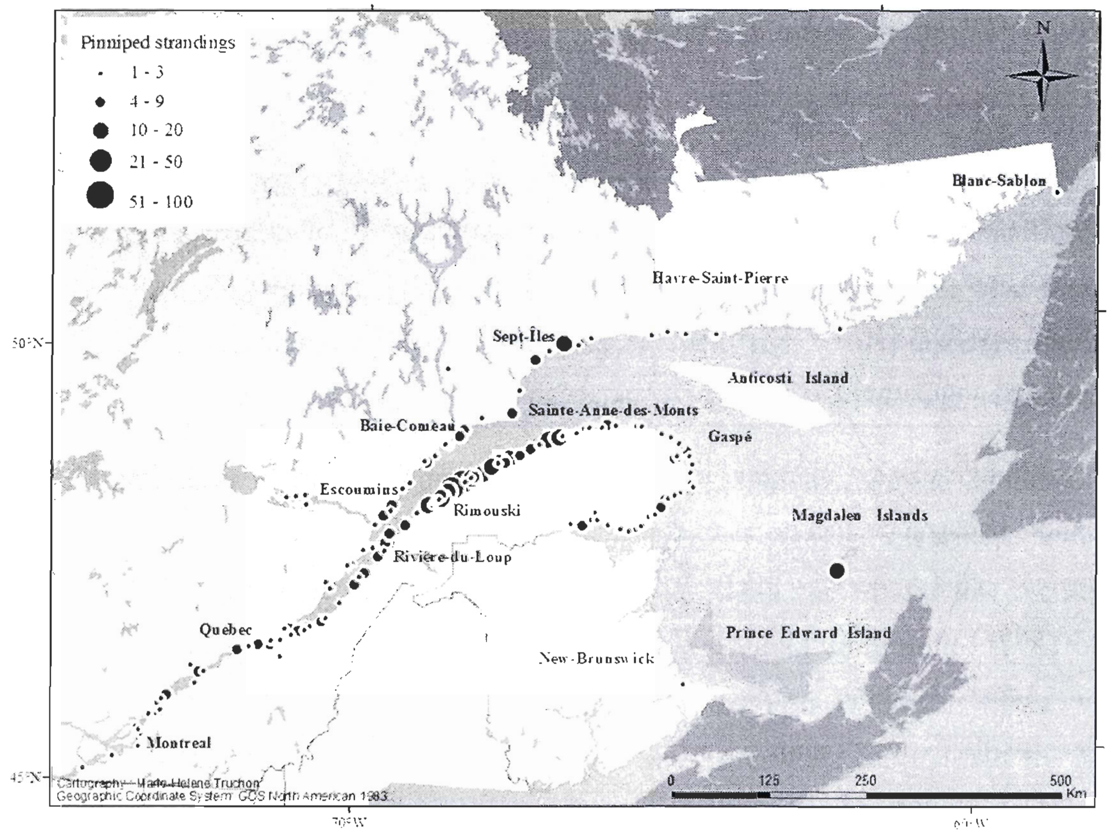

Figure 2.3 Distribution of seal stranding events in the Estuary and the Gulf of St. Lawrence, Quebec, Canada, from 1994 to 2008.

Temporal variability in stranding events

We investigated temporal variability in stranding patterns. Overall, stranding reports were significantly more frequent during summer compared to other seasons (Figure 2.4). This trend held for odontocete ($F_{3,179} = 56.74$, $p < 0.001$), pinniped ($F_{3,179} = 33,53$, $p < 0.001$) and mysticete ($chi^2 = 37.02$, df = 3, $p < 0.001$), while stranding numbers during the fall remained comparable to summer for cetaceans.

Although marine mammal stranding events seemed to follow cyclic patterns over years, their occurrence increased overall during the past 15 years ($R^2 = 0.59$, $p < 0.001$) (Figure 2.5). This trend was likely driven by the lows at the beginning of the time series (1994 to 1998) followed by highs at the mid-end (1999–2007) and the very end (2008) of the time series. Harbour porpoises most closely fit this trend where stranding events recorded for that species showed an upward shift in 2000, remained high afterward and finally peaked in 2008 ($R^2 = 0.50$, $p < 0.05$) (Figure 2.6a). Strandings of four other species (beluga whale, hooded seal, harbour seal and grey seal) remained consistently low over time but stately peaked at the end of the time serie (Figure 2.6b).

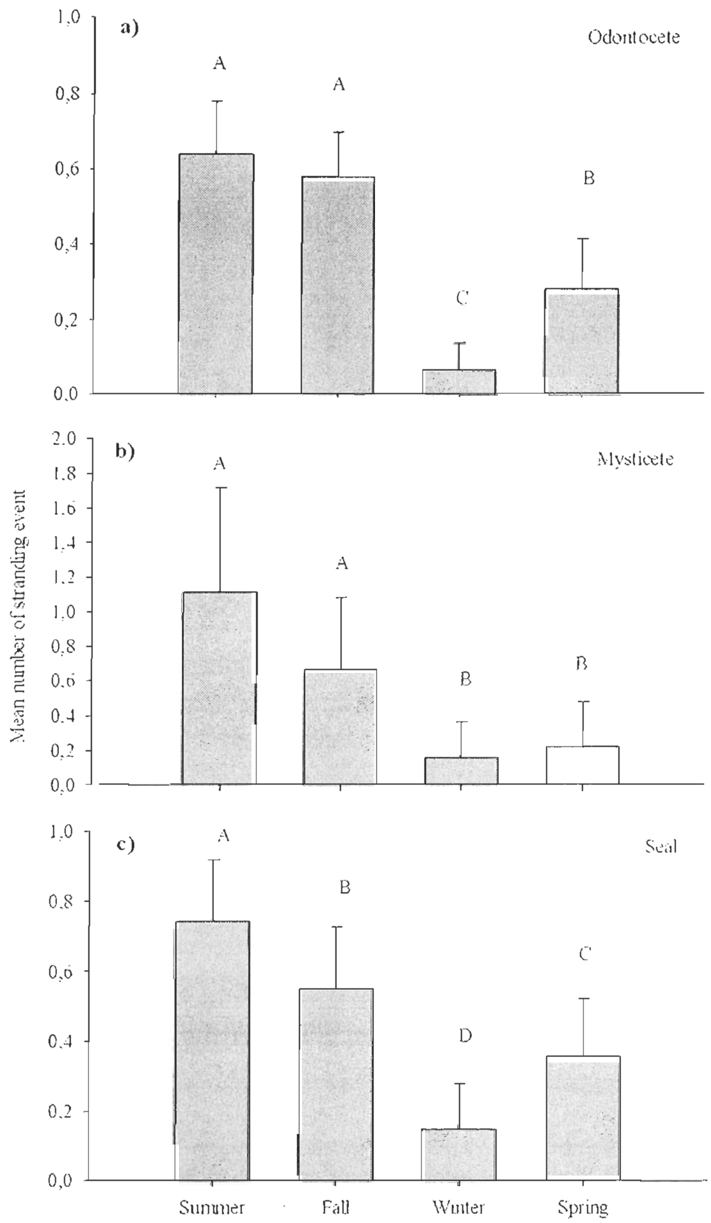

Figure 2.4 Seasonnal variability in mean number of marine mammal stranding events in the Estuary and the Gulf of St. Lawrence, Quebec, Canada, for the period 1994–2008: a) odontocetes, b) mysticetes, c) pinniped species. Letters indicate statistical groupings.

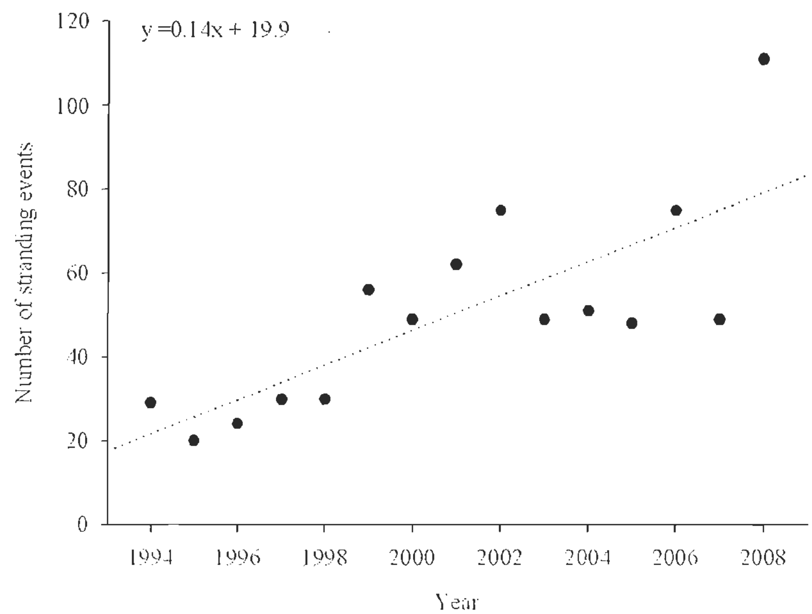

Figure 2.5 Inter-annual variation in marine mammal stranding events along shores of the Estuary and the Gulf of St. Lawrence, Quebec, Canada, over the period 1994–2008.

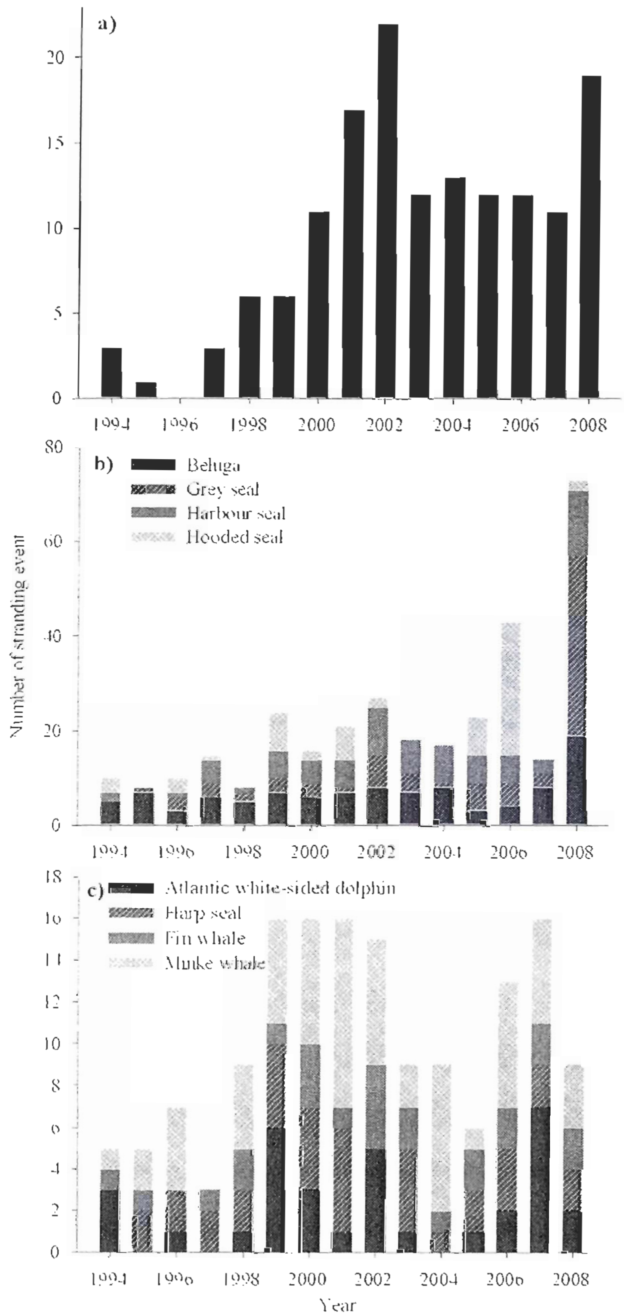

Figure 2.6 Inter-annual variation of stranding events: a) harbour porpoises, b) beluga whales in summer (black bars), grey seals (hatched bars), harbour seals (grey bars) and hooded seals (squared bars) and c) Atlantic white-sided dolphins (black bars), harp seals (hatched bars), fin whales (grey bars) and minke whales (squared bars) in the Estuary and the Gulf of St. Lawrence, Quebec, Canada, from 1994 to 2008.

The first peak in stranding events observed in 2006 was specifically related to a higher-than-usual (28 stranding events in 2006 compared to 4 stranding events per year from 1994–2008) number of reports for hooded seal juveniles (blueback) ($chi^2 = 27.07$, $p = 0.02$, Figure 2.6 b). The second and most major stranding event peak was observed in 2008 and apparently resulted from multi-species stranding reports that involved beluga whales ($R^2_{adj} = 0.28$, $F_{14,44} = 2.22$, $p = 0.03$), harbour porpoises ($R^2_{adj.} = 0.26$, $F_{14,44} = 2.10$, $p = 0.04$), harbour seals ($R^2_{aj} = 0.27$, $F_{14,44} = 2.19$, $p = 0.04$) and grey seals (Figure 2.6a and b). During this particular event, more than 65 marine mammals were found stranded (carcasses) on the south coast of the St. Lawrence Estuary within one month only (in August). Grey seals were particularly affected during this time span. For that species, the number of stranding events in August 2008 was 35 individuals, 122 times the 1994–2007's average for that month. Results from necropsies performed on dead marine mammal carcasses found stranded during August 2008 indicated that most animals were in good nutritional condition with no lesions attributable to any infectious, parasitic or other etiological agent (Stéphane Lair, University of Montréal, *pers. comm.*). However, high-performance liquid chromatography (HPLC) revealed the presence of paralytic shellfish poisoning toxins, attributable to *Alexandrium tamarense*, in marine mammals tissues (namely beluga whale, harbour porpoise, harbour seal and grey seal), and into flesh from various other animals including invertebrates and fishes species (Michael Quilliam, National Research Council of Canada, *unpubl.data*). These findings indicate that these unusual stranding events documented in August 2008 were apparently caused by a harmful algal bloom of *Alexandrium tamarense*. Marine mammal carcasses were found ashore after the bloom passed during its drift from Tadoussac to the south shore, to Rimouski and then towards the end of the Gaspé Peninsula. High concentrations of *A. tamarense* were confirmed by analysis of water samples (Michel Starr MLI, *unpubl. data*).

