Review of Oil Spill Trajectory Modelling in the Presence of Ice

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Les établissements de l’ancien secteur des Sciences et Levés océaniques dans les régions et à l'administration centrale ont cessé de publier leurs diverses séries de rapports en décembre 1981. Vous trouverez dans l'index des publications du volume 38 du *Journal canadien des sciences halieutiques et aquatiques*, la liste de ces publications ainsi que le dernier numéro paru dans chaque catégorie. La nouvelle série a commencé avec la publication du rapport numéro 1 en janvier 1982.

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Abstract

A. Drozdowski, S. Nudds, C. G. Hannah, H. Niu, I. Peterson and W. Perrie. 2011. Review of Oil Spill Trajectory Modelling in the Presence of Ice. Can. Tech. Rep. Hydrogr. Ocean Sci. 274: vi + 84 pp.

This report addresses marine oil spill trajectory modelling with a focus on the Arctic environment. The primary goals are a synthesis of the state-of-knowledge on oil spill trajectory modelling and the identification of the key gaps in this knowledge as it applies to the Canadian Arctic. The review addresses all the components of a comprehensive oil spill trajectory model including 1) a blowout plume model to determine the distribution of oil in the water column for spills that occur at depth, 2) models for the physical environmental forcing (wind, air temperature, precipitation, ocean currents, sea ice and waves); and 3) an oil fate-and-effects model to address weathering, evaporation, ice-oil interactions, and other details of the oil's interplay with the environment. Novel challenges presented by the Arctic environment include the presence of sea ice, sparse observations of ocean currents and limited ability to monitor the spill's evolution.

Résumé

A. Drozdowski, S. Nudds, C. G. Hannah, H. Niu, I. Peterson and W. Perrie. 2011. Review of Oil Spill Trajectory Modelling in the Presence of Ice. Can. Tech. Rep. Hydrogr. Ocean Sci. 274: vi + 84 pp.

Ce document porte sur la modélisation des trajectoires des déversements d'hydrocarbures en milieu marin, plus particulièrement dans l'Arctique. Les objectifs visés sont de faire la synthèse des connaissances actuelles sur la modélisation des trajectoires des déversements d'hydrocarbures et de déterminer les principales lacunes concernant l'application de ces connaissances à l'Arctique canadien. Tous les aspects de la modélisation complète des trajectoires des déversements d'hydrocarbure sont abordés, dont les suivants : 1) modèle de panache d'éruption permettant de déterminer la répartition des hydrocarbures dans la colonne d'eau pour les déversements se produisant en profondeur, 2) modèles de forçage du milieu physique (vent, température de l'air, précipitations, courants océaniques, glaces de mer et vagues); et 3) modèle sur le devenir et les effets des hydrocarbures rendant compte de l'altération, de l'évaporation, des interactions glace-hydrocarbures et d'autres aspects de l'impact des hydrocarbures sur l'environnement. Le milieu arctique pose des défis particuliers, notamment en raison de la présence de glaces de mer, de la rareté des données d'observation sur les courants océaniques et de la capacité restreinte de surveiller l'évolution des déversements.

Executive Summary

This report addresses marine oil spill trajectory modelling with a focus on the Arctic environment. With growing international demand for the mostly untapped Arctic oil and gas resources, the Canadian Arctic will be exposed to increasing risk of oil spills from drilling operations, pipelines, and marine transport. Oil spill trajectory models are an essential tool for risk assessment related to potential environmental impacts in sensitive areas and for planning spill response measures. In the event of a spill, the models can be used operationally to assist the response team.

This study is a review of the oil spill modelling literature and personal communications with oil spill experts. Special emphasis was placed on the Arctic waters. The first goal is a synthesis of the results into a state-of-knowledge report on oil spill trajectory modelling and its various components. The second goal is the identification of the key gaps in this state-of-knowledge as it applies to the Canadian Arctic.

The main task of a spill trajectory model is to predict where the oil is most likely to go based on information about the ocean currents, winds and other environmental variables. This task remains the same no matter where the spill occurs. Novel aspects in the Arctic environment include the presence of sea ice, sparse observations of ocean currents and limited ability to monitor the spill's evolution.

Overall, longer and more accurate forecasts will be demanded from the trajectory models in the Arctic. When an oil spill occurs at temperate latitudes, response is typically almost immediate. The same will not be true for the Arctic. The remote and harsh environment means that spill response will necessarily be slower. In addition, the limited ability to observe oil-under-ice and oil-on-water in the presence of ice means that observations of the spill location during drift will be few and the trajectory modelling process will receive little feedback from observations. Techniques for observing oil-on-water using satellite

remote sensing should be extended to Arctic conditions and tested for their ability to detect oil-on-water in the presence of sea ice.

There is an extensive knowledge (based on lab and field work) of oil interactions with the ice, water, air, and other elements of the environment. This knowledge has been used to develop trajectory models. The literature abounds with modelling studies in various parts of the world. Although applications in ice infested parts of the oceans are much less common, they do exist. In the past, the main obstacle to modelling in the Arctic was effective description of the ice cover. Now satellite remote sensing can offer maps of ice concentration and ice drift and there are ice-ocean models which can offer nowcasts, forecasts and hind-casts of sea ice and ocean conditions.

There are many ways that oil and ice can interact: the oil can be on the surface of the ice or absorbed in the snow, encapsulated by the ice, trapped within cracks in a broken ice field or in open water regions between ice floes, and it can get trapped under the ice by keels that extend into the water. These are small-scale processes that are not generally resolved by the current generation of commonly-used sea ice models, which typically have a resolution of 10 to 100 kilometres and provide only the sea ice thickness and coverage information for each model cell. Sea ice models that incorporate ice roughness and features such as cracks, leads, and rubble fields are still under development.

A comprehensive oil spill trajectory model for the Canadian Arctic would include the following components: 1) a blowout plume model to determine the distribution of the oil in the water column for spills occurring at depth, 2) models for the physical environment (wind, air temperature, precipitation, ocean currents, sea ice and waves), and 3) an oil spill model to address weathering, evaporation, ice-oil interactions, and other details of the oil’s interplay with the environment. A key gap is the integration of these components into a single system that can be used operationally in the event of a spill.

The quality and reliability of the oil spill trajectories will be largely controlled by the accuracy of the wind, ocean current, wave, and sea ice simulations used to drive the oil spill model. Systematic use of available real time observations (e.g. ice beacons and satellite remote sensing) offers the potential to improve the ice and ocean model predictions which, in turn, should improve the trajectory modelling. It may also be possible to track oil-in-ice using only remotely sensed data. Model validation will be a key component to getting stakeholders to accept the utility of any modelling system.

Further improvements are needed in the hydrodynamic and ice models. These models have achieved a high level of sophistication, but moderate resolution models of the entire Arctic Basin are not suitable for detailed trajectory modelling. This is particularly true in the near shore, where without adequate coastline resolution, modelled trajectories are questionable. Using a basin-scale model to drive a high-resolution coastal model of the region of interest would be a credible approach.

An ice feature that has the potential to play an important role in determining spill trajectories in the Canadian Arctic is the rubble field that develops at the interface between the land fast ice and the offshore mobile pack ice. This ice extends deep into the water column and is known to act as an inverted dam trapping fresh water from the Mackenzie River on the shelf. The rubble field can affect oil spill trajectories in two ways: 1) limiting the movement of oil between the offshore and the coastal zone and 2) storing oil in the ice during the winter and then releasing it during the summer as the ice melts away. Remote sensing will play an important role here, as a combination of satellite and airborne sensors can provide information on ice thickness and drift.

The comprehensive oil spill trajectory modelling system can be expected to provide reliable short term predictions, perhaps for several days to a week. This seems to be the standard in the oil spill response community. However a spill that occurs in the fall may be inaccessible for 6 or more months. The reliability of the predictions for such a scenario has not been assessed. A careful analysis of the limits of predictability and the sources of error in the system would identify the key research and development needs.

