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Modelling Oceanic Fates of Oil, Drilling Muds and Produced Water from the Offshore Oil and Gas Industry, with Application to the Queen Charlotte Basin

Modélisation du devenir du pétrole, des boues de forage et de l'eau produits par l'industrie extracôtière du pétrole et du gaz appliquée au bassin de la Reine-Charlotte

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ABSTRACT

This manuscript describes the fate of oil, produced water and drilling muds that may be introduced into the ocean by offshore oil exploration and production, and also discusses models of these fates. Oil releases are generally accidental, whereas produced water and drilling muds enter as a normal part of oil exploration and production.

Efforts to model the oceanic fates of contaminants from the offshore oil and gas industry require both generic models and site-specific models. Generic models, which simulate the behaviour of contaminants in the ocean, have been developed over a period of several decades, and include the cumulative knowledge of laboratory and field experiments, theoretical studies, and experience with acute and chronic releases of contaminants, assembled to provide the industry and regulatory agencies with guidelines for safe, environmentally benign operations. Oil spreading on the ocean, oil advection over the ocean by winds, and oil evaporation are examples of such processes.

The role of combining these individual processes into a computer application that will provide reasonable accounting of the risks and impacts of contaminants, is filled by integrated computer models. In the past decade several commercial products have been developed to fill this requirement, along with a few additional products developed by government and non-profit agencies. These integrated models address two issues. First, the contaminant spread and drift through the ocean must be simulated prior to exploration to answer questions such as:

- If contaminant is spilled at a given spot, what shoreline locations are likely to be affected?
- Where might a spill occur that could threaten a particular shoreline location of concern?
- What concentrations of contaminants will likely reach a given spot, through individual releases of large quantities, or smaller volume but more frequent releases?

Second, if hydrocarbon exploration proceeds, integrated models must be available to predict the motion of any contaminant released, to enable clean-up and protection operations.

It is expected that integrated models will be available to provide the means to address issues such as these for release of floating contaminants. In the case of drilling muds and produced water, which might be released into the ocean at reasonably small rates over the entire life of an oil and gas production region, the computer applications may require additional development. All integrated models require site-specific information. Processes such as oil evaporation, spreading, and emulsification depend on features of local oil. Processes such as drift, emulsification, and shoreline adhesion require knowledge of shoreline slope and material, ocean currents, tidal currents, wind and wave regime, usually at each site in the basin, at each season of the year.

Funding was provided until 1996 by the Panel for Energy Research and Development (PERD) and by Fisheries and Oceans Canada to examine the physical oceanography of the Queen Charlotte Basin, with concentration of effort for seasons between late spring and early autumn. These studies provided information on the general oceanographic properties of this region, as presented by Cretney *et al*. (2003), and began the development of numerical hydrodynamical models of ocean currents for input to the integrated computer models. The faster computers and cheaper memory and disk storage now available will enable the required improvement of these numerical models.

Recommendations

- Successful modelling of sub-lethal impacts of drilling muds and produced water requires an active laboratory program measuring the dose-response relationships for the contaminants of concern and the organisms of interest.
- Integrated models of contaminant fates must be implemented for the Queen Charlotte Basin, and applied to determine risk of contaminant impact on sites within this region. If oil is discovered during exploration, its properties must be determined and input to integrated models of fates of contaminants in this region prior to oil and gas development. These models must include local meteorological, oceanic and shoreline characteristics.
- Several numerical, hydrodynamical, ocean models have been applied to the Queen Charlotte Basin, and evaluated with oceanographic observations. PERD funding for this program ceased in 1996. Faster computers and improved hydrodynamical models have been developed by the international community in the years since the completion of this program, and funding should be provided to apply these improvements to the Queen Charlotte Basin. Upgrades are required to improve simulations of winter currents, tidal currents, bottom currents, rate of exchange of water between basins, penetration of contaminants into inlets, channels and bays, and the potential of oil to sink below surface brackish water and penetrate into inlets below surface.
- Additional observations are required to provide better model simulations of ocean currents and drift. A program to measure winter currents using surface drifters will help determine the penetration of oil-on-surface into inlets. Better measurement of bottom currents will help determine transport of drilling muds away from well heads, and toward unique biological features such as sponge reefs.
- Since completion of the PERD-funded field program in 1996, there have been major inter-annual changes in seawater properties in the northeast Pacific Ocean that appear to have impacted fish stocks in the Queen Charlotte Basin. Funding should be provided for an ongoing program to determine inter-annual changes in the seawater properties of the Queen Charlotte Basin, and their impact on the ecology and fish stocks. Without such research, it will be difficult to distinguish changes in ecology due to contaminants from changes due to climate variability and change.
- Accurate wind measurements and forecasts are essential for spill prediction and risk assessment. The present array of Canadian Weather Buoys on the Pacific Coast should be considered a minimum number for data input to oil-spill models and for evaluation of regions-at-risk. Canadian Weather Buoys measure winds in mid-strait, and do not provide needed information on near-shore winds that will influence adhesion of oil on the beaches, or into inlets and narrow channels. Real-time winds as measured at Canadian Weather Buoys and forecast winds based on regional, high resolution models must be available to oil spill responders in the event of an oil spill, if hydrocarbon exploration is to take place.

RÉSUMÉ

On expose dans ce document le devenir du pétrole, de l’eau produite et des boues de forage qui peuvent s’échapper dans l’océan dans le cadre des activités d’exploration et de production en plus d’examiner les modèles utilisés pour l’étudier. Les dégagements de pétrole sont généralement accidentels alors que l’eau produite et les boues de forage sont normalement déversés dans le cadre de l’exploration pétrolière et de la production de pétrole.

Les efforts de modélisation du devenir dans l’océan des contaminants libérés par l’industrie pétrolière et gazière exigent l’utilisation de modèles génériques et de modèles spécifiques à des emplacements. Des modèles génériques, simulant le comportement des contaminants dans

l'océan, ont été mis au point pendant un intervalle de plusieurs décennies et englobent les connaissances cumulées issues d'expériences en laboratoire et sur le terrain, d'études théoriques et d'expériences sur des dégagements aigus et chroniques de contaminants assemblées dans le but de fournir à l'industrie et aux organismes de réglementation des lignes directrices pour une exploitation sécuritaire et sans danger pour l'environnement. L'étalement du pétrole sur l'océan ou son advection par les vents et l'évaporation du pétrole constituent des exemples de processus modélisés.

Les modèles informatiques intégrés ont comme fonction la combinaison de ces processus individuels dans des applications logicielles fournissant des évaluations raisonnables des risques que posent les contaminants et de leur incidence. Au cours de la dernière décennie, plusieurs produits commerciaux ont été mis au point pour satisfaire ces besoins et quelques outils additionnels ont été mis au point par des organismes gouvernementaux et sans but lucratif. Ces modèles intégrés abordent deux problèmes; premièrement, l'étalement et la dérive des contaminants dans l'océan doivent être simulés avant l'exploration afin de répondre à des questions comme les suivantes.

- Si des contaminants sont déversés en un point donné, quels emplacements littoraux seront vraisemblablement touchés?
- Où pourrait se produire un déversement qui menacerait un emplacement littoral particulièrement préoccupant?
- Quelles concentrations de contaminants atteindraient vraisemblablement un emplacement donné lors de déversements isolés de grandes quantités ou de déversements plus fréquents de volumes moindres?

Deuxièmement, s'il y a exploration à la recherche d'hydrocarbures, des modèles intégrés de prévision des déplacements de tout contaminant déversé doivent être disponibles pour permettre les opérations de nettoyage et de protection.

On s'attend à ce que des modèles intégrés soient disponibles pour l'étude de tels problèmes en cas de déversements de contaminants flottants. Dans le cas des boues de forage et de l'eau produite, dont de raisonnablement petites quantités peuvent être déversées dans l'océan pendant toute la durée de la production pétrolière et gazière dans une région, il pourra s'avérer nécessaire de mettre au point de nouvelles applications. Tous les modèles intégrés exigent comme intrants de l'information spécifique à des emplacements. Des processus comme l'évaporation, l'étalement et l'émulsification du pétrole dépendent de caractéristiques du pétrole local. Des processus comme la dérive, l'émulsification et l'adhérence aux rivages exigent des connaissances de la pente et des matériaux des rivages, des courants océaniques, des courants de marée, des régimes des vents et des vagues et ce en chaque emplacement du bassin ainsi que pour chaque saison de l'année.

Jusqu'en 1996, un financement était fourni par le Groupe interministériel de la recherche et du développement énergétiques (GRDE) et Pêche et Océans Canada pour l'étude de l'océanographie physique du bassin de la Reine-Charlotte en concentrant les efforts sur les saisons entre la fin du printemps et le début de l'automne. Ces études ont fourni de l'information concernant les propriétés océanographiques générales de la région (Cretney et coll. (2003)) et ont permis de commencer à mettre au point des modèles hydrodynamiques numériques des courants océaniques à introduire dans les modèles informatiques intégrés. Les ordinateurs plus rapides et d'une capacité de stockage en mémoire et sur disque à moindre coût aujourd'hui disponibles permettront l'amélioration nécessaire de ces modèles.

Recommandations

- La réussite de la modélisation des impacts sub-létaux des boues de forage et de l'eau produite exige un actif programme de mesure en laboratoire des relations doses-réponses pour les contaminants en cause et les organismes d'intérêt.
- Des modèles intégrés du devenir des contaminants doivent être mis en oeuvre pour le bassin de la Reine-Charlotte et appliqués afin de déterminer les risques d'incidence des contaminants pour des emplacements dans cette région. Si du pétrole est découvert pendant les travaux d'exploration, ses propriétés doivent être déterminées et introduites dans des modèles intégrés du devenir des contaminants dans la région avant la mise en valeur du pétrole et du gaz. Ces modèles doivent tenir compte des caractéristiques météorologiques, océaniques et littorales locales.
- Plusieurs modèles hydrodynamiques numériques de l'océan ont été appliqués au bassin de la Reine-Charlotte et évalués d'après des observations océanographiques. Le financement de ce programme par le GRDE a cessé en 1996. Depuis la fin de ce programme, des ordinateurs plus rapides et des modèles hydrodynamiques améliorés ont été mis au point par la communauté internationale et un financement devrait être assuré pour l'application de ces améliorations à l'étude du bassin de la Reine-Charlotte. Il est nécessaire d'améliorer les simulations hivernales des courants, des courants de marée, des courants sur le fond, des taux d'échange d'eau entre bassins, de la pénétration des contaminants dans les bras de mer, les chenaux et les baies ainsi que des possibilités que du pétrole s'enfonce sous l'eau de surface saumâtre pour pénétrer dans les indentations du littoral sous la surface.
- Des observations additionnelles sont nécessaires pour l'obtention de meilleures simulations des courants océaniques et de la dérive. Un programme de mesure des courants en hiver au moyen de bouées dérivantes facilitera la détermination de la pénétration en surface du pétrole dans les indentations du littoral. De meilleures mesures des courants sur le fond faciliteront la détermination de la dispersion des boues de forage autour des têtes de puits vers les entités biologiques exceptionnelles comme les récifs à éponges.
- Depuis la fin du programme sur le terrain financé par le GRDE en 1996, il y a eu dans le nord-est de l'océan Pacifique des changements majeurs d'une année à l'autre des propriétés de l'eau de mer qui semblent avoir eu une incidence sur les stocks de poissons dans le bassin de la Reine-Charlotte. Un financement devrait être assuré pour un programme permanent de détermination des changements des propriétés de l'eau de mer d'une année à l'autre et de leur incidence sur l'écologie et les stocks de poissons. Si de telles recherches ne sont pas effectuées, il sera difficile de distinguer les changements écologiques attribuables aux contaminants de ceux engendrés par la variabilité et le changement climatiques.
- Des mesures et des prévisions précises des vents sont essentielles pour la prévision du comportement des déversements et l'évaluation des risques. L'actuel réseau de bouées météorologiques canadiennes sur la côte du Pacifique devrait être considéré comme le minimum requis pour l'obtention des données à introduire aux fins de la modélisation des déversements de pétrole et de l'évaluation des régions menacées. Les bouées météorologiques canadiennes permettent la mesure des vents au centre des chenaux et ne fournissent pas l'information nécessaire sur les vents près des littoraux qui auront une incidence sur l'adhérence du pétrole aux plages et sur sa pénétration dans les indentations et les chenaux étroits. Des données en temps réel sur les vents telles que celles fournies par les bouées météorologiques canadiennes et des prévisions des vents basées sur des modèles régionaux à grande résolution doivent être mises à la disposition des équipes d'intervention en cas de déversement si des travaux d'exploration à la recherche d'hydrocarbures doivent être exécutés.

TABLE OF CONTENTS

INTRODUCTION

Continental shelves are the most important regions of the world ocean from the perspective of marine ecosystems and sustainable harvest of resources by humans. On the other hand, these regions are also the most vulnerable to change and to impacts due to human activities (transport, disposal, inputs from rivers and coasts and so on). Therefore, non-sustainable activities such as oil and gas development and mineral extraction should be entered into with a great deal of care to prevent irreversible harm and to preserve as a legacy the sustainable activities. Offshore oil and gas activities have physical, chemical and biological impacts. Here we present a perspective of the fate of contaminants released by offshore oil exploration and production to the Queen Charlotte Basin.

Contaminants derive from two fundamentally different sources:

1) Day-to-day, chronic releases of materials including cuttings, muds, deck washings, domestic wastes, small oil spills, and products of combustion (from flaring or incineration).
2) Acute releases of oil or gas from blowouts, spills from tankers, storage facilities and underwater pipelines.

The impact, containment and mitigation of these two kinds of releases differ dramatically.

In anticipating the effects of any contaminant, the identification of the environmental pathways is crucial to understanding how the contaminant is likely to impinge on living resources. The correct assessment of pathways will anticipate "surprises" and help to prepare for them. Hydrocarbons, because they are hydrophobic, tend to favour surfaces and it is here that they do their greatest harm. Initially, spilled oil will spread on the surface of the sea where it causes well-known mortality to birds and marine mammals such as sea otters. Later, the non-volatile, insoluble portions of the oil become attached to solid surfaces and end up on beaches and in marine sediments where they continue to harm animals in those habitats. Estuaries, which are hatcheries and nurseries for many marine organisms, are probably the most sensitive habitats that could be impacted by oil. As the oil weathers, much of it evaporates, dissolves or is metabolized by microbes.

Chronic releases of contaminants from offshore activities can generally be controlled and mitigated through good housekeeping and through careful treatment of wastes. In particular, past experience shows that oil-based muds – especially those using diesel oil – have caused some of the more obvious impacts, and such drilling-fluid components can and should be avoided. Fortunately, replacements for oil-based muds are available, although they might entail greater expense. Of the chronic releases, produced water poses the greatest concern simply due to volumes that range from 15,000 – 500,000 m^3/day for a production basin, depending on location and age of individual wells. Older production wells normally emit larger volumes; exploration wells emit smaller volumes. Produced waters, which contain residual hydrocarbon, metals and, at times, radionuclides, are one of the main sources of oil pollution for offshore production. Clearly, the treatment of these waters and the monitoring of their composition will be central to the reduction of chronic chemical impacts from any offshore activity.

Acute or catastrophic oil spills are perhaps the best known and most feared aspects of offshore oil exploration, production and transport. Here it is important to note that each region has its own sensitivity to such spills simply due to the ecosystem (biological resources, estuaries, migratory pathways) and the physical environment (e.g., waves, winds, currents). In the case of the impact of potential oil spills in the Queen Charlotte Basin, the experience at Hibernia off Canada's Atlantic coast provides little guidance. Models evaluating hypothetical oil spills using historical climatology (winds) at Hibernia suggest that spilled oil will seldom, if ever, reach the shore. For Queen Charlotte Sound and Hecate Strait, particularly in winter, prevailing winds and storm systems will undoubtedly transport spilled oil onto shores.

Following recommendations by the West Coast Offshore Exploration Environmental Assessment in 1986, DFO has conducted a number of studies of physical processes in the region which will be helpful in the operation and design of offshore facilities and also in modelling the transport of spilled oil. Ocean water properties, waves, and currents were all studied during a seven-year field program completed in mid-1990s. These studies provide background information to enable predictions of oil motion should a catastrophic spill occur, and to assist in any decision on the future of the federal and provincial governments' moratoria on West Coast offshore drilling for oil and gas.

The scientific and petroleum communities have investigated these effects for many years, assembling a very impressive scientific literature on these processes, and a series of integrated models to simulate most processes. The first two parts of this paper examine the scientific literature that describes the known as well as unknown processes and includes brief summaries of some integrated software packages that address these issues. We discuss site-independent algorithms and integrated models that can be enabled for specific hydrocarbon exploration regions.

As a consequence of the present moratoria on hydrocarbon exploration in the Queen Charlotte Basin, few of these models are presently enabled for this region. This enabling process requires local knowledge of:

1) The nature of any oil presently below the ocean bottom of the Queen Charlotte Basin.
2) Local ocean winds and currents to simulate the motion of oil-on-water.
3) Wave climate, shoreline characteristics and bottom substrate to determine the weathering of oil and adhesion to bottom and shore.

Once these features are defined in an integrated model, users will be able to simulate fate of oil in the Queen Charlotte Basin, and to eventually consider biological and ecological impacts. As oceanographers we are best able to describe feature (2) noted above. The second section of this paper describes the present status of some deterministic, hydrodynamical ocean models of the Queen Charlotte Basin developed at the Institute of Ocean Sciences, based on hydrodynamical equations and on field studies conducted up to the mid-1990s, with funding from Fisheries and Oceans Canada and the Panel for Energy Research and Development (PERD). These hydrodynamical models include simulations of tidal currents, wind-driven currents and even buoyancy currents due to variations in water density, which combine to move contaminants through these waters. We evaluate the accuracy of the hydrodynamical models, and note future work required. We also present several model-based scenarios of surface particle drift due to these ocean surface currents. These scenarios do not simulate oil motion, but instead show the underlying motion of surface waters in the Hecate Strait Region. Simulations of individual particles are run for twenty days to provide a general guide for the geographical extent of possible current drift.

The final section of this paper presents a summary of research by Canadian scientists at the Bedford Institute of Oceanography, funded by the Panel for Energy Research and Development and by Fisheries and Oceans Canada, to investigate impacts of drilling waste discharge, based mainly on the experience over the past decade. This final section also presents a review of commercial and research models available for this topic.

1 OIL SPILL BEHAVIOUR

Various physicochemical processes govern the behaviour of crude oil and natural gas in the environment. A qualitative description of the processes helps in understanding how they affect the fate of an oil or gas release into the environment. A qualitative description of the processes is provided in this section.

A quantitative description of the various processes, however, is crucial to building oil or gas spill behaviour models that are capable of prediction. When a spill event occurs or preferably before it occurs, the behaviour models can forecast the movement of hydrocarbons on, above, and below the surface of a body of water. They can forecast what shoreline areas will be effected. They can estimate the degree of exposure to oil or gas of organisms and the probable effects. Quantitative behaviour models provide grounding for decisions regarding responses to spills.

Oil or gas spill behaviour models are constructed of mathematical process models. The process models may be based on known physicochemical principles or on experimentally determined relationships. The former process models are theoretical and the latter, empirical. Process models may also be classified as deterministic or stochastic. Deterministic models are generally mathematical expressions that give a unique answer for each set of values for parameters and variables. Stochastic models have built in randomness that provides a range of answers for given input values. Process models are generally either deterministic or a combination of deterministic and stochastic.

Most mathematical formulations can be categorised as theoretical or empirical, and deterministic or stochastic. Theoretical models are based on knowledge of the underlying physical or chemical principles of a process and may be solved by analytical or numerical computational methods. Analytical models are generally computationally simpler to solve than numerical models. Empirical models result from experimental studies of processes, but are not underpinned by theoretical knowledge. Deterministic models, as noted, generally give a single output or answer for a given set of input values. Because input values may vary in time and space, deterministic models may be run over and over again with varying input values to build a probability distribution of outputs. Such iterative models are sometimes referred to as probabilistic models. Stochastic models provide a range of outputs distributed according to the probability of random occurrences. Some process models may have elements of each category. Categorisation can be useful for distinguishing among models formulated by different groups at different times. Important processes described by process models are advection, spreading, evaporation, dispersion, dissolution, emulsification, sedimentation, oil-shoreline interactions, photodegradation, and biodegradation.

a) **Advection-diffusion**

The transport of oil and gas from a spill or blowout is governed by some combination of wind, wave, surface currents and oceanic or atmospheric turbulent diffusion. The net transport rate and direction of a spill is given by a vector sum of the individual processes acting on it (ASCE Task Committee, 1996). In real spill and blowout conditions oil or gas are not released instantaneously at a single point. Rather the release may take place over an extended period. Sophisticated models in use employ a mathematical device to aid in the prediction of how spilled material will behave. The spill is considered to be made up of a large number of pieces or parcels that move independently. These parcels or pieces are sometimes referred to as spillets or puffs. This method of simulating slick or gas movement is referred to as the Lagrangian approach (Huang, 1983) and is useful for tracking spills over large geographical areas (e.g., >100 km^2). The trajectory of the centres of spillets in the case of a surface spill is determined by a vector combination of wind, wave and current. Dividing each into a large number of contiguous packets or particles (e.g., Hodgins *et al*. 1991) simulates the spread of the individual spillets by turbulent diffusion. The particle centres move apart with time on the surface in a random walk process (Huang, 1983, Hodgins, 1991). The oil is effectively stretched by turbulence of the water. Droplets of oil may also be mixed down or dispersed into the water in 3D models (ASCE Task Committee, 1996, French, 1998) (see later discussion). Sophisticated 3D hydrodynamic models of a water body can provide input for predicting the motion of Lagrangian oil particles on the surface and in the near surface.