Finally, mysticetes, white-sided dolphins and harp seals did not follow previously mentioned patterns in their stranding events. While stranding events in minke whale followed a polynomial (inversed bell curve) trend, fin whale, white-sided dolphin and harp seal stranding events did not significantly vary over time (Figure 2.6c).

Influence of the environment on inter-annual stranding variation

Multiple linear regression models showed that inter-annual changes in environmental parameters significantly influenced the occurrence of marine mammal stranding events over the period 1994–2007 (*i.e.*, models significantly differed from the null models, $p < 0.05$) (Table 2.2). Explanatory power of models including several environmental parameters greatly varied according to the species considered (ranging from 12% to 80% for the best models, Table 2.3). In the particular case of harp seals, as the best model weakly explained individual stranding variation, we substituted individual stranding events with mass stranding events which involved several individuals at time. The explanatory power of our models then reached 62% and thus represented a more solid analysis. Species for which models had the best predictive power included hooded seals (80%), harbour porpoises (57%), harbour seals (47%), minke whales (47%) and fin whales (31%) (Table 2.3).

Table 2.2 Model selection results (Aikaike information criterion, AIC) from multiple linear regressions including environmental parameters as predictor of inter-annual variation in marine mammal stranding events in the Estuary and Gulf of St. Lawrence, Quebec, Canada, for the period 1994–2007. See legend below.

	Species	Models	AIC	ΔAIC
Resident species	*Phoca vitulina*	SST + FW + Vol 0	66.27	0
		SST + FW + Vol 0 + Krill a + resICEV	66.50	-0.23
		SST + FW + Vol 0 + resICEV	67.28	-1.01
		SST + FW + Vol 0 + resICEV	67.28	-1.01
		Tair + SST + FW + Vol 0 + krill a	67.43	-1.16
		SST + FW + Vol 0 + Krill a + TB + resICEV	67.55	-1.28
		Tair + SST + FW + Krill a	67.65	-1.38
		Tair + SST + FW + Vol 0	67.74	-1.47
		FW+ Vol 0 + Krill a + resICEV	68.06	-1.79
		SST + FW + Vol 0 + TB	68.07	-1.80
	Delphinapterus leucas	SST + FW	71.43	0
		FW	72.04	-0.61
		FW + Vol 0 + SST	72.54	-1.11
		SST + FW + TB	72.57	-1.14
		FW + Vol 0	72.80	-1.37
		Tair + FW	73.01	-1.58
		Tair + FW + TB	73.08	-1.65
		Tair + SST + FW	73.25	-1.82
		FW + TB	73.25	-1.82
		SST + FW + Vol 0 + TB	73.30	-1.87
Migrant species	*Phocoena phocoena*	SST + FW + Vol 0 + Krill a	85.38	0
		SST + FW + Vol 0 + Krill a + TB	85.42	-0.04
		SST + FW + Vol 0 + TB	85.78	-0.40
		FW + Krill a	85.94	-0.56
		SST + FW + Krill a	86.17	-0.79
		Tair + FW + Vol 0 + krill a + TB + resICEV	86.22	-0.84
		SST + FW + Vol 0	86.23	-0.85
		FW + Vol 0 + Krill a	86.44	-1.06
		Tair + FW + Vol 0 + Krill a + resICEV	86.56	-1.18
		Tair + SST + FW + Vol 0 + Krill a	86.84	-1.46
	Lagenorhynchus acutus	FW + Vol 0	6.58	0
		Vol 0	7.02	-0.44
		FW + resICEV + TB	7.58	-1.00
		FW + Vol 0 +TB	7.80	-1.22
		SST + FW + Vol 0	8.01	-1.43
		FW + Vol 0 + resICEV	8.33	-1.75
		FW + resICEV	8.38	-1.80
		SST + Vol 0	8.51	-1.93
		FW + Vol 0 + Krill a	8.52	-1.94
		Tair + FW + Vol 0	8.57	-1.99

Table 2.2 continued.

Migrant species	*Halichoerus grypus*	Vol 0	59.49	0
		Vol 0 + Krill a + resICEV	60.12	-0.63
		SST + Vol 0	60.14	-0.65
		Krill a + TB	60.16	-0.67
		Vol 0 + resICEV	60.18	-0.69
		Vol 0 + Krill a	60.21	-0.72
		Vol 0 + Krill a + TB	60.28	-0.79
		Vol 0 + TB	60.37	-0.88
		Krill a	60.57	-1.08
		SST + Vol 0 + TB	61.04	-1.55
	Balaenoptera acutorostrata	Tair + FW + Krill a + TB + resICEV	54.14	0.00
		Tair + FW + Vol 0 + Krill a + TB + resICEV	55.00	-0.86
		SST + FW + Krill a + TB + resICEV	55.27	-1.13
		FW + Krill a + TB + resICEV	55.51	-1.37
		Tair + SST + FW + Krill a+ TB + resICEV	55.67	-1.53
		Tair + Krill a + TB + resICEV	55.68	-1.54
	Balaenoptera physalus	SST + FW + TB + resICEV	40.68	0
		SST + Vol 0	41.01	-0.33
		Tair + FW + Vol 0 + TB	41.24	-0.56
		Vol 0	41.38	-0.70
		SST + FW + Vol 0	41.55	-0.87
		SST + FW + Vol 0 + TB + resICEV	42.12	-1.44
		Tair + FW + Vol 0	42.15	-1.47
		FW + Vol 0	42.22	-1.54
		Tair + SST + FW + Vol 0 + TB	42.23	-1.55
		FW + TB + resICEV	42.37	-1.69
Pagophilic species	*Cystophora cristata*	SST + FW + Vol 0 + TB + resICEV	2.08	0
		Tair + SST + Vol 0 + TB + resICEV	2.46	-0.38
		SST + FW + Vol 0 + Krill a + TB + resICEV	3.90	-1.82
	Phoca groenlandica mass strandings	Vol 0 + TB + resICEV	36.09	0
		FW + Vol 0 + TB + resICEV	36.77	-0.68
		SST + Vol 0 + TB + resICEV	37.32	-1.23
		Vol 0 + resICEV	37.5	-1.41
		Tair + FW + Vol 0 + TB + resICEV	37.53	-1.44
		Tair + Vol 0 + TB + resICEV	37.61	-1.52
		SST + FW + Vol 0 + TB + resICEV	37.77	-1.68
		Vol 0 + Krill a + TB + resICEV	38.06	-1.97

Variables	Abbreviations	Units
Air temperature	Tair	^oC
Sea surface temperature	SST	^oC
Cold intermediate layer volume at 0^oC	Vol 0	Km^3
Ice cover volume residuals	resICEV	Km^3
Freshwater runoff	FW	$10^3m^3s^{-1}$
Abundance of krill	Krill a	ind. m^{-3}
Abundance of toxic algae	TB	cell L^{-1}

Table 2.3 Multiple linear regression model coefficients for environmental parameters tested as predictors of inter-annual variation in marine mammal stranding events in the Estuary and Gulf of St. Lawrence. Quebec, Canada, for the 1994–2007 period.

	Resident species			Migrant species				Pagophilic species	
Variables	Pv	Dl	Pp	Log. La	Hg	Ba	Bp	Log. Cc	Pg
SST	-2.27 Δ	-2.19	-3.49				$-7.91e^{-01}$	$5.26e^{-01}$ **	
Tair						$2.91e^{-01}$			
Vol 0	$-6.787e^{-04}$*		$-8.71e^{-04}$	$-6.74e^{-05}$ Δ	$-4.90e^{-04}$*			$-2.08e^{-04}$***	$-2.78e^{-04}$**
resICEV						$-1.49e^{-10}$ *	$-7.20e^{-11}$ *	$-3.61e^{-11}$**	$-1.27e^{-10}$**
FW	-0.001*	-0.001*		$-1.17e^{-04}$		$-8.49e^{-04}$	$-5.38e^{-04}$*	$1.91e^{-04}$ **	
Log. Krill a			-7.07			-2.87 Δ			
Log.TB						3.15*	-1.17	$6.26e^{-01}$ **	$9.94e^{-01}$
Adjusted R^2	0.47	0.29	0.57	0.28	0.22	0.74	0.30	0.80	0.62

Δ $p < 0.1$ *$P < 0.05$ **$P < 0.01$ ***$p < 0.001$

Pv = *Phoca vitulina,* harbour seal
Dl = *Delphinapterus leucas*, beluga whale
Pp = *Phocoena phocoena*, harbour porpoise
La = *Lagenorhynchus acutus*, Atlantic white-sided dolphin
Hg = *Halichoerus grypus*, grey seal
Ba = *Balaenoptera acutorostrata*, minke whale
Bp = *Balaenoptera physalus*, fin whale
Cc = *Cystophora cristata,* hooded seal
Pg = *Phoca groenlandica*, harp seal

Water condition in general, including cold intermediate layer (CIL) volume, sea surface temperature (SST) and freshwater runoff, were recurrent variables selected in models. Indeed, these three variables were negatively correlated to stranding events in cetaceans (*i.e.* harbour porpoise, minke whale and fin whale). However, the relationship between seal stranding events and water condition was somewhat more complex and species-dependent. While stranding events of harbour seals were negatively correlated to CIL volume, SST and freshwater runoff, hooded seal and harp seal (pagophilic species) stranding events were nonetheless positively influenced by SST.

Relationships between marine mammal stranding events and other environmental parameters were less ubiquitous but species-dependent. Ice condition was negatively correlated to stranding events for both pagophilic seals (hooded and harp seals) and mysticete species (minke and fin whales). Furthermore, krill abundance was negatively correlated to stranding events in harbour porpoises and minke whales. Finally, concentrations of *Alexandrium tamarense* (toxic algal bloom) were positively correlated to stranding events in minke whales, harp seals and hooded seals but negatively correlated to stranding events in fin whales.

Discussion

The influence of environmental parameters on inter-annual variation in stranding events has rarely been examined for marine mammals. Using a long-time series of stranding reports, we detected strong seasonality and inter-annual variation in marine mammal stranding events. Regardless of species-dependent differences observed in inter-annual variation patterns, we noticed a significant increase in marine mammal stranding events over the 1994–2008 period. This tendency was partly explained by two peaks in stranding events observed at the end of the time series (in 2006 and 2008), and by an upward shift in harbour porpoise stranding events in 2000. The most major peak occurred in 2008, affected several marine mammal species and was apparently caused by algal toxic bloom of *Alexandrium tamarense*. Water conditions (cold intermediate layer volume, freshwater runoff and sea surface temperature) negatively influenced stranding events in most species yet some exceptions were noticed. Ice cover indeed influenced pagophilic seal species and mysticetes, but in the same direction (a negative association was found for both groups). Krill abundance specifically influenced stranding events in harbour porpoises and minke whales.

Overall, these results give support to our hypothesis which stipulated that the nature and direction of environmental parameters influencing marine mammal stranding events vary among species. Our first prediction was confirmed. Indeed, the relationship between water conditions and stranding events match the prediction for CIL, FW and SST predictors. Our second prediction was partly confirmed. Stranding events in pagophilic seal were indeed negatively influenced by ice cover, but stranding events in mysticetes were also negatively associated to that variable, which did not match our prediction. Our third prediction was also partly supported. Stranding events in mysticetes were indeed negatively influenced by krill abundance, but in the minke whale case solely. Moreover, we found a negative relationship between stranding events in harbour porpoises and krill abundance, which was somewhat unexpected.

Although we highlight the importance of environmental predictors to explain inter-annual variation in marine mammals stranding events recorded in the St. Lawrence ecosystem, we still lack detailed information regarding the nature of the ecological mechanisms underlying such linkages. Hence, the assumption that our conclusions based on stranding reports may extend to individual mortality has to be considered with care. Based on our best knowledge of the system, we suggest that species distribution in the St. Lawrence ecosystem might also partly influence stranding events in marine mammals. Indeed, if population distribution was actually influenced by environmental parameters in some species, variation in stranding events observed in such case might have arisen from changes in individual abundance in the study area, which would likely influence the total number of mortality events (yet the mortality per capita could be the same or even lower in good years). To better understand whether environmental changes mostly impact individual mortality or individual distribution (total mortality) in our study area, we would indeed need to conduct a multi-year investigation of marine mammal abundance. Based on our current knowledge of the species biology, we can nonetheless suggest that stranding events may serve as an index of individual mortality in resident species (*e.g.*, beluga whale for which distribution and abundance are stable over the years (Hammill *et al.* 2007); and in pagophilic seals (individual mortality is known to depend on ice conditions (Johnston *et al.* 2005, Hammill and Stenson 2008)), but not in migratory species (*e.g.*, mysticetes which use the St. Lawrence ecosystem as feeding ground likely vary in their distribution over the years according to the availability of resources (Edds and MacFarlane 1987; Forcada 2002, Robillard *et al.* 2005)). Overall, our conclusions drawn on stranding events provide insights into potential environmental mortality causes at least in some marine mammal species. For the other (migratory) species, further analyses dealing with abundance data are still required.

Stranded species and distribution

The species composition of marine mammal stranding events in the St. Lawrence ecosystem likely reflects the presence (and to some extent the distribution) of species and particularly during summer time. Indeed, resident species (beluga whales and harbour seals), although they are less abundant than some seasonal visitors (hooded seals, harp seals and grey seals; Robillard et al. 2005, Lesage et al. 2007), were substantially represented in stranding records as they occur all year long in the study area. Minke whales and grey seals were the most common migrating species found stranded but apparently because they occur in relatively large numbers during summer (Lawson and Gosselin 2009). The species composition in stranding events observed during our study period (1994-2008) is quite different from the one previously reported by Béland *et al.* (1987; 1992) for the same region (1982–1990). In both studies, stranding events mostly involved minke whales for mysticetes, beluga whales for odontocetes, and harbour seals and grey seals for pinnipeds, yet their respective proportions slightly changed from 1982–1990 to 1994–2008 (from 15 to 11%, 43–50% to 37% and 21–39% to 12-12% for minke whales, beluga and harbour and grey seals, respectively; Beland *et al.* (1987; 1992)). Such differences could be attributable to the duration of the study (8 years in Béland *et al.* (1992) *vs* 15 years in our study), to identification accuracy (53 % of the specimens was not identified in Béland et al. (1992) compared to 36 % in the present study) and to study objectives (Béland et al. (1992) indicated a greater interest for beluga stranding reports). General tendencies in the two studies nonetheless greatly overlap and hence suggest some consistency in the composition of stranded species over time.