1. Introduction

The international demand for fossil fuels continues to grow. With more traditional sources being depleted, the attention of oil companies is turning to the, for the most part untapped, Arctic reserves. From 1960-1980 exploration by several companies led to the identification of significant oil and gas potential in Canadian Arctic waters (SL Ross, 2010). The US Geological Survey (USGS) estimates that the area north of the Arctic Circle contains about 20% of the undiscovered, removable, oil and gas resources in the world (USGS, 2008). Increased exploration and production in the Arctic will increase the risk of oil spills from drilling operations, pipelines, and transportation by ship. The presence of ice further increases this risk as it poses threats of ice damaging oil rigs, large ice keels and ice islands gouging the seafloor and damaging pipelines, and threats to shipping as collisions with ice may result in an oil spill.

This report deals with oil spill trajectory modelling with a focus on the Arctic environment. Oil trajectory models are an essential tool for risk assessment related to potential environmental impacts associated with exploration and transport in sensitive areas and for planning of spill response measures. In the event of a spill, the models can also be a useful operational tool by providing information on where the oil can be found.

The fundamental task of an oil spill trajectory model is to use information on ocean currents, winds, waves and other environmental factors, in addition to natural spreading behaviour, to predict where the oil is likely to go. This task remains the same no matter where the spill occurs. The novel aspects for the Arctic environment include the presence of sea ice, sparse observations of ocean currents, and limited ability to monitor the spill's evolution in the presence of sea ice. While there are many ice-ocean models for the Arctic Ocean, there are very few validated operational models of ocean currents and sea ice that can be depended on to provide the complex information required for computing trajectories.

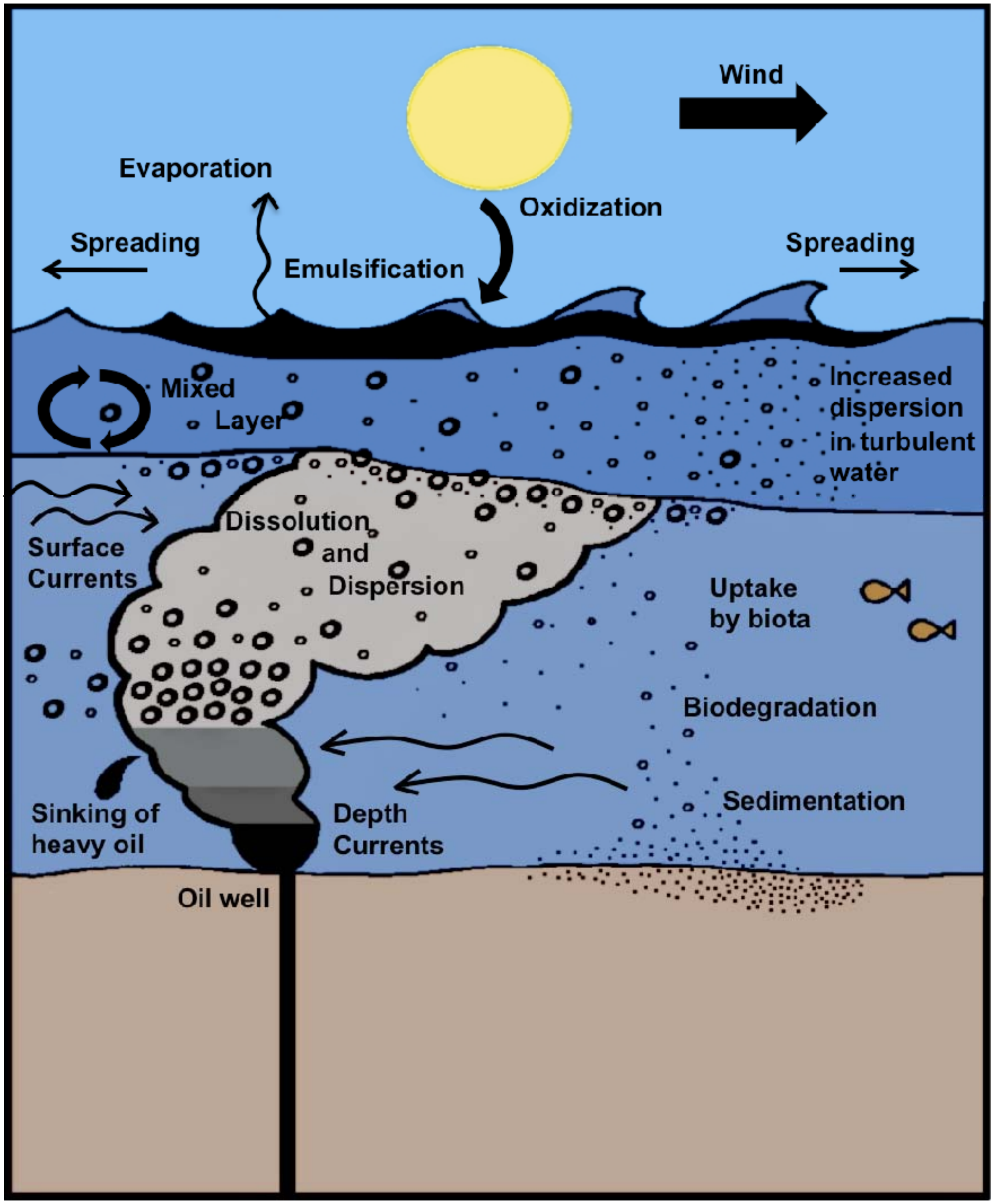


Figure 1 Diagram of basic oil in water processes related to spill trajectory modelling. The figure is not to scale.

The basic ocean processes related to oil spill trajectory modelling are illustrated in Figure 1. There are essentially two ways oil can be introduced into the marine environment: 1) damage to oil rigs or pipelines releasing oil below the surface, and 2) spill from a rig or ship producing an oil slick at the surface. It is crucial when modelling to know where the oil is situated in the water column because the strength and direction of ocean currents vary with depth. For surface spills, the oil can often be tracked without knowledge of the 3D current structure. Under calm to moderate wind and wave conditions, the oil will tend to stay at the surface as a slick, spreading naturally under gravitational, viscous, and surface tension forces, and following the surface currents which are a combination of local wind forcing, tides, wave induced drift and residual circulation. A simple 2-dimensional circulation model (or even just a wind slab layer model) can do a good job in this case. However, strong winds and waves can promote vertical mixing by breaking up the slick into small droplets and mixing the oil into the water column (Tkalich, 2003; Fingas *et al.*, 2006a), in which case the simple model may not suffice. Similarly, for blowouts or leaking pipes on the seafloor, a three-dimensional model is required to track the oil as some oil will likely remain in the water column. In some cases, the oil may be heavier than sea water and will sink to the bottom (Beegle-Krause *et al.*, 2006). The importance of tracking subsurface oil was demonstrated during the Deepwater Horizon spill in the Gulf of Mexico. The injection of chemical dispersants at the well head was successful in reducing the amount of oil that reached the surface but it resulted in a large volume of oil drifting at depth.

An important feature not shown in Figure 1 is that the ocean currents vary in time and space. Thus, information at one location or at one instant in time is not sufficient for tracking an oil spill for more than a few kilometres or a few hours. It is expected that the spilled oil will follow a variety of pathways and therefore reliable oil spill trajectory modelling requires numerical ocean models that resolve the spatial and temporal variability of the ocean currents and have been validated against observations. The systematic incorporation of real-time ocean data (data assimilation) can increase the reliability of the predicted trajectories.

The presence of sea ice adds additional complexity to trajectory modelling. As shown in Figure 2, there are many ways that oil and ice can interact: the oil can be on the surface of the ice or absorbed in the snow, encapsulated into the ice, between cracks in a broken ice field or in open water regions between ice floes, and it can get trapped under the ice by ridges and keels that extend into the water. These are relatively small scale processes that are not generally resolved by the current generation of sea ice models which typically have a resolution of a few to tens of kilometres and provide only the average thickness and coverage for several predetermined ice categories in each model cell.