The hydrodynamic models are deterministic and correctly represent the interaction among various flow components and obey conservation laws such as those of mass and momentum

(ASCE Task Committee, 1996). They require powerful computers to perform calculations, much good quality data on winds and currents for input, special handling at boundaries, and validation of the outputs (Spaulding, 1995; ASCE Task Committee, 1996). The present models do not handle the strong surface gradients well (Spaulding, 1995; ASCE Task Committee, 1996). Although transport of oil at scales of 10-100 m is important because of concentration of floating oil by Langmuir or windrow circulation, algorithms representing such circulation are not yet in general use (Reed *et al*., 1999a). Circulation modes such as these or nutrient upwelling can potentially concentrate organisms and oil within the same structural elements of a water body. Lagrangian trajectory models built upon a hydrodynamic model provide trajectories of spilled oil or gas under the specific conditions of wind, wave, source type and position that are input into the model when it is run. Different conditions produce different trajectories. An ensemble of input conditions must be used to provide a distribution of probable trajectories for use in response planning and risk assessment (Galt and Payton, 1999).

b) **Spreading**

The spreading of a spill under the Euleurian/Lagrangian framework discussed above preserves the oil in spillets or parcels. Even upon the quiescent waters, oil slicks spread under control of gravitational, inertial, viscous and interfacial forces (Huang, 1983, and references therein). Indeed, process models were first elaborated by Fay (1971) and others (Huang, 1983) to simulate spreading of oil on still waters. Versions of these Fay models are still used in most spill behaviour models today (Reed *et al*., 1999a). Refinements of the Fay models generally make them more realistic. One such variant is the Mackay thick-thin coupled slick model (Mackay *et al*., 1980a,b), which is still used in oil spill behaviour models such as Spillsim. The model is an empirical one based on experiments and observations of real spills. Thick slicks are surrounded by thin ones of greater area. However, the general use of the Mackay model appears to be inhibited by the lack of a theoretical basis for the phenomenon it describes.

Shear spreading has been incorporated into advanced models. This phenomenon results from turbulent and breaking-wave shear that disperses droplets of oil into the water. These droplets subsequently resurface. While submerged, the droplets' horizontal trajectory can be different from that of the surface slick. Once gravity spreading has ceased, shear spreading is considered "as the correct explanation of the physics behind the spreading phenomenon" (Reed *et al*., 1999a).

Spreading of oil on water controls the rate at which other processes, such as evaporation, dissolution, photo-oxidation and biodegradation, take place. Some of the processes in turn can influence the spread of oil on water.

c) **Evaporation**

Of all the processes acting on a spill, evaporation has the greatest influence on the fate of constituent chemicals in the oil or gas. It can account for a 60% loss in volume of a light crude oil (Huang, 1983). The simplest model to implement is the thermodynamically based analytical model of Stiver and Mackay (1984), which relates evaporation rate to an oil's distillation curve. Others have developed the theory further (Johansen and Skroges, 1988; Reed *et al*., 1999a) to include change in evaporative loss with variable wind speed. Fingas (1997) provides empirical relationships between evaporative loss over time and distillation data for various crude oils. The most reliable and flexible of the modelling methods are the actual component or pseudocomponent models (Reed *et al*., 1999a). These models require the measurement of individual compounds or groups of compounds of similar chemical properties in the oil. An actual or pseudocomponent model for evaporative loss is preferable when the evaporation of specific components needs to be known for toxicological purposes (Stiver and Mackay, 1984).

Actual or pseudocomponent models, however, are computationally intensive. The concentration of each component of toxicological interest (e.g., individual aromatic compounds) in the oil is required as a minimum. If the object is to consider the loss of material from the oil slick, then computationally simpler analytical and empirical methods are suitable (Reed *et al*., 1999a). In any case, samples of the spilled oil are required for analysis to obtain data required for modelling the rate of its evaporation and the compositional changes taking place during evaporation.

Oil from the Queen Charlotte Basin has not been discovered. No data are available except what might be inferred from oil shows. Although generic crude oils may be used for process models and integrated oil behaviour models, if oil is discovered its properties must be determined and made available for use in models.

d) **Atmospheric dispersion**

Wind fields disperse oil components that have vaporised from spilled oil, natural gas and associated condensates from a blowout, and surfacing oil or gas from an underwater pipeline rupture, as well as smoke from oil or gas that has been set on fire. Atmospheric dispersion models can predict the fate of air-borne plumes of materials over sea and land (e.g., Elliot, 1999; Zheng and Yapa, 1997). Blowout and pipeline rupture models forecast the fate of jets and plumes of gas, oil and gas/oil mixtures (e.g., Zheng and Yapa, 1997; Yapa *et al*., 2001). A similar Euleurian/Lagrangian framework to that used for oil spill modelling underpins these atmospheric and underwater dispersion models. Continuous emissions of oil or gas may be broken up into a series of mathematically equivalent spillets or puffs (generally the former when referring to oil, and the latter to gas or smoke). A random walk process simulates the effect of turbulent diffusion in air and water. In the case of the underwater release of an oil or oil /gas mixture, an oil spill trajectory or behaviour model can be implemented when the oil reaches the water surface. An interesting aspect of underwater oil jets and plumes, the physics of which is not yet fully understood (Zheng and Yapa, 1997), is the propensity of the oil to break up into droplets (i.e., < 5 mm in size) before reaching the surface. The gas model can continue to simulate the dispersion of the gas as it breaks through the surface of the water into the air (Zheng and Yapa, 1997).

Elliot (1999) has described an interesting application of a spill model and atmospheric dispersion model. Simulations were carried out to hindcast the evaporated-petroleum track that had been determined by public reports of gasoline smell and land measurements of benzene, a major volatile constituent of the spilled gasoline. Although the benzene fraction of the gasoline would have been expected to evaporate within about 3 hours from the slick, its track could only be explained by assuming that the emission of benzene extended over a 12-hour period. The proffered explanation was that the oil dispersed into the underlying water, extending the period of evaporation (Elliot, 1999).

e) **Natural dispersion**

Natural dispersion is a process that results in the transfer of oil droplets from an oil slick into the water column under natural forcing conditions, such as wind, turbulence, and breaking waves (ASCE Task Committee, 1996; Reed *et al*., 1999a and references cited therein). Mackay and coworkers' (1977, 1980a,b) early mathematical dispersion model takes into account the sea state, as a function of wind speed only, the thickness and area of the oil slick, the viscosity of the oil and the oil/water interfacial tension. The dispersion equations can be applied to both the thick and thin slicks. The model also includes an estimate of the fraction of oil in droplets that are small enough to be considered as permanently dispersed. Other models have ignored the thin slick, thereby likely underestimating the overall dispersion rate (Reed *et al*., 1999a).

Empirical relationships have been devised for the entrainment rate (oil mass dispersed per unit time) and size distribution of oil droplets in water, as a function of oil properties, slick thickness, breaking wave energy and temperature (Delvigne and Sweeney, 1988). In addition, Delvigne and Sweeney (1988) provided a relationship between the intrusion depth of oil droplets and wave height.

The calculated oil drop distributions can be incorporated into multidimensional vertical diffusion models (Daling *et al*., 1990; ASCE Task Committee, 1996). The exposure of fish and other organisms in the water column is estimated based on the subsurface movement of dispersed and dissolved oil components (French, 1998). The work by Delvigne and Sweeney (1988) also supports the shear-spreading model mentioned above.

Dispersion or entrainment models based on the work of Delvigne and Sweeney are the most common oil-spill models in use today (Reed *et al*., 1999a). Examples of applications are:

- NOAA's automated data inquiry for oil spills (ADIOS), an oil weathering model,
- SINTEF's oil weathering model (The acronym represents *S*tiftelsen for *IN*dustriell og *TE*knisk *F*orskning ved Norges Tekniske Hoegskole, with English translation: The Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology),
- SINTEF's oil spill contingency and response (OSCAR) model (Reed *et al*., 1999b),
- Applied Science Associates' oil spill trajectory and fate model with GIS integration, OILMAP,
- Applied Science Associates' spill impact model application package, SIMAP.

f) **Dissolution**

Dissolution is the process by which a substance dissolves in another. In the context of oil spills, it refers to the oil dissolving in water. Because oil is a complex mixture of compounds of widely varying solubility, the dissolution of oil actually involves the partitioning of these constituents (components) between the oil and water phases. Partitioning of oil constituents in slicks can occur directly from the slicks and indirectly from dispersed droplets (Mackay and Leinonen, 1977). Dissolution accounts for loss of a smaller proportion of an oil spill than does evaporation and is often ignored in determining mass balances in spill models (ASCE Task Committee, 1996). Yet, some constituent compounds of oil dissolved in the water can partition into organisms. The partitioning of compounds from spilled oil into water is of great toxicological significance (ASCE Task Committee, 1996). Component-specific models estimate the concentration of individual compounds in water, based on thermodynamic properties (ASCE Task Committee, 1996). Thus, the exposure of organisms to specific compounds of toxicological interest, such as the aromatic hydrocarbons benzene, anthracene and benzo[a]pyrene, can be estimated as well. Furthermore, multimedia and food-web models can provide estimates of aromatic hydrocarbon concentrations in tissues.

g) **Emulsification (water-in-oil)**

Water-in-oil emulsions form when water is dispersed into oil. Such emulsions are often referred to as "chocolate mousse", because they have a colour and consistency reminiscent of the dessert. Incorporation of water in oil can increase the oil's apparent viscosity over a thousand-fold (ASCE Task Committee, 1996). Fingas *et al*. (1999) classify water-in-oil emulsions into three categories: stable, mesostable and unstable. Stable emulsions have true viscosities of about 500-800 times larger than the starting oil, appreciable elasticity, and a red to brown colour. Left alone, stable emulsions can last for years without separating. Mesostable emulsions tend to be red-to-black in colour, have true viscosities of about 20-200 times the starting oil, and less elasticity than stable emulsions. Mesostable emulsions generally separate in a few days or weeks. Both stable and mesostable can retain up to 90% water. Unstable emulsions of oils retain almost no water when removed from an energetic environment, and the colour and other properties of unstable emulsions and neat oils do not differ.

Fingas *et al*. (1999) note that water can be entrained by sea energy into highly viscous oils as large droplets. Although the concentration of entrained water can be quite high (ca. 90%), the colour, viscosity and elasticity of the mixture is essentially unchanged from that of the oil. The separation of oil and water begins within hours. The rate of separation can be very slow, because the high viscosity of the oil slows the coalescence and migration of oil droplets.

The stability of an emulsion is a property of constituents of oil called surfactants (surface active compounds) that like to reside at the interface between oil and water, but are more soluble in oil than in water (Canevari and Fiocco, 1997). The asphaltenes, resins and porphyrins are such surfactants. According to Fingas *et al*. (1999), stable emulsions form when the asphaltene concentrations exceed 7% by mass in oil. They further note that mesostable emulsions form when the combined asphaltenic and resin concentrations in oil exceed 3%, but the BTEX (benzene, toluene, ethylbenzene and xylene) fraction is less than 3%. Stable emulsions also form when the nickel and vanadium levels in crude oil exceed 0.0015% (Canevari and Fiocco, 1997). The metals are present in oils as metal-porphyrin as well as non-porphyrin complexes. The porphyrins arise in oil from chlorophyll, haemoglobin and similar natural products. The concentrations of metal porphyrins may act as a surrogate measure of the asphaltene content of oil.

Most oil spill models use equations formulated by Mackay *et al*. (1980a,b), or variations thereof, to simulate emulsification of oils in water (ASCE Task Committee, 1996). These equations relate the rate of water incorporation into oil to the square of wind speed, the fraction of water incorporated in the oil, and a rate constant dependent on the oil type. They also estimate the viscosity of the emulsion from the starting oil's viscosity and the amount of water incorporated in the oil. Estimates based on the surfactant composition of the oil are clearly warranted by the research of Fingas *et al*. (1999). An emulsification model developed in the 1970's at the University of Southern California incorporated asphaltene and resin content, mixing energy, pH, and temperature, but is considered complex and data intensive (Huang, 1983). It probably warrants a revisit. At any rate, emulsification predictions based on oil composition soon should be available (Reed *et al*., 1999a). In the case of the Queen Charlotte Basin oil, should any be found, reliable estimates of its propensity to emulsify will require compositional analysis and laboratory experiment.

Accurate estimation of the rate and extent of emulsification is extremely important to forecasts of the fate and effects of spilled oil. Emulsification modifies the outcome of almost all other processes affecting oil. It drastically slows evaporation, dissolution and spreading into thin slicks. It prevents dispersion, except in very high-energy wave fields. These characteristics of the emulsified oil are directly related to the up-to-thousand-fold increases in the viscosity of stable emulsions. As a consequence of emulsification, spill response decisions become limited. Recovery, chemical dispersion and ignition become more difficult for emulsified compared to neat oil (Canevari and Fiocco, 1997). A larger amount of oil may come to shore than would otherwise. On the other hand, there may be situations where emulsification may mitigate environmental damage by limiting evaporation, dispersion, dissolution and spreading. Simulations and real, controlled spills are useful to aid in making appropriate response decisions. Controlled spills of any oil discovered in this region would be useful to determine environmental behaviour, but the risk of controlled spills to the environment may be considered too great to compensate for the knowledge gained.

h) **Sedimentation**

Sedimentation of crude oil can occur by density increase through weathering, by ingestion and elimination in faecal pellets, by contact with natural suspended particulate matter (SPM), or by contact with bottom sediments through turbulent mixing. The first process is unlikely in cold waters (Spaulding, 1988), such as found off the B.C. coast. The last will be possible in waters that are less deep than 2-5 times the breaking-wave height (Reed *et al*., 1999a). The second two processes are likely to be the principal means of sedimentation. Turbulent shear provides a wide distribution of oil droplets from a slick, some of which can be expected to enter the food-size range of zooplankton. Chemical dispersants can generate vast numbers of oil droplets. Coagulation of oil droplets with SPM and settling would appear to be the main process of sedimentation of oil from a spill.

Explicit models for the interaction of oil droplets and SPM seem to be absent from modern oil spill fate and effect models. The process is not discussed in two major reviews of oil spill modelling (ASCE Task Committee, 1996; Reed *et al*., 1999a). The process is clearly important, because near total dispersion can occur by turbulent mixing in storms and by application of chemical agents. The answer to the exclusion of such an important process may be "the solution to pollution is dilution." Once the oil is entrained permanently in the water column, it may rapidly become too dilute to have an environmental impact and be degraded through natural processes, such as biodegradation and photodegradation. Still, "absence of knowledge is not knowledge of absence" to quote another homily. A critical pathway may lurk unknown and unexplored, if better understanding of the oil-SPM process is not obtained for reliable modelling.

Throughout the world's oceans, particulate aggregates appear to be the dominant form of settling material (Jackson and Burd, 1998). Such aggregates may have settling velocities of 50-100 m/d, which is up to 1000-fold faster than those of single cells (Jackson and Burd, 1998). Association with such rapidly settling aggregates, may rapidly transfer oil droplets to the ocean floor.

Cycles of particle aggregation and disaggregation occur, brought about by chemical and biological processes (Smith *et al*, 1992; Wells and Goldberg, 1993; Chin *et al*., 1998). Millimetre or larger aggregates may be made up of individual living cells, algal or bacterial, or colloids (Jackson and Burd, 1998; Guan *et al*., 1998). Oceanic colloids are probably submicron assemblages of macromolecules. Predators may consume food-sized aggregates. Associated oil droplets and their toxicant load could thus enter the food web.

Marine aggregates are characterised by their fractal (Mandelbrot, 1983) dimension (D), which generally varies in the range 1.3-2.3 (Jackson and Burd, 1998). The mass (M) of a fractal aggregate (not including internal water) is proportional to its diameter (d) raised to the power D: $M \propto d^D$. Because the volume (V) occupied by the aggregate (including internal water) is given by $V \propto d^3$, the aggregate's density (ρ), as given by $\rho \propto M/V = d^D/d^3 = d^{D-3}$, decreases for $1.3 < D < 2.3$ (e.g., for D=2, $\rho \propto 1/d$).

The open areas become ever larger as the aggregate size increases. The open areas are channels through which water can flow, when the particles settle or encounter turbulence (Li and Ganczarczyk, 1988). Thus, the aggregates can filter smaller particles entrained in the water flow through the aggregates (Li and Logan, 1997a,b; Jackson and Burd, 1998; Li and Yuan, 2002). Hence, oil droplets can interact with aggregates by collisions with similar-sized and smaller aggregates or by being filtered out in larger aggregates. Oil associated with aggregates can be expected to settle rapidly, although blockage of the flow through the aggregates by the oil droplets would tend to slow the settlement (Li and Ganczarczyk, 1988). Should low density oil droplets be of sufficient size and number to make an aggregate positively buoyant, the assemblage would rise rather than fall through the water.

Although, as noted above, explicit models for the interaction of oil droplets and SPM seem to be absent from modern oil spill fate and effect models, an early USC model (described in Huang, 1983) included oil-sediment adherence and sedimentation submodels. The adherence submodel was a function of sediment load and salinity. The sedimentation submodel was derived under the generally unrealistic assumption that oil-sediment flocs were "spheres in a calm and uniform medium" (Huang, 1983). Li and Logan (1997a,b) have investigated the collision frequencies of small particles with fractal aggregates of latex microspheres under conditions of both differential sedimentation and turbulence. Li and Yuan (2002) have recently extended the work to include fractal microbial aggregates. In principle, with suitable parameter estimations, the expressions that these researchers have derived could be incorporated into oil spill fate and effects models for organic SPM under oceanic conditions. A number of oil-biodegradation experiments in marine mesocosms (volume ≈10 to 100 m^3) have been marked by the appearance of microbial flocs (Cretney, 1992). Cretney (1992) examined the possible advantages and disadvantages of flocculation to microbial oil degraders. The principal disadvantages could be removed by assuming that the flocs were fractal with a dimension between 1.6 and 2.2.

Sedimentation of oil components can take place following partitioning from oil slicks and droplets into SPM via dissolution in the water phase. Most oil components are hydrophobic and will tend to sorb into organic SPM of all sizes. Hence, oil components sorbed on aggregates will sink with them, though they can desorb while passing through less contaminated water.

Dissolved oil components can partition into non-sinking particles such as free-living bacteria. Pelagic, free-living bacteria and similar-sized microbes (ca. 0.2-2 μm) sorb hydrophobic organic contaminants (HOC), such as PAHs, as effectively as larger living, particulate carbon entities (ca 2-90 μm), such as phytoplankton (Broman *et al*., 1996). Bacteria may sorb the HOC directly from the water or by utilisation of HOC-associated dissolved organic matter (DOM). Broman *et al*. (1996) speculate that the bacteria may be a significant link between the DOM-associated HOC pool and zooplankton-eating fish.

The fate of oil dispersed in pelagic waters is complex, but researchers are revealing the relevant processes in growing detail. New models for interaction and sedimentation of oil with SPM will help answer questions about the fate and effects of oil that is naturally, chemically or mechanically dispersed.

i) **Oil-shoreline interactions**

The story of the fate and effects of marine oil spills complicates when the oil reaches land. Hence, process models that predict the extent and intensity of oiling along a shoreline are crucial to good decision making in responding to an oil spill. A large number of factors are important to beach oiling, such as the longshore average current velocity, onshore average wave-surface velocity, and the oil-holding capacity of the shoreline material. The oil-holding capacity depends on the type of shoreline material. A sandy beach can be expected to hold more oil than a rocky one. High-viscosity oil can be expected to coat more thickly than low viscosity oil. Depth of penetration depends also on the shoreline material and oil viscosity. Penetration could be non-existent on a rocky shore, but quite high on a gravely one. Oil-holding capacities have been determined for a variety of oil and shoreline types (Gundlach, 1987; Reed *et al*., 1999a). Reed *et al*. (1999a) choose to calculate holding capacity from oil viscosity and sediment permeability and porosity, and the tidal motion. These shoreline, oil and water motion characteristics are incorporated in the spill model COZOIL (<u>Co</u>astal <u>Z</u>one <u>Oil</u>spill Model)

Oil-shoreline interaction models in use are primarily empirical (Cheng *et al*. 2000). Cheng *et al*. (2000) provide a new analytical model of oil transport and deposition in the surf zone. They derive an expression that shows the average onshore sea-surface velocity as a function of beach slope, wave period and water depth. They also derive the average longshore sea-surface velocity as a function of the longshore current at the breaker line and the relative strength of the lateral mixing to the bottom friction. The oil holding capacity is related to the tidal range and width of the swash zone, includes both the surface and subsurface loadings and is parametrised using values determined by Gundlack (1987). The model also allows for a fraction of deposited oil to be remobilized and for the quantity of oil that exceeds the shoreline substrates holding capacity to be transport farther along the shoreline. For computational purposes the shoreline is divided into segments, as it is for COZOIL.