The location of a stranded animal was strongly dependent on oceanographic features (*e.g.* marine currents, tide, etc.) that drift the carcass onto the shoreline. In our study area, most stranding events were reported on the south shore of the Estuary. This phenomenon could be associated to the Gaspé current that creates a main residual downstream current which would make carcasses drift to the south shore of the Estuary. In addition, the north shore of the Estuary is represented by high and abrupt rocky landscape which would decrease odds that carcasses get stranded and detected compared with beaches from the south shore. Moreover, additional methodologically-linked biases such as heterogeneity in human population density (south shore being more inhabited) might influence the number of stranding reports and would then impact stranding distribution (Béland et al. 1987; 1992). Despite such limitation, stranding occurrence has nonetheless been documented to accurately reflect species relative abundance at regional scale (Norman *et al.* 2004). Consequently, we acknowledge that marine mammal stranding events observed in our study area does not necessarily fit its real distribution nor its abundance, but they nonetheless confirm the presence of the species in the study area.

On the other hand, distribution of stranding events may be closely related to actual local distribution in harbour seals and grey seals (most common seal species found stranded) as these species occur in close association with the shoreline during summer (they use isolated rocks, exposed reefs or sand banks to rest; (Robillard *et al.* 2005). According to the distribution of these haul-out sites, harbour seals and grey seals were more susceptible to strand along the south shore of the Lower Estuary (Robillard *et al.* 2005).

Seasonal variation in stranding events

The seasonal variation observed in stranding events appeared to reflect well the seasonality in species distribution, which is influenced by the temperate nature of the St. Lawence ecosystem and the availability of resources (Sergeant *et al.* 1970, Lavigueur *et al.* 1993, Robillard *et al.* 2005). During summer, the upwelling at the head of the Laurentian channel mix nutrient-rich cold water which enables phytoplankton blooms (Therriault and Levasseur 1985) that support zooplankton (Simard 1996), fishes and marine mammal communities (Simard 1996; 2008). Most species of marine mammals migrate into the Gulf and the Estuary in summer and meso-scale features (*i.e.* eddies and fronts) of the St. Lawrence have been correlated with the distribution of whales exploiting patchy prey species that they require in dense concentrations (Doniol-Valcroze *et al.* 2007, Simard 2008). Hence, the distribution of marine mammals reflects those oceanographic areas where productivity is high (Simmonds and Isaac 2007) which, in turn, influence the number of individuals present in the St. Lawrence ecosystem during summer. During the fall, some species (*e.g.*, mysticetes) migrate to other areas to breed (Sears *et al.* 2000, Lesage *et al.* 2007) so that no stranding events are further reported after species departure. During winter and early spring, ice covers major part of the St. Lawrence ecosystem and considerably constrain marine mammal distribution, decreasing the likelihood to find migratory species in the stranding records (Béland et al. 1987).

Environmental changes

Occurrence of marine mammal stranding events has greatly varied among species from 1994 to 2008, where the overall tendency was toward a significant increase over time.

This result likely reflect a real pattern in stranding events as sampling effort was quite consistent over time. Indeed, stranding records of beluga whales, the most charistmatic and most reported species, has not significantly changed over time since 1982, a tendency consistent with population trajectory which is thought to have remained stable over at least the past 22 years (Hammill *et al.* 2007). Hence, the lows in the total stranding events observed at the beginning of the time series, and the highs observed at the end of it, were likely due to real changes in species mortality and/or distribution. If toxic algal bloom was clearly identified as the direct cause of sporadic highs in individual mortality for 2008 (which partly drives the increasing trend over time), the nature of environmental parameters which generated inter-annual variation in stranding events from 1994 to 2007 was less intuitive as these patterns were variable and species-specific.

Water conditions

Environmental parameters representing water conditions (cold intermediate layer volume CIL, freshwater runoff FWR and sea surface temperature SST) consistently (same direction) explain stranding events variation among species yet some exceptions were noticed. Inter-annual changes in the CIL volume, FWR and the SST were negatively associated with stranding variations. This was likely due to an indirect influence of CIL volume, FWR and SST on individual mortality (by affecting body condition) through a direct impact on resource availability. These variables have been identified as ones of the most important factors driving phytoplankton production in the St. Lawrence Estuary as they directly contributes to water stratification and upwelling (Therriault and Levasseur 1985, Sourisseau *et al.* 2006)(Saucier et al. 2003) which act on prey aggregation and assemblage (Moore *et al.* 2000, Huntington 2000). As the abundance and quality of resources influence body condition in marine mammals, lower resource availability (*e.g.*, low CIL and FWR values) might actually decrease resilience of individuals to infectious diseases or parasitism (Simmonds and Mayer 1997, Measures 2008). This hypothesis might particularly suits resident species (*i.e.*, beluga whales and harbour seals) as they strictly depend on the resources produced within the St. Lawrence ecosystem for their entire life cycle.

However, prolonged or strengthened stratification can have negative impacts on productivity when the thermocline turns into a real barrier limiting upward movement of nutrient-rich waters. For example, in some areas of the world, increase in stratification slowed down coastal upwelling and nutrient availability which significantly decreased zooplankton biomass (Bindoff et al. 2007). In the St. Lawrence ecosystem, if the CIL volume, FW and SST overpass a certain stratification threshold, the productivity may decrease and this would likely attract less individuals and then decrease the odds that stranding events occur. This would stand particularly true in migrating species (*i.e.*, grey seals, harbour porpoises, white-sided dolphins, minke whales and fin whales) for which it is still more complex to assess whether CIL volume, FWR and SST influenced individual mortality and/or distribution as those species are known to greatly vary in their abundance over the years. Hence, the negative relationships found between CIL volume, FWR and SST and stranding events in migrating seals (CIL), odontocetes and mysticetes (but not for CIL) apparently result from a real impact on individual distribution where lower availability of resource led to lower occurrence of individuals. In the particular case of mysticetes, CIL temperature (strongly correlated to CIL volume in our study) has been previously documented to negatively influence blue and fin whale habitat selection (distribution), particularly in feeding areas in the Gulf of St. Lawrence (Doniol-Valcroze 2008). According to this, we should have detected a negative relationship between CIL volume (as it is co-linear with CIL temperature) and stranding events as higher CIL values would attract more individuals in the study area which, in turn, would increase the odds that stranding events occur. Nevertheless, CIL volume predictor was not selected. However, the understanding of environmental influences on organism distribution is much more complex and involves several ecological mechanisms such as conspecific and inter-specific interactions in the area (Doniol-Valcroze *et al.* 2007). Hence, the description of the influence of water conditions on migrating species require a multidisciplinary approach involving various aspects of the biology of species including ecological interactions into the marine community at different scales.

Ice condition

Our analyses confirm that ice cover was an important predictor of stranding events in pagophilic seals (hooded and harp seals) in the St. Lawrence ecosystem. Individual and mass stranding events in hooded seals and harp seals, respectively, were negatively influenced by ice cover volume. This result totally matches our prediction and was most likely explained by the direct impact of ice cover conditions on individual mortality (particularly juveniles). At the opposite of the other migrating species studied, pagophilic seals perform their migration in the St. Lawrence ecosystem during the fall and winter time to complete their reproductive cycle and remain in the area until the spring. For hooded seals and harp seals, ice pack represents a crucial habitat used by females to whelp and to nurse their pups (Bowen *et al.* 1985). If the ice cover is absent or too unstable during that critical time, pups may fall into the water where they may die from drowning or hypothermia (Johnston *et al.* 2005, Hammill and Stenson 2008). For example, poor ice conditions in the Gulf of St. Lawrence has led to important mortality in young harp seals in the Northwest Atlantic population (Sergeant 1991, Hammill and Stenson 2008). In 2006, abnormally low ice cover volume (the lowest observed since 1969; (Galbraith *et al.* 2008) in the Estuary and the Gulf of the St. Lawrence led to a peak in individual stranding events in juvenile (blue back) hooded seals. Since then, the occurrence of massive stranding events in juvenile harp seals has noticeably increased in the study area following warmer water temperatures.

Otherwise, our results showed that ice cover volume was also negatively correlated to stranding events in mysticetes, which does not fit our prediction. Hence, instead of directly influencing individual mortality (e.g., entrapment incident; Sears et al. 2000), ice cover would affect individual distribution. Indeed, by constraining the movement of large whales into the Gulf and, to some extent, the Estuary during winter and spring, ice conditions may act as a barrier which reduces access to habitat and then influence the distribution of animals (Bowen and Siniff 1999). Hence, in years of extensive ice cover, access of mysticetes to the St. Lawrence ecosystem would be limited, thus decreasing the odds of strandings in our study area. Extensive ice cover may also shorten the feeding season for large cetaceans and therefore reduce body conditions of individuals which, in turn, could cause higher mortality levels (Le Boeuf *et al.* 2000, Perryman *et al.* 2002).

Resource availability

Inter-annual variation in krill abundance influenced (negatively) stranding events of minke whales and harbour porpoises. This result partly fit our predictions as harbour porpoises are a piscivorous species. Direction of the relationship suggest an indirect impact of krill availability on individual mortality (fewer stranding events were observed during year with great abundance of krill), yet this relationship was drawn with migrating species which greatly fluctuate in numbers among years. Hence, even if reduced krill abundance might decrease body condition and weaken individuals for their migration, we cannot omit the potential influence of krill abundance on species distribution (Simard 2008). Indeed, krill is known to be unevenly distributed in the St. Lawrence ecosystem (Plourde *et al.* 2002) and its patchy aggregation might influence habitat selection in mysticete species which will feed into predictable areas (Doniol-Valcroze et al., 2007). Nevertheless, if krill abundance would have exclusively influenced distribution of species, a positive relationship would have been detected between that predictor and stranding events (*i.e.*, higher abundance of krill would attract greater number of individuals which increase total mortality in the study area).

While euphausiids are important preys for minke whales, relationship between krill abundance and harbour porpoise strandings was likely more indirect. As krill represent a key prey for several species in the St. Lawrence food web (marine fish, birds; (Bamstedt 1988, Descroix *et al.* 2005), inter-annual trend in its abundance may accordingly affect species of higher trophic level. For example, distribution of Atlantic herring, one of the most important prey for harbour porpoises (Fontaine et al. 1994), is closely associated to zooplankton aggregation in the Bay of Fundy (Jonhston et al. 2005). Thus, in the specific case of harbour porpoises, zooplankton abundance may reflect the overall availability of resource among years in the St. Lawrence ecosystem. Indeed, the overall tendency to decline in the abundance of krill biomass since 1994, as reported by Harvey and Devine (2008), was closely associated to the stately shift in harbour porpoise stranding events during the same period.

The effects of climate change on higher trophic levels can be particularly difficult to investigate because they involve relationships affected by time and space scales (Simmonds and Isaac 2007). Stranding networks and long-term data are crucial in detection and response to unusual mortality events (Wilkinson and Worthy 1991, Malakoff 2001). Overall, this empirical study highlights the importance of environmental changes on marine mammals stranding events in the St. Lawrence ecosystem. It also reveals the importance of long-term stranding records as a real biological indicator that provides insights on potential mortality causes in marine mammal populations. For example, mortalities of young pagophilic phocids related to recent light ice conditions in the Gulf during the weaning period. This study also points out an unusual mortality event of many species caused by a *A. tamarense* bloom at the mouth of the Saguenay River (one of the most important feeding grounds for marine mammals in the St. Lawrence ecosystem) in 2008. We need further research using environmental data to examined, more precisely, relative impacts of recent environmental changes on marine mammal mortality in the St. Lawrence.

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CHAPITRE 2

INFLUENCE DES ACTIVITÉS ANTHROPIQUES SUR LES ÉCHOUAGES DE MAMMIFÈRES MARINS DANS L'ESTUAIRE ET LE NORD-OUEST DU GOLFE DU SAINT-LAURENT, INCLUANT LE PARC MARIN SAGUENAY–SAINT-LAURENT

2.1 RÉSUMÉ EN FRANÇAIS DU DEUXIÈME ARTICLE

L'analyse des données d'échouage de mammifères marins peut nous fournir des informations sur l'écologie des populations. Dans les aires côtières abondamment fréquentées, les mammifères marins font face à plusieurs menaces d'origine anthropique. Afin de mieux comprendre la nature des activités anthropiques causant la mortalité des mammifères marins, nous avons analysé systématiquement les événements d'échouage dans l'estuaire et le nord-ouest du golfe du Saint-Laurent, de 1994 à 2008, pour des évidences de signes anthropiques. Au cours de cette période, les activités anthropiques ont été associées à 9% de la mortalité des mammifères marins : 28% pour les grands cétacés, 8% pour les petits cétacés et 6% pour les pinnipèdes. Contrairement aux cétacés, la mortalité résultant d'interactions anthropiques avec les phoques était faible et consistait majoritairement en des événements d'arme à feu avec les phoques gris et communs (26%, N=8 pour les deux). Globalement, les signes d'activités anthropiques sur les mammifères marins ont été rapportés majoritairement en été, ce qui résulterait de la saisonnalité des activités humaines (*c.-à-d.* activités récréatives, trafic maritime, la majorité des pêcheries, etc.) et de la présence des espèces dans l'aire d'étude. Les signes d'activités anthropiques sur les mammifères marins ont augmenté significativement au cours des années. Cette tendance a été causée par une augmentation des prises accidentelles et des autres activités anthropiques pour les mysticètes (petit rorqual 42%, N=39 et rorqual à bosse 13%, N=12)

et le marsouin commun, respectivement. Les cas de prises accidentelles de petits rorquals excédaient certaine années le prélèvement potentiel biologique (PBP) du « stock » de l'estuaire et du golfe du Saint-Laurent. Nous suggérons quelques hypothèses pour expliquer la récente augmentation des prises accidentelles de petits rorquals et de rorquals à bosse : i) une augmentation de l'effort d'échantillonnage, ii) des changements dans les pratiques de pêche et iii) un changement de la distribution de ces deux espèces dans l'estuaire, lié possiblement à des changements de la structures et de la dynamique de l'écosystème du Saint-Laurent (*c.-à-d.* l'effondrement des poissons de fonds, l'expansion de la distribution du capelan et le déclin de l'abondance de la biomasse d'euphausidés). Les événements d'échouage du marsouin commun avec des signes de d'autres activités anthropiques (67%, N=16) consistaient majoritairement en des morceaux de carcasses trouvés annuellement dans le parc marin Saguenay–Saint-Laurent, suggérant une chasse illégale. Cette étude souligne les impacts des activités anthropiques sur quelques espèces protégées dans l'estuaire et le parc marin. Les résultats confirment aussi l'utilisation des données d'échouage pour effectuer un suivi de la mortalité des mammifères marins causée par l'homme et, pour quantifier l'efficacité des mesures de conservation dans une aire marine protégée.