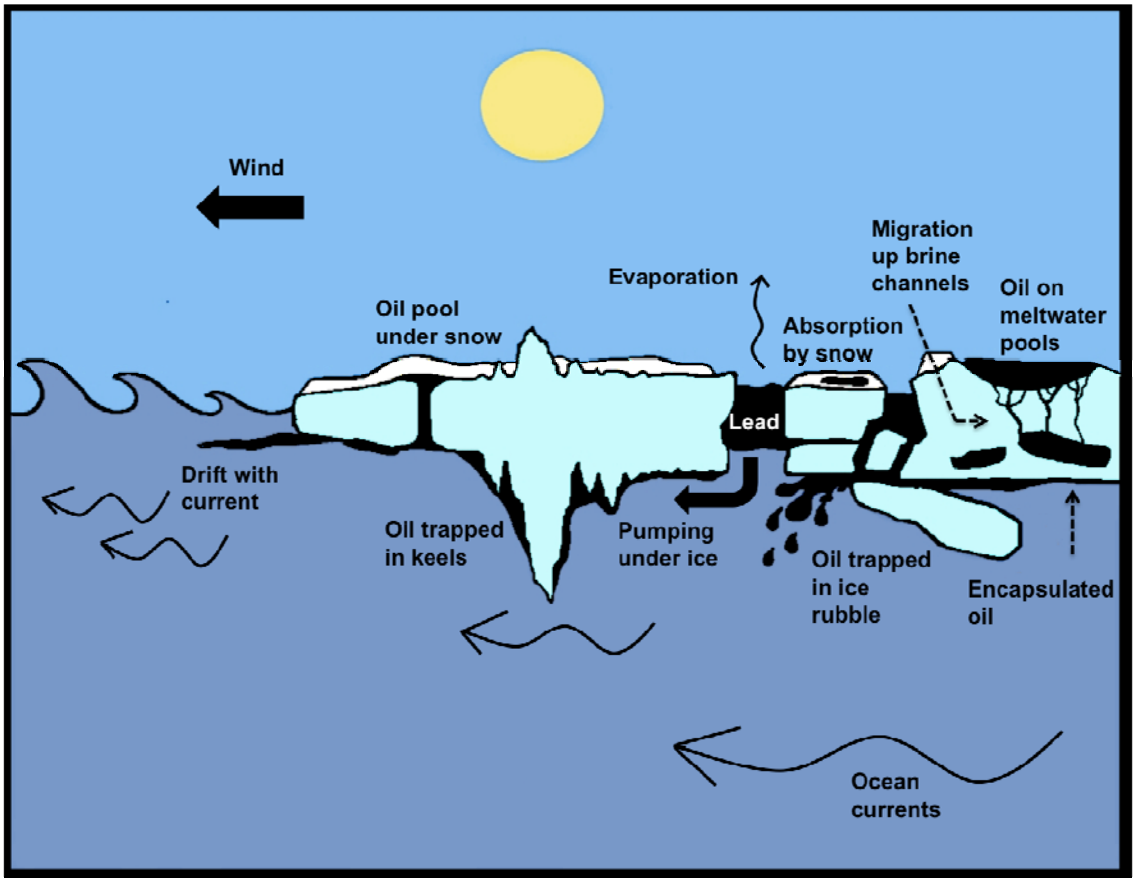


Figure 2 Interactions between oil and ice related to spill trajectory modelling (modified from Allen, 2008).

When oil and ice interact, some fraction of the oil will move with the sea ice, which does not necessarily follow the ocean currents. In cases where the oil is trapped between large ice floes, the oil is generally contained quite well, follows the ice, and allows for efficient recovery (Sørstrøm *et al.*, 2010). The presence of ice can also shelter the oil from wind and wave action, subsequently slowing down spreading and weathering of the oil. This gives responders more time to contain and eliminate the spill, but becomes a problem if the spill is left for natural remediation. Land fast ice, whose offshore extent evolves during the ice season and varies between regions, may act as a natural boom, keeping the oil from impacting the shoreline where there is increased risk of damage to animal habitat and pristine environments. However, during the spring melt, any oil stored within the rubble field at the land fast ice edge will either be released into the ocean or move with the ice edge as it retreats toward the coast.

Overall, more will be demanded from the trajectory models in the Arctic. When an oil spill occurs at temperate latitudes, response is typically almost immediate. The same is not true for the Arctic. The remote and harsh environment means that spill response will necessarily be slower and more protracted (Bronson *et al*., 2002). The limited ability to observe oil under ice means that observations of the location of the spill during drift may be few and the trajectory modelling process will receive little feedback from observations. Remote sensing from satellites offers some potential to detect oil on water with good coverage in space and time and this is explored in Sections 4 and 5.

This review is structured as follows. In section 2 we review the physical components of an oil spill trajectory model. This includes a discussion pertaining to atmospheric forcing, currents, ice and waves. The section focuses on a nature of these physical parameters and how they pertain to the oil spill model. Attention is given to how each component is modelled and the role it plays in a comprehensive modelling system. Section 3 presents the mechanics of the internal workings of the oil spill model itself. We discuss various processes that affect the behaviour of oil, such as oil-ice interactions, weathering and dispersive properties of the oil, and how they affect the fate of the oil spill trajectory. We also include a brief discussion of the subsurface blowout phase. Section 4 presents a brief review of real time data, such as that available from satellite-based remote sensing, and how emerging technology in this field could enhance the trajectory prediction. Section 5 provides a review of existing oil spill trajectory models and their potential application to the Arctic environment. Section 6 provides an overview of existing Arctic Ocean models that include a sea ice component. This provides information on the scientists and laboratories that are actively engaged in ice-ocean modelling and the modelling tools that could be used for trajectory modelling. Section 7 identifies key gaps that exist in the knowledge (or the implementation of that knowledge) of modelling oil spill trajectories in the Arctic environment.

For oil spill modelling this report draws on the key findings from the reviews of Huang (1983), Spaulding (1988), ASCE (1997), Reed *et al*. (1999), Lewis (2000), Gjosteen *et al*., (2003) and Khelifa (2010), supplemented by more recent work. This report is not a detailed review of the current state of research on oil-water, oil-ice or oil-air interactions. It is a review of oil spill trajectory modelling in the presence of ice and thus discusses these interactions as they pertain to trajectory modelling.

As part of this study we reviewed the last decade of papers from the Arctic and Marine Oilspill Program (AMOP) conference proceedings. This provides a view of the state-of-the-art in oil spill research. In each section we have listed relevant AMOP papers so that the interested reader can investigate the literature more thoroughly.

2. Physical Environment

The core idea of an oil spill trajectory model is relatively straightforward; given the local atmospheric forcing, ocean currents, oil properties and spill location, integrate the currents forward in time to predict the future locations of the oil. However, there are several components to a model and various processes that complicate this simple idea. In this section we review the components of a comprehensive oil spill trajectory model with a focus on those processes that affect the trajectory calculation.

2.1 Atmospheric Forcing

Atmospheric conditions such as wind, radiation, temperature, humidity and precipitation, are important driving forces for ocean currents, ice and oil behaviour. Thus it is important to have good meteorological data and forecasts to determine oil spill trajectories. This is particularly true when tracking oil spills operationally (to simulate a particular spill when it occurs) as opposed to running simulations for the purpose of risk assessment where unknowns can be addressed through simulation of multiple scenarios with different forcing fields.

Accurate modelling of surface currents depends greatly on the effective description of the wind which is variable in space and time. Due to the sparseness of offshore wind data, ocean models rely on output from atmospheric models which provide nowcasts (present state), forecasts for two to ten days (Environment Canada, 2011) or hind-casts (reanalysis) that go back a few decades (Large and Yeager, 2004). These forecasts then permit short-term forecasting of ocean currents and ice distribution and properties.

Additional Relevant AMOP Publications:
Fingas and Ka'aihue, 2004.

2.2 Ocean Currents

In the absence of ice, ocean currents determine play a major role in the fate of the oil spill. The currents can be obtained by either direct measurement or calculation. The high variability of currents in space and time make the use of direct measurement impractical for tracking the oil for extended periods. One exception is the use of high frequency radar systems (Wyatt, 2005). These systems have improved significantly over the years and can be used to determine surface currents (as well as waves and wind in real time). Direct measurement is also limited to past and present and can not be used to predict future currents without making gross assumptions.