Being an analytical expression, the model can be easily incorporated into oil spill trajectory, fate and effects models. As Chen *et al*. (2000) point out, however, the model does not include wind-driven onshore currents, the propensity for oil to deposit on the surface during the tidal ebb, and the interaction of oil with the seabed through vertical mixing. The model ignores processes such as evaporation and dissolution, which can be dealt with by other process models. It also doesn't compute the oil holding capacity and penetration depth of shoreline materials, as is done in COZOIL (Reed *et al*., 1999a).

Oil-shoreline interaction models still need to describe better the physicochemical processes involved in remobilization of oil from a beach face during and after the oiling event (Reed *et al*., 1999a). In particular, inclusion in models of the phenomenon of clay-floc formation on beaches, first observed by Bragg and Yang (1993), would be useful. These nearly neutrally buoyant clay-oil flocs appear to be mobilized with minimal wave action (Bragg and Yang, 1993; Bragg and Owens, 1994; Owens *et al*., 1994a,b) and could be carried long distances by currents (Bragg and Yang, 1993).

j) **Chemical degradation (photomodification, photooxidation)**

Photooxidation of oil is stimulated by the interaction of light absorbing molecules in oil and molecular oxygen. Polycyclic aromatic hydrocarbons (PAHs), as well as aromatic moieties in resins and asphaltenes, have the right electronic structure to absorb sunlight energy and pass it onto oxygen to generate reactive oxygen species, which in turn can attack oil components. Photooxidation has been referred to as a "potentially significant process in the degradation of crude oil spilled at sea" (Garrett *et al*. 1998). Its impact on spilled oil has been considered to be unimportant during the initial few days (Spaulding, 1998), and this belief may account for the absence of a photooxidation algorithm in most oil spill models. The University of Southern California model might be the only oil spill model to have included an expression for the rate of photooxidation of oil slicks at sea (Huang, 1983; Spaulding, 1988). More recent reviews of aquatic oil-spill behaviour models have ignored the process (ASCE Task Committee, 1996; Reed *et al*., 1999a) except for its involvement in mousse formation in some oils (ASCE Task Committee, 1996). Indeed, Thingstad and Pengerud (1983) presented evidence that photooxidation is essential for emulsion formation from some crude oils low in natural emulsifiers. They showed that the addition of the antioxidant β-carotene could prevent mousse formation. They also suggested that addition of antioxidants to oil spills could delay mousse formation and extend the time window for deciding on the option of chemical dispersal. They reiterated the suggestion (Larson and Hunt, 1978) that the addition of antioxidants could minimise the photo-induced toxicity of crude and refined oils.

Phototoxicity of petroleum can arise from the formation of compounds more toxic than their progenitors in the oil. In addition, aromatic constituents acting as photosensitizers can cause the formation of reactive free radicals and singlet oxygen in tissues (Pelletier *et al*., 1997; Calfee *et al*., 1999; Little *et al*. 2000). The interaction of an oil constituent with light depends on overlap of its absorption spectrum with the attenuated (by air and water) emission spectrum of the source, which in the environment is the sun. Measurements of the penetration depth of sunlight are underway in some coastal waters impacted by petroleum, with a view to assess the enhancement of toxicity by sunlight (Barron *et al*., 2000).

The interaction of a compound with light depends on electronic characteristics of the compound other than spectral overlap with sunlight (Krylov *et al*., 1997; Mezey *et al*., 1998)). PAHs receive the most attention for photoenhanced toxicity. Process models are under development to describe the phenomenon (Krylov *et al*., 1997; Mezey *et al*., 1998). It seems clear that photoactivation within tissues is the prerequisite for phototoxicity of PAHs, and two routes are involved that act additively rather than synergistically: photosensitization with formation of singlet oxygen and photomodification of PAHs to give toxic products (Krylov *et al*., 1997).

k) **Biodegradation**

Biodegradation process models seem not to be under development for inclusion in oil spill fate and effects models. The arguments against developing such models are: the rates are too slow to affect the spilled oil over a relevant time period of a few weeks (Huang, 1983), the processes are too complex, and extrapolations are too large from laboratory conditions to the marine environment (Spaulding, 1988). On the other hand, Cretney (1992) examined degradation rates of the n-alkanes in various oils at various marine sites in mesocosms of 17 m^3 and 60 m^3 volume and found that the rate constants were remarkably similar, whether the oil was chemically or mechanically dispersed. Half the n-alkanes were removed in about 1.5 days. Biodegradation, however, significantly affected only the dispersed oil and was found to commence after a variable lag phase of up to several days. Still, for the dispersed component of an oil spill, developing a process model seems appropriate and doable. Although developing biodegradation algorithms for oil-spill models tends to be ignored (ASCE Task Committee, 1996; Reed *et al*., 1999a), the biodegradation of mechanically (Dutta and Harayama, 2000) and chemically (Bruheim and Eimhjellen, 1998) dispersed oil in salt water continues to be a research topic of interest. Furthermore, the above-mentioned formation of flocs of oil and mineral fines facilitates biodegradation of oil in sea water (Weise *et al*, 1999). The morphology and mineralogy of these flocs continue to be investigated (Lee and Stoffyn-Egli, 2001; Lee *et al*., 2002) to determine factors that control their formation. Biodegradation will be a dominant process in the eventual break down of oil, but these long term processes are not part of the general set of models considered here.

l) **Langmuir circulation**

Langmuir circulation (LC) is the tendency for near-surface waters to form circulation cells whose axes of rotation are horizontal. Adjacent cells are separated by tens of metres, and rotate in opposing directions, forming alternating surface convergence and divergence regions on the ocean surface. Floating debris that collects in convergence regions forms long windrows aligned generally with the wind direction. Researchers generally agree that Langmuir circulation results from the interaction of wind-driven surface currents and waves (Lehr, 2000).

As yet, integrated oil spill behaviour models do not encompass Langmuir circulation (LC) and other fine scale near-surface oceanographic processes. This exclusion may be about to change, as the capability of practitioners in modelling slick behaviour now appears to have advanced enough to consider such processes (Lehr and Simecek-Beatty, 2000). Langmuir circulation is indeed fine scale with widths of cells roughly in the range of 10-100 m for typical wind and sea conditions (Rye, 2000). Perhaps, the more computationally demanding feature of LC cells are lifetimes on a scale of minutes to hours for variable wind conditions (Lehr and Simecek-Beatty, 2000). Large stable LC cells, nevertheless, probably have greater significance than small intermittent cells to the spread, transport and vertical dispersion of oil as well as to the interaction of oil and biota.

The effect of LC on oil slicks can be seen in aerial photographs and in infrared (IR) and ultraviolet (UV) images, particularly when the current and wind directions intersect at about 45-90^o (see pictures in Rye, 2000). In the case of an underwater release of oil (Rye, 2000), the main slick shows tendril-like, somewhat regularly spaced, protrusions in the downwind direction. Comparison of IR images, which show oil thicknesses greater than about 10 μm, and UV images, which show thicknesses greater than about 1 μm, clearly delineates a pattern that resembles a plowed field.

Such patterns almost certainly are caused by LC. In cross section, LC consists of a series of counter-rotating vortices or cells. Convergent zones, which are created where adjacent cells are rotating towards each other at the sea surface, are interspersed with divergent zones, created where they are rotating apart. The oil slick thickens in the convergent zones or "windrows" and thins elsewhere. The water within windrows moves faster than the water between windrows, and oil within windrows may achieve speeds up to 5.5% of wind speed (Lehr and Simecek-Beatty, 2000).

An important aspect of LC is that the water is downwelling under convergent zones and upwelling under divergent zones. Because the LC downwelling velocity at the sea surface is zero (Farmer and Li, 1994), particles from an oil slick must be injected downward through some process such as turbulent diffusion. For neutrally buoyant particles and those with diameters less than 50-100 μm, which are effectively neutrally buoyant (Lehr and Simecek-Beatty, 2000), LC and diffusion will eventually lead to their homogeneous distribution through the cells, given that coalescence does not occur (Farmer and Li, 1994). The fate of millimetre-sized buoyant particles is more interesting. For them, their rise velocity may be balanced by the downwelling velocity at depth (Farmer and Li, 1994; Lehr and Simecek-Beatty, 2000), within what is known as the Stommel zone after the person who first described the concept (Stommel, 1949). Subsurface oil under LC conditions can be expected to show subsurface banding under the windrows.

Inclusion of LC in models would be expected to predict increased removal rates from slicks through vertical dispersion. Advances in analytical modelling of LC would appear to make practical the inclusion of LC in integrated oil spill behaviour models. Inclusion of LC would make for more realistic models of oil fate that could aid clean-up activities. Having more realistic models of oil fate by itself may not justify the required data input to provide the necessary temporal and spatial resolution. The ecological significance of the distribution of oil by Langmuir circulation and other phenomena that generate oceanic convergences must be considered as well.

The Stommel zones can be trapping zones for plankton as well as oil (Rye, 2000). Thus, LC has the potential to increase the exposure to oil of organisms that collect in the windrows or under them in Stommel zones. Potential ecological consequences of LC during oil spills have been known to the scientific community for some time (Barstow, 1983). A number of oceanic processes besides LC create interfaces between water masses, and these interfaces may be biologically important to some marine organisms (Wolanski and Hamner, 1988; Bakun, 1996). Concentration of oil and organisms by these processes can lead to more serious exposure than would be identified by vertically homogeneous models for the distribution of oil or organism.

2 INTEGRATED FATE AND EFFECTS MODELS FOR MARINE ECOSYSTEMS

The suite of public and commercial computer software available for prediction of the integrated fate and effects of oil and gas in the ocean is too extensive to summarise here. The software packages are continuously expanding, and at least one periodical, *Spill Science and Technology Bulletin*, provides peer-reviewed papers on relevant research and products. A number of annual conferences are also devoted to this topic.

We provide brief overviews here of the approach by several software suppliers to address this topic. In all cases the material was provided by the suppliers through Internet sites in September 2002.

a) **NOAA Office of Response and Restoration**

The Office of Response & Restoration of National Ocean Service of NOAA (U.S. National Atmospheric and Oceanic Administration) has developed a set of public domain software for aspects of oil and toxic chemicals in the ocean. Their Internet site lists several packages that can be downloaded. The following was copied from their web site in September 2002.

> GNOME (the General NOAA Oil Modeling Environment) is a free computer program you can use to
> - predict how wind, currents, and other processes might move and spread oil spilled on the water.
> - learn how predicted oil trajectories are affected by inexactness ("uncertainty") in current and wind observations and forecasts.
> - see how spilled oil is predicted to change chemically and physically ("weather") during the time that it remains on the water surface.
>
> To use GNOME, you describe a spill scenario by entering information into the program; GNOME then creates and displays an oil spill "movie" showing the predicted trajectory of the oil spilled in your scenario. Along with GNOME, most users also will want to download the location files for their regions of interest. Location files contain prepackaged tide and current data and make it easier to work with GNOME. [Note from authors: The Queen Charlotte Assessment Region does not have a prepackaged location file as of September 2002.]
>
> - ADIOS2 (Automated Data Inquiry for Oil Spills) is an oil weathering model that runs both on Macintosh computers and in Windows. ADIOS2 incorporates a database containing more than a thousand crude oils and refined products, and provides quick estimates of the expected characteristics and behavior of oil spilled into the marine environment. The predictions it makes, presented as both graphics and text, are designed to help answer questions that typically arise during spill response and cleanup. For example,
> - By predicting change in an oil's viscosity (resistance to flow) over time, ADIOS2 offers an answer to the question: Can the oil still be dispersed with chemical dispersants?
> - By predicting the rate of increase in an oil's water content over time, ADIOS2 offers an answer to questions like: If 1,000 gallons of crude oil has spilled, will more than 1,000 gallons of oil-and-water mixture need to be cleaned up and disposed of? How much more?

- The Trajectory Analysis Planner (TAP) is a software tool designed to help answer the crucial question in any Area Contingency Plan: How do I develop a plan that protects my area against likely spills?
- TAP presents graphical output in four modes:
- Shoreline Impact Analysis helps to answer: If oil is spilled at a given spot, what shoreline locations are likely to be affected?
- Site Oiling Analysis, helps you visualise how a given location of concern would be likely to be oiled by a spill at a given location.
- Resource Analysis helps you estimate the level of response needed to adequately address impacts if modelled spills, and the quantity of a particular resource that could be impacted by given spills.
- Threat Zone Analysis helps to answer: Where might a spill occur that could threaten a particular shoreline location of concern?

How TAP Works.
You use TAP to see the probability that any oil spill will reach a specific segment of shoreline. TAP analyzes statistics from potential spill trajectories generated by a NOAA OR&R oil spill trajectory model. This model predicts how an oil spill will spread and move within a local area. It takes into account:

- the bathymetry and shoreline configuration of a particular body of water, including its channels, bays, and significant rivers;
- currents and winds; and
- shoreline characteristics that determine beaching and refloating of oil.
- Then for each season, the model generates 500 individual oil spill trajectories from each of about 300 potential spill locations. The model then compiles statistics for where, when, and how much oil impacts receptor sites into data files for TAP.
- TAP displays a map of a specific local area, including a major water body and the adjacent land. The map displays shoreline segments that represent the locations of shoreline resources such as seabird colonies or marine mammal hauling grounds, sites of particular socioeconomic value such as tourist beaches or large marinas, or areas where remediation measures would be difficult or expensive. You can use TAP to evaluate the probable threat to any of these sites from an oil spill that originates at any point within the mapped water body.

b) **Oil Spill Contingency and Response Model (OSCAR)**

The following was copied from web sites of the Alaskan Oil Spill Recovery Institute in September 2002.

> In 2000 the Alaskan Oil Spill Recovery Institute committed funds for developing state-of-the-art oil spill modeling capabilities for Prince William Sound. The Oil Spill Contingency and Response Model for Prince William Sound (OSCAR) is the end product of this effort. Developed by SINTEF Applied Chemistry, a non-profit research institute headquartered in Norway, OSCAR utilizes advanced numerical modeling methods to analyze both the physical and chemical processes which determine a specific oil spills fates and effects.
>
> In determining the chemical fate of spilled oil OSCAR relies [on] the Advanced Management of Oil Spills (AMOS) developed by SINTEF and funded by the US Mineral Management Service (MMS) at $2.5 million. OSCAR utilizes AMOS in conjunction with

an oil weathering model to simulate the chemical and physical processes (dispersion, dissolution, evaporation, degradation, etc.) that influence the toxicological parameters of the oil

The concept is a step-wise approach:
Step 1: Definition of relevant Oil Spill Scenarios.
A set of oil spill scenarios relevant for the installation is defined. This includes whether it is a land based or offshore installation, possibilities for instantaneous or continuous releases, depth of the release (subsea or surface), release ratios, gas-to-oil ratio (GOR) etc.
Step 2: Oil Weathering Properties.
Functional and cost-effective oil spill contingency planning requires a good knowledge about the weathering and dispersibility properties of the relevant oil. Experimental data created through laboratory investigations are used as input to the SINTEF Oil Weathering Model (OWM), for predictions of weathering behaviour at sea. The SINTEF OWM is a part of the OSCAR model system.
Step 3: Simulation of underwater spreading by the DeepBlow model.
Spreading of the oil from a subsea releases is simulated using the DeepBlow model. The simulations are based on water depth, oil flow rate, gas-to-oil ratio (GOR), outlet temperature, outlet diameter, hydrographical data and current profiles. The simulations give an indication of plume trajectory, plume parameters along the trajectory and expected oil film thickness. Hydrate formation and gas dissolution are taken into account.
Step 4: Stochastic drift and spreading on the surface by the SLIKMAP model. The drift and spreading of the surface oil from a subsea release or a surface release is simulated using the SLIKMAP model. These simulations give an indication of the area of the potential influence and are used for selection of weather scenarios to be used in the oil spill response analysis and definition of relevant sensitive areas both offshore and along the coastline.
Step 5: Oil spill response analysis by the OSCAR model system.
The objective of the oil spill response analysis is to identify the countermeasures needed to fulfil the specific requirements for the effectiveness of the response. The Oil Spill Contingency And Response (OSCAR) model system was developed by SINTEF for the specific purpose of comparing alternate oil spill response strategies as part of an oil spill response analysis. The output from the OSCAR simulations is used as input to the Actions Plans for dimensioning of an optimal response.

c) **OILMAP and SIMAP, products of Applied Science Associates Inc. (ASA)**

In the 1990s a consortium of government agencies and oil companies contracted to ASA to develop a software product called Worldwide Oil Spill Model (WOSM) to be used by oil spill responders. This concept has now been incorporated by ASA into a more extensive set of software tools called OILMAP. The following was copied from web pages of Applied Sciences Associates Ltd in September 2002.

OILMAP is delivered with an oil spill trajectory & fates model, an interactive GIS and environmental data tools. The oil spill model predicts oil trajectories for either instantaneous or continuous release spills and includes algorithms for spreading, evaporation, emulsification, entrainment, oil-shoreline interaction, and oil-ice interaction. The oil's distribution and mass balance are predicted for the type of oil spilled. Model predictions may be up-dated to agree with observed oil locations, boom may also be added to implement simple booming strategies, and dispersant may be applied to simulate dispersant application.

Stochastic Mode (for Risk Assessment and Oil Spill Contingency Planning)
This model generates multiple stochastic simulations for user selectable spill locations using statistical or historical wind time series. The model can be run to determine most likely spill paths for spills on a monthly, seasonal, or annual basis. Output includes maps showing probabilities of oiling the water surface and shorelines in the vicinity of the spill site, and contours of oil travel time. Results can be used to determine the probability of oiling static resources (e.g., biological, industrial, archeological) which are stored in the GIS.

Receptor Mode (for Oil Vulnerability Analysis)
The receptor mode performs reverse trajectory calculations from user selectable sites. Calculations can be used to identify probable release locations of spills given current oil locations, or principal avenues of vulnerability for important resources. Outputs of the receptor mode are maps showing probabilities that the spill trajectory passed through a given area, and minimum time contours for spills to reach resources of concern.
The receptor model is generally used in two modes:

- to determine the vulnerability of a particular site (e.g. Desalination Plant) to oil spills based on lightering sites or tanker traffic routes,
- to determine possible sources of oil when oil has been observed at a particular site.

Subsurface Transport
This module contains all the weathering algorithms described in the fates and trajectory model, but also predicts the subsurface transport of entrained/dissolved oil. Subsurface particles are generated from the surface oil during the entrainment process and are then forced by mean currents and also a depth varying, wind induced current profile. Resurfacing of subsurface spillets is included in the formulation.

Features
Since the quality of model predictions is dependent on the quality of the environmental data, a suite of tools allow the user to handle environmental data efficiently. A variety of graphically based tools are included which allow the user to:

- Specify spill scenarios
- Display spill trajectories
- Grid any area within the geographic location for model operation
- Input wind time series
- Generate steady current fields
- Generate tidal current fields
- Import current data from hydrodynamic models
- Enter and edit oil types in the oil library
- Enter data into OILMAP's Geographic Information System (GIS)
- Display GIS resources impacted by the oil trajectory

SIMAP is a computer modeling software application that estimates physical fates and biological effects of releases of oil and hazardous chemicals. Both the physical fates and biological effects models are three-dimensional. There is also a two-dimensional oil spill model for quick trajectories and screening of scenarios and a three-dimensional stochastic model for risk assessment and contingency planning applications. The models are coupled to a geographic information system (GIS), which contains environmental and biological data, and also to databases of chemical properties and biological abundance, containing necessary inputs for the models.

d) **Spillsim, product of Seaconsult Marine Research Ltd, Vancouver, BC.**

The following was copied from the web page of Seaconsult Marine Research Ltd in September 2002.

> Spillsim is a complete information management system for spill response, combining an equipment inventory database with a sophisticated trajectory and fate model supported by structured, hierarchical wind and current databases.
> Generic formats for wind and current input accept a wide range of data from simple on-site observations to remotely-sensed currents and model output.
> Processes modelled include transport and horizontal mixing, spreading, evaporation, emulsification, vertical dispersion, shoreline oiling, boundary losses, and on-water recovery.
> Generic formats for wind and current input allow Spillsim to accept a wide range of data, from simple on-site observations to remotely-sensed currents and model output.
>
> The scenario editor allows a user to specify the combination of current data sources appropriate for a particular locations, choosing from:
> - Databases - seasonal mean currents, tidal harmonics
> - On-site observations - subjective time-series
> - Current meters - ASCII time-series input
> - SeaSonde radar - surface current maps
> - Models - 2D and 3D hydrodynamic models
>
> Crucial wind data are readily input using the wind editor. Data entry is rapid and easily edited as conditions change, using any of the following tools:
> - Databases - seasonal mean currents, tidal harmonics
> - On-site observations - subjective time-series
> - Current meters - ASCII time-series input
> - SeaSonde radar - surface current maps
> - Models - 2D and 3D hydrodynamic models (e.g. C3), FD and FEM formats
> - Crucial wind data are readily input using the wind editor. Data entry is rapid and easily edited as conditions change, using any of the following tools:
> - Bull's eye editor - point-and-click wind vectors
> - LUTs - speed and direction tables
> - ID - reference site names
> - Stick plot - convenient speed/direction checking plot
> - WIN - database software for automated downloading of national weather service data; maintains a current 30-day regional database, including forecasts.