Ce deuxième article, intitulé *« Influence of anthropogenic activities on marine mammal strandings in the Estuary and northwestern Gulf of St. Lawrence, including the Saguenay St. Lawrence Marine Park »*, fut co-rédigé par moi-même ainsi que par la chercheure Lena Measures et notre collaborateur Jean-Claude Brêthes. En tant que premier auteur, ma contribution à ce travail fut la récolte des données sur le terrain en 2008, la classification et la validation de la base de données, les analyses statistiques et la rédaction du mémoire. Lena Measures, la seconde auteure, a agit comme directrice de recherche en guidant l'étudiante lors de la rédaction et la récolte de données. Jean-Claude Brêthes, le troisième auteur, a principalement aiguillé l'étudiante tout au long du projet. Les données d'échouage à long-terme ont été fournit par l'Institut Maurice-Lamontagne (1994–2002) et par le Réseau québécois d'urgence pour les mammifères marins (2003–2008). L'effort de terrain a été réalisé par plusieurs intervenants œuvrant au sein du Réseau québécois d'urgence pour les mammifères marins (RQUMM), Station de recherche des Îles Mingan, Réseau d'observation des mammifères marins, Centre québécois pour la santé des animaux sauvages (CQSAS), Institut national d'écotoxicologie du Saint-Laurent (INESL), Fondation Québec-Labrador, Amphibia Nature, Centre d'éducation et de recherche de Sept-Îles (CERSI), Exploramer et Zoo sauvage de Saint-Félicien). Une version abrégée des résultats de cet article a été présentée lors d'une conférence à la faculté de médecine vétérinaire de Saint-Hyacinthe en novembre 2009.

2.2 INFLUENCE OF ANTHROPOGENIC ACTIVITIES ON MARINE MAMMAL STRANDINGS IN THE ESTUARY AND NORTHWESTERN GULF OF ST. LAWRENCE, INCLUDING THE SAGUENAY- ST. LAWRENCE MARINE PARK

Marie-Hélène Truchon, [1,2] Lena Measures [1] and Jean-Claude Brêthes [2]

[1] Institut Maurice-Lamontagne, Pêches et Océans Canada, 850 route de la Mer, Mont-Joli, Qc, G5H 3Z4, Canada

[2] Institut des sciences de la mer, Université du Québec à Rimouski, 310 allée des Ursulines, Rimouski, Qc, G5L 3A1, Canada.

Abstract

Examination of marine mammal stranding data can provide insights into the ecology of populations. In widely frequented coastal areas, marine mammals face numerous anthropogenic-derived threats. To better understand the nature of anthropogenic activities underlying marine mammal mortality, we systematically investigated stranding events recorded in the Estuary and the northwestern Gulf of St. Lawrence from 1994 to 2008 for evidence of anthropogenic signs. During this period, anthropogenic activities were associated to 9 % of marine mammal mortalities: 28 % for large cetaceans, 8% for small cetaceans and 6% for pinnipeds. In contrast to cetaceans, mortality as a result of anthropogenic incidences in seals was low and consisted mostly of gunshot events involving grey and harbour seals (26%, N=8 for both).Overall, anthropogenic incidences on marine mammals were mostly reported during summer which resulted from seasonality in human activities (*e.g.* recreational activities, intense maritime traffic, most fisheries, etc.) and presence of species in the study area. Anthropogenic incidences on marine mammals significantly increased over the years. This tendency was driven by an increase of entanglement reports and other anthropogenic activities for mysticetes (minke 42%, N=39 and humpback whales 13%, N=12) and harbour porpoises (67%, N=7), respectively. Entanglements in fishing gears exceeded some years the potential biological removal (PBR) of the minke whale stock of the Estuary and Gulf of St. Lawrence. We suggest some hypothesis that could explain the recent increase of fishery entanglements of minke and humpback whales: i) increase of stranding sampling effort, ii) changes in fishery practices and iii) shift in distribution of these two species into the Estuary possibly related to changes in the structure and dynamic of the St. Lawrence ecosystem (*e.g.* groundfish fishery collapse, expansion of capelin distribution and decline of abundance in euphausiid biomass). Harbour porpoise stranding events with other anthropogenic incidences (N=16, 67%) mostly consisted in finding pieces of carcasses on a yearly basis in the Saguenay–St. Lawrence Marine Park, suggesting illegal hunting. This study highlights anthropogenic activities impacting some protected species in the Estuary and the marine park. Results also confirm the usefulness of stranding data to monitor human-caused mortality in marine mammal populations and, effectiveness of conservation measures in a marine protected area.

Key words: marine mammal, mortality, anthropogenic activities, by-catch, gunshot, marine protected area.

Introduction

Human interactions with marine mammals have occurred for many centuries, but with human population growth, increasing industrialization of fisheries and maritime traffic, these interactions will likely increase in the future (De Master *et al.* 2001). In the last decade, demand for seafood products and changes in fishery practices have led to fishing activities resulting in mortality of millions of marine mammals each year worldwide (Simmonds and Hutchinson 1996, Anderson 2001b, Schipper *et al.* 2008). Anthropogenic incidences on marine mammals are not limited to incidental by-catch or entanglement in fishing gear (Simmonds and Hutchinson 1996) and include: ship collision (Anderson 2001b, Laist *et al.* 2001), gunshot (Goldstein *et al.* 1999), anthropogenic noise (Nowacek *et al.* 2007) and loss and degradation of habitat (Kemp 1996, Harwood 2001). In many areas, our understanding of the effect of anthropogenic activities on marine mammals is inadequate due to a lack of information on anthropogenic activities (*e.g.* fishing and recreational activities) and dynamics of marine mammal populations (*e.g.* distribution and mortality) (Read 1996).

Marine mammal stranding data can provide long-term insights into population dynamics and threats to their survival (Leeney *et al.* 2008). Recent studies, using evidence of human incidences to classify stranded carcasses and estimate levels of anthropogenic activities, confirm the usefulness of stranding data as an indicator of anthropogenic interactions such as fishery by-catch (Goldstein *et al.* 1999, Lopez *et al.* 2002, Kemper *et al.* 2005, Byrd *et al.* 2008). However, stranding data are limited by the condition of carcasses and operational logistics and efficiencies in stranding networks. Multi-year datasets can take years to become available for analysis and consequently delay actions to prevent negative anthropogenic activities (Byrd *et al.* 2008). Hence, to document human interactions with marine mammals and collect baseline data, stranding events must be recorded in a systematic and rigorous manner and, involve extensive coverage of shorelines (Byrd *et al.* 2008).

The St. Lawrence Estuary (SLE) and Gulf of St. Lawrence (GSL) are two important feeding areas for marine mammals in summer (Sourisseau *et al.* 2006, Simard 2008). Some species such as the SLE beluga (*Delphinapterus leucas*) and harbour seals (*Phoca vitulina*) are resident year-round. Other species are seasonal visitors, for example: summer in the case of grey seals (*Halichoerus Grypus*) and winter for harp (*Phoca groenlandica*) and hooded (*Cystophora cristata*) seals. A great diversity of whales also migrate to these areas in summer (Kingsley and Reeves 1998), which has led to a well-developed whale-watching industry (Michaud and Giard 1998, Lien 2001). Whale-watching combined with considerable marine traffic (Blane and Jackson 1994, Lesage *et al.* 1999, Henry and Hammill 2001) and commercial fisheries may be a significant threat to resident and seasonal marine mammal populations.

There are a few studies in the St. Lawrence ecosystem that report considerable numbers of marine mammal mortalities associated with anthropogenic interactions (Béland *et al.* 1987, Béland *et al.* 1992) especially by-catch of harbour porpoises (*Phocoena phocoena*) in groundfish gillnets (Fontaine *et al.* 1994a, Lesage *et al.* 2006). Little information is available on the influence of other anthropogenic activities (*i.e.* ship collision and gunshot) on marine mammals in the Estuary. Some species may be especially at risk such as the threatened St. Lawrence Estuary beluga population (COSEWIC 2004) and the endangered blue whale (*Balaenoptera musculus*) in Canadian Atlantic waters (Sears and Calambokidis 2002). Anthropogenic activities may have important consequences on the demography of these populations (Clapham *et al.* 2002, Hammill *et al.* 2007).

The objective of this study was to examine stranding data for evidence of anthropogenic incidences on marine mammals, to study temporal variations thereof, and to identify which anthropogenic activities (*i.e.* fishery by-catch, ship collisions and gunshot) may be involved in stranding events for the period from 1994 to 2008 in Quebec waters.

Methods

Study area

The study area includes the St. Lawrence River, the St. Lawrence Estuary (SLE) and the northwest part of the Gulf of St. Lawrence (NWGSL) (Northwest Atlantic Fisheries Organisation (NAFO) Divisions 4S and 4T) (Figure 3.1). The Estuary and the northwestern Gulf of St. Lawrence have important oceanographic features (*i.e.* tidal interactions with bathymetry, wind-driven upwelling and mean circulation) that favour recurrent aggregations of prey and thus, are important feeding grounds for various marine mammal species in summer (Simard *et al.* 2002, Sourisseau *et al.* 2006, Simard 2008). Based on the critical status of the Estuary for the conservation of marine mammals (review in Lesage *et al.* (2007)), active conservation measures were undertaken in 1998 with the creation of the first marine protected area in eastern Canada, the Saguenay-St. Lawrence Marine Park. This protected area is located at the confluent of the Saguenay Fjord and the Estuary and covers over 1245 km^2 of sea surface. Despite conservation efforts, it nonetheless appears that the St. Lawrence remain an ecosystem largely used by human for commercial (maritime traffic and fisheries) and ecotourism (whale-watching) activities (Blane and Jackson 1994, Lesage *et al.* 1999, Henry and Hammill 2001). Indeed, a well-developed whale-watching industry operates throughout the summer in the marine park (Michaud and Giard 1998, Lien 2001). Moreover, few fisheries were authorized along the coasts of the Estuary and around the Magdalen Islands in summer: mostly gillnet fishery for Greenland halibut and herring, fishery for capelin with trap and fishery for crab and lobster with pot (MAPAQ 2008). All these human activities may be significant threats to resident and seasonal marine mammal populations.

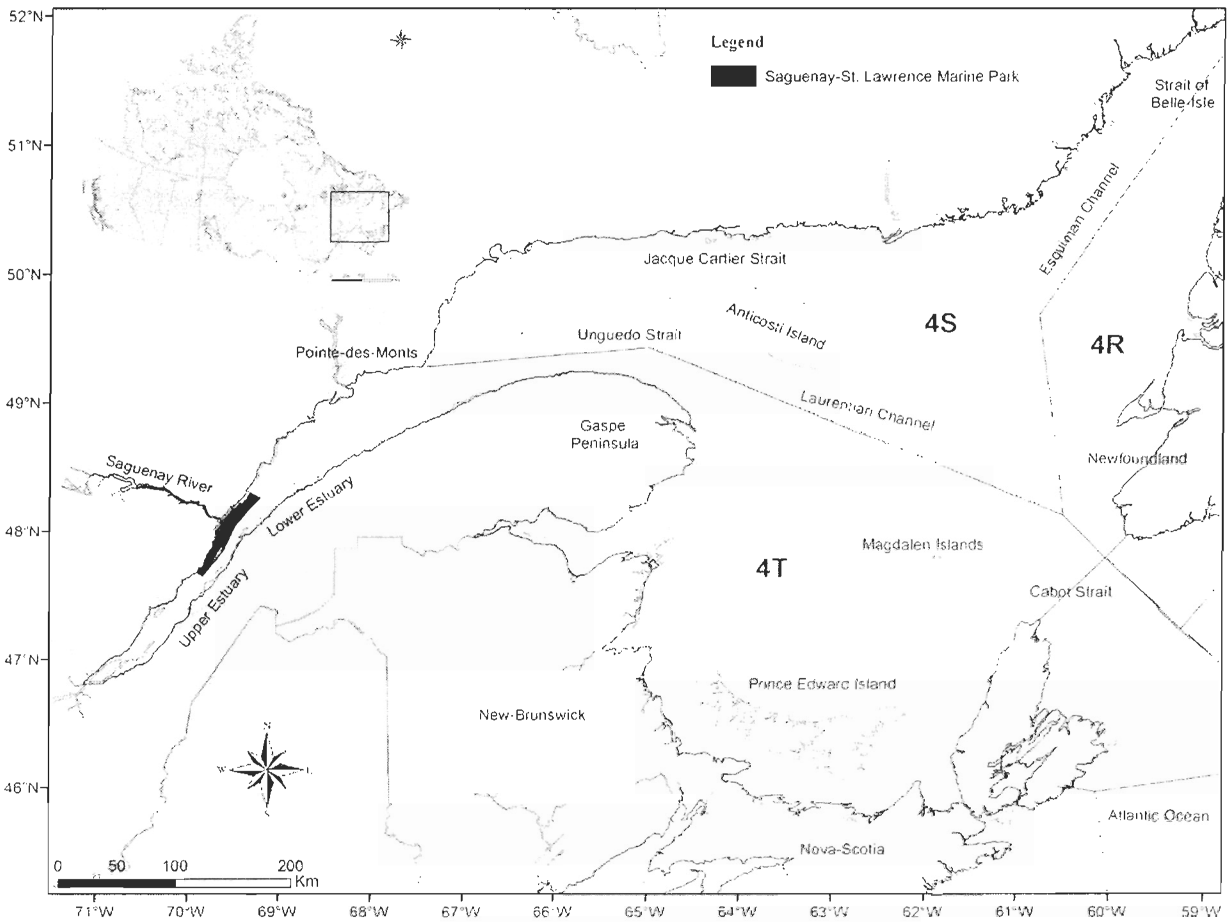

Figure 3.1 Study area showing the St. Lawrence Estuary and the Gulf of St. Lawrence.