In most cases it makes sense to calculate the currents. The currents are induced by the combination of wind stress, pressure gradients, density gradients, tidal forcing and wave induced (Stokes) drift. In open water, wind-induced drift is often the most important factor determining surface oil slick trajectories over time scales of a few days (Spaulding, 1988), unless the spill occurs in an area of strong mean or tidal currents. Past modelling efforts assume that the surface layer (where the oil resides) moves at a speed which is 2.5 to 4.4% of the wind speed (ASCE, 1997; Spaulding, 1988; Reed *et al.*, 1999) and at an angle (the Ekman veering angle) of 0 to 25 degrees clockwise (typically 10 to -17 degrees) relative to the wind direction (ASCE, 1997, Spaulding, 1988, Samuels *et al.*, 1982). These values (or range of values) are strictly empirical. Tests show that the Ekman veering angle approximation works best in deep water, away from the coastline, and in low to moderate wind/wave conditions.

The modelling of currents as a wind induced slab layer (as described above) depends entirely on the effective description of the wind which is variable in space and time. In the past, the standard approach was to use observed wind statistics and stochastic methods to generate multiple wind field scenarios (e.g. Huang, 1983; Smith *et al.*, 1982). Due to the sparseness of offshore wind data, modelled winds are now commonly used, as described in the previous section.

With the increased availability of high-powered computation (HPC) machines in the last few decades, the use of three dimensional hydrodynamics models to calculate ocean currents has become standard. The model itself combines the effects of wind, pressure and density gradients and, in some cases tides and waves, and solves for the currents by time–stepping forward the governing equations of motion. This provides a time-varying description of the three-dimensional ocean currents.

Reed *et al*. (1999) stress the need for three-dimensional currents in modelling the behaviour and drift of oil. They point out that the two-dimensional modelling becomes inadequate at higher wind speeds due to entrainment of oil in the water column where current shears and the vertical profiles of concentration become important. They point to several studies (Johansen, 1984; Elliott *et al*., 1986; Delvigne and Sweeney, 1988; Singsaas and Daling, 1992; Reed *et al*., 1994) which underline the inadequacy of using only surface currents.

Most hydrodynamic models do not adequately resolve the surface layer (approximately the top meter). This is a high gradient regime in which currents and other water properties can vary drastically. In most models, the uppermost layer (representing the ocean surface) is a few meters thick. As a result the surface current speeds are underestimated. This can be a major problem for trajectory modelling. A common remedy is to add 1-3% of the wind speed to the model solution (Wang *et al*., 2010).

In addition, oil slicks on the surface can break up and align with what are called Langmuir cells (long, shallow horizontal vortices with axes aligned with the wind). This process is not usually incorporated into spill trajectory modelling because it is such a small-scale process; however, research suggests that useful parameterizations are possible (Simecek-Beatty and Lehr, 2000).

Coupled ice-ocean hydrodynamics models are reviewed in Section 6.

Additional Relevant AMOP publications:
Schmidt Etkin *et al.*, 2007; Fingas and Ka'aihue, 2004.

2.3 Ice

The Arctic Ocean is ice-covered for much of the year. Regional ice charts for the Arctic can be found at www.ec.gc.ca/glaces-ice/. These data products are the synthesis of remote sensing and other technologies, and represent the best knowledge of present and past ice conditions. Ice chart frequency in the Western Arctic is presently once every two weeks from January to March, daily from 15 July to 15 Oct, and weekly for the remaining periods. Chart frequency may increase in the future.

Accurate forecasting of ice conditions requires a sophisticated numerical ice model. The presence of ice has a significant impact on the current structure below and around the ice, and therefore influences the spill trajectory. Thus, when modelling spill trajectories in the Arctic Ocean (or high latitude regions), it is important to use a coupled ice-ocean model. Oil-ice interactions are discussed in detail in the next section and sea ice models are discussed in Section 6.

Typical ice-ocean models for the Arctic have a resolution of 10 to 100 kilometres and are limited to simulating average thickness and ice concentration for several ice-thickness categories in each cell. However, oil interacts with sea ice through several small-scale features (cracks, ridges, open areas; Figure 2). Such detailed modelling of oil-ice interactions would require a model with 100 m or less, with information about ice roughness and ice type (Mark Reed SINTEF, pers. comm. 2011). Typical ice models can not simulate such details. However, roughness and ice type can be supplied directly from remote sensing (see Section 4.2).

2.4 Wind-driven Surface Waves

Wind-driven surface waves can influence an oil spill trajectory in three major ways:

1. The waves can mix the oil from the ocean surface down into the water column (entrainment). This will significantly change the drift trajectories if the current profile is non-uniform.

2. The waves can give rise to a mean drift at the surface (‘Stokes drift’), which can be an important contribution to the surface drift (Tang *et al*., 2008; Tang *et al*., 2007; Perrie *et al*., 2003). This effect is particularly significant in coastal, near-shore and surf zone regions, but it is also important on the open shelf.

3. The waves from a storm in one location have been observed to breakup pack ice in another location (Barber *et al*., 2009). The change from pack ice, with relatively little open water, to a field of small floes with lots of open water will alter the drift trajectories.

Waves can also have a direct influence on the ocean currents through contributions to the bottom stress (Warner *et al*., 2010) and direct forcing through a radiation stress mechanism (Ardhuin *et al*., 2009). This is particularly important in shallow regions such as the Mackenzie shelf.

Furthermore, turbulent mixing caused by breaking waves can cause the oil to form an oil-water emulsion in the surface layer which would have different physical properties from that of the oil itself (see Sec. 3.9).

Wave Models

The simulation and forecasting of intense storms and the extreme waves that they can generate are important issues due to the increased potential for severe damage to human activities and societal infrastructure. Rapidly-varying winds can develop in intense storms that drive large, complex ocean waves, able to propagate thousands of kilometres away from the storm center, resulting in dramatic variations of the wave fields in space and time (Barber and Ursell, 1948). In recent years, numerical wave modelling has demonstrated skill in forecasting waves on global and regional scales, and results have been compared and validated with measured directional spectra. For example, Moon *et al*. (2004) validate simulations of ocean wave spectra from WAVEWATCHIII^{TM} (Tolman, 2002), with buoy data and NASA Scanning Radar Altimeter observations, using a model spatial resolution of 1/12°×1/12° to capture the rapidly varying wave field generated by Hurricane Bonnie, which is much finer than is typically implemented in operational forecasting. For example, the fine-resolution wave model grid for the Gulf of Maine Ocean Observing System (GoMOOS; www.gomoos.org) is 1/5°×1/5°.

Presently there are three modern and widely-used third-generation spectral wave models: (a) SWAN (Booij *et al*., 1999), (b) WAM (WAMDI Group, 1988), and (c) WAVEWATCHIII (hereafter WW3), (Tolman, 2002; Tolman *et al*., 2002). WAM and WW3 used for global, regional (basin-scale) and shelf-scale applications, while SWAN is more suitable for high resolution coastal and near-shore applications.

Fine resolution is necessary to simulate coastal processes such as depth-induced wave breaking and nonlinear wave-bottom interactions. For fine-resolution simulations, a hierarchical system of nested grids is often used. Nested grids have the ability to simulate swell waves generated in the open ocean propagating into coastal areas while avoiding excessively expensive high-resolution grids for the entire domain. Although high-resolution nested grids are not generally essential for simulations of the entire continental shelf, they minimize the biases due to interpolation of model results to observation locations. For additional discussion of these models and their ability to simulate ocean waves in coastal areas, see Padilla-Hernández *et al*. (2007).

Additional Relevant AMOP Publications:
Øksenväg *et al.*, 2009; Botrus *et al.,* 2008; Wickley-Olsen *et al*. 2007; Sulzberger, 2000.