3 APPLICATIONS TO THE QUEEN CHARLOTTE BASIN

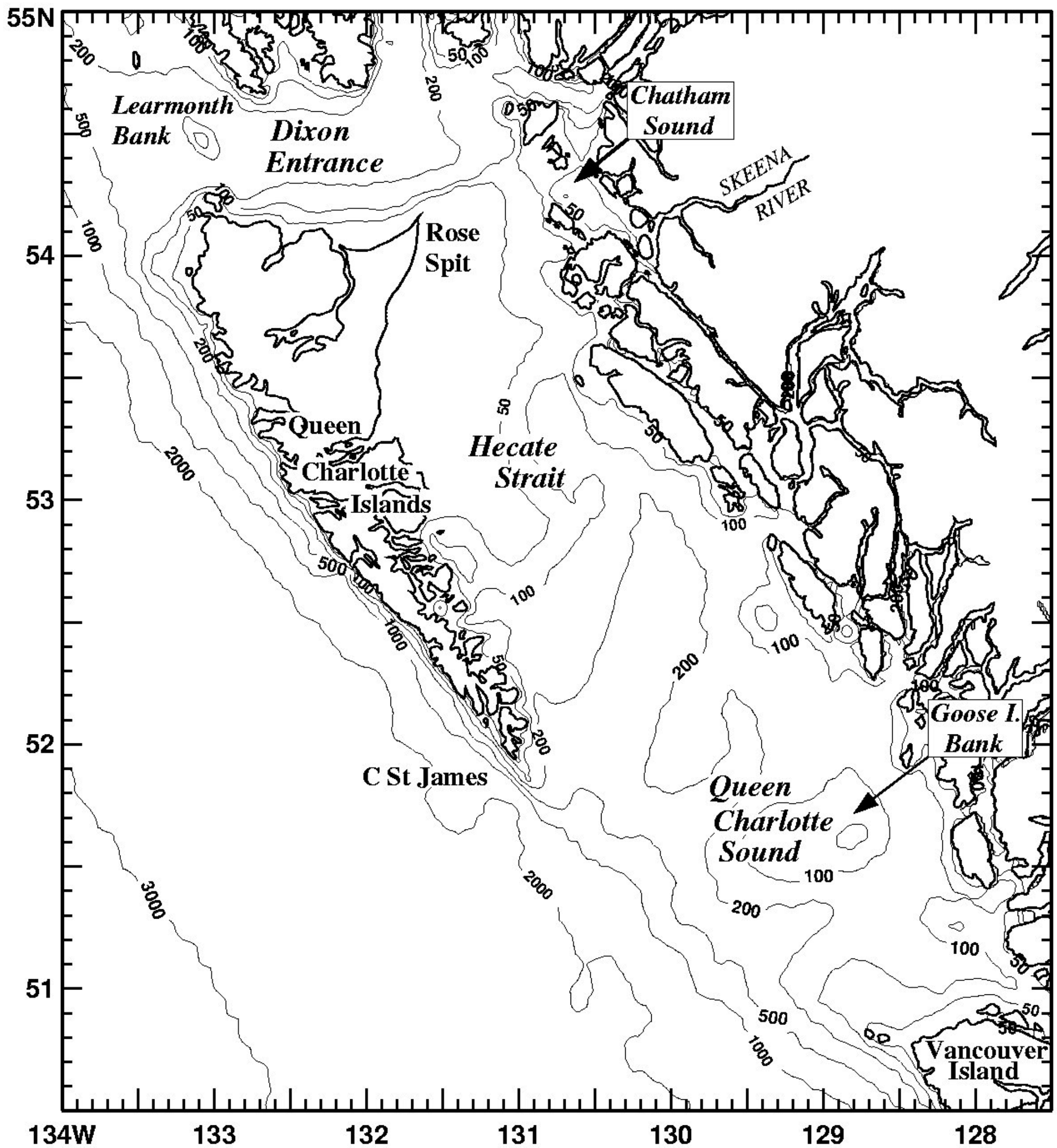

Figure 1. Queen Charlotte Basin.

a) **Links between hydrodynamical ocean models and integrated oil fate models.**

Hydrodynamical ocean models are deterministic numerical models, based on the equations of physics of fluid motion, set up by physical oceanographers to simulate and predict the ocean currents, in a manner analogous to the models applied by the meteorological community for weather forecasting. These models are of varying complexity, and may be applied to any one or all of the tidal currents, wind-driven currents, fresh water flows over the ocean surface, other buoyancy-generated flows, and to the motion of deep-ocean eddies. A challenge for the oceanographic and oil spill communities is to input ocean current models, or currents defined by these models, into an integrated oil spill model. This section will present, first, the ways that ocean currents from hydrodynamical models can be applied to oil fate integrated models. The next part describes several ocean current models developed at the Institute of Ocean Sciences (IOS) in the early 1990s with PERD and DFO funding, and applied to the Queen Charlotte Basin, and a final part presents a series of maps with ocean current simulations in this region.

(1) Combined current and oil models

One approach is to embed the hydrodynamical model into the integrated oil spill model. This technique requires that all the hydrodynamical equations and grid parameters be part of the integrated oil spill program. The OR&R models can apply this approach, usually using very simple hydrodynamic models for the domain. OILMAP also includes this feature, again with simple hydrodynamical models. As the hydrodynamical models become more complex and require more expertise and computer time, it is more appropriate to embed the oil spill behaviour into the hydrodynamical model. In general one of the current or oil models will be simplistic, unless great effort is applied to a specific region.

(2) Offline current model

A second approach is to run the models separately. The hydrodynamical model is run “off line” and the current vectors defined by this model, at simulation intervals of 10 minutes, for example, are input to the oil spill model to advect, diffuse and spread the oil in a physically correct manner. Algorithms in the oil spill model and in ocean wave component models are then applied to handle the remaining processes specific to the oil itself. The hydrodynamical models require the attention of a physical oceanographer, attending to real-time input of wind observations and forecasts over the model domain, and in some cases even to the density structure of the ocean. Both OILMAP and SPILLSIM include this feature. The off-line models can include sophisticated near-real-time observations. For example, Tinnis and Hodgins (1997) describe how radar-measured surface currents are assimilated into a hydrodynamical model of surface currents for oil spill modelling in the Strait of Georgia.

(3) Look-up tables of currents

A third approach is to embed look-up tables of ocean currents in the oil spill model. These look-up tables are based on prior development of hydrodynamical models for the region. Tidal currents are defined by tidal constants of each of 8 or more tidal constituents, at each of several thousand grid points. Both OILMAP and Spillsim include this feature. This method is most appropriate for use by on-scene commanders during spill incidents.

The largest tidal constituent is M2, the principle lunar semi-diurnal tide, and will be presented here as an example. M2 tidal currents have a period of 12.4 hours, and phase that depends on the position of the moon and the local lag of the M2 current behind the lunar forcing. There are four tidal constants associated with the M2 tidal current: amplitude and local phase lag of each of east-west and north-south currents. These four constants have unique values for each of the thousands of grid points in the region. For example, one model applied to northern British Columbia by Patrick Cummins of IOS has a 5-km spacing between grid points, and extends from northern Vancouver Island to Alaska (Cummins and Oey 1997). It requires about 10,000 grid points to define currents in this domain. With 10,000 grid points, 8 tidal constituents, 4 tidal constants per constituent, the embedded look-up table for total tidal currents requires 320,000 numbers. Spillsim as applied to southern British Columbia employs even more tidal current constituents on a domain with more closely spaced grid points, so its requirements will be even greater. Today’s computers can easily handle these large files.

The oil spill model will examine the tidal constants provided by the look-up table at grid points nearby the oil, or all through a larger oil patch, and apply tidal current prediction algorithms to determine the tidal currents over periods of days required for the simulation. The prediction algorithms are identical to those applied by the Canadian Hydrographic Service to predict tidal currents for the *Canadian Tide and Current Tables*. All were developed and upgraded over the past decades by Michael Foreman of the Institute of Ocean Sciences (Foreman, 1978). The technique of embedding tidal current constituents in an application model in this manner was developed in the 1970s by James Stronach of Vancouver, in a software package to predict drift of boats and bodies for the Search and Rescue Program of the Canadian Coast Guard, Pacific Region. The technique is now in use in numerous Canadian and international software packages for search and rescue, oil spill simulations and marine navigation.

Seasonal currents can also be defined and entered into the look-up table of tidal currents, in the form of an average current vector at each grid point. A wind response is entered by the user to the model at run time, or even as a default value. For example, oil is often assumed to move at 3% of wind speed. In narrow channels oil moves directly downwind, in wider channels it moves to the right of the wind in the northern hemisphere, due to influence of Earth's rotation. Hodgins *et al*. (1992) used a variable angle, dependant on wind speed and viscosity, in their evaluation of oil drift near Cape St. James. Hodgins *et al*. (1991) applied an angle of 10 degrees in Vancouver Harbour. In a wide strait such as Queen Charlotte Sound the oil on the sea surface in mid-sound might drift at about 30 to 40 degrees to the right of the wind. The two parameters, percentage of wind speed and angle to the right of wind, are normally defined by the user, based on previous studies, and are required by these models to be uniform in space over the domain.

It is difficult for this approach to account properly for the influence of synoptic winds on local ocean currents. However, this model, once set up for a region, is relatively easy for spill responders to operate and provides timely and useful output.

b) **Tidal current models**

Deterministic hydrodynamical models of tidal heights and currents are usually easier to set up accurately than are models of oceanic wind-driven response. Tidal models can be run independently of models of other ocean processes, and are described separately here.

The two types of ocean tidal models that have been applied to northern British Columbia are a version of the Princeton Ocean Model (POM) and a series of finite element models (FEM). Both were developed as part of a PERD-funded program to study the physical oceanographic features of this region. POM applies the hydrodynamical equations to a rectangular grid over the region, accounting for effects of varying water density at different depths (baroclinicity) and simulating currents at various depths through the water column (Cummins and Oey, 1997). It is one of the standard models developed by oceanographers for ocean current simulation. Cummins and Oey apply 17 layers in the vertical, and adapted a domain developed by Hannah *et al*. (1991) defined by set of grid points separated on a *regular grid* by 5-km. The four tidal constituents evaluated are M2, S2, K1 and O1, the two largest semi-diurnal (twice-daily) and diurnal (daily) tidal constituents, respectively. Vertical seawater density changes were assumed to be horizontally uniform over the region, and represented typical summer conditions near the outer continental shelf.

FEM applies the hydrodynamic equations to an *irregular grid* over the region, enabling more accurate representation of shorelines, and better resolution in narrow channels. As applied to the Queen Charlotte Basin (Ballantyne *et al*. 1996, based on Foreman *et al*., 1993, and Walters, 1992), the ocean was assumed to be of uniform seawater density and baroclinic effects (i.e. motion due to different seawater densities in different regions) were therefore not considered. A three-dimensional version was applied, simulating varying currents at different depths due to enhanced turbulence near ocean bottom and surface.

Both Cummins and Oey (1996) and Ballantyne *et al*. (1996) developed new techniques for ocean modelling. Cummins and Oey (1996) are able to simulate the large internal tides observed along the continental margin and in Dixon Entrance that set up semi-diurnal currents of more than one knot in speed, although their simulated currents are somewhat lower in magnitude in Dixon Entrance than observed tidal currents. Their paper was the first to accurately simulate internal tides along a continental slope. Crawford *et al*. (1998a) describe how a smaller grid size and better resolution of bottom topography in their model would likely improve simulations of internal tidal currents on the continental shelf, especially in Dixon Entrance. Ballantyne *et al*. (1996) are able to represent steady, baroclinic seasonal currents and barotropic tidal currents on the same grid using the same numerical model (FEM), but applied in two different modes.

Crawford *et al*. (1998a) evaluated the application of POM and FEM to northern British Columbia waters, by comparing model simulations of semi-diurnal tidal currents to observations of these currents using near-surface, radio-reporting ocean drifters between 1990 and 1995. Comparison applied to the open waters of Queen Charlotte Sound, Hecate Strait, Dixon Entrance and portions of the West Coast of the Queen Charlotte Islands for late spring and summer conditions. This project was funded by the Panel for Energy Research and Development between 1989 and 1996, with additional funding from Fisheries and Oceans Canada. Crawford *et al*. (1998a) compared tidal currents as represented by current ellipses composed of clockwise and counterclockwise rotating vectors at the periods of tidal constituents. The figures on the next few pages present observed and simulated tidal current ellipses at regions at times of observations.

Tidal current ellipses can be explained as follows. If a vector represents the speed and direction of a tidal current at any one point and time, then the progression of this tidal current at any single point in the ocean, throughout the semi-diurnal period, can be represented by the rotation of this vector in time. Individual vectors can be defined for individual tidal constituents. For example, the M2 semi-diurnal tidal constituent has a period of 12.4 hours. Its rotating current vector will return to the same point every 12.4 hours, and the length of this vector will vary during this cycle of motion. The path traced out by the tip of this vector is an ellipse, which may be used to define the character of the M2 current.

Tidal ellipses of each tidal constituent can be evaluated by using the Foreman (1978) tidal current analyses software on observations of tidal currents at hourly intervals, provided the observations extend over many months. Crawford, *et al*. (1998b) developed a method to extract semi-diurnal tidal current ellipses from drifter track observations that extend over periods of days or longer. This method was applied by Crawford *et al*. (1998a) to compute semi-diurnal ellipses of observed currents presented in Figure 2a.

Most tidal currents on continental shelves of British Columbia rotate in a clockwise direction. Counterclockwise rotating ellipses in the following figures are shaded, to represent the few exceptions in the Queen Charlotte Basin.

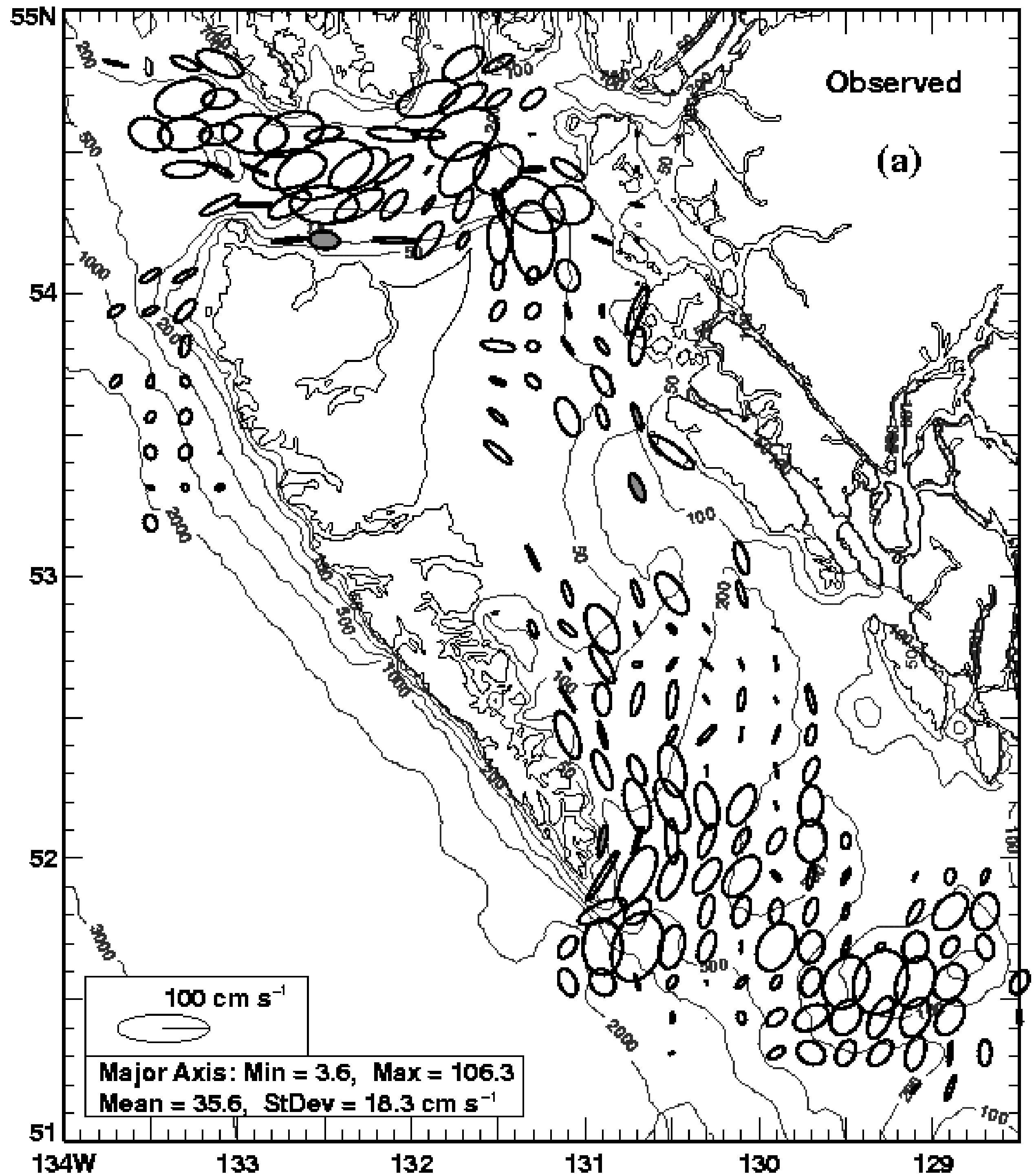

Figure 2a. Current ellipses representing semi-diurnal currents in summer at sites sampled by drifter tracks. Empty ellipses denote clockwise rotary, while shaded ellipses denote counter-clockwise rotary. For clarity the data were sub-sampled from 648 ellipses, showing only ellipses nearest to regular grid points. (From Crawford *et al*. (1998a)).

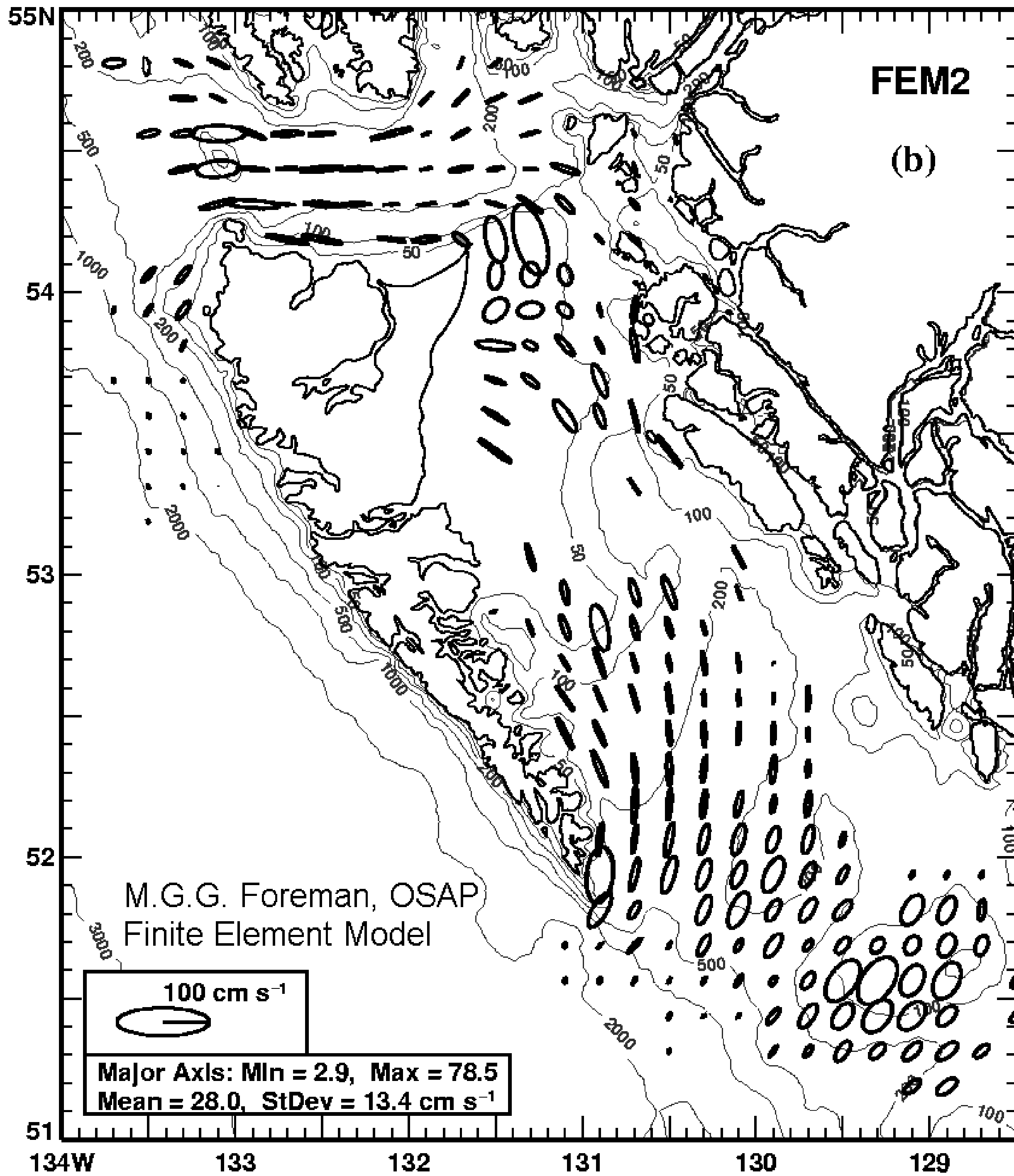

Figure 2b. Same as 2a, except semi-diurnal current ellipses are from *Ballantyne et al* [1996] model (FEM) of M2, S2, N2 and K2 constituents. (From Crawford *et al*. (1998a)).