Data collection

Data used in the following analyses comprise marine mammal stranding records collected over a 15-year period by Fisheries and Oceans Canada at the Maurice Lamontagne Institute (MLI) from 1994 to 2002 and by a marine mammal emergency network, RQUMM (Réseau québécois d'urgences pour les mammifères marins), from 2003 to 2008. We systematically analyzed stranding records from these two databases, extracting information on anthropogenic incidences on marine mammal stranding events including by-catch events (including events not necessarily leading to a stranding per se) which occurred offshore in fixed gears (*i.e.* nets, traps and pots). Numbers of stranding events were used as the sampling unit for analysis and not the number of animals in each event, either single or mass strandings (Geraci and Lounsbury 2005b), to minimize bias and over-estimation of events. Analysis of stranding data included only those cases where identification of marine mammals was based on verifiable criteria (pictures and/or a reliable observer). Ambiguous cases of species identification or equivocal reports of strandings were excluded from analyses. Carcasses for necropsy were selected based on their condition, size and accessibility and stranding network operational logistics and efficiencies. Necropsies were performed by biologists (MLI) or pathologists (the University of Montreal, Faculty of Veterinary Medicine at Saint-Hyacinthe).

Anthropogenic incidences were classified into five categories: by-catch, severe injury, ship collision, gunshot and other. Cases with gross evidence of human incidence observed by network partners were examined and only those that could be classified in one of the five categories were retained for analyses. These categories were based on specific definitions from the literature: 1) entanglement: defined as the presence of unhealed, narrow, linear lacerations or indentations in the epidermis most commonly around the head, dorsal fin, flukes and flippers (Read and Murray 2000), the presence of fishing gear on animals and release interventions. In this study, this category includes by-catch, that part of a fishery capture that is discarded at sea, dead (or injured such that death results) (Alverson *et al.* 1994, Hall 1996). 2) Severe injury: defined as injuries related to human activities but not diagnostic of entanglement in fishing gear. These include evidence of knife cuts, missing organs or appendages, and mutilations (Read and Murray 2000). 3) Ship collision: defined as a powerful impact between any part of a vessel and a live marine mammal, resulting in physical trauma (bone fractures with ante-mortem haemorrhages) (Laist *et al.* 2001, Waerebeek *et al.* 2007). This category includes propeller strikes as evident by helical cuts at regular intervals. 4) Gunshot: defined as the presence of a bullet in vital organs (liver, heart, brain, etc) observed at gross necropsy or the presence of penetrating circular wounds consistent with a gunshot (Read and Murray 2000). 5) Other: defined as evidence of anthropogenic incidences that do not fit the other above definitions or that had confounding evidence of anthropogenic incidence. Carcasses too decomposed or with severe scavenger damage precluding an adequate evaluation of the anthropogenic activity involved were excluded.

Statistical analyses

Anthropogenic incidences were identified for each marine mammal group and each species. We examined both lethal and live incidences. Pie charts were used to illustrate the percentage of each lethal anthropogenic incidence on marine mammals. Linear and polynomial regressions were used to fit inter-annual variations in anthropogenic incidences. Logarithm transformations were applied to data that were not normally distributed and when the homogeneity of variance was not respected (Zar 1999). In all analyses, a P value < 0.05 was considered statistically significant. We assumed that data were independent and statistical tests were done using R v2.4 computer software (R Development Core 2009).

Results

From a total number of 1590 events (1994 to 2008), 192 involve anthropogenic activities, 92 evidences of fishery entanglement (48%), 36 evidences of ship collision (19%), 31 evidences of gunshot (16%), 24 other anthropogenic interactions (13%) and nine severe injury events (5%) (Table 3.1). These records include six species of large cetaceans, three species of small cetaceans and four species of seals. Of all marine mammal species, the minke whale (*Balaenoptera acutorostrata*) appears to have the greatest number of anthropogenic incidences (24.5 %) (Table 3.1), mostly fishery entanglement (86.6%), of which 11 events involved fishing traps and 12 events involved other unidentified fishing nets. From the large cetacean group, minke whales experienced the majority of incidences followed by harbour porpoises in the small cetacean group. Harbour seals and grey seals have more reported incidences than other seal species involving mostly gunshot events.

Differences between cetacean species are observed in the number of events within anthropogenic categories (Table 3.1). Entanglement was the most common incidence on large cetaceans, except for fin whales (*Balaenoptera physalus*) that appear to be involved mostly in ship collisions. Small cetaceans were represented mostly by harbour porpoise and beluga. While the SLE beluga has a diversity of health issues, in this study, ship collision was the most common human incidence recorded, in contrast to harbour porpoise which was commonly affected by other anthropogenic interactions in the Saguenay–St. Lawrence Marine park.

In Quebec waters, about 9.1 % of anthropogenic incidences were lethal for marine mammals, 5.8 % for seals and 13.8 % for cetaceans (Figures 3.2-3.4). For the latter group, lethal anthropogenic incidences were reported more often for large (28%) than small cetaceans (8 %). Large cetacean mortality is associated mainly with entanglement (19.5%). in fishing gears while small cetacean mortality is associated mainly by other incidence (3.7 %) (Figures 3.4.c-d). Moreover, ship collision with large whales (8.2%) and small whales (2.8%) is the second most frequent lethal anthropogenic incidences recorded in the cetacean group. Although there is no evidence of gunshot for large cetaceans and only few (0.2%) for the small cetaceans, it nonetheless appears that gunshot events are more frequently associated with seal mortalities than other categories (Figure 3.3).

Table 3.1 Anthropogenic incidences by category associated with live and dead marine mammal stranding events by species from 1994 to 2008 in Quebec, Canada.

Species	Categories of anthropogenic incidences										Total events	
	Entanglement		Gunshot		Ship collision		Severe injury		other			
	N[1]	%[2]	N[1]	%[2]	N[1]	%[2]	N[1]	%[2]	N[1]	%[2]	N[1]	%[2]
Large cetacean												
Balaenoptera acutorostrata	39	42.4			8	22.2					47	24.5
Balaenoptera physalus	3	3.3			8	22.2					11	5.7
Balaenoptera musculus	2	2.2									2	1.0
Megaptera novaeangliae	12	13.0							1	4.2	13	6.8
Eubalaena glacialis	3	3.3									3	1.6
Physeter macrocephalus					1	2.8					1	0.5
subtotal	59	64.1			17	47.2			1	4.2	77	40.1
Small cetacean												
Phocoena phocoena	5	5.4	1	3.2	5	13.9	1	11.1	16	66.7	28	14.6
Delphinapterus leucas	3	3.3			8	22.2					11	5.7
Lagenorhynchus acutus							1	11.1			1	0.5
subtotal	8	8.7	1	3.2	13	36.1	2	22.2	16	66.7	40	20.8
Unidentified cetacean	11	12.0			3	8.3					14	7.3
subtotal cetaceans	78	84.8	1	3.2	33	91.7	2	5.6	17	70.8	131	68.2
Seals												
Phoca vitulina	6	6.5	8	25.8			2	22.2	1	4.2	17	8.9
Halichoerus grypus	3	3.3	8	25.8	1	2.8					12	6.3
Phoca groenlandica			5	16.1	1	2.8	2	22.2	1	4.2	9	4.7
Cystophora cristata	1	1.1	1	3.2	1	2.8	1	11.1	1	4.2	5	2.6
Unidentified seal	4	4.3	8	25.8			2	22.2	4	16.7	18	9.4
subtotal seals	14	15.2	30	96.8	3	8.3	7	77.8	7	29.2	61	31.8
Total	92	47.9	31	16.1	36	18.8	9	4.7	24	12.5	192	100

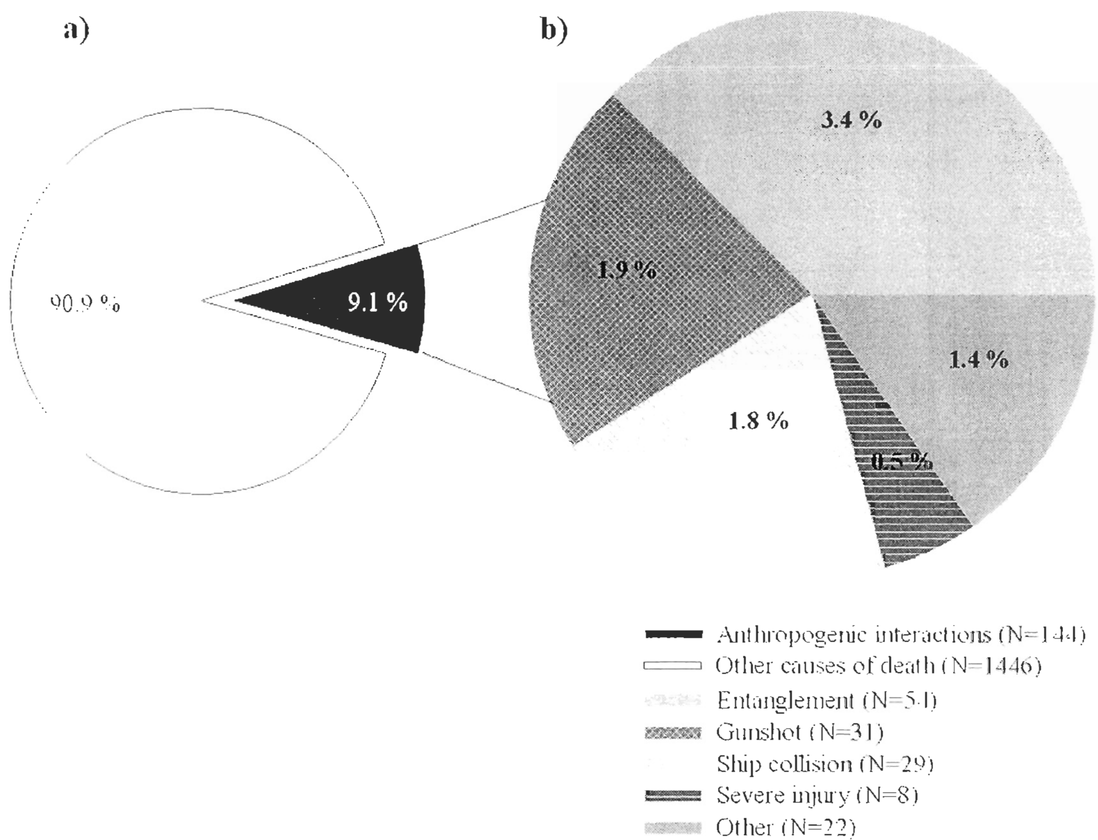

Figure 3.2 a) Proportion and b) causes of lethal anthropogenic incidences on marine mammals in Quebec (1994 to 2008).

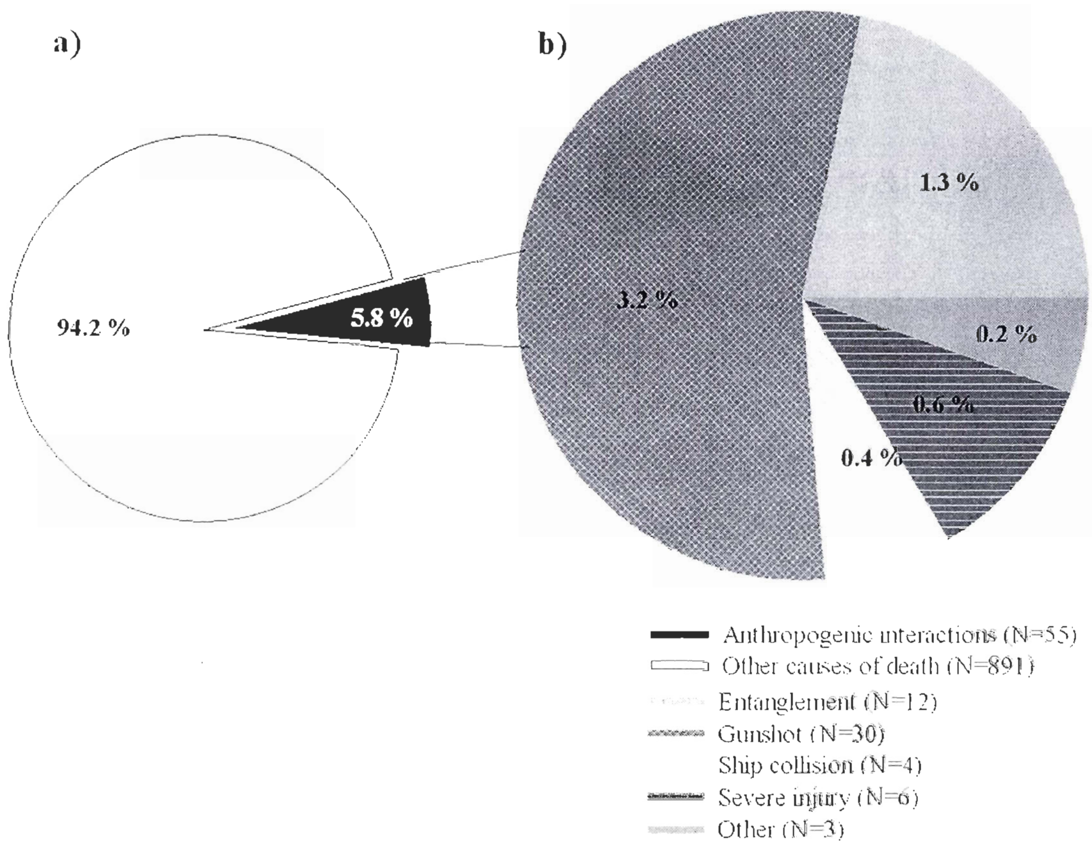

Figure 3.3 a) Proportion and b) causes of lethal anthropogenic incidences on seals in Quebec (1994 to 2008).