2.5 Summary of Main Points

- Atmospheric forcing is of primary importance for all modelling components. Observational data are sparse but good models for forecasts and hindcasts exist.
- Ocean currents contribute to the motion of both ice and oil. Due to the limited ability to measure currents, the best way to obtain accurate currents is to calculate them using hydrodynamic models.
- Because the Arctic Ocean is ice covered much of the year, accurate knowledge of ice conditions is important for determining the trajectory of an oil spill. Operational ice charts exist, but to forecast several days into the future, an ice model coupled with a hydrodynamic model is very useful.
- Surface wind waves are an important forcing mechanism for oil trajectory modelling. Strong waves can mix the oil into the water column and thus change the oil trajectory or they can directly alter the ocean currents.
- Advanced numerical wave models exist and can be included in a comprehensive oil spill modelling system.
- Waves are particularly important for shallow shelf regions such as the Mackenzie Delta.

3. Processes in an Oil Spill Model

This section discusses the inner workings of an oil spill model, starting with the methods used to partition the spilled oil volume into discrete pieces which can be modeled numerically. Next we describe chemical details of oil followed by the behaviour of the oil as it interacts with the various environmental components, water column, atmosphere, ice, sediment and shoreline.

3.1 Oil Tracking Methods

Three methods have been developed to simulate the movement of oil in an ocean or ice-ocean model: particle-tracking, tracers, and spillets.

For the particle-tracking method, oil is parameterized as a finite number of particles, each assigned an initial location and mass. Advection is provided for each particle independently from the ocean (or ice) velocity field. Random processes can be added (as random kicks) to simulate the dispersion (spreading, diffusion) of the oil, independent of ocean current. The distribution of particles represents the whole oil spill in a statistical fashion. For example, if 30% of the particles end up along the coast, then we say that 30% of the spilled oil reached the coast. Thus, the number, or density, of particles must be sufficient to compute reliable statistics. The higher the resolution of the model and the longer the simulation, the more particles are required to achieve reasonable statistics over the resolved current structure and to account for the spreading of the particles over time. For example, if a simulation is performed with two particles per grid cell, and these particles encounter a velocity sheer (adjacent currents travelling in opposing directions) across that cell, one particle (50%) may go one way and the other the opposite way. If, however, a density of 25 particles per grid square is used, depending on how well resolved that current structure is, 15 (60%) may go west, 5 may go east, and 5 may go south, resulting in a completely different statistical distribution and information content.

For the tracer method, the area where the oil spill to be tracked is represented by a fine-resolution grid (preferably less than 1 km). The spill occupies the cells that best represent its physical extent. At each time step, the oil field is advected from cell to cell using the local currents, in combination with imposed diffusion/spreading such that mass is conserved. In addition each cell sees its own environment and interacts with the atmosphere, ocean or ice accordingly. An advantage of the tracer approach is that, due to the time -difference method of formulating the conservation/advection equations, it lends itself well to adding empirical formulae describing the local changes/interactions of the oil with the environment. Another advantage is the ability to increase resolution to exactly the level that would capture features of ice fields or coastlines that one is trying to model. The disadvantage is that the number of grid cells needs to be large in order to provide necessary resolution and contain the entire study area. As a result the computation takes longer than the other methods. Another disadvantage is the relative complexity of the formulation compared to the other methods.

The spillet method is almost identical to the particle approach with the exception that the spillet has more degrees of freedom than a particle. The extra degrees of freedom can be the area or thickness represented by each spillet. In essence, the total spill is represented by a number of smaller spills, each with the ability to spread according to a spreading theory such as Fay’s equation (Fay, 1969). The spillet model can be regarded as a compromise between the particle and tracer methods (Gjosteen *et al.*, 2003).

Additional Relevant AMOP Publications:
Niu *et al.*, 2009; Khelifa *et al.*, 2004b; Sterling *et al.*, 2003.

3.2 Descriptive Spill Details

A variety of oils can enter the marine environment, each exhibiting different physical and chemical properties. Differences in viscosity, density and hydrocarbon composition result in differences in spreading, evaporation rate, buoyancy, weathering, and ice or snow interaction. Thus, taking into considering the type of oil that has been spilled will help decide the degree to which these processes are important and how they should be parameterized for a given environment. The type of oil may also influence what method of tracking (particle, tracer, or spillet) is used.

The exact type of oil isn't always known, particularly when modelling for risk assessment, but can usually be approximated by standard category types. Data bases of numerous oils, along with their attributes, exist for this purpose (Wang *et al*., 2005c; Comerma *et al*., 2003).

Knowing the amount of spilled oil is also important as it is directly related to the persistence of the spill (Buist *et al*., 2005). For ship spills, the maximum amount of spilled oil is given by size of the ship's reservoir, but in cases of well blowouts or broken pipes it is more difficult to estimate and often remains unknown.

How the oil was spilled can also influence the evolution of the spill. For example, a slow continuous discharge will behave differently from a sudden blowout.

The location and time of the spill are also important. With increasing resolution of the model, the accuracy of spill location and time become more important. Knowing the time of the spill is particularly difficult in remote regions like the Arctic where the spill might persist for long periods of time before it is detected (as discussed in the introduction). Common practice is to use the time and location of the initial sighting as the starting point.

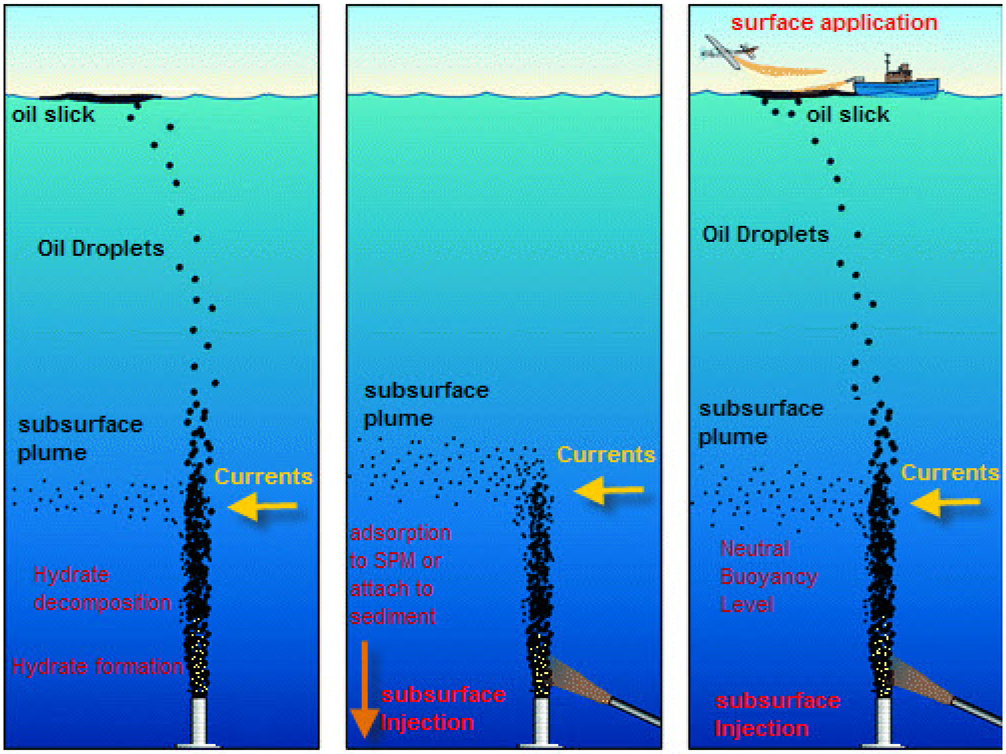
Additional Relevant AMOP Publications:
French-McCay *et al*. 2009; Schmidt Etkin *et al*. 2009; Fingas, 2007; Little *et al*., 2003; Guyomarch and Merlin, 2000.

3.3 Subsurface Blowouts

The scenarios of subsurface (deep or shallow) oil/gas blowouts are schematically shown in Figure 3. Unlike surface spills, release from a blowout is always a combination of oil and gas. For example, the oil volume percentage for the *Deepwater Horizon* spill is estimated to be 44% at the exit (TFISG-OBCSET, 2010). Natural gas behaves differently than oil and this needs to be considered if one wants to model the behaviour of the gas as well.