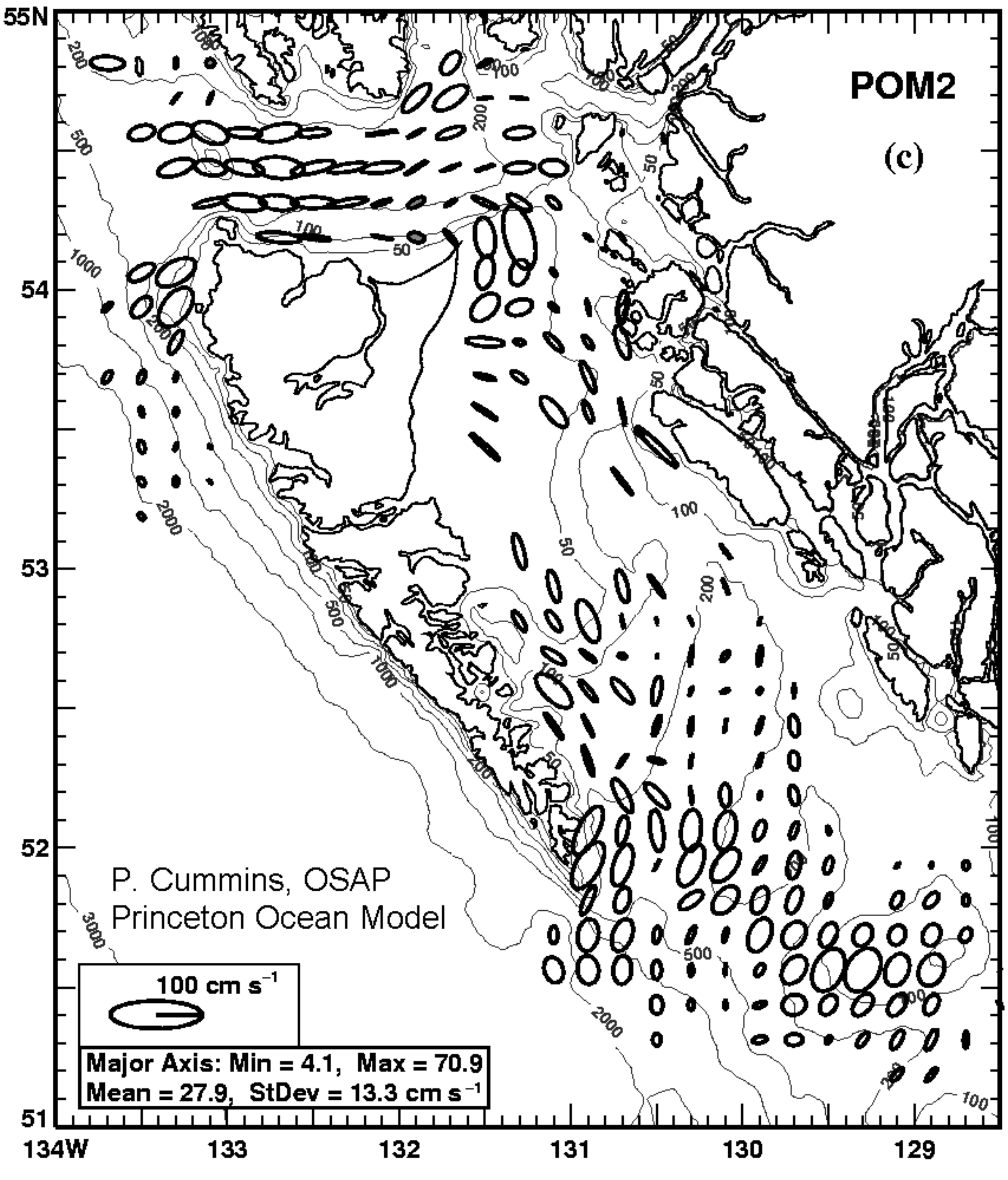

Figure 2c. Same as Figure 2a, except semi-diurnal current ellipses are from *Cummins and Oey* [1996] model (POM) of M2 and S2 constituents. (From Crawford *et al*. (1998a)).

The following three paragraphs are extracted from Crawford *et al*. (1998a) to describe features of this model evaluation. The baroclinic model is POM2; the barotropic model is FEM.

- Agreement among these observations and the two models was found to be best in the shallow waters of northern Hecate Strait, where a typical bottom depth is 20 metres and peak semi-diurnal tidal currents vary from 0.2 m s^{-1} to 1 m s^{-1}. In this region the ocean is well-mixed vertically most of the time and internal waves are not present. The magnitudes of observed and model currents are similar throughout Queen Charlotte Sound and Hecate Strait. However, the observed tidal currents in Dixon Entrance clearly exceed model currents in speed, and the observed tidal ellipses are more clockwise rotary.
- A systematic comparison of the differences between model and observed semi-diurnal currents shows the mean bias to be less for the baroclinic model when the water depth is greater than 100 m, with even better performance in waters deeper than 1000 m. However, the standard deviation of these differences is greater for the baroclinic model. It seems that the baroclinic model is representing internal tides near the shelf break reasonably well on average, but occasionally it creates internal tides that are much too big or too small. This may be due to the bathymetric smoothing necessary for its 5-km grid, or the use of vertical density profiles that are horizontally uniform.
- Spatial distribution of differences between model and observed clockwise speeds shows largest deviations in summer in Dixon Entrance, and near Cape St. James. Generally, the baroclinic model agrees best with observations near the shelf break, and the barotropic is best in regions far inshore of the shelf break. Two cruises in the springs of 1994 and 1995 examined currents in southern Queen Charlotte Sound. At this time of year, stratification is much weaker than in summer, and POM2, representing summer conditions, performs less well than the barotropic model.

In the following years the FEM domain was expanded to include much of the Gulf of Alaska to simulate tidal heights (Foreman *et al*., 2000). A separate research effort, led by D. Stucchi of the Institute of Ocean Sciences (IOS), is pushing the FEM tidal current simulations southward through Broughton Archipelago for aquaculture applications. Development of POM in this region stopped in the 1990s, due to lack of PERD funding and need for faster computers. New computers are able to run simulations that required too much time in 1995.

Tidal current constituents from FEM have been applied to a license of OILMAP owned by Burrard Clean Operations, and to the software product Tideview, developed by Channel Consulting of Victoria, BC.

c) **Non-tidal current models**

The Princeton Ocean Model (POM) was applied to simulate non-tidal ocean currents in northern British Columbia, as part of the modelling effort by P. Cummins of IOS. POM is a deterministic "time-stepping" model that solves the hydrodynamical equations of motion at each grid point every few minutes of simulation time. The same model run simulates tidal and non-tidal currents, and both tides and winds were applied to force the simulated ocean currents. Wind forcing was provided by a daily average wind field as defined by Cherniawsky and Crawford (1996), based on hourly observations of winds over the ocean at Canadian weather buoys in 1995, and interpolated in space to each of the 5-km-spaced grid points, and in time to every 10 minutes of simulation. The model outputs currents every 10 minutes, at each grid point and each of 17 depths. This type of output could be useful for input to the first two types of spill motion models noted above: (1) *combined current and oil*, and (2) *offline current model*. If these time varying currents are averaged over a season, the resulting steady, seasonal currents could be input to the third type of model: (3) *look-up table of currents*.

Steady seasonal currents are simulated by a version of FEM prepared by Crawford *et al*. (1996) in a similar manner to the effort of Ballantyne *et al*. (1996) for non-tidal currents. Non-tidal steady seasonal currents and tidal currents require separate applications of FEM, unlike POM. The steady seasonal currents provided by FEM are suitable for only models of type (3). Newer numerical models that overcome this limitation have been applied on a trial basis, but have not been evaluated as thoroughly as have the models discussed above.

(1) Model evaluation in Dixon Entrance and Northern Hecate Strait

The application of a type (3) model for non-tidal currents was evaluated by Crawford *et al*. (1996, 1997) for northern Hecate Strait and Dixon Entrance currents observed in the summer of 1991. Radio-tracked, Loran-C-positioned, near-surface drifters were deployed in these waters in July to August 1991, with 5-metre-high drogues centred at 3 metres below surface (Woodward and Crawford, 1992). These drifters were deployed as part of the PERD-funded program from 1989 to 1996 to examine oceanographic conditions in the waters surrounding the Queen Charlotte Islands. The complete set of meteorological and physical oceanographic data of this program are presented on CD-ROM by Crawford (2001). This PERD program examined ocean conditions throughout the annual cycle, with concentration of observation in late spring to early autumn, following the Report and Recommendations of the West Coast Offshore Exploration Environmental Assessment Panel (1986), "that exploratory drilling operations outside the 20-km exclusion zone be initially confined to the months of June to October inclusive …."

Drifters tracked the near-surface currents in these waters in 1995, and the Crawford *et al*. (1996, 1997) papers describe efforts to hindcast these currents using a look-up table of seasonal currents together with simple wind forcing, whereby the surface current drifts at some fraction (A) of seasonal flow speed, rotated at some angle (B) to the right of this current, plus a wind-forced component at some fraction (C) of the wind speed, at some angle (D) to the right of the wind. The wind field was interpolated from Canadian Weather Buoy observations in 1995. The seasonal current field was defined from application of FEM to the region, as described below.

Crawford *et al*. (1996) applied the steady state, baroclinic version of (FEM) that solves the linearised, shallow water equations for a specified three-dimensional density field defined at each element of an irregular grid of triangular elements, and for specified boundary conditions. They applied the FEM grid developed by Foreman *et al*. (1993) and Ballantyne *et al*. (1996), after removing offshore regions, and inlets with sparse density data. Resulting currents represent average surface flow in summer. (A more complete analysis of application of FEM techniques to the study of currents in these waters is presented by Jacques (1997)).

A least-squares-fit of modelled to observed currents was applied, based on the best fit of parameters A through D described above. Each of these four parameters was allowed to vary, provided all current vectors throughout the domain were scaled by the same factors A and C, and rotated by angles B and D. Best fit values are listed below.

	Seasonal Speed % A	Seasonal Rotation B (Deg.)	Wind-driven Speed % C	Wind driven Rotation D (Deg.)	Correlation East (North)	Mean (Diff.)
Dixon Entrance	76	7	1.6	43	0.60 (0.68)	16.4 (12.7)
Hecate Strait	112	20	1.9	57	0.34 (0.83)	13.3 (8.2)

Table 1 Results of least-squares-fit of wind-drift and seasonal currents to observed drifter velocities in Dixon Entrance and Hecate Strait. Adapted from Crawford *et al*. (1996).

Best fit seasonal currents were 76% of model currents in Dixon Entrance and 112% in Hecate Strait. The best fit seasonal currents in both regions are rotated relative to the model currents. The 7-degree rotation in Dixon Entrance is not significant, but the 20-degree rotation is significant in Hecate Strait. The wind-driven, near-surface currents flow on average at 1.6% and 1.9% of the wind speed. Most interesting is the relatively large rotation of wind-driven currents compared to the wind direction. The larger angle in Hecate Strait may be due to channel configuration, because the currents will tend to flow North-South along the axis of this strait, whereas the winds tend to blow Northwest-Southeast, roughly a 45 degree rotation, which adds to the Ekman rotation normally present (Crawford *et al*., 1996). The rotation of 43 degrees in Dixon Entrance suggests a significant Ekman effect there as well.

Some sensitivity tests were applied. Crawford *et al*. (1996) replaced the wind time series with a set of random vectors and also generated a set of random (in space) seasonal currents. Use of a random wind in Dixon Entrance did not reduce the East-West correlation significantly, but did lower the North-South correlation. The random seasonal current field reduced the East-West correlation coefficient. East-West currents in summer in Dixon Entrance are largely associated with the Rose Spit Eddy in eastern Dixon Entrance, first noticed in oceanographic observations by Crean (1967) and described by Crawford and Greisman (1987) and Bowman, *et al*. (1992).

All correlation coefficients for East-West motion were small in Hecate Strait, but the East-West currents are very small there as well. Replacing the actual wind with a random wind significantly lowered the North-South correlation coefficient. Using random current in place of seasonal currents changed the correlation little. Seasonal currents here are small compared to wind-forced motion. The latter reversed direction frequently in summer with the changing winds; therefore the weak contribution of seasonal current to the best fit is expected (Crawford *et al*., 1996).

Typically, the drift was between 1.6% and 1.9% of wind speed. In predicting the motion of oil on these waters, one would increase the fractional wind response and reduce the rotation angle, since the Loran-C drifters had drogues 5-m high, centred at 3-m depth, which was deeper than the depth of a significant oil slick in moderate winds. (Crawford *et al*., 1996).

(2) Model evaluation in Queen Charlotte Sound and southern Hecate Strait

An evaluation of non-tidal current predictions in Queen Charlotte Sound and southern Hecate Strait in late spring and summer is presented by Crawford, *et al*. (1999). In this case both POM and FEM model currents were evaluated, and the POM evaluation is relevant for predictions of oil motion of type (2) *Offline current model*, as well as type (3) *Look-up tables of currents*. Observed currents derive from drift tracks of more than 30 surface drifters deployed in spring and summer 1995 in Queen Charlotte Sound and southern Hecate Strait. With drogues in the top one metre of the ocean, these drifters provide tracks that more closely resemble the drift of particles on the water surface than do the drifters used in Dixon Entrance. Drifter positions were determined between 4 and 12 times a day by Service Argos Inc., using the French Argos satellite system, to a nominal accuracy of about 250 m, and each drifter transmitted for 60 days from the time of first transmission. Drifter positions were interpolated to hourly values using cubic splines. A low-pass Kaiser (1974) filter (1/4 power at 30-hour period) was applied to these hourly positions, and daily average velocities were computed from the filtered time series, and assigned to the daily mean location of the 24-hour track. (Crawford, *et al*., 1999).

POM simulations were derived from the same model runs that were used for tidal currents, discussed above. Daily averages of both wind and POM currents closest to surface were computed. For this simulation the Fundy5 finite element model (FEM) was applied, following the approach of Namie *et al*. (1994), Hannah *et al*. (1996a), and Loder *et al*. (1997). FEM currents are already a seasonal average and require no additional averaging. To evaluate model currents against observed currents, the model currents from either FEM or POM were interpolated in space to the median point of the daily track of each drifter.

The observed and model time series were combined into a set of complex equations to determine the four factors A to D noted in Table 1. Results are presented in Table 2 below.

Model	Wind	Fraction of model speed	Model rotation angle (deg)	Fraction of wind speed	Wind rotation angle (deg)	Corr. coef. East North	RMS diff. (cm s^{-1})	$g(\gamma^2)$
Random	Random	0.03	N/A	0.001	N/A	0.04 0.02	15.2	0.2%
Random	Weather Buoy	0.07	N/A	0.022	-36	0.32 0.76	11.3	42%
Fundy5	Weather Buoy	0.43	-3	0.022	-33	0.34 0.77	11.2	43%
Fundy5	Random	0.63	34	0.001	N/A	0.15 0.18	14.7	3%
POM	Random	1.04	1	0.000	N/A	0.43 0.74	11.4	42%

Table 2. Results of the least squares fit of winds and model currents to observed daily mean drifter velocities in Queen Charlotte Sound and adjacent seas, summer 1995 (from Crawford, *et al*., 1999).

Different combinations of wind, POM and FUNDY5 were applied, as well as sets of random winds and currents, to determine a goodness-of-fit factor $g(\gamma^2)$, defined as $g(\gamma^2) = 100(1-\gamma^2)$, where γ^2 = variance of least-squares-fit error/variance of observed currents, as defined by Thompson and Sheng (1997).

Application of seasonal Fundy5 currents and random winds accounted for almost no success, and other trials with Fundy5 confirmed its poor representation of time-varying currents in Queen Charlotte Sound. For example, an insignificant statistical improvement resulted from adding Fundy5 currents to weather buoy wind forcing. Much of the poor showing of FEM seasonal currents is due to relatively weak observed mean currents compared to fluctuating currents in Queen Charlotte Sound in summer (Crawford *et al*. 1985). These results contrast with the more successful results in Dixon Entrance, described previously. The presence of strong prevailing currents in the Rose Spit Eddy in Dixon Entrance, as simulated by Fundy5 currents, likely explains this success.

Best results derive from POM, or the Weather Buoy winds. (POM currents derive from application of Weather Buoy winds to the model, so the weather buoy winds were not included in a trial with POM currents.) These results account for 42% of current variance. POM currents required no significant amplification or rotation to best fit the observed currents, a result that is speaks highly of this model. No tuning of any of the POM coefficients took place; only the generic constituents were used. The trial with only Weather Buoy winds showed the near-surface drifters to move at 2.2% of wind speed, rotated 36 degrees to the right of the wind. This rotation is less than found in northern Hecate Strait and Dixon Entrance, as expected for the shallower drogues used in Queen Charlotte Sound. However, it is significant and must be considered in oil spill simulations.

Crawford *et al*., (1996) comment, "Although average speed and rotation angles are well simulated by POM, much of the observed current variance is unexplained and may be due to features that the model is unable to reproduce. For example, the stratification input as the initial condition is horizontally uniform, and does not readily allow set-up of cold-water plumes observed in these waters by Crawford *et al*. (1995). ….. In addition, the simulation did not include influence of fresh water run-off from the mainland, nor any unusual ocean water masses that may have been advected from the Pacific Ocean, nor propagation of continental shelf waves into the region."

Although POM did not outperform simulations based only on winds, POM can be upgraded as noted above, and did predict near-shore currents better than did the wind-forced simulations.

d) **Scenarios of drift of surface particles.**

Patrick Cummins (personal communication, 2002) archived the POM simulation of tidal plus non-tidal currents for ocean and winds of late spring and summer of 1995. We applied these simulations to determine the expected drift of floating material on these surface waters. Simulated particles were released from a single location continuously from day 151 (May 31) until day 251 (September 8). Each particle was tracked for 20 days. These simulations are presented to show the extent of spread of material on water by surface currents and winds only. Proper evaluation of oil spill risks requires introduction of oil fates into the scenarios, and an ensemble of simulations to determine more quantitative analysis of the statistics of risks.

We denote these drifters as "floating material" rather than oil for several reasons noted below.

- A constant 2% of wind speed was applied to floating material drift, to account for motion over the surface currents simulated by POM. Staff members of the Office of Response & Restoration of NOAA normally apply a factor that randomly varies between 1% and 6% of wind speed for this drift.
- The simulation computed no oil spreading due to ocean turbulence, natural oil spreading over water, wind gusts, evaporation, or other fates noted earlier.
- The simulation represents late spring and summer conditions only. Summer winds tend to blow from the North or Northwest, and account for the generally southward drift in these simulations. Winter winds blow strongest from the South or Southeast, and will push oil more toward the north, and toward the eastern shore. Such winds generally begin to blow strongly in mid-October.
- The POM simulation does not represent motion due to surface waves near shore. Nor does it include sea breeze effects near shore. Therefore, it may predict too little oil encountering shore.

Figure 3 presents three scenarios, each with a different release location in Hecate Strait. These three release locations are in regions of high hydrocarbon potential as presented in Figure 5.8 in the report *British Columbia Offshore Oil and Gas Technology Update*, October 19, 2001, prepared for the BC Ministry of Energy and Mines by Jacques Whitford Environmental Limited.

Regions coloured dark blue represent drift in late spring 1995. Red regions depict late summer 1995. Colours for days between spring and late summer 1995 follow the rainbow between blue and red. Normally the late autumn and winter winds blow from the S or SE, beginning sometime around mid-October. By late spring these winds relax, and are replaced by weaker winds in summer from the NW. Storms bring S and SE winds in any season and the strong S and SE winds of winter are due to the greatly increased number of storms.