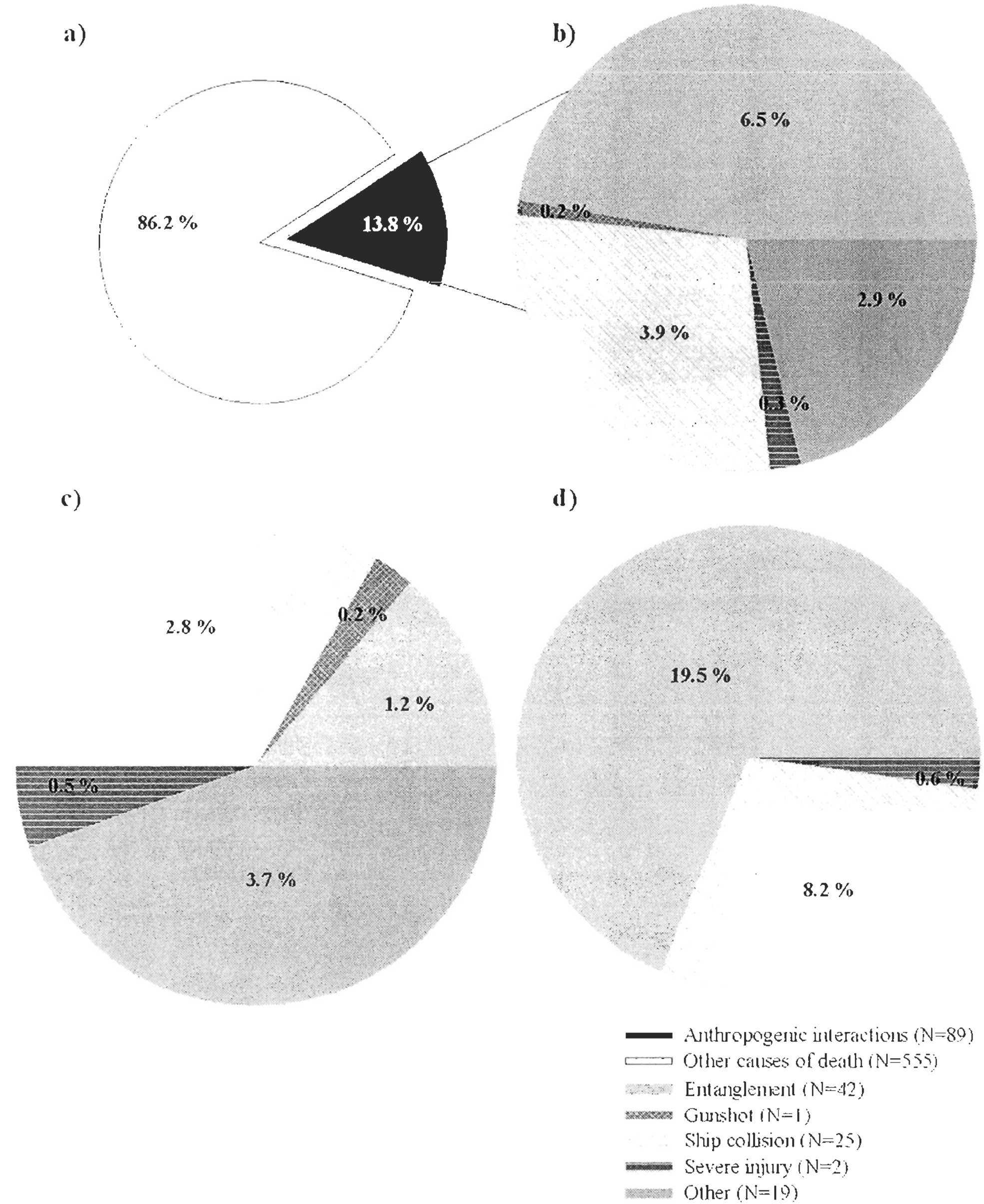

Figure 3.4 a) Proportion and causes of lethal incidences on b) all cetaceans, c) small cetaceans and d) large cetaceans in Quebec (1994 to 2008).

Temporal variations

Evidence of anthropogenic incidences observed on dead and live marine mammals increase during summer (Figure 3.5) and over the study period (1994–2008) (R^2_{adj} = 0.48, $F_{2,12}$ = 7.54, p = 0.008), while the number of incidences has remained relatively constant over recent years (Figure 3.6.a). This annual tendency is positively correlated with entanglement events ($R^2_{adj.}$ = 0.47, $F_{2,12}$ = 7.22, p = 0.009) and other anthropogenic incidences ($R^2_{adj.}$ = 0.45, $F_{1,13}$ = 12.44, p = 0.004), which increased during the time period (Figure 3.6.b). Entanglement events involved mostly minke ($R^2_{adj.}$ = 0.80, $F_{1,13}$ = 51.49, $p < 0.001$) and humpback whales (*Megaptera novaeangliae*) ($R^2_{adj.}$ = 0.22, $F_{1,13}$ = 5.0, p = 0.04) (Fig. 3.7 a-b), and other anthropogenic incidences involved mostly harbour porpoises ($R^2_{adj.}$ = 0.87; $F_{1,14}$ = 97.97; $p < 0.001$) (Figure 3.7.c). Although severe injury, ship collision and gunshot remained significantly constant over time, we observed since 2002 a decreasing number of stranding events reported with evidence of gunshot, mostly of seals (Figure 3.6.c). Overall, entanglements of marine mammals were mostly reported in Division 4T (63%).

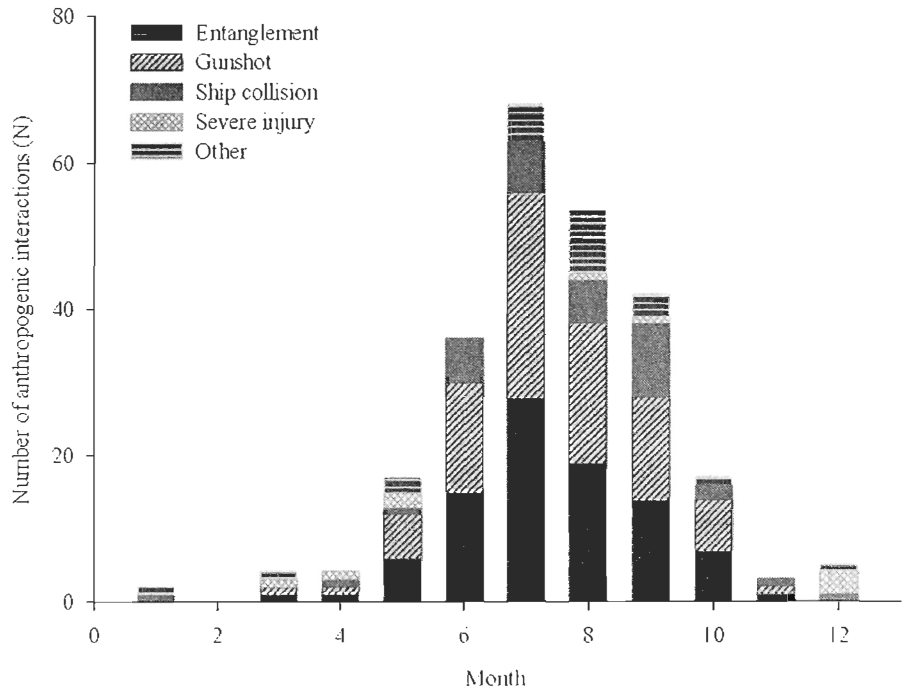

Figure 3.5 Seasonnal variability in anthropogenic incidences on live and dead marine mammals in Quebec, 1994 to 2008.

a)

b)

c)

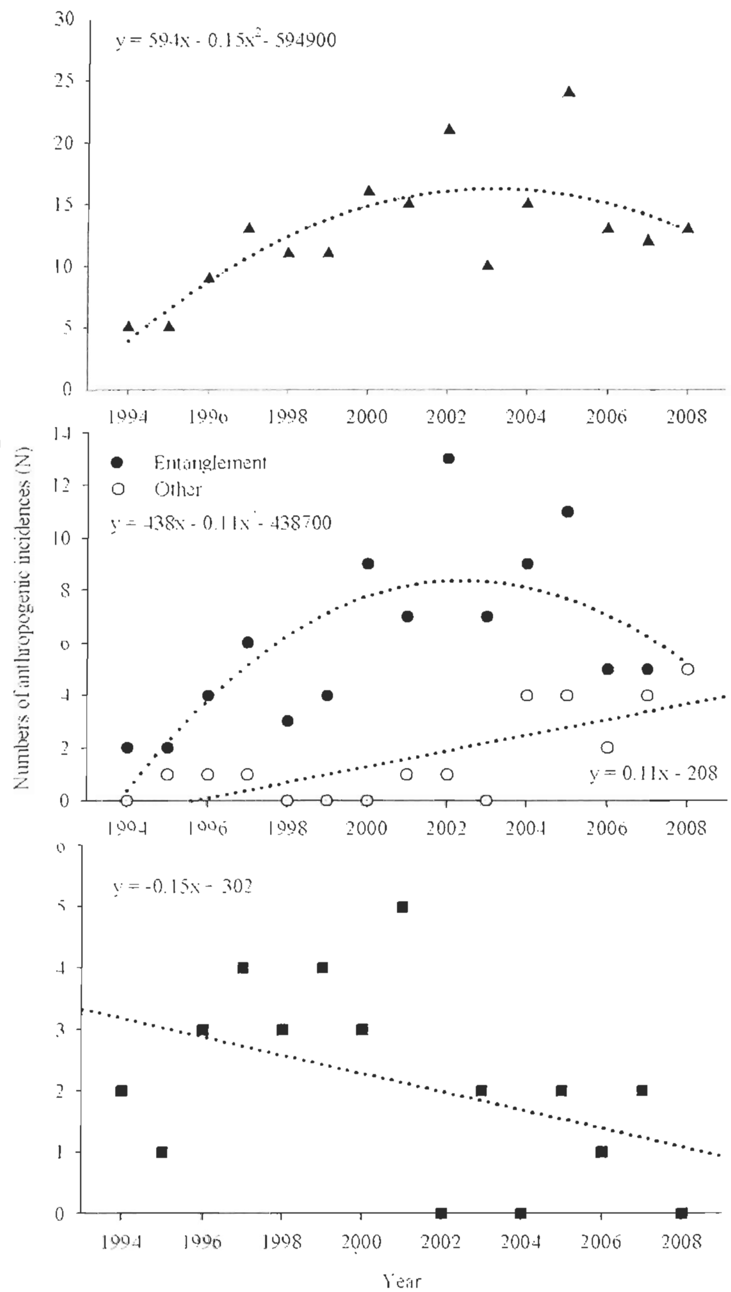

Figure 3.6 Inter-annual variability in the number of live and dead marine mammals with evidence of anthropogenic interactions reported a) globally, b) for entanglements (black circles) and other causes (open circles) and c) gunshot only.

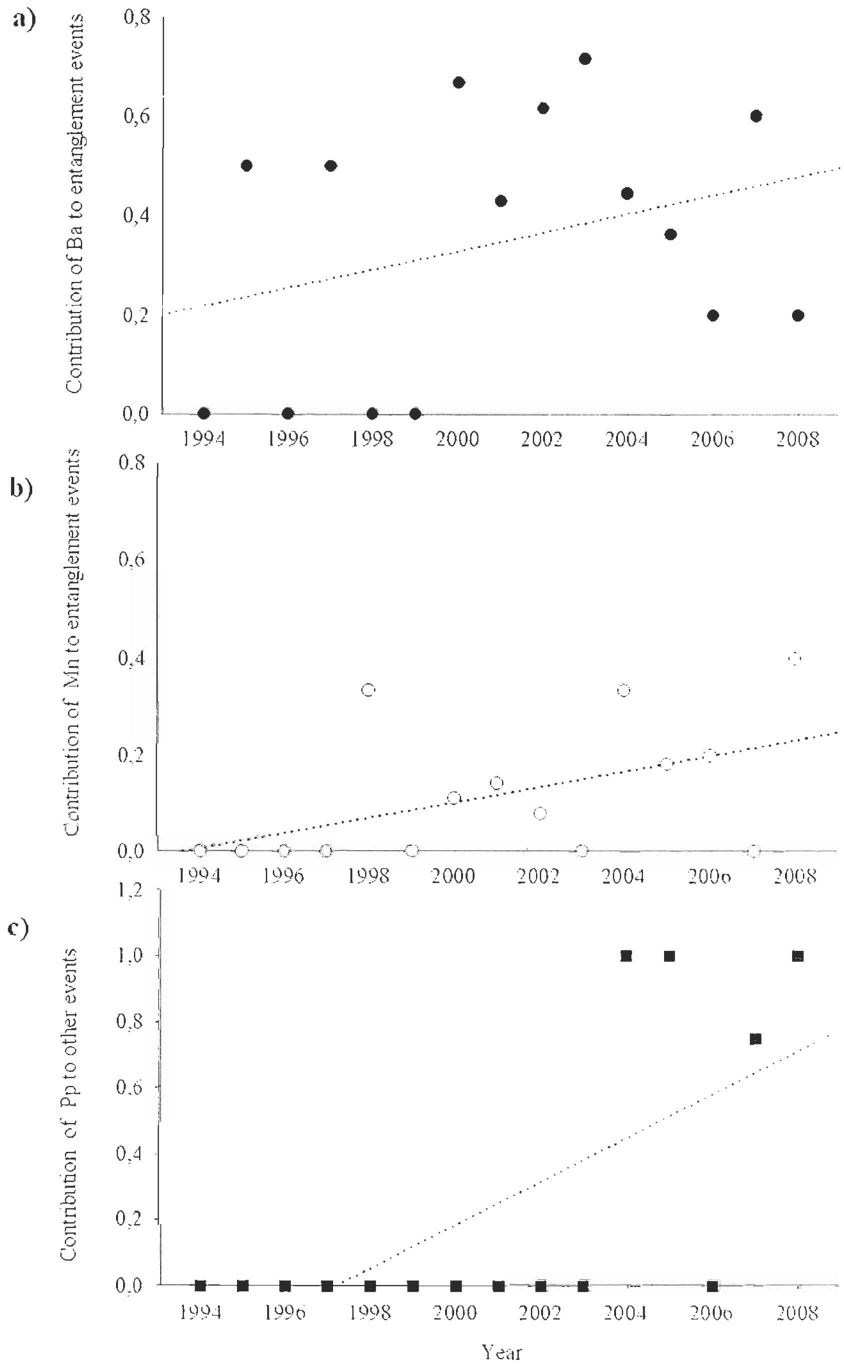

Figure 3.7 Contribution of a) minke whale (Ba) and b) humpback whale (Mn) to all by-catch events and contribution of c) harbour porpoise (Pp) to all other anthropogenic incidences recorded in Quebec, 1994-2008.