Once released (Figure 3a), the oil/gas mixture rises as a jet/plume due to initial increased velocity from well pressure. As the jet/plume progresses, it loses its momentum and buoyancy due to the entrainment of seawater. The pressure drop causes the gas to expand, increasing the buoyancy of jet/plume. If the ascending jet/plume achieves a neutral buoyancy level, oil and gas rise as individual gas bubbles and oil droplets. For some discharges, a neutral -buoyancy level may not be reached due to the properties of release and ambient stratification conditions. If the blowout is from deepwater, gas may form slush-like solid gas hydrates due to high pressure and low temperature. Once the jet/plume reaches a level of lower pressure, the hydrate can decompose into water and gas again (Zheng *et al.*, 2002). The individual oil droplets separated from the plume will continue to rise to surface (Figure 3a,c). Rise speed depends on the size of droplets and ambient turbulence (Zheng and Yapa, 2000b). At the surface, an oil slick may be formed (Figure 3a,c).

Chemical dispersants contain surfactants that reduce the interfacial tension between oil and water, resulting in the formation of smaller oil droplets that naturally disperse (Li *et al*., 2009). According to Kujawinski *et al.* (2011) approximately 2.17 million gallons of dispersant were applied during the response to the Deepwater Horizon spill, 1.4 million gallons at the surface and 0.77 million gallons subsurface. In such a case, if sufficient amounts were added subsurface and the mixing were ideal, all the oil may be well dispersed in the lower water column and unlikely to reach the surface (Figure 3b). However, if the mixing was not ideal or the chemical dispersant were insufficient to breakdown all the oil, a certain fraction of oil (larger droplets) may still rise to surface. If chemical dispersant is also applied at the surface, a fraction of that oil may be redispersed and re-entrained into the water column (Figure 3c). Figure 3a and Figure 3c look similar but the former has a larger surface fraction (from the surfacing of larger droplets) and latter has a larger water column fraction (from the suspension of smaller droplets). At any stage, oil droplets may be adsorbed to suspended particle matter (SPM) and settle to the bottom. The oil plume may also hit the bottom due to a change in bathymetry and result in oil attaching to sediment.



(a) No CD

(b) subsurface injection of CD (fully dispersed)

(c) subsurface injection & surface application (partially dispersed)

Figure 3 Illustration of oil/gas plume behaviour from a deepwater blowout (modified from Zheng *et al*., 2002a and Kujawinski *et al*., 2011). CD=Chemical Dispersant, SPM=Suspended Particle Matter.

For a literature review of the recent advances in blowout plume modelling see Appendix B.

Additional Relevant AMOP Publications:

Wang *et al.*, 2005a; Spaulding *et al*. 2004; Yapa *et al.*, 2003; Chen and Yapa, 2000; Spaulding *et al.*, 2000.

3.4 Oil interaction with Ice and Snow

Oil modelling efforts can be made difficult by the complex interactions among oil, ice and snow (refer to Figure 2). Ice fields have been observed to drift rapidly on some occasions: 80 km during a 5-day period (Sørstrøm *et al.*, 2010), 100 km over 7 days (Peterson *et al.*, 2008) and 1667 km of drift over a 5 month season (Melling *et al.*, 2005). Therefore tracking oil in ice is important on time scales of Arctic oil spill response,

Tracking the oil by estimating the partitioning between the amount of near-surface oil moving with the ocean currents and the amount moving with the ice is likely the best approach for ice-ocean models with a typical resolution of ~10 km. There are several processes to consider when making this approximation. Oil can get trapped in ice in three different ways.

1) Oil can become frozen in a solid ice body and remain there until the ice melts. The water beneath an ice sheet will continue to freeze in the early part of the ice season. Oil under an ice sheet or pack ice will be completely encapsulated within 18 to 72 hours, depending on the time of year (Dickins and Buist, 1981; Buist and Dickins, 1983; Buist *et al.*, 1983).
2) It can be trapped between ice fragments in broken ice fields. Studies have shown that the oil will generally drift with the ice for ice concentrations greater than 30%. For smaller concentrations, the oil will behave as it does in water. This scenario is very common and occurs during freeze up and in broken ice field conditions.
3) It can get trapped on the under-ice surface in small cavities. This oil can become encapsulated, but not necessarily.

The first process is easiest to model since the oil is essentially moving at the same velocity as the ice. The second is more complicated, but, since ice-ocean models calculate ice concentrations directly, these estimates can used as an index for whether the oil trajectory follows the ice trajectory or the water trajectory. The third process is the most complex to model.

The amount of oil that gets trapped on the under-ice surface depends on the type of ice and the velocity of the currents below. Rougher ice exhibits a higher holding capacity simply because there are more under-ice cavities in which the oil can get trapped. The volume of oil retained by the ice decreases as the current speed increases because the oil can be swept out of the cavities (Lewis, 2000). The deeper the cavities, the less influence the current will have on removing the oil from the cavities. Thus, rough ice with a strong current below may exhibit the same holding capacity as smoother ice with a weak current.

Increased model resolution provides the potential to model these, and other, processes explicitly. According to Lewis (2000), advection of oil under ice is described reasonably well by algorithms based on the work of Sayed and Abdelmour (1982), Uzuner *et al*. (1979) and Cox & Shultz (1981a,b). Buist *et al*. (2009) have developed algorithms not only for the stripping velocity of oil under ice, but also oil spreading in ice and snow. Lack of field observations however hinders the validation of most model simulations.

If oil becomes encapsulated in ice, it can then migrate upward to the surface. The rate at which the oil migrates upward is strongly dependent on the amount of brine drainage within the ice. As ice warms up and melts, the brine (salt-water) drains out leaving vertical channels in the ice through which the oil can travel (Martin, 1979). Thus, vertical migration of the oil is low during the ice growth season and increases rapidly once daily air temperatures remain consistently above freezing (Lewis, 2000). The rate of oil migration was also observed to be lower in multi-year ice for similar reasons; the ice is thicker and has fewer and less interconnected brine channels.

Spreading of oil amidst ice is also an important consideration as oil spreading behaviour changes drastically in the presence of ice. The process is naturally slowed by cold water and the formation of a wax layer, but the presence of ice further limits spreading by herding the oil.

Additional Relevant AMOP Publications:
Øksenvag *et al.*, 2009; Nemirovskaya and Shevchenko, 2008; Mullin *et al.*, 2008; Buist *et al.*, 2007; Buist and Morrison, 2005; Faksness and Brandvik, 2005; Nemirovskaya and Novigatsky, 2006; Nemirovskaya and Novigatsky, 2004; Owens and Belore, 2004; Rytkönen *et al.*, 2003; Nemirovskaya *et al.*, 2002; Jensen *et al.*, 2002; Bronson *et al.*, 2002; Solsberg et al., 2002; Dickins and Owens, 2002; Fingas and Hollebone, 2002.

3.5 Spreading

Oil spreading is the name given to the process of the spilled volume of oil, under the action of viscous, gravitational, buoyancy and, ultimately, surface tension forces, spreading into a thin slick covering a large area. The process of oil spreading in still water is fairly well understood. Gjosteen *et al.* (2003) mentions several models of spreading have been developed over the last decades, e.g. Blokker (1964), Fay (1969), Hoult (1972), Fannelop and Waldman (1972), Di Pietro and Cox (1979) and Mackay *et al.* (1980).

The oil spreading behaviour changes drastically in the presence of ice. The process is naturally slowed down by cold water and the formation of the wax layer. The ice further limits the spread by herding the oil. Many experiments were conducted over the years to study spreading in ice infested waters. Based on the review by Gjosteen *et al.*, (2003), some of the earliest work was done by Glaeser and Vance (1971). They conducted experiments to measure oil spreading under solid ice. Hoult *et al.* (1975) studied spreading on and under ice. Further advances as quoted in Gjosteen *et al.*, (2003):

1) Large field trials on oil spills in ice were conducted in the Canadian Beaufort Sea (NORCOR, 1975; Buist *et al.* 1980).

2) SL Ross and Energetex (1985) proposed a modified version of Fay's equation for spreading in brash ice.
3) Yapa and Chowdhury (1990) suggest equations for spreading of oil under ice, based on the Navier-Stokes equations
4) Venkatesh and El-Tahan (1992), using many of the same considerations as Fay (1969), developed a new set of equations which included the viscosity of oil.