These three sets of simulations are intended to reveal the extent to which winds and surface tidal and non-tidal currents can move floating particles through the Queen Charlotte Basin. Most regions of Hecate Strait and Queen Charlotte Sound are impacted, as well as regions west of the northern part of Vancouver Island and to some extent in Dixon Entrance. Tracks over any one period of twenty days depend on weather patterns and storms that pass through. Therefore, one should not expect that particles started on their way on day 200 of 1995 would follow the same route on day 200 in other years. More significance can be placed on the ensemble average over the summer of 1995, as typical of expected summer conditions.

Day 151 of this simulation lies on 31 May, 1995, a time of decreasing strength of winds from the S and SE. Therefore few drifters enter Dixon Entrance in this simulation from the three sites selected. Simulations with additional release sites in northern Hecate Strait, and over several other summers will be required to determine if the relatively low number of particles reaching Dixon Entrance is a robust result. Studies in the 1980s revealed little *average* North-South flow through northern Hecate Strait, but significant *variable* North-South flow due to wind forcing (Crawford *et al*., 1988). Drifter studies in 1991 revealed motion from Hecate Strait into Dixon Entrance and Chatham Sound when winds blew from the South.

POM currents do not reproduce well the ocean currents near Cape St. James at the southern tip of the Queen Charlotte Islands, due to intense local turbulence and mixing of difference water masses whose physical processes are poorly understood. The drift of oil past Cape St. James in these three scenarios does not agree with the observed behaviour of near-surface drifters released here in the summers of 1990 and 1991. The simulation shows no oil drifting to the west past the cape, whereas observed drifters in this region almost always turned westward to flow out of Queen Charlotte Sound past this Cape (Crawford *et al*., 1995). Hodgins *et al*. (1992) evaluated spill predictions at Cape St. James using type (3) simulations with no seasonal currents. They compared simulations against currents observed in this region using shore-based radar sensors, and also determined that model-based, surface current simulations disagreed with actual observed currents. Therefore the impact of oil spills on this region, which is a part of the Gwaii Hanas Marine Conservation Area, cannot be determined with present hydrodynamical models.

POM currents do not include as yet the surface ocean motion due to outflow of fresh and brackish waters from the mainland inlets along the east side of Hecate Strait and Queen Charlotte Sound. Upwelling processes and tidal mixing combine here to produce a complicated pattern of plumes in summer (Cretney *et al.*, 2003) that require additional study. Winter surface currents here are even less well known.

Many of these processes are forced by small-scale winds near shore that are poorly measured, if at all. Better current simulations will require development of accurate mesoscale meteorological models of the region.

Despite these qualifications, the three simulations do provide a broad view of extent of surface drift in these waters due to a short spill from a rig or supply vessel, or a long-duration spill from a blow-out. Most particles do stay in coastal waters for at least twenty days, and can spread over considerable extent during this time. There is strong variability from one twenty day period to the next, and, as noted above, most regions of Hecate Strait and Queen Charlotte Sound seem to be vulnerable.

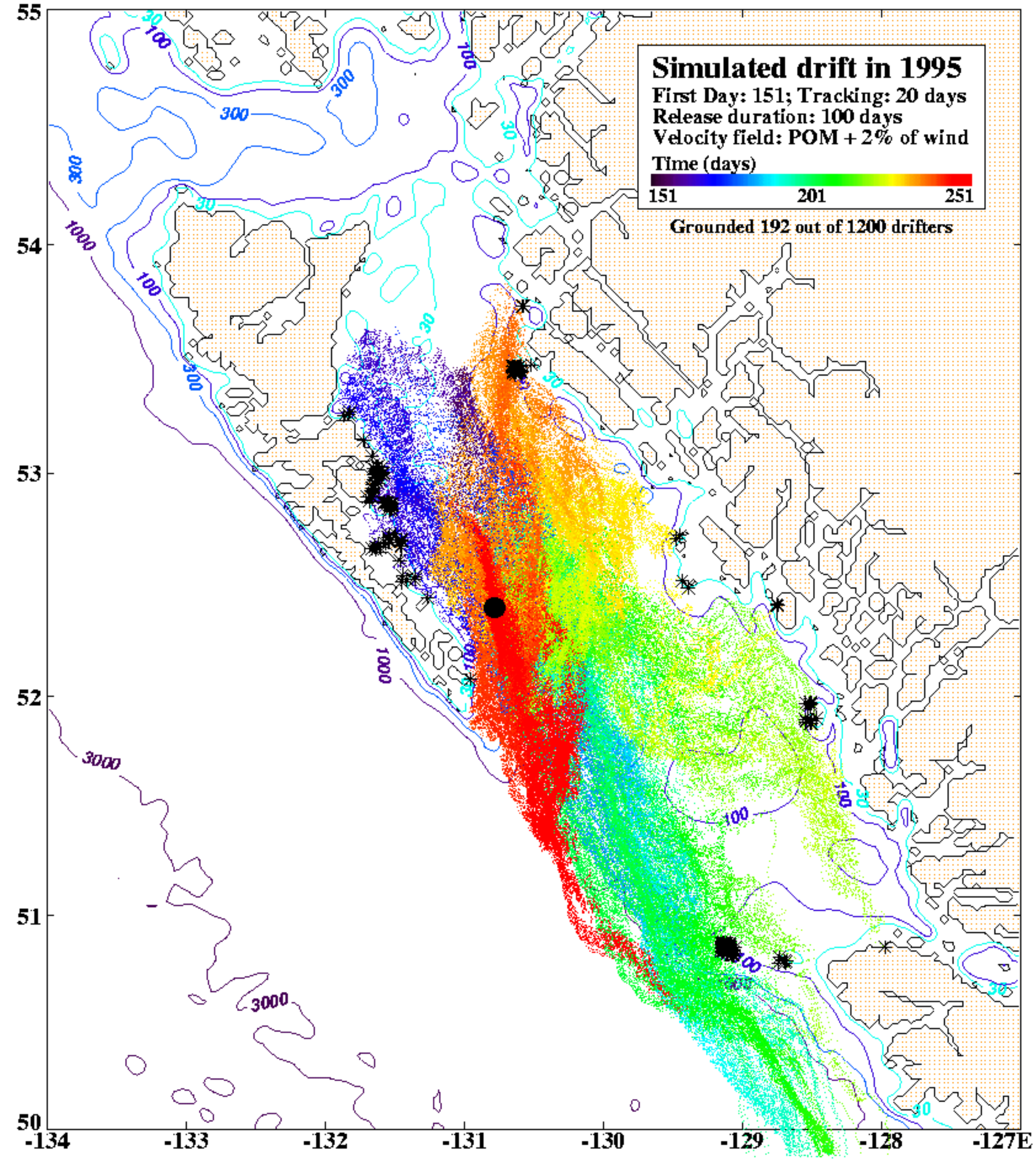

Figure 3a Drift simulation 1a: Drift of particles released from a single location in Hecate Strait (marked by a black solid circle). Particles are released every two hours from day 151 to day 251 in the summer of 1995 and the position of each element is plotted during twenty days of drift. The colours denote day in 1995 of each element, with Jan. 1 as day 1. Black asterisks show where particles encountered shore. Depth contours are in metres.

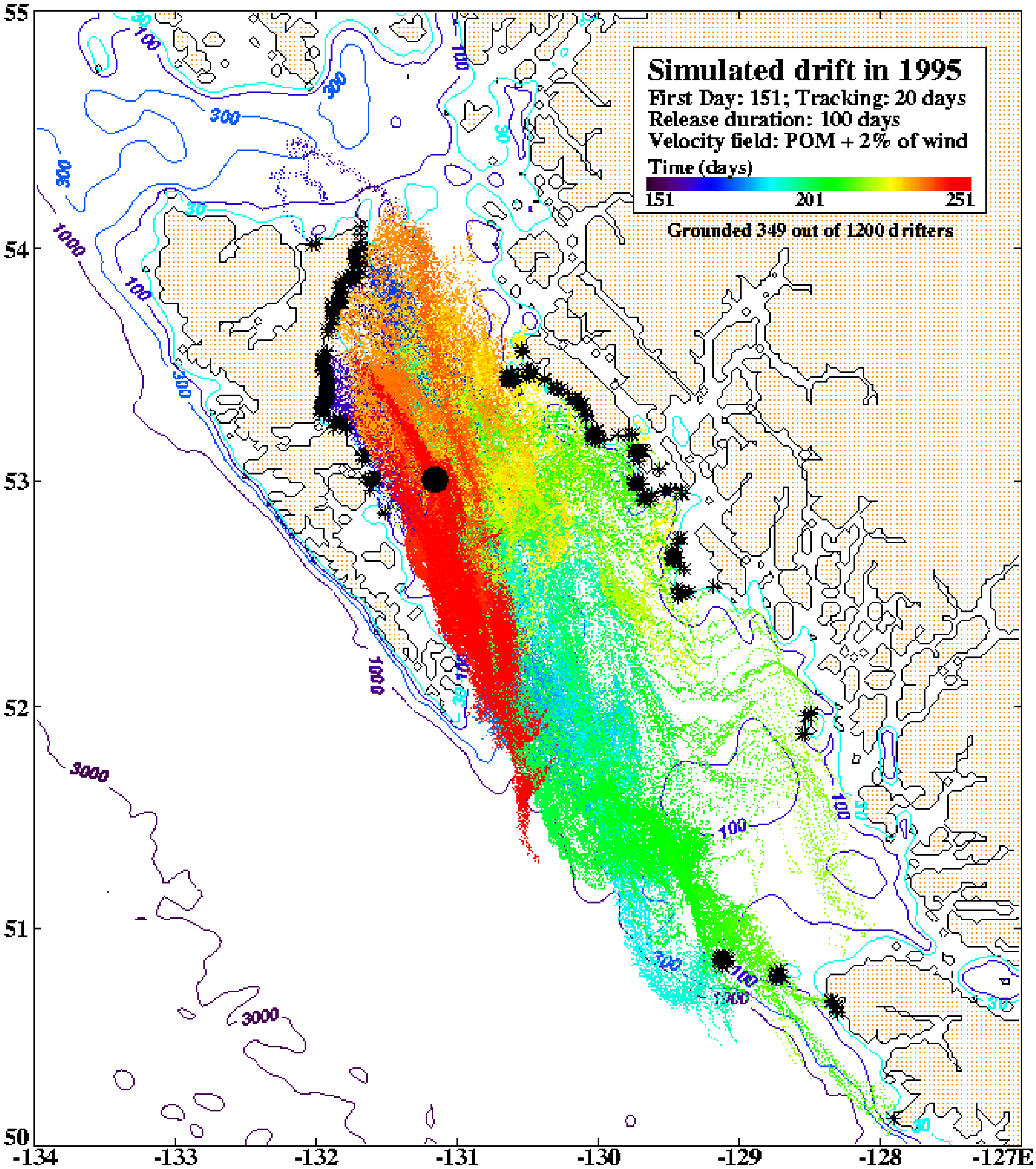

Figure 3b Drift simulation 1b: same as Figure 3a, but with a different oil release location.

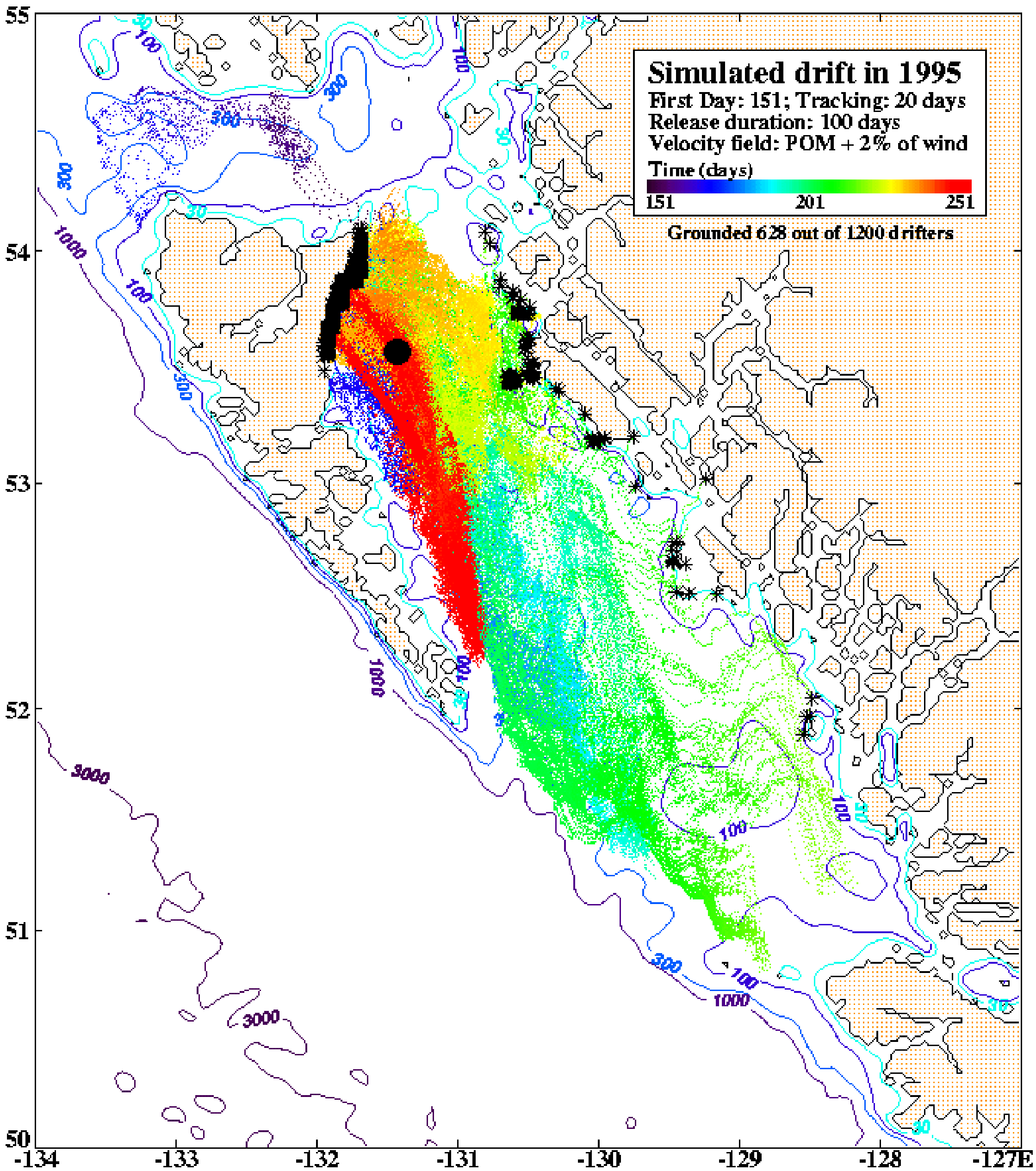

Figure 3c Drift simulation 1c: same as Figure 3a, but with a different oil release location.

4 MODELLING THE FATE OF DRILLING MUDS AND PRODUCED WATER.

In response to concerns about the effects of drilling mud discharged into the ocean from offshore oil and gas drilling, PERD has funded a multi-disciplinary program on offshore environmental impacts in Atlantic Canada, from the late 1980s to the present. Much of the work has been undertaken by scientists of Fisheries and Oceans Canada (DFO) at Bedford Institute of Oceanography in Nova Scotia, with additional funding from DFO. The discussion below draws on experience gained during this program.

In this section 'regulations' refers to the 1996 Offshore Waste Treatment Guidelines published by the Canada-Nova Scotia Offshore Petroleum Board (CNSOPB), the Canada - Newfoundland Offshore Petroleum Board (C-NOPB) and the National Energy Board (NEB). We note that revisions to the Guidelines were approved in August 2002 (www.cnsopb.ns.ca).

a) **Drilling muds**

An important part of the environmental impacts program has been the development of the benthic boundary layer transport (bblt) model, which estimates the drift, dispersion and near bottom concentrations of drilling mud discharges (Hannah *et al*. 1995, 1996b, 1998; Xu *et al*. 2000; Tedford *et al*. 2001, 2002). Predictions of potential impacts on scallops have been made by combining dose-response relationships derived from laboratory experiments with near-bottom concentrations predicted by bblt (Gordon *et al*. 2000, Cranford *et al*. submitted). Before discussing details there is an important general point to be made. The drift and dispersion of drill mud constituents can be modelled in a variety of ways. The modelling is best done in an environment where you know (or expect to know in the future) the answer to the question 'What concentrations of drill mud components will cause a problem?' The modelling at Bedford Institute of Oceanography (BIO) has concentrated on sub-lethal impacts, such as reduced growth, because the regulations eliminating the direct discharge of oil-based muds (OBM) have reduced the concerns about lethal effects of drill mud discharges. Successful modelling of sub-lethal impacts requires an active laboratory program measuring the dose-response relationships for the organisms of interest.

Gordon *et al*. (2000) provide a good description of all the factors that must be considered when attempting to model the fate and effects of drilling mud discharges on the marine environment. The context for their work was the review of the moratorium on exploration drilling on Georges Bank. Modelling the fate and effects of drilling mud discharged into the ocean requires knowledge in five areas:

1) the physical, chemical and biological properties of the drill mud and its components;
2) the pathways by which drill mud components move in the environment;
3) the partitioning of the drill mud between the different pathways;
4) the dose-response of the organisms of interest to the drill mud components;
5) the physical and biological environment receiving the discharges.

Below we show how all these components are linked together in the approach taken at BIO. Most of the BIO modelling work has concentrated on water-based muds (WBM) because the direct discharge of oil-based muds (OBM) and synthetic muds (SBM) is restricted by regulations in Canadian waters. The primary constituents of WBM are bentonite and barite. Bentonite consists of the clay mineral montmorillonite, an aluminium silicate that flocculates readily in seawater. Barite is the common name for barium sulphate. Laboratory experiments have shown that small barite particles (< 5 μm) can flocculate like bentonite, however the larger particles tend to behave more like individual grains.

There are three primary modes of discharge of drilling mud into the ocean: ‘open circuit drilling’, ‘mud stuck to cuttings’ and bulk discharge:

1) At the beginning of the well the mud and rock from the drill hole (‘cuttings’) are discharged at the sea floor because the drilling system is not sealed; the system is running as an open circuit. The mud pumped into the drill string at the top comes out of the hole at the sea floor.
2) Once the well is deep enough the drilling system is sealed off and the drilling fluids are returned to the deck. Once the material is back on deck, the cuttings are separated from the drilling fluids and the cuttings are discharged over the side. The drilling fluids are reused.
3) Some drill mud sticks to the cuttings and is discharged with the cuttings. A bulk discharge of WBM can occur when the driller wants to change the drilling fluid. The old WBM is discharged into the ocean.

In Canada, open circuit drilling and the bulk dumps can only be done with WBM because the direct discharge of OBM and SBM is limited by regulation. The amount of ‘mud stuck to cuttings’ is also limited by regulation. For SBM, the regulatory regime in Nova Scotia for Jan 2000 to August 2002 resulted in the mud and cuttings being shipped to shore for disposal.

The bulk discharge of WBM has been the focus of much of the modelling work because of the large mass discharged in a short time. The initial convective descent phase and associated entrainment of sea water determines how much of the material reaches the sea floor. Some of the material will float to the surface and cause a surface slick, some may reach a neutral density surface and enter a passive diffusion phase, and some will reach the bottom as a rain of heavier-than-water particles. If the plume does not reach a neutral density surface, then most of the plume hits the seafloor. The plume dispersion models available in the public domain are not very sophisticated with respect to multi-constituent material. They do not allow for the separation of the plume into different constituents with different properties. They do not account for material transformations such as flocculation, by which particles can aggregate and change their buoyancy, and adhesion, by which particles can attach themselves to oil drops and rise to the surface. As a result, partitioning of the discharge plume into different possible pathways is crude.

The settling velocity of the drill mud is a critical parameter. Along with the bottom stress, it governs the vertical distribution of the material. Flocculation, the process whereby fine material aggregates and achieves settling velocities larger than that of the individual grains, is an important process in controlling the settling velocity. Laboratory experiments have shown that OBM and WBM readily flocculate and can achieve settling velocities in excess of 0.5 cm/s (about 500 metres/day). In addition, observations in the field have shown that naturally occurring flocs are ubiquitous and that a representative settling velocity is 0.1 cm/s (Hill *et al*. 1998, 2000). As mentioned above, some of the barite will be caught up in the flocculation processes and some will not. The maximum in the barite size spectrum is around 50 μm, which results in a single grain settling velocity close to 0.5 cm/s.

Flocculation is a concentration-dependent process. We expect that it occurs during a bulk discharge, but it may not occur when the drill mud is winnowed from the cuttings during and after the descent to the bottom. It is not clear whether flocculation occurs during open circuit drilling. Thus the appropriate settling velocity depends on the mode of discharge. In addition, recent observations suggest that natural flocs break up when the turbulent shear stress exceeds 0.1 Pa (roughly equivalent to a bottom friction velocity of 1 cm/s). Thus the heavy flocs that result from the bulk discharge may break up when the turbulent stress exceeds this critical break-up stress. This deflocculated material would then be incorporated into the natural floc population, with lower settling velocity, when the stress decreases. However the large barite particles would not change settling velocity. The different material properties and the different discharge pathways create the potential for a very complex partitioning of the discharge. A much simpler approach was used for the model applications for the Georges Bank moratorium review process (Gordon *et al*. 2000).