Finally, if we consider only lethal anthropogenic incidences (*i.e.* excluding release of entangled animals), we observe no significant temporal tendency in any anthropogenic category. However, the number of these events seemed to decrease over recent years, except for a peak in 2005, and are significantly correlated ($R^2_{adj.} = 0.74$, $F_{1,14} = 39.97$, $p < 0.001$) with that of lethal entanglement events, mostly of minke whales (Figure 3.8). Despite the general increase of entanglement events from 1994 to 2008, these events involving only dead animals seemed to decrease since 2003. In 2003, the marine mammal emergency network, RQUMM, had set up a program with fishermen and other organizations to disentangle marine mammals from fishing gear. Since then, nine large cetaceans were successfully disentangled, including six minke whales and three humpback whales.

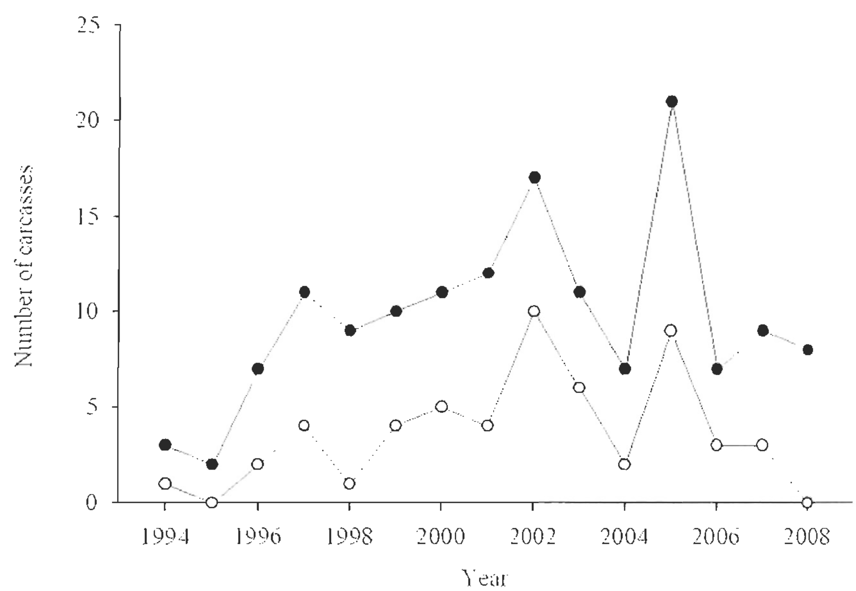

Figure 3.8 Inter-annual variability in lethal anthropogenic incidences on marine mammals (black circles)

Discussion

From a conservation perspective, this study provides information on the influence of anthropogenic activities on marine mammals in an area heavily used by humans, including the Saguenay–St. Lawrence marine park. Examination of anthropogenic incidences on marine mammals in the St. Lawrence Estuary is essential in the management and conservation of marine mammals, particularly for protected and resident species such as the St. Lawrence Estuary beluga and the harbour seal. Using a stranding database spanning over 15 years (1994–2008), we found that anthropogenic activities were associated to 9 % of marine mammal mortality: 28 % for large cetaceans, 8% for small cetaceans and 6% for pinnipeds. In contrast with cetaceans, anthropogenic incidences on mortality of pinnipeds were low and consisted mostly in gunshot of grey and harbour seals. Overall, anthropogenic incidences on marine mammal strandings increased over the years and were recorded mostly during summer. This trend over time was driven by an increase in recent years of reports of fishery entanglements and other anthropogenic incidences of mysticetes (*e.g.* minke and humpback whales) and harbour porpoise in the Estuary and the marine park, respectively. Moreover, we estimated that fishery entanglement of minke whale had exceeded some years the potential biological removal of the St. Lawrence "stock". Hence, results highlight two vulnerable species to human activities in the Estuary, the minke whale and the harbour porpoise. This study also points out preoccupant levels of human-induced mortality in the national marine park.

As expected, human incidences on marine mammals occur mostly in summer and early fall in Quebec. This is likely due to the seasonality of human activities such as recreational activities, marine traffic and fisheries which are more intensive in summer than other seasons (Béland *et al.* 1987). This seasonality has been observed as well in other temperate regions, such as California (Goldstein *et al.* 1999) and North Carolina (Byrd *et al.* 2008). Stranding events are also more likely to be reported in summer when observers are present and more active (*i.e.* walking on the beach, boating or involved in other recreational activities) and thus find and report stranded carcasses (Béland *et al.* 1987). This seasonality is also a function of seasonal migration and movements of marine mammals (Sergeant 1979, Lopez *et al.* 2002, Byrd *et al.* 2008, Bogomolni *et al.* 2010) which, for the majority of species, bring them to the GSL and SLE during summer to early fall to forage (Edds and MacFarlane 1987, Lesage *et al.* 2007, Simard 2008) (Lavigueur *et al.* 1993, Kingsley and Reeves 1998). Considering that the probability of anthropogenic interactions with marine mammals increases with the density of marine mammals, anthropogenic incidences on marine mammals were mostly likely to occur during summer. Nonetheless, anthropogenic incidences remained high in September when fishing (Lesage *et al.* 2006) and recreational activities (Henry and Hammill 2001) declined. Lesage et al. (2006) suggest that the late September peak of harbour porpoise by-catch could be associated with movements of animals inshore in response to an increased abundance of prey.

Overall, we estimated that 9 % of marine mammal carcasses examined had evidence of anthropogenic incidence, mostly evidence of entanglements (48%). This is considerably smaller than the 50% reported by Béland *et al.* (1992) for marine mammal mortalities other than beluga that could be attributable to human activities from 1988−1990 in Quebec waters. However, if we consider only cetaceans, a relatively high percentage of anthropogenic incidences involved large whales particularly minke whales (36 % of mortalities showed evidence of anthropogenic incidences). This result is consistent with Béland *et al.* (1992) who reported evidence of human-related wounds in 34 % of the large whale strandings in the Estuary. A variety of biological factors can influence entanglement of marine mammals such as species distribution, behavioural traits (curiosity, exploration, social patterns and feeding activities) (Fertl and Leatherwood 1997, Morizur *et al.* 1999), sensory capacities and attention (Perrin *et al.* 1994). Feeding activities of marine mammals make them especially vulnerable to entanglement and may be an important component in many incidental captures (Lien 1994, Fertl and Leatherwood 1997). The patchiness of resources in the marine environment and high feeding requirements and high energetic costs of feeding strategies mostly of large mysticetes (Piatt and Methven 1990, Heithaus and Dill 2002, Doniol-Valcroze *et al.* 2007) make fishing gears particularly attractive for feeding activities. Although large whales seem to be more vulnerable to human activities than other marine mammals (*i.e.* small cetaceans and seals), it nonetheless appears that seals might be under-represented in stranding data. In the study area, seals are considered as a nuisance and, as a result, carcasses could be less reported by fishermen. Moreover, the charismatic status and impressive size of large whales make strandings more likely to be reported than other species such as seals.

In spite of this general trend in anthropogenic incidences on marine mammals, we observed differences within all anthropogenic categories between seals, small cetaceans and large cetaceans and between species.

Anthropogenic incidences on seals

Anthropogenic interactions with seals consisted primarily in gunshot (97%) and involved two species, grey and harbour seals. These results were consistent with other studies, which reported that gunshot was the most common anthropogenic cause of mortality among pinnipeds (Stroud and Roffe 1979, Béland *et al.* 1987, Béland *et al.* 1992, Goldstein *et al.* 1999). Gunshot events occurred during summer, a period when the Estuary is closed to hunting and therefore does not account for the higher occurrence of gunshot events during this time (Lesage and Hammill 2001). Moreover, the harbour seal is a species protected from hunting in eastern Canada (COSEPAC 2007), while grey seal is protected in the Estuary during summer. In the study area, fishermen have a negative attitude towards seals as they cause considerable damage to fishing gears (Fontaine *et al.* 1994a) while removing target species from them, causing substantial financial loss (Beddington *et al.* 1985, Lesage *et al.* 2001). In addition, the well-recognized conflict between seals and fishermen for marine resources given the numerous grey and harbour seals in the Estuary during summer (Lavigueur *et al.* 1993) and an increasing Northwest Atlantic grey seal population since 1970 (Hammill 2005) have led to a high susceptibility of seals to interact with human activities in summer and thus, being shot during fishery activities in the Estuary and the Gulf of St. Lawrence. As the size of the resident population of harbour seals is unknown (COSEPAC 2007), this source of mortality may be of concern in the Estuary and possibly elsewhere in eastern Canada. Harbour seals are particularly sensitive to human disturbance due to their coastal nature (Henry and Hammill 2001) and distribution in areas used by humans (Robillard *et al.* 2005, COSEPAC 2007).

Anthropogenic interactions with small cetaceans

For small cetaceans, the species most likely to be reported with human incidences was the harbour porpoise, and surprisingly, the main anthropogenic incidence was other than entanglement. By-catch is the most common anthropogenic incidence reported for small cetacean mortalities worldwide (Read and Murray 2000), especially for harbour porpoise and dolphin species (Baker and Martin 1992, Fontaine *et al.* 1994a, Simmonds and Hutchinson 1996, Lesage *et al.* 2006). However, in contrast to other regions, another cause of mortality seemed to be significant, even much important, for harbour porpoise in Quebec water, and consisted of finding pieces of carcasses (large cubes of blubber) clearly cut with a knife. These reports came from a single region, near Grandes-Bergeronnes, a municipality located on the north shore of the protected waters of the Saguenay–St. Lawrence Marine Park. Alternatively, these events may suggest accidental entanglement. Indeed, fishermen occasionally mutilate, cut appendages or slit the abdomen of marine mammal carcasses to facilitate disentanglement and protect their gear (Read and Murray 2000, Byrd *et al.* 2008). Thus, it is conceivable that a proportion of these events are entanglements in fishing gears. Nonetheless, fishery activity in the sector of Grandes-Bergeronnes is low to nonexistent and corroborates the illegal hunting presumption. At this time, these events continue to be reported and are under investigation by Parks Canada to prevent further cases.

Ship collision was the second most frequent anthropogenic incidence on cetaceans and involved mostly minke whales, fin whales and beluga whales (22%). This result is particularly important for the SLE beluga as the resident population has relatively few individuals and does not show any sign of recovery (Hammill *et al.* 2007). Although ship collision with belugas are known to occur in the SLE (Hammill *et al.* 2007, Measures 2008), evidence of anthropogenic incidence with beluga was found in only 4 % of the beluga carcasses as reported by Béland *et al.* (1987; 1992) and Measures (2008). Human interactions such as fishery entanglement and ship collision are not considered to be an important cause of mortality for SLE beluga (Béland *et al.* 1992, Fontaine *et al.* 1994a, Hammill *et al.* 2007). Nevertheless, ship collision has been identified as a factor potentially contributing to the lack of recovery of this population with other factors such as chemical contamination, anthropogenic noise and disturbance related to marine traffic in its summering habitat (Lesage *et al.* 1999, Hammill *et al.* 2007). Habitat loss and degradation is considered the greatest threat for resident coastal species such as the SLE beluga (Kemp 1996).

Anthropogenic interactions with large cetaceans

Entanglement was the main human incidence on large whales in the St. Lawrence Estuary (SLE) and the northwestern Gulf of St. Lawrence (NWGSL) and involved mostly minke whales and humpback whales as previously observed by Béland *et al.* (1992). Similarly to tendencies reported in Newfoundland-Labrador, entanglement in fishing gear was higher in minke whales than humpback whales (Lien 1994). The increase in entanglement, mostly in the NAFO Division 4T (63%), could not simply be explained by an improvement of public awareness and sampling effort as there was variation in entanglement between years for specific species suggesting that other biological processes were involved. We propose three explanations for this increase in entanglement: 1) a shift in minke and humpback whale distribution, 2) changes in fishery practices and 3) increase of sampling effort in the SLE and NWGSL from 1994 to 2008.

The SLE and NWGSL are important feeding grounds in summer, where many cetacean species migrate and may interact with fishery activities. In the St. Lawrence ecosystem, distribution of rorqual species is associated with aggregation of prey (*e.g.* capelin and krill) (Sourisseau *et al.* 2006, Doniol-Valcroze *et al.* 2007, Simard 2008). Changes in prey distribution may influence distribution of rorquals which concentrate where their prey are located. If cetacean distribution changes in response to prey location and occurs in a fishing area, the probability of entanglement would also increase for cetaceans, resulting in mortality (Leeney *et al.* 2008). Whitehead and Carscadden (1985) suggested that the high number of humpback whales observed off eastern Newfoundland from 1977 to 1980 may have contributed to the high number of entanglements. They found also a correlation between observations of humpback whales and abundance of capelin, their main prey (Baird 2003b). Similarly in the NWGSL, Comtois (2010) observed an increased number of humpback whales as well as a shift in their geographical distribution. She suggested an association between this distributional shift, cold sea bottom temperature and the collapse of demersal fish predators by overfishing in the late 1980s and early 1990s (Savenkoff *et al.* 2007, Morissette *et al.* 2009). Overfishing is also suspected to have contributed to significant geographical expansion in the distribution of capelin in the mid 1990s throughout the entire Gulf (particularly in Division 4T) (DFO 2001, Grégoire *et al.* 2008) due to the collapse of its major predator, the Atlantic cod (Carscadden *et al.* 2001). Likewise, the expansion of the distribution of capelin in the SLE and southern GSL may likely attract foraging minke and humpback whales and consequently may lead to high entanglement events recorded in Division 4T. However, we could not validate this hypothesis due to a lack of information on the distribution of minke and humpback whales in the SLE, but we suspect that these changes in the St. Lawrence ecosystem (*i.e.* abundance and distribution of preys) probably had an thoughtful implication on the distribution of these marine mammal species and therefore on temporal patterns in entanglement.