Oil spreading can be an important part of trajectory modelling because once the oil has spread sufficiently far it starts to experience horizontal shears in the currents, winds and waves which can lead to different parts of the spill moving in different directions.

Processes such as weathering, emulsification, dissolution, and aggregate formation affect the evolution of physical and chemical properties of the oil and as such they influence the dispersibility (Guyomarch and Merlin, 2000). The importance of these processes for the trajectory calculation depends on the size of the spill relative to the horizontal resolution of the ice-ocean model. If the spill is small relative to the resolution, then these processes will not greatly influence the trajectory calculation. However if the scale of the spill is large enough that the dispersibility causes the spill to spread to occupy several model gird points, then the physical properties (viscosity, density, diffusivity, etc.) of the oil will influence the trajectories.

Additional Relevant AMOP Publications:
Fingas, 2007; Khelifa *et al.*, 2007; Goncharov *et al.*, 2005; Goodman *et al.*, 2004.

3.6 Evaporation

The rate of evaporation will differ drastically between winter and summer in the Arctic where there are periods of 24 hours of darkness and 24 hours of sunlight, respectively. Evaporation increases the density of the oil, thus, the more sunlight a surface slick is exposed to, the less oil will remain at the surface (Fingas *et al.*, 2006a). The presence of ice also influences the rate of evaporation. Buist *et al*. (2009) have developed algorithm for evaporation on ice, under snow, and amidst drift ice.

Additional Relevant AMOP Publications:
Fingas, 2007.

3.7 Temperature

In general, the viscosity of oil increases with decreasing temperature. Thus its ability to spread naturally, under gravitational forces and flow independent of ocean currents, is limited in cold environments. This is important when discussing oil spills in Arctic regions where the water temperature is very low, around the freezing temperature of seawater in regions where ice is forming (typically -1.8C).

Oil has what is called a pour point; the temperature at which the oil ceases to flow (under gravity (e.g. in a test tube turned sideways;) (Buist *et al.*, 2009). When modelling an oil spill in water that has a temperature below the pour point of the oil, the natural spreading parameters related to gravity can essentially be set to zero and the oil will then disperse solely by the ocean currents. Buist *et al*. (2009) developed an algorithm for the spreading of oil in cold water which could be incorporated into oil spill models.

Additional Relevant AMOP Publications:
Fingas *et al*. 2005; Khelifa *et al.*, 2005; Owens and Belore, 2004; Fingas *et al.*, 2002c; Fingas and Hollebone, 2002.

3.8 Salinity

In the Arctic salinity makes a substantial contribution to the density of the water. River inflows, ocean inflows to the Arctic Ocean, and processes such as ice melt and brine rejection during ice growth, influence the salinity and thus the vertical and horizontal density structure. The vertical gradients in the density influence the vertical migration of oil in water column and can determine whether or not the oil reaches the surface. Because of the density difference, oil released in salt water will rise to the surface more quickly than oil released in freshwater. Fingas *et al*. (2002a) developed equations that describe and predict concentrations of oil (bitumen) in the water column, showing a complex interaction between salinity, time and temperature. Salinity gradients must be considered when computing the vertical distribution of oil from deep water blowouts and pipeline leaks.

Additional Relevant AMOP Publications:
Fieldhouse, 2007; Fingas *et al*. 2005; Khelifa *et al.*, 2005; Fingas and Ka'aihue, 2005; Fingas *et al*., 2002c.

3.9 Emulsification

When water-in-oil emulsions form, the physical properties of oil spills change significantly (Fingas, 2009). Oil emulsions are categorized in four distinct water-in-oil types based on water content and rheological (physical) measurements: stable, meso-stable, entrained and unstable. Each type exhibits unique physical properties and thus should be considered when setting dispersion parameters in a trajectory model. The length of time that an emulsion will exhibit the same physical properties is also important so that parameters can be adjusted depending on the length of the model simulation.

Stable emulsions have the highest water content (average 80%) and remain stable for at least 4 weeks and commonly up to a year. The viscosity of stable emulsions increases significantly within a week. Meso-stable emulsions contain less water (average 65%) and generally breakdown within a week. They exhibit a slower and smaller increase in viscosity. Entrained water-in-oil types (average water content of 45%) also break down within a week, with an even smaller increase in viscosity with time. Unstable emulsions do not hold any significant amount of water and thus the viscosity does change significantly over time.

If emulsification occurs at depth (during a well blow out for example) an increase in density could make the oil neutrally buoyant at depth, and it would then drift with different currents from those at the surface.

Merv Fingas (University of Alberta) and colleagues have done substantial work on water-in-oil emulsions (e.g. Fingas and Banta, 2009). They developed a new emulsion formation model which uses density, viscosity, asphaltene and resin content of various oils to predict the emulsion type, and to estimate both the viscosity of the resulting water-in-oil state, and the time to formation at a given sea state (turbulence or mixing factor). This could be a very useful tool to estimate viscosity and diffusion coefficients for trajectory modelling.

Additional Relevant AMOP Publications:
Fingas and Fieldhouse, 2008; Fieldhouse, 2007; Fingas, 2007; Fingas and Fieldhouse, 2006; Fingas and Fieldhouse, 2005; Fingas and Fieldhouse, 2004; Fingas, 2003; Fingas and Fieldhouse, 2003; Fingas *et al.*, 2002a; Fingas *et al.*, 2002c; Fingas *et al.*, 2001a; Fingas *et al,*. 2001b; Fingas *et al*. 2000a, Fingas *et al*. 2000b;

3.10 Oil Suspended Particulate Matter

Oil-Suspended Particulate Matter Aggregates (OSAs) are formed if oil and suspended particulate matter interact in an aquatic environment and have significance when discussing oil dispersion. It is one way in which the oil will sink as opposed to naturally rising to the surface. The amount of OSAs that form will effect the how much oil reaches the surface, and how much will remain at depth.

The rate of OSA formation varies with mixing conditions. Increased mixing conditions raises the oil trapping efficiency, thus decreasing the amount of oil that reaches the surface, and increasing the amount of oil at depth and oil-to-sediment ratio of settled material (Sun *et al.*, 2009). That is, if oil is released in a highly turbulent region, less oil is likely to reach the surface or stay at the surface than if it were spilled in a low turbulence region. OSA formation also increases (exponentially) with mixing time. If the region is turbulent for a long period of time (i.e. a big storm is passing through), more OSA formation takes place, reducing the amount of oil in the surface layer and increasing the amount of oil at depth.

Additional Relevant AMOP Publications:
Niu *et al.*, 2009; Nemirovskaya and Shevchenko, 2008; Khelifa *et al*. 2008; Simecek-Beatty, 2007; Khelifa *et al.*, 2005; Khelifa *et al*. 2004a.

3.11 Shoreline Interactions

In general, trajectory models are only expected to predict the length of time it would take the spill to reach the shore, but sometimes it is necessary to model what the oil might do when it gets there.

Interactions between oil and coastal sediments are complex due to a variety of competing processes including deposition on the beach surface, incorporation of suspended sediments, penetration into coastal sediments, and re-floatation. Further complicating the matter, the environmental forcing mechanisms such as waves and currents tend to become more intense and variable in the nearshore. Trajectory modelling beyond the point of contact with land is not very common. Many trajectory models follow the oil spill until it contacts a shoreline, at which time the simulation ceases. The wealth of recent observations, however, allows a much more comprehensive picture of the processes governing oil-shoreline interactions, and should be reflected in future modelling efforts (ASCE, 1997).

Additional Relevant AMOP Publications:
Øksenvag *et al.*, 2009; Sergy and Owens, 2009; Sergy, 2008; Schmidt Etkin *et al*., 2008; Owens and Sergy, 2004; Bergueiro *et al*. 2002; Sublette *et al.*, 2002; Goto *et al*., 2001; Owens and Mauseth, 2001.

3.12 Application of Dispersants

Dispersants are an important response tool for removing large quantities of oil from the surface layer of the water (Owens and Belore, 2004). Dispersants change the physical and chemical properties of oil, and increase the entrainment and dissolution of oil in the water column (French McCay and Payne, 2001), thus changing the evolution of the oil spill. Understanding how dispersants change the dispersive properties of the oil will lead to better trajectory forecasts for spills where dispersants have been applied, but also enable modellers to test whether applying a dispersant is the best approach for controlling the spill. In some cases, applying a dispersant might accelerate the spreading, but that means the oil could reach ecologically significant regions sooner.