The biological effects have focussed on the sea scallop (*Placopecten magellanicus*) because of its economic value on Georges Bank and of its life history. Once the juveniles settle to the seabed, their mobility is limited. As bottom dwelling filter-feeders they obtain their food particles from the benthic boundary layer where drill waste concentrations are expected to be largest. The analysis has focussed on sub-lethal effects, such as impaired growth, because neither barite nor bentonite is observed to be highly toxic to scallops (Cranford and Gordon 1992; Cranford *et al*. 1999). The observed sublethal effects from barite and bentonite appear to arise from the negative influence of fine inorganic particles on the scallop feeding process. Barite has an impact on scallop growth at much lower concentrations than bentonite for reasons that are not understood (Peter Cranford, BIO, pers. comm. 2002). Barlow and Kingston (2001) also provide evidence that 'barite affects marine organisms to a degree that is out of proportion to its theoretical toxicity.'

The overall modelling procedure followed by Gordon *et al*. (2000) for the Georges Bank moratorium review process was as follows. The fraction of the material reaching the bottom at different locations was estimated from the plume dispersion calculations of Andrade and Loder (1997). Drill mud concentrations were estimated at different sites using settling velocities of 0.1 cm/s and 0.5 cm/s to bracket the expected range of settling velocities. These composite drill mud concentrations were partitioned 50:50 between bentonite and barite, based on the drilling scenario. The potential growth days lost for the different sites and settling velocities were estimated using the dose-response relationships derived from laboratory experiments (Cranford and Gordon, 1992; Cranford *et al*. 1999).

Now we focus on the bblt (benthic boundary layer transport) model. The development of bblt model has been focussed on the fate of the fine particulate fraction and has been guided by three key ideas:

1) Flocculation of the fine particles provides a pathway for an impact on the benthic environment because the settling velocity of the flocculated material is higher than the settling velocity of the individual grains;
2) Shear dispersion, due to the interaction of vertical mixing and vertical shear in the horizontal currents, is a crucially important dispersion process in the benthic boundary layer;
3) Site specific information on currents is usually limited to that from two or three current meters.

The model applications have shown that shear dispersion is an effective mechanism for horizontal dispersion from a point source and that the settling velocity is a crucial factor in determining the vertical distribution and the resulting horizontal spreading of the material (Hannah *et al*. 1996b, 1998).

A key modelling issue has been the settling velocity. Simulations on Georges Bank, the Scotian Shelf and the Grand Bank have shown that the two settling velocities of 0.1 and 0.5 cm/s used by Gordon *et al*. (2000) tend to result in very different vertical distributions of the material, often the difference between the material being almost uniformly distributed in the vertical and being contained close to the bottom. The resulting near-bottom concentrations can be very different. Clearly flocculation processes are very important.

Most of the bblt model applications aimed at drill mud discharges on the Atlantic Canadian shelf have used several constant settling velocities to bracket the likely range of settling velocities. However recent observations suggest natural flocs break up when the turbulent shear stress exceeds 0.1 Pa (Hill *et al*. 2001). To incorporate this idea we constructed a stress dependent settling velocity for use with the bblt model (Tedford *et al*. 2002).

If one accepts the floc break-up concept, then bottom stress provides a useful indicator of the likelihood of large settling velocities (and high concentrations) if the critical break-up stress of the flocs is known. As a result, accurate bottom stress estimates become very important. Two useful indices are 1) the fraction of time the bottom stress is above the break-up stress and 2) the probability that the bottom stress does not exceed the break-up stress for some number of days

(Tedford *et al*. 2002). Overall we expect that the fate and impact of the drill mud will be critically dependent on the discharge conditions and the bottom stress environment. The discharge conditions will determine how much material reaches the seafloor and whether the discharged material forms dense (fast settling velocity) flocs on discharge. The bottom stress environment will control the size distribution (settling velocity) of the floc population, determine whether dense initial flocs are broken up quickly and control the vertical distribution of the material.

The BIO modelling program has focussed on bentonite and barite because they are the primary components of WBM and they have a measurable impact on scallops, a valuable resource. As well, on shallow banks a major fraction of a surface discharge can be expected to reach the seafloor. This focus resulted in many areas being neglected. These areas include sediment transport processes such as deposition and erosion, long term accumulation, the cuttings pile, and trace chemical in the drilling mud. These are discussed briefly below.

The conceptual model of the drill mud fines being incorporated into flocs has resulted in an approach that assumes that the material is always in suspension. We have not been concerned with the deposition, erosion, critical shear stress, or bedload transport. No one has postulated a critical shear stress for flocculated drill mud fines. Bblt is capable of allowing for deposition, erosion, and a critical shear stress for suspension. For example, an application to Sydney Harbour (N.S.) used observations to specify the fraction of material in suspension as a function of the bottom shear stress (Petrie *et al*. 2001).

The offshore banks of Atlantic Canada are high-energy environments with substantial sediment transport, especially during the winter. This knowledge has led to an explicit assumption that the drilling mud discharges are dispersed to negligible concentrations during the winter. As a result the focus has been on fate and effects on time scales of days to weeks. Consistent with this focus, there has not been any work on sequestering of drill mud material in the sediment or on long term accumulations. With new PERD funding there will be a modest observational program looking for evidence that some barite is being sequestered in the sediment around drilling activity on Sable Island Bank. The results of this work will be used to assess the potential for long term accumulation of barite and to improve the modelling of the partitioning of barite between the water column and the sediment.

There has been no modelling of the long-term winnowing of the drill mud from the cuttings pile. We have assumed that most of the drill mud components are winnowed from the cuttings during descent and have treated them as an instantaneous discharge. This assumption maximises the short-term concentrations. The properties of the cutting pile, such as its cohesion and its erosion rates, will depend heavily on the properties of the drill mud.

The modelling has not addressed the fate and effects of any of the trace chemicals in the drill mud. Overall the volume of discharge from an exploratory well is small and the concentrations decay rapidly in space and time. Therefore extreme toxicity or a concentration mechanism is required to have an effect on marine organisms. Likely candidates for a concentration mechanism are the bottom boundary, the surface boundary, a local low energy environment, sequestering in the sediment, and bioaccumulation. There are probably others.

Due to the limited amount of site specific information, most of the bblt applications have been done with a local version of the model, where the currents and the bottom stress are assumed to be horizontally homogeneous. A version of bblt that allows for spatial variations in the currents has been developed for applications on Georges Bank using tidal and seasonal mean currents (Xu et al. 2000). The integration of bblt into a comprehensive 3-d circulation model is planned as part of a new PERD project.

The bblt is not the only modelling approach for estimating the fate of drill mud discharges. However much of the other model development work is being done by consulting companies and the models, algorithms and results are difficult to find. There are at least two commercially available modelling packages that are relevant here:

- CHEMMAP (Applied Science Associates; www.appsci.com)
- PROTEUS (BMT Marine Information Systems; www.bmtmis.com)

From the online literature, CHEMMAP is a chemical discharge model that can be applied to drilling mud and produced water problems. PROTEUS is aimed directly at the oil and gas market. On their web site, BMT MIS claims that 'PROTEUS models all the major processes (physical, geochemical and biological) influencing the dispersion and behaviour of drilling and production discharges throughout the entire life-cycle of an offshore field.' A real strength of these packages is that they have databases of the physical, chemical and biological properties of the enormous number of chemicals that might be related to oil and gas activities. From the online literature, it is not clear whether these packages deal with flocculation, adhesion, and other processes that can affect the transport pathways of chemicals. It is also unlikely that the databases include information on sub-lethal effects as these are generally organism specific.

One of the issues being raised in the relation to potential hydrocarbon exploration in the Hecate Strait Region is the potential impact of drill mud discharges on some sponge reefs found in both Hecate Strait and Queen Charlotte Sound, generally near 200-m depth. As a first point, we note that smothering is a distinct possibility if the drilling takes place very near a sponge bed. The cuttings piles on the Scotian Shelf have been observed to be confined to about 100 m of the drilling rig. Modelling potential impacts due to the transport of drill mud material from the drill site to the sponge bed will require answers to the questions such as

- Is the discharge plume likely to reach the bottom?
- How often the bottom stress exceed 0.1 Pa at the drill site and at the sponge beds?
- Will clay (bentonite) concentrations of 0.1 – 10 mg/l affect the sponges?
- Does barite affect the sponges?
- Are scallops a reasonable proxy for sponges?
- Are the sponges sensitive to any of the trace chemicals in the proposed drill mud? If so at what levels?

b**) Produced water**

Produced water is the water that is extracted from the well along with the oil and gas during the production process. It consists of formation water, which is the water naturally occurring in the geological formation; injection water that is injected into the well during the process; and/or in the case of gas production, condensed water; and/or in the case of oil production, seawater that has been injected to maintain reservoir pressure, and other technological waters (i.e. treatment chemicals such as emulsion breakers, corrosion inhibitors, biocides, etc). The formation-water component of production water is, in effect, a brine which derives its salinity from the major ions found in seawater. However, depending on the nature of the formation, they also contain a number of metal and organic constituents of environmental interest including:

1) hydrolysis metals,
2) heavy metals,
3) organic chemicals including petroleum hydrocarbons,
4) nutrients,
5) radionuclides, and
6) treating chemicals.

Produced water is the largest volume waste stream from oil and gas production activities.

The state-of-the-art of produced water modelling in 1995 is covered by the papers in the proceedings of the 1995 International Produced Water Symposium (Reed and Johnsen 1996). Since then there has been significant development work aimed at modelling sub-lethal and chronic effects from produced water. For example a Norwegian consortium is developing a modelling package called DREAM (Dose-related Risk and Effects Assessment Model; Karman, 2000; www.sintef.no/units/chem/environment/numerical_modelling.htm) which is based on a previous package called PROVANN (Reed *et al*. 1996). In addition, these commercial packages mentioned in the drilling mud section, CHEMMAP (French McCay and Isaji, 2002) and PROTEUS (Sabeur and Tyler 2002), are intended for produced water modelling.

These packages contain large data bases of physical, chemical and biological properties and contain sub-models that deal with a wide range of physical and chemical processes such as plume discharge, transport of dissolved and particulate material, evaporation and sedimentation. A brief review of the online literature indicates that these models represent the state-of-the-art and they should be evaluated for application in Canadian waters. However the publication of the model details will likely be limited and the cost of the software will likely be too large for a typical research budget.

Produced water modelling for the environmental assessments for oil and gas projects on the East Coast of Canada have generally used a plume dispersion model (also called a convective descent model) to model the near-field concentrations of produced water and an advection-diffusion model to look at concentrations further from the production platform. The results generally show that there is sufficient dilution to reduce the concentrations in the water column below levels where lethal effects are expected. There has been very little work on sublethal effects, transport pathways of individual contaminants or potential concentration mechanisms such as particles adhering to oil droplets and rising to the surface. There is a need to understand the chemical kinetics of the contaminant fraction in produced water as it can influence its environmental transport and biological effect.

Recently, a joint study by the Institute of Marine Research, Norway, and the University of Gothenburg, Sweden, (www.imr.no) was released describing sublethal effects in cod (*Gadus morhua*) caused by alkylphenols, which are natural constituents of produced water. Because no concentration measurements of alkylphenols from produced water in pelagic fish or sea water around North Sea platforms were available, the dosing levels were chosen based on model simulations by Rye *et al*. (1996). The model simulations indicated that fish could accumulate body burdens of 1-10 ng/g in the vicinity of platforms on Halten Bank in the Norwegian Sea. Realistic dosing levels based on these theoretical body burdens provided evidence of reproductive impairment affecting both male and female cod. At the lowest levels studied, slowed development of eggs in females was estimated to result in a 3-week delay in spawning of treated fish compared to controls. Treated males had reduced testosterone levels, began to produce the egg-yolk protein vitellogenin and produced fewer sperm than controls.

Dr. Ole Arve Misund, Director of the Institute of Marine Research, was quoted to have said: "Apart from the obvious problem that smaller eggs produce smaller larvae and so reduce the chances of cod surviving, they also produced at the wrong time, so that the spring plankton bloom which is the baby cod's main food source, would have disappeared." (www.gasandoil.com/goc/news/nte21655.htm). Such a mismatch could have dire consequences to cod stocks, if exposure to produced-water alkylphenols affects significant proportions of populations.

The study of the effects of alkylphenols on North Sea cod demonstrates the value of modelling in setting realistic levels of dosing for experiments. Clearly, actual measurements of fish body burdens and seawater concentrations are required to confirm model results. Even so, models that encompass produced water discharges from all producing wells in an area could provide estimates of the collective risk to fish populations from producing wells. The oil and gas industry should be encouraged to continue to develop and use models such as the ones mentioned above.

The overall goal of the produced water modelling at BIO is to estimate the likely concentrations of the constituents of produced water in the vicinity of the production platform. The focus is on transport pathways of the contaminants, possible concentrating mechanisms and sub-lethal effects. As with the drill waste modelling, the work is being done in conjunction with a field program and a laboratory program. The BIO modelling program will not compete with the comprehensive modelling package mentioned above. Rather it will focus on critical mechanisms and pathways that are identified by lab work and field work at BIO and elsewhere in the world. Under the current PERD program the bblt model is being improved with the inclusion of generic parameters for use on the West Coast.

The models will become increasingly sophisticated as the observation program provides information on chemical and biological transformations that may provide different transport pathways for different constituents. For example, can high concentrations of some contaminants be achieved at the surface as particles adhere to oil droplets that rise to the surface, and do the chemical transformations (such as degradation rates) depend on the biological state of the ocean (e.g., spring bloom conditions compared with summer or winter conditions)?

Produced water from crude oil production may contain high levels of nutrients (e.g. ammonia) and other constituents (e.g. hydrocarbons) that may be stimulatory or inhibitory to microbial production. The modelling of Rivkin *et al*. (2000) suggests that the likely impacts of the expected additional input of ammonia and dissolved organic carbon at Hibernia are an increased channelling of primary production into the microbial food web and an increased vertical flux of detritus to the benthos. These ideas will be explored further using the the lower trophic level model of Vezina and Pahlow (2002) and Pahlow and Vezina (2003) forced by environmental conditions and produced water inputs relevant to the Cohasset site on Sable Island Bank and the Hibernia site on the Grand Bank.

REFERENCES

ASCE Task Committee 1996. State-of-the-art review of modeling transport and fate of oil spills. *J. Hydraulic Engineering.* 122: 294-609.

Andrade, Y., and Loder, J.W. 1997. Convective descent simulations of drilling discharges on Georges and Sable Island Banks. *Can. Tech. Rep. Hydrog. Ocean Sci*. 185: vi+83 pp.

Bakun, A. 1996. *Patterns in the Ocean: Ocean Processes and Marine Population Dynamics*. University of California Sea Grant College Program; United States NOAA; Centro de Investigaciones Biologicas del Noroeste (Mexico), xiv + 323 p.

Ballantyne, V.A., Foreman, M.G.G., Crawford, W.R., and Jacques, R. 1996. Three-dimensional model simulations for the north coast of British Columbia. *Cont. Shelf Res*. 16:1655-1682.

Barlow, M.J., and P.F. Kingston. 2001. Observations on the effects of barite on gill tissues of the suspension feeder *Cerastoderma edule* (Linné) and the deposit feeder *Macoma balthica* (Linné). *Marine Pollution Bulletin.* 42:71-76.

Barstow, S.F. 1983. The ecology of Langmuir circulation: a review. *Marine Environmental Research*. 9:211-236.

Barron, M.G., Little, E.E., Calfee, R., and Diamond, S. 2000. Quantifying solar spectral irradiance in aquatic habitats for the assessment of photoenhanced toxicity. *Environ. Toxicol. Chem.* 90:920-925.

Bowman, M.J., Vissar, A., and Crawford, W.R. 1992. The Rose Spit Eddy in Dixon Entrance: Evidence for its existence and underlying dynamics. *ATMOSPHERE-OCEAN. 30*:70-93.

Bragg, J.R., and Yang, S. H. 1993. Clay-oil flocculation and its effect on the rate of natural cleansing in Prince William Sound following the *Exxon Valdez* oil spill. In: P.G. Wells, and Butler, J.N., editor. Exxon Valdez Oil Spill-Rate and Effects in Alaskan Waters. Philadelphia, USA. *Amer. Soc. Testing Mater*. p 178-214.

Bragg, J.R., and Owens, E.H. 1994. Clay-oil flocculation as a natural cleansing process following oil spills: Part 1-Studies of shoreline sediments and residues from past spills. In: *Seventeenth Arctic and Marine Oilspill Program* (AMOP). Vancouver, British Columbia, Environment Canada. p 1-23.

Broman, D., Naf, C., Axelman, J., Bandh, C., Pettersen, H., Johnstone, R., and Wallberg, P. 1996. Significance of bacteria in marine waters for the distribution of hydrophobic organic contaminants. *Environ. Sci. Technol*. 30:1238-1241.

Bruheim, P., and Eimhjellen, K. 1998. Chemically emulsified crude oil as substrate for bacterial oxidation: differences in species response. *Can. J. Microbiol*. 44:195-199.

Calfee, R.D., Little, E.E., Cleveland, L., and Barron, M.G. 1999. Photoenhanced toxicity of a weathered oil on *Ceriodaphnia dubia* reproduction. *Environ. Sci. Poll. Res*. 6:207-212.

Canevari, G.P., and Fiocco, R.J. 1997. Crude oil vanadium and nickel content can predict emulsification tendency. In: *Proceedings: 1997 International Oil Spill Conference*. April 7-10. Fort Lauderdale, Florida, USA. p 309-314.

Cheng, N.-S., Law, A.W-K., and Findikakis, A.N. 2000. Oil transport in the surf zone. *J. Hydraulic Engineering.* 126:803-809.

Cherniawsky, J., and W.R. Crawford, 1996: Comparison between weather buoy and Comprehensive Ocean-Atmosphere Data Set wind data for the west coast of Canada. *Journal of Geophysical Research.* 101(C8):18,377-18,389.

Chin, W.-C., Orellana, M.V., and Verdugo, P. 1998. Spontaneous assembly of marine dissolved organic matter into polymer gels. *Nature.* 391:568-572.

Cranford, P.J. and Gordon Jr., D.C., 1992. The influence of dilute clay suspensions on the sea scallop (*Placopecten magellanicus*) feeding activity and tissue growth. *Neth. J. Sea Res*. 30: 107-120.

Cranford, P.J., Gordon Jr., D.C., Lee, K., Armsworthy, S.L., and Tremblay, G.-H. 1999. Chronic toxicity and physical disturbance effects of water- and oil-based drilling fluids and some

major constituents on adult sea scallops (*Placopecten magellanicus*). *Mar. Env. Res*. 48: 225-256.
Cranford, P.J., Gordon Jr., D.C., Hannah, C.G., Loder, J.W., Milligan, T.G., Muschenheim, K.D., and Shen, Y. (submitted). Modelling potential effects of petroleum exploration drilling on northeastern Georges Bank scallop stocks. *Ecological Modelling*.
Crawford, W.R. 1997. Physical oceanography of the waters around Queen Charlotte Islands. In: Vermeer, K., and Morgan K.H., editors. *The ecology, status and conservation and marine and shoreline birds of the Queen Charlotte Islands*. Canadian Wildlife Service. p 8-17.
Crawford, W.R. 2001. Oceans of the Queen Charlottes Islands, 2001. In. *Can. Tech. Rep. of Fish. Aq. Sci*. No.2383:1CD-ROM. Fisheries and Oceans Canada, Institute of Ocean Sciences, Sidney, B.C..
Crawford, W.R., and Greisman, P. 1987. Investigation of permanent eddies in Dixon Entrance, British Columbia. *Continental Shelf Res*. 7:851-870.
Crawford, W.R., Huggett, W.S., and Woodward, M.J. 1988. Water transport through Hecate Strait, British Columbia. *ATMOSPHERE-OCEAN.* 26:301-320.
Crawford, W.R., Huggett, W.S., Woodward, M.J., and Daniel, P. 1985. Summer circulation of the waters of Queen Charlotte Sound. *ATMOSPHERE-OCEAN.* 23:393-413.
Crawford, W.R., Woodward, M.J., Foreman, M.G.G., and Thomson, R.E. 1995. Oceanographic features of Queen Charlotte Sound and Hecate Strait in the summer. *ATMOSPHERE-OCEAN.* 33:639-681.
Crawford, W.R., Cherniawsky, J.Y., and V.A. Ballantyne. 1997. Current predictions for oil spill models. *Proceedings of the Twentieth Arctic and Marine Oilspill Program (AMOP).* Published by Environment Canada, Ottawa. p 877-885.
Crawford, W.R., Cherniawsky, J.Y., and Cummins, P. 1999. Surface currents in British Columbia coastal waters: Comparison of observations and model predictions. *ATMOSPHERE-OCEAN.* 37:255-280.
Crawford, W.R., Cherniawsky, J.Y., Cummins, P.F., and Foreman, M.G. 1998a. Variability of tidal currents in a wide strait: A comparison between drifter observation and numerical simulations. *J. Geophys. Res*. 103:12,743-12,759.
Crawford, W.R., Cherniawsky, J., and Foreman, M.G.G. 1998b. Rotary velocity spectra from short drifter tracks. *J. Atmospheric and Oceanic Technology*. 15:731-740.
Crawford, W.R., Cherniawsky, J.Y., Hannah, C.G., and Ballantyne, V.A. 1996. Current predictions for oil spill models. *Spill Sci. Technol. Bull*. 3:235-239.
Crean, P.B, 1967. Physical Oceanography of Dixon Entrance, British Columbia. *Bulletin* 156, Fisheries Research Board of Canada, 66 pp.
Cretney, W.J. 1992. Fate of petroleum hydrocarbons in marine ecosystem enclosures and relevance to oil spills. In: Harrison, P.J., and Wong, C.S., editors. *Proceedings of an International Symposium on Marine Ecosystem Enclosure Experiments*, May 9-14, 1987. Beijing, Peoples Republic of China. Published by International Development and Research Centre, Ottawa. p 122-139.
Cretney, W.J., Crawford, W., Masson, D., and Hamilton, T., 2003. Physical oceanographic and geological setting of a possible offshore oil and gas industry in the Queen Charlotte Basin, Document 2002/004, Pacific Science Advice Review Committee, Fisheries and Oceans Canada, Nanaimo, British Columbia. 38 pp.
Cummins, P.F., and Oey, L-Y. 1997. Simulation of barotropic and baroclinic tides of northern British Columbia. *Journal of Physical Oceanography.* 27:762-781.
Delvigne, G.A.L., and Sweeney, C.E. 1988. Natural dispersion of oil. *Oil and Chemical Pollution.* 4:281-310.
Daling, P.S., Mackay, D., Mackay, N., and Brandvik, P.J. 1990. Droplet size distribution in chemical dispersion of oil spills: towards a mathematical model. *Oil and Chemical Pollution*. 7: 173-198.