Another possible explanation for the increase of entanglement events may be changes in fishery practices in recent years. Following the groundfish collapse in the early 1990s, the number of groundfish landings decreased while the number of invertebrate landings increased (DFO 2010). Benthic species (*i.e.* crabs, lobsters and dogfishes), which are caught with traps and pots, are known to pose a high risk of entanglement for large whales in the Bay of Fundy (Johnston *et al.* 2007). Few fisheries were authorized in the Estuary in summer and mostly involved fisheries of crabs and lobster with traps. Indeed, during the study period, minke whale entanglements occurred mainly in invertebrate traps. Some minke and humpback whales were observed swimming with attached lines from traps; subsequently they became exhausted and immobilized, confirming the potential lethal risk of this fishing gear for large cetaceans in the Estuary. Furthermore, the Estuary is an important feeding ground for large whales in summer and thus, feeding activities may make whales more susceptible to interact with fishing gear along coasts. Hence, changes in fishing practices may have driven the increase in entanglement events of large whales that we observed. We could not confirm this potential association as we did not analyze entanglement events with respect to fishing effort using traps and pots for the study period, due to complexity of data (*e.g.* multispecies, many different fishing areas at different times).

The last explanation for the increase in entanglement may be an improvement of public awareness and sampling effort. The use of stranding data to quantify the incidence of human interactions with marine mammals such as entanglement is the most controversial and problematic aspect in stranding studies (Lopez *et al.* 2002). Stranding data are subject to multiple biases such as sampling effort and public awareness, so it is important to consider that stranding data are not random samples from populations (Goldstein et al. 1999). Despite biases related to stranding studies, our data cover a long time-series and multiple species, which makes it a valuable source of information for anthropogenic interactions with marine mammals in the SLE and NWGSL. Temporal trends observed in this study, such as the increase of entanglement events, were not explained by sampling effort as SLE beluga stranding events recorded by the network were constant since 1994. The beluga is a resident of the SLE and a carcass recovery program for this species has been in place since 1982, making it an indicator of stranding effort and public awareness. As well, variations of specific anthropogenic incidences between years involving a few species suggest that other ecological mechanisms were involved.

The decline in entanglement events of dead large cetaceans since 2003 was concurrent with the creation of the marine mammal emergency network (RQUMM) in Quebec. Our results indicated that the disentanglement program of the network prevented and reduced mortality due to entanglement of large cetaceans in the SLE and NWGSL. Large whales are more likely to survive entanglement, even if they drag attached gear (Perrin *et al.* 1994, Hall *et al.* 2000). Human disentanglement of large whales is known to prevent death (Hall *et al.* 2000) as reported in the Bay of Fundy and Newfoundland since the establishment of the marine mammal entrapment assistance program (Lien 1994).

Incorporating uncertainty

Long-term stranding data may be useful to obtain a global overview of human incidence on marine mammals, but it must be combined with other more direct methods in management. Recently, it was suggested to incorporate uncertainty in analyzing human-induced mortality (Wade 1998, Slooten *et al.* 1999, Taylor *et al.* 2000, Hammill and Stenson 2009). The population biological removal (PBR) approach has been proposed and developed in the 1994 amendments to the U.S. Marine Mammal Protection Act (MMPA) in response to deficiencies of previous management schemes where populations are not sufficiently known. The objective is to maintain the population above a sustainable optimum corresponding to 50–80 % of the estimated pristine population size (Wade 1998).

This requires that total annual human-caused mortality and serious injury be less than the PBR. Rigorous simulation tests show that the PBR is robust when model assumptions are relaxed and a plausible uncertainty is included (Palka 2002). The PBR approach is also a more direct measure because it monitors the human activity that caused mortality (Taylor *et al.* 2000). The PBR is defined as:

$$PBR = N_{min} \times 0.5\ R_{max} \times F_r$$

where, N_{min} is the estimated population size using the 20-percentile of the lognormal distribution, R_{max} is maximum population growth rate, and F_r is the recovery factor (between 0.1 and 1.0) (Wade 1998).

We estimated the total annual human-induced mortality of minke whales from anthropogenic interactions. Using a minke whale population estimate for the GSL of 325 individuals (Lawson and Gosselin 2009) and default values for F_r at 0.5 to account for unknown biases and an R_{max} of 0.04 due to a paucity of data on minke whale maximum growth rate (see Wade 1998), we calculated that the mortality due to anthropogenic activities should be less than 3 individuals per year (PBR). In 2000, 2002, 2003 and 2005 this estimated PBR was exceeded (8, 5 and 4 deaths respectively associated to entanglement events) in our study area. This suggests that the minke whale may experience unsustainable mortality during some years in the SLE and NWGSL. However, this is a rough estimate of mortalities induced by entanglement on minke whale and involves multiple biases. First, our results contained only those cases observed and reported to the network in Quebec waters. Second, not all fishermen report their entanglement. Finally, some dead animals sink, are consumed by scavengers and never come ashore where they can be reported to a stranding network (Kingsley 2002, Hammill *et al.* 2007). Nevertheless, it is important for data-poor populations to consider tools such as PBR (Hammill and Stenson 2009) to address sources of uncertainty (Lewison *et al.* 2004), which estimate a target level of acceptable mortality (Taylor *et al.* 2000).

Conclusion

This study presented a comprehensive analysis of temporal trends of anthropogenic interactions with several species of marine mammals of the Estuary and the northwestern Gulf of St. Lawrence, confirming that anthropogenic interactions with marine mammals occur mostly during summer. Our results show that some anthropogenic interactions with some marine mammal species are of concern, including shooting of harbour seals, a protected species in eastern Canada, suspected illegal hunting of harbour porpoises, a species of special concern (Baird 2003a) in a marine park, and entanglement of minke whales that may exceeded the estimated PBR in some years. However, we lack sufficient information to evaluate threats to these three species, especially for the minke whale as there are no data on distribution, few and sporadic data on trends in abundance of marine mammals and no data on capelin abundance (Carscadden et al. 2001, DFO 2001, Bundy *et al.* 2009), and entanglement levels have not been thoroughly investigated for large whales in the Estuary (*e.g.* location, type of fishing gear and species involved annually).

Hence, our findings highlight the need for more information on cetacean abundance, distribution and the magnitude of human interactions with marine mammals, particularly in the Saguenay–St. Lawrence Marine Park, the SLE and NWGSL, areas identified as Ecologically and Biologically Significant for marine mammals (Lesage *et al.* 2007).

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CONCLUSION GÉNÉRALE

Nos résultats suggèrent que les variations dans les conditions environnementales de l'estuaire et du nord-ouest du golfe du Saint-Laurent peuvent en partie expliquer les variations dans l'occurrence des échouages de mammifères marins observés de 1994 à 2008. Bien que les mécanismes expliquant cette relation n'aient pu être identifiés dans le cadre de notre étude, notre analyse suggère toutefois que certains facteurs environnementaux pourraient être liés aux événements d'échouages en influençant (de manière indirecte) la distribution des espèces migratrices et la mortalité individuelle des espèces résidentes et pagophiles. Dans le cas particulier des floraisons d'algues toxiques (2008), les répercussions sur la mortalité individuelle semblent être plus directes. Globalement, le nombre d'événements d'échouages augmente depuis 1994 et il est plus important en été, période où la plupart des mammifères marins sont présents. Les résultats montrent une influence négative des conditions de l'eau (volume de la couche intermédiaire froide, température de surface et débit d'eau douce) sur les événements d'échouage de la plupart des espèces. D'autres changements environnementaux ont également été observés et associés spécifiquement à certaines espèces : i) une relation négative entre le volume de glace et l'occurrence des échouages de phocidés pagophiles et de mysticètes, ii) une relation négative entre l'abondance d'euphausiacés et l'occurrence des événements d'échouages du petit rorqual et du marsouin commun.

Dans un deuxième temps, nos résultats révèlent que les activités humaines dans l'estuaire affectent particulièrement les cétacés. Les prises accidentelles de petits rorquals et de rorquals à bosse et les autres activités anthropiques impliquant le marsouin commun ont augmenté significativement depuis 1994. Les prises accidentelles de petits rorquals ont été rapportées principalement dans des casiers d'invertébrés et excèdent certaines années le prélèvement biologique potentiel (PBP) du « stock » de petits rorquals du golfe et de l'estuaire. Dans le cas du marsouin commun, les cas ont été rapportés principalement dans la région du Parc Marin Saguenay–Saint-Laurent, suggérant une chasse illégale.

Dans le cadre de notre étude, les précisions acquises sur l'influence des facteurs environnementaux et anthropiques sur la mortalité des mammifères marins nous permettent de mieux comprendre les relations entre les récents changements observés dans l'écosystème (diminution du couvert de glace, floraison d'algue toxique, etc.) et la communauté de mammifères marins. Ces connaissances sont essentielles à l'élaboration de mesures de gestions et de conservation des mammifères marins de l'estuaire et du nord-ouest du golfe.

Néanmoins, il est important de considérer que certains événements d'échouages ne sont pas rapportés et donc, l'échouage représente une approximation de la mortalité et non une évaluation pour une population entière. De plus, il est difficile de contrôler les biais associés à l'effort d'échantillonnage (effort variable entre les espèces et entre les années) des échouages. Cet échantillonnage toutefois, semble relativement constant entre 1994-2008. Nous sommes conscients de la limite de cette étude et que dans certains cas, l'échouage est un outil important pour comprendre les changements environnementaux pouvant causer la mortalité (*p. ex.* floraison d'algue toxique). Afin de discerner l'influence des changements environnementaux sur la distribution et la mortalité, les données d'échouages devraient être couplées à des données d'abondance dans l'aire d'étude. Ces données permettraient de valider ou d'infirmer la relation entre l'abondance des individus et la fréquence d'échouage localement pour une espèce donnée. Cette information serait aussi d'une grande valeur pour quantifier l'impact des activités anthropiques sur les mammifères marins dans l'estuaire, une région fortement exploitée par l'homme (tourisme, trafic maritime, pêche commerciale, etc.) mais également un des berceaux de la conservation du milieu marin au Québec. De plus, l'abondance de capelan pourrait être ajoutée aux modèles environnementaux puisque cette espèce est une proie importante pour plusieurs mammifères marins (Marchand *et al.* 1999) et qu'elle est l'espèce clef de l'écosystème, à la suite de l'effondrement de la pêche aux poissons de fond vers les années 1980 (Grégoire *et al.* 2008). Ceci permettrait de mesurer les répercussions de ces changements dans la structure de la communauté, induite par la surpêche, sur les mammifères marins de l'écosystème du Saint-Laurent. Cependant, peu de données d'abondance historique ne sont disponibles sur l'ensemble de la région pour les espèces de mammifères marins concernées ainsi que sur l'espèce clef, le capelan.

Avec le réchauffement climatique global anticipé, nous pouvons nous attendre à un déclin continu du couvert de glace et de la productivité biologique dans les environnements marins (Schmittner 2005). De telles modifications dans les conditions abiotiques de l'écosystème du Saint-Laurent sont susceptibles d'influencer les processus démographiques (*p. ex.* les taux de survie des jeunes phoques pagophiles) ou la distribution individuelle chez les espèces de mammifères marins (*p. ex.* l'accessibilité à un habitat ou la disponibilité des ressources pour les grands cétacés). À l'hiver 2009, le réseau québécois d'urgence pour les mammifères marins observa à Gaspé la présence, peu habituelle, de grands rorquals et un grand nombre d'échouages de jeunes phoques du Groenland pendant la saison de reproduction. Ces deux événements furent de toute évidence associés à l'absence de couvert de glace dans le golfe du Saint-Laurent. Dans ce cas-ci, l'absence de glace semble avoir entraîné une grande mortalité juvénile chez le phoque du Groenland, mais a augmenté l'accessibilité à un habitat pour les cétacés. Une présence accrue de grandes baleines augmente la probabilité d'interactions avec les activités humaines comme les pêcheries et conséquemment peut entraîner une augmentation du nombre de prises accidentelles de grands cétacés. Or, les prises accidentelles ne sont que très peu documentées et nos résultats suggèrent une prédisposition de ces espèces dans l'estuaire. Une menace pèse également sur la communauté marine en raison de la floraison d'*Alexandrium tamarense* documentée dans l'estuaire en 2008. Cette algue toxique est connue pour s'enkyster et entrer en dormance dans le sédiment (Fauchot *et al.* 2005). Il est donc possible d'observer d'autres événements de mortalité causée par des floraisons dans les prochaines années à l'embouchure du Saguenay, une des aires d'alimentation les plus importantes de tout l'écosystème (Simard 2008).

Subséquemment, les recherches futures sur les populations de mammifères marins du Saint-Laurent devront intégrer davantage les récents changements environnementaux observés, c'est à dire la diminution du couvert de glace et la modification de la structure de la communauté marine (Savenkoff *et al.* 2007, Galbraith *et al.* 2008). Étant au sommet du réseau trophique de l'écosystème du Saint-Laurent (Morissette *et al.* 2006), les diverses réponses de ces prédateurs pourraient nous renseigner sur l'effet de ces changements sur la structure et le fonctionnement de l'écosystème marin et prédire sa réponse aux changements climatiques futurs.

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