Dutta, T.K., and Harayama, S. 2000. Fate of crude oil by the combination of photooxidation and biodegradation. *Environ. Sci. Technol*. 34(8):1500-1505.
Elliot, A.J. 1999. Simulations of atmospheric dispersion following a spillage of petroleum at sea. *Spill Sci. Technol. Bull*. 5:39-50.
Farmer, D., and Li, M. 1994. Oil dispersion by turbulence and coherent circulations. *Ocean Engineering.* 21(6):575-586.
Fay, J.A. 1971. Physical processes in the spread of oil on a water surface. *In Proceedings of Joint Conference on the Prevention and Control of Oil Spills*. Washington, D.C., June 15-17, 1971. Published by American Petroleum Institute, Washington, D.C. p 463-467.
Fingas, M. 1997. The evaporation of oil spills: prediction of equations using distillation data. *In* 20th *Arctic Marine Spill Program Technical Seminar*. Vancouver, B.C., June 11-13, 1997. Environment Canada, Ottawa, Ontario. p 1-20.
Fingas, M., Fieldhouse, B., and Mullin, J. 1999. Water-in-oil emulsions: results of formation studies and applicability to oil spill modelling. *Spill Sci. Technol. Bull*. 5:81-91.
Foreman, M.G.G., 1978, Manual for tidal currents analysis and prediction, *Pacific Marine Science Report* 78-6, Institute of Ocean Sciences, Sidney, B.C., Canada. 70 pp.
Foreman, M.G.G., Henry, R.F., Walters, R.A., and Ballantyne, V.A. 1993. A finite element model for tides and resonance along the north coast of British Columbia*. J. Geophys. Res.* 98:2,509-2,531.
Foreman, M.G.G., Crawford, W.R., Cherniawsky, J.Y., Henry, R.F., and Tarbotton, M. 2000. A high-resolution assimilating tidal model for the northeast Pacific Ocean. *Journal of Geophysical Research*. 105:28,629-28,652.
French, D.P. 1998. Evolution of oil trajectory, fate and impact assessment models. In: Garcia-Martinex, R. and Brebbia, C.A., editors. *Oil and Hydrocarbon Spills, Modelling, Analysis and Control.* Wessex Institute of Technology, Southampton, U.K. p 73-86.
French McCay, D.P., and Isaji, T. 2002. Evaluation of the consequences of chemical spills using modelling: chemicals used in deepwater oil and gas operation. *J. Marine Systems*. Accepted in a special issue for the International Marine Environmental Seminar 2001.
Galt, J.A., and Payton, D.L. 1999. Development of quantitative methods for spill response planning: a trajectory analysis planner. *Spill Sci. Technol. Bull*. 5:17-28.
Garrett, R.M., Pickering, I.J., Haith, C.E., and Prince, R. 1998. Photooxidation of crude oils. *Environ. Sci. Toxicol*. 32:3719-3723.
Gordon Jr., D. C., Cranford, P. J., Hannah, C. G., Loder, J. W., Milligan, T. M., Muschenheim, D. K., and Shen, Y. 2000. The potential effects of exploratory hydrocarbon drilling on Georges Bank scallop populations. *Can. Tech. Rep. Fish. Aquat. Sci*. No. 2317, 116 pp.
Guan, J., Waite, T.D., and Amal, R. 1998. Rapid characterization of bacterial aggregates. *Environ. Sci. Technol*. 32:3735-3742.
Gundlach, E.R. 1987. Oil holding capacities and removal coefficients for different shoreline types to simulate spills in coastal waters. In: *Oil Spill Conference* 1987. Washington, D.C.: American Petroleum Institute. p 451-457.
Hannah, C.G., LeBlond, P.H., Crawford, W.R., and Budgell, W.P. 1991: Wind-driven barotropic circulation in Queen Charlotte Sound and Hecate Strait. *ATMOSPHERE-OCEAN.* 29:712-736.
Hannah, C.G., Loder, J.W., Shen, Y., and Muschenheim, D.K. 1995. bblt: Formulation and exploratory applications of a benthic boundary layer transport model. *Can. Tech. Rep. Hydrog. Ocean Sci*. 166: vi+52 pp.
Hannah, C.G., Loder, J.W., and Shen, Y. 1996a. Shear dispersion in the benthic boundary layer. In: *Estuarine and Coastal Modeling*: *Proceedings of the 4th International Conference*. Spaulding, M.L., and Cheng, R.T. eds. ASCE. p 454-465.
Hannah, C.G., Loder, J.W., and Wright, D.G. 1996b. Seasonal variation of the baroclinic circulation in the Scotia Maine Region. In *Buoyancy Effects on Coastal Dynamics, Coastal*

and Estuarine Studies. (Adbrey, D. and Friedrichs, C. Eds.), Vol. 53. American Geophysical Union, Washington, DC. p 7-29.

Hannah, C.G., Xu, Z., Shen Y., and Loder, J.W. 1998. Models for suspended sediment dispersion and drift. In: *Estuarine and Coastal Modeling: Proceedings of the 5th International Conference.* ASCE. pp. 708-722.

Hill, P.S., Syvitski, J.P., Cowan, E.A., and Powell, R.D. 1998. In situ observations of floc settling velocities in Glacier Bay, Alaska. *Marine Geology*. 145:85-94.

Hill, P.S., Milligan, T.G., and Geyer, W.R. 2000. Controls on effective settling velocity of suspended sediment in the Eel River flood plume. *Continental Shelf Res*. 20:2095-2111.

Hill, P.S., Voulgaris, G., and Trowbridge, J.H. 2001. Controls on floc size in a continental shelf bottom boundary layer. *J. Geophys. Res*. 106:9543-9549.

Hodgins, D.O., Huang, J-H., Dunbar, D.S., and Hodgins, S.L.M. 1991. A high-resolution coupled hydrodynamic and oil spill modelling system applied to the Port of Vancouver. In: *Fourteenth Arctic and Marine Oilspill Program Technical Seminar*. Vancouver, B.C.: Environment Canada. p 39-56.

Hodgins, D.O., Huang, J.H., and Fingas, M.F. 1992. Oil spill modelling using remote sensed surface currents. *Proceedings of the Fifteenth Arctic and Marine Oilspill Program (AMOP),* Edmonton. Environment Canada. p 381-405

Huang, J.C. 1983. A review of the state-of-the-art fate/behaviour models. In: *1983 Oil Spill Conference.* American Petroleum Institute. p 313-322.

Jackson, A.J., and Burd, A.B. 1998. Aggregation in the marine environment. *Environ. Sci. Technol*. 32:2805-2814.

Jacques, R., 1997: *Modelling the Circulation of Northern British Columbia Waters*, Ph. D. Thesis, Department of Earth and Ocean Sciences, The University of British Columbia. 240 p.

Johansen, O., and Skrognes, K. 1988. Statistical simulations of oil drift for environmental risk assessments and consequence studies. In: *11th Arctic Marine Spill Program Technical Seminar.* Vancouver, B.C.: Environment Canada. p 355-356.

Kaiser, J.F., 1974: Nonrecursive digital filter design using the I_o-sinh window function, *Proc. 1974 IEEE International Symp. on Circuits and Systems*. San Francisco. pp. 20-23.

Karman, C.C. 2000. The role of time in environmental risk assessment. *Spill Sci. Technol. Bull.* 6: 159-164.

Krylov, S.N., Huang, X-D., Zeiler, L.F., Dixon, D.G., and Greenberg, B.M. 1997. Mechanistic quantitative structure-activity relationship model for the photoinduced toxicity of polycyclic aromatic hydrocarbons: I. Physical model based on chemical kinetics in a two-compartment system. *Environ. Toxicol. Chem*. 16:2283-2295.

Larson, R.A., and Hunt, L.L. 1978. Photooxidation of a refined petroleum oil: inhibition by B-carotene and role of singlet oxygen. *Photochem. Photobiol*. 28:553-555.

Lee, K., Stoffyn-Egli, P., and Owens, E.H. 2002. The OSSA II pipeline oil spill: natural mitigation of a riverine oil spill by oil-mineral aggregate formation. *Spill Sci. Technol. Bull*. 7(3-4):149-154.

Lee, K., and Stoffyn-Egli, P. 2001. Characterization of oil-mineral aggregates. In *Proceedings of the International Oil Spill Conference*. American Petroleum Institute, p 991-996.

Lehr, W.J. 2000. Langmuir circulation and oil spills: a tale of two tribes. *Spill Sci. Technol. Bull*. 6(3/4):207.

Lehr, W.J., and Simecek-Beatty, D. 2000. The relation of Langmuir circulation processes to the standard oil spill spreading, dispersion, and transport algorithms. *Spill Sci. Technol. Bull*. 6(3/4):247-253.

Li, D.-H., and Ganczarczyk, J. 1988. Flow through activated sludge flocs. *Water Research.* 22(6): 789-792.

Li, X., and Logan, B.E. 1997a. Collision frequencies of fractal aggregates with small particles by differential sedimentation. *Environ. Sci. Technol*. 31:1229-1236.

Li, X., and Logan, B.E. 1997b. Collision frequencies between fractal aggregates and small particles in a turbulently sheared fluid. *Environ. Sci. Technol.* 31:1237-1242.
Li, X.-Y., and Yuan, Y. 2002. Collision frequences of microbial aggregates with small particles by differential sedimentation. *Environ. Sci. Technol.* 36:387-393.
Little, E.E., Cleveland, L., Calfee, R., and Barron, M.G. 2000. Assessment of the photoenhanced toxicity of a weathered oil to tidewater silverside. *Environ. Toxicol. Chem*. 19:926-932.
Loder, J.W., Han, G., Hannah, C.G., Greenberg, D.A., and Smith, P.C. 1997. Hydrographic and baroclinic circulation in the Scotian Shelf region: winter versus summer. *Can. J. Fish. Aquat. Sci*. 45(Supplement 1):40-56.
MacKay, D., and Leinonen, P.J. 1977. *Mathematical model of the behaviour of oil spills on water with natural and chemical dispersion*. Environmental Protection Service, Department of Fisheries and Environment. Ottawa, Ontario. EPS-3-EC-77-19. viii+84p.
Mackay, D., Buist, I., Mascarenhas, R., and Paterson, S. 1980a. *Oil Spill Process Models*. Dept. of Chemical Engineering, University of Toronto. unpublished manuscript prepared for Environmental Protection Service, Environment Canada, Ottawa, Ontario, iv + Ch1-1 - Ch7-2 +3 p.
Mackay, D., Paterson, S., and Trudel, K. 1980b. *A Mathematical Model of Oil Spill Behaviour.* Environmental Protection Service, Environment Canada, Ottawa, Ontario, iii + 40 p.
Mandelbrot, B. B. 1983. *The Fractal Geometry of Nature*. New York, NY, W.H. Freeman and Co. 468 pp.
Mezey, P.G., Zimpel, Z., Warburton, P., Walker, P.D., Irvine, D.G., Huange, X-D., Dixon, D.G., and Greenberg, B.M. 1998. Use of quantitative shape-activity relationships to model the photoinduced toxicity of polycyclic aromatic hydrocarbons: electron density shape features accurately predict toxicity. *Environ. Toxicol. Chem*. 17:1207-1215.
Namie, C.E., Loder, J.W., and Lynch, D.R. 1994. Seasonal variation of the 3-D residual circulation on Georges Bank. *Journal of Geophysical Res*. 99(C8):15,967-15,989.
Owens, E.H., Humphrey, B., and Sergy, G. 1994a. Natural cleaning of oiled coarse sediment shorelines in Arctic and Atlantic Canada. *Spill Sci. Technol. Bull*. 1:37-52.
Owens, E.H., Bragg, J.R., and Humphrey, B. 1994b. Clay-oil flocculations as a natural cleansing process following oil spills: Part 2 - Implications of study results in the understanding of past spills and for future response decisions. In: *Seventeenth Arctic and Marine Oilspill Program (AMOP).* Vancouver, British Columbia: Environment Canada. p 25-35.
Pahlow, M. and Vézina. A. 2003. Adaptive model of DOM dynamics in the surface ocean*. J. Mar. Res*. in press.
Pelletier, M.C., Burgess, R.M., Ho., K.T., Kuhn, A., McKinney, R.A., and Ryba, S.A. 1997. Phototoxicity of individual polycyclic aromatic hydrocarbons and petroleum to marine invertebrate larvae and juveniles. *Environ. Toxicol. Chem*. 17:2190-2199.
Petrie, B., Bugden, G., Tedford, T., Geshelin, Y., and Hannah, C. 2001. Review of the Physical Oceanography of Sydney Harbour. *Can. Tech. Rep. Hydrogr. Ocean Sci.* 215:vii + 43 pp.
Reed, M., and Johnsen, S. 1996. (Eds.), Produced Water 2. Environmental Issues and Mitigation Technologies. *Environmental Science Research* (52). Plenum, New York. 536 pp.
Reed, M., Johnsen, S., Melbye, A., and Rye, H. 1996. PROVANN. A model system for assessing potential chronic effects of produced water. In: Reed, M., Johnsen, S. (Eds.), Produced Water 2. Environmental Issues and Mitigation Technologies. *Environmental Science Research* (52). Plenum, New York. p 317-330
Reed, M.J., O., Brandvik, P.J., Daling, P., Lewis, A., Fiocco, R., Mackay, D., and Prentki, R. 1999a. Oil spill modeling towards the close of the 20th century: overview of the state of the art. *Spill Sci. Technol. Bull.* 5:3-16.
Reed, M., Ekrol, N., Rye, H., and Turner, L. 1999b. Oil spill contingency and response (OSCAR) analysis in support of environmental impact assessment offshore Namibia. *Spill Sci. Technol. Bull*. 5:29-38.

Rivkin, R.B., Tian, R.T., Anderson, M.R., Payne, J.F., and Deibel, D. 2000. Ecosystem level effects of offshore platform discharges – identification, assessment and modelling. An extended abstract in: Penney, K.C., Coady, K.A., Murdoch, M.H., Parker, W.R., and Niimi, A.J. (eds). 2000. Proceedings of the 27th Annual Aquatic Toxicity Workshop: October 1-4: 2000, St. John's Newfoundland. *Can. Tech. Rep. Fish. Aq. Sci*. 2331:139 p.

Rye, H. 2000. Probable effects of Langmuir circulation observed on oil slicks in the field. *Spill Sci. Technol. Bull*. 6(3/4):263-271.

Rye, H., Reed, M., Slagstad, D., Melbye, A., and Johnsen, S. 1996. Modeling transport and dilution of produced water and the resulting uptake and biomagnification in marine biota. In Vol. 2. *Proceedings, The Third International Conference on Health, Safety & Environment In Oil & Gas Exploration and Production*. New Orleans, Louisiana, USA, June 9-12, 1996. Published by Society of Petroleum Engineers, SPE 35911, p 231-246.

Sabeur Z., and A. Tyler. 2002. Validation and Application of the PROTEUS Model for Simulation of the Dispersion, Geochemical Behaviour and Biological Impacts of Produced Waters. *Journal of Marine Sciences*, (Accepted for publication). (This reference is taken directly from www.bmtmis.com)

Smith, D.C., Simon, M., Alldredge, A.L., and Azam. F. 1992. Intense hydrolytic enzyme activity on marine aggregates and implications for rapid particle dissolution. *Nature* 359:139-142.

Spaulding, M.L. 1988. A state-of-the-art review of oil spill trajectory and fate modeling. *Oil and Chemical Pollution*. 4:39-55.

Spaulding, M.L. 1995. Oil spill trajectory and fate modeling: state-of-the-art review. In: *Proceedings of the Second International Oil Spill Research and Development Forum*, May 23-25, 1995. London, U.K.: International Maritime Organization. p 508-516.

Stiver, W., and Mackay, D. 1984. Evaporation rate of spills of hydrocarbons and petroleum mixtures. *Environ. Sci. Technol*. 18:834-840.

Stommel, H. 1949. Trajectories of small bodies sinking slowly through convective cells*. J. Mar. Res*. 8:24-29.

Tedford, T., Gonzalez, E., and Hannah, C.G. 2001. bblt Version 3.1 User's Manual*. Can. Tech. Rep. Hydrog. Ocean Sci*. 213: v+48 pp.

Tedford, T., Hannah, C.G., Milligan, T.G., Loder, J.W., and Muschenheim, D.K. 2002. Flocculation and the fate of drill mud discharges. In: *Estuarine and Coastal Modelling: Proceedings of the 7th International Conference* (St. Petersburg Fl., 5-7 November, 2001). M.L. Spaulding (Editor). ASCE. p 294-309.

Thingstad, T., and Pengerug. B. 1983. The formation of "chocolate mousse" from Statfjord crude oil and seawater. *Mar. Poll. Bull*. 6:214-216.

Thompson, K.R., and J. Sheng. 1997. Subtidal circulation on the Scotian Shelf: Assessing the hindcast skill of a linear, barotropic model. *J. Geophys. Res.* 102(C11):24,987-25,003.

Tinis, S.W., and Hodgins, D.O. 1997. Assimilations of radar measured surface current fields into a numerical models for oil spill modelling. *Proceedings of the Twentieth Arctic and Marine Oilspill Program (AMOP).* Published by Environment Canada, Ottawa. p 863-875.

Vézina, A.F., and Pahlow, M. 2002. Reconstruction of food web flows using inverse methods: how well do they work? *J. Mar. Sys*., accepted for publication March 13, 2002.

Walters, R.A. 1992. A three dimensional finite element model for coastal and estuarine circulation. *Continental Shelf Research*. 12:83-102.

Wells, M.L., and Goldberg, E.D. 1993. Colloid aggregation in seawater. *Mar. Chem*. 41:353-358.

Woodward, M.J., and Crawford, W.R. 1992: Loran-C drifters for coastal ocean measurements. *Sea Technology*. 33:24-27.

Xu, Z., Hannah, C.G., and Loder, J. W. 2000. A 3D shear dispersion model applied to Georges Bank. In: *Estuarine and Coastal Modeling: Proceedings of the 6th International Conference*. ASCE. p 581-596.

Yapa, P., Zheng, L., and Chen, F. 2001. A model for deepwater oil/gas blowouts. *Mar. Poll. Bull.* 43:234-241.
West Coast Offshore Exploration Environmental Assessment Panel. 1986. *Offshore Hydrocarbon Exploration.* Minister of Supply and Services Canada Cat. No. En 105-37/1986E 123 pp.
Weise, A.M., Nalewajko, C., and Lee, K. 1999. Oil-mineral fine interactions facilitate oil biodegradation in seawater. *Environmental Technology* 20:811-824.
Wolanski, E., and Hamner, W.M. 1988. Topographically controlled fronts in the ocean and their biological influence. *Science*. 241:177-181.
Zheng, L., and Yapa, D. 1997. A numerical model for buoyant oil jets and smoke plumes. In: *Proceedings of the 20th Arctic and Marine Oil Spill Technical Seminar*. Environment Canada, Ottawa. p 963-979.