Dispersant effectiveness has been tested in cold water and in the presence of ice. Results showed that the presence of ice enhanced the dispersion process. Regions with higher ice concentrations required less wave energy to disperse the oil (Owens and Belore, 2004). Dispersant effectiveness is also linked to salinity (Fingas *et al.*, 2005; Fingas and Ka'aihue, 2005).

Dispersed oil will also resurface over time (Fingas *et al.*, 2002b; Fingas *et al.*, 2003). This time scale of resurfacing might be important depending on how long the oil needs to be tracked.

Additional Relevant AMOP Publications:
Fingas and Banta, 2009; Mullin *et al.*, 2008; Wickley-Olsen *et al.*, 2007; Mukherjee and Wrenn, 2007; Khelifa *et al.*, 2007; French-McCay *et al.*, 2007; Fingas, 2007; Payne *et al.*, 2007; Fingas and Ka'aihue, 2006; Fingas *et al.*, 2006b; French McCay *et al.*, 2006; Fingas, 2003; Sterling *et al.*, 2003; Moles, 2002; Simecek-Beatty *et al.*, 2002.

3.13 Summary of Main Points

- Chemical properties of the oil are important; particularly for the subsurface blowout plume phase where oil droplet size determines the upward migration rate.

- Dispersive properties of the oil should be considered but the necessity to include them in the model depends on the scale of model being used. For example, dispersive properties become more important as the resolution of the model increases.
- Oil interactions with ice must be considered because the oil will move with ice under certain conditions and move with water under other conditions. Therefore the partitioning of the oil between the ice and the water is a key component of an oil spill modelling system.
- Processes such as emulsification, evaporation, coastline interactions and aggregate formation are all important, but their importance is determined by specific conditions of the spill and special and temporal scales of the modelling effort.
- Addition of dispersants alters the chemical and physical properties of the oil and can have serious implications for modelling, particularly for the plume models.

4. Real-Time Data

An effective oil spill model should take advantage of available observations in order to improve the accuracy of the trajectory simulations. Potential observations include ice motion, surface oil extent and ice thickness from various sources (remote sensing, ice beacons, aerial surveys and ice charts). Incorporating observations into a model is often called data assimilation. Straight-forward uses of data include providing initial conditions for the model and using information on the slick extent to update the modelled extent. More sophisticated approaches include using statistical methods to combine the observations and models and keep the model simulations close to the observations.

Data assimilation is a very active field of research in ocean and atmospheric modelling. In this section we discuss some of the data types that may be useful for Arctic oil spill modelling.

4.1 Ice Motion: Remote Sensing and Ice Beacons

Sea ice motion data can be extracted from sequential satellite images, most commonly using a cross-correlation technique. Passive microwave data such as SMMR and AMSR-E provide daily ice motion fields over the entire Arctic Ocean (Fowler, 2003); data from satellite-tracked beacons are also incorporated into these ice motion fields. The resolution of passive microwave data is at best about 6 km. Another source of ice motion data is the synthetic aperture radar (SAR) satellites such as Envisat and RADARSAT. The resolution of these satellites depends on the mode selected, and there is a trade-off between image resolution and spatial coverage. RADARSAT ScanSAR imagery, which has a swath width of 500 km and provides the greatest coverage, has a resolution of 100 m. Unfortunately the temporal coverage is not as good as the passive microwave satellites and daily ice motion fields cannot be derived from the SAR data.

Assimilating ice motion data into an ice-ocean model should improve the prediction of ice motion, and thus the prediction of the motion of oil in the ice, in leads, or between ice keels.

4.2 Ice Concentration, Thickness, and Roughness

The ice charts produced by the Canadian Ice Service are based primarily on analysis of synthetic aperture radar (SAR) data from RADARSAT-1 and -2. Although the analysis is currently performed manually, automated methods are being developed, in part because a much larger data stream will be available with the next generation of RADARSAT, the RADARASAT Constellation Mission. The resolution of the ice charts is generally very coarse, with polygons often tens of kilometres in diameter.

The ice charts provide information on the ice concentration (the fraction of the ocean that is covered in ice) and the thickness of level ice. They do not provide information on the deformed ice. SAR data can be used to provide spatial information on ice roughness features such as ridges and rubble fields, but it cannot provide information on the thickness of the roughness features.

Ice thickness data from satellite based sensors have been extracted from the IceSat mission (no longer operating), and will soon be available from CryoSat (www.esa.int/SPECIALS/Cryosat/index.html), but with a resolution much coarser than the 100 m resolution that has been suggested is required for detailed modelling of the interactions between oil and ice greater than 100 m (see Section 2.4).

Ice thickness profiles with a footprint of about 20 to 70 m can be collected with a helicopter-borne EM-laser system over flight lines generally several tens of kilometres in length, or with a fixed-wing system over longer distances (Peterson *et al*., 2008). This provides detailed information on features such as ridges and rubble fields. However such data are usually collected during research surveys once a year at best. There is no operational use of such high resolution instruments.

Additional Relevant AMOP Publications:
Øksenvag *et al.*, 2009; Catalano, 2008.

4.3 Surface Oil Extent

Recent developments allow oil on water to be detected from space using RADARSAT-2 imagery (Zhang *et al*., 2011), however, the detectability of the oil is highly dependent on wind speed and direction.). This technology provides direct information on the extent of the surface oil spill. Two advantages of RADARSAT are that the satellite orbit provides good coverage of the Canadian Arctic and that the radar can see through clouds. We note that while the capacity was demonstrated for the open waters of the Gulf of Mexico, it has not been tested in the Arctic or in the presence of ice. This technique would be useful during periods of open water, and potentially for detecting oil in leads.

Additional Relevant AMOP Publications:

Sergy and Owens, 2009; Levin *et al*., 2009; Donnay, 2009; Mullin *et al*., 2008; Fingas and Brown, 2007; Coolbaugh *et al*. 2008; French-McCay *et al*., 2007; Boulé and Blouin, 2005; Dickins *et al*., 2005; Montero *et al*., 2003.

4.4 Surface Currents

Recent advances in high frequency (HF) radar technology (e.g. WERA [Wyatt, 2005], CODAR [Barrick, 2008]) have made it possible to obtain synoptic views of surface currents, winds and waves over coastal areas ranging from 40 x 40 to 150 x 150 km (Wyatt, 2005). The technology is based on the analysis of the radar signal backscatter from the sea surface. Typically 3 or more antennae are used to obtain quality directional information. The spatial resolution of these systems is variable and there is a trade off between the resolution and the total area of coverage. The processing time is generally less than an hour and so the data are available in near-real time. HF radar is challenging to validate because this technology measures the velocity of the surface of the ocean averaged over some horizontal region and *in situ* instruments do not usually measure the currents at the very surface of the ocean.

The authors have not reviewed the applicability of this technology in the Arctic. However, we note that such an HF radar capability could feed information into an oil spill modelling system and improve trajectory forecasts.

Additional Relevant AMOP Publications:
Payne *et al*., 2007; Tissot *et al*., 2001; Stone, 2001.

4.5 Summary of Main Points

- Ice drift data from beacons and satellite remote sensing should be used as part of a comprehensive approach to oil spill trajectory modelling in the Arctic.
- The capacity to estimate ice roughness from RADARSAT imagery is in the early stages of development and may prove useful when supplemented by remotely sensed thickness data.

- High resolution ice thickness data from helicopter- or airplane -borne sensors would be useful in the event of a spill.
- The technical capacity to identify oil on water from RADARSAT imagery exists and needs to be developed and tested in Arctic conditions.

5. Oil Spill Models

This section focuses on identifying the functionality of key existing oil spill models and then discussing potential application to the Canadian Arctic.

5.1 Existing Models

Many oil spills models have been developed over the years. Huang (1983) presents a review based on thirty six oil spills models and the review of ASCE (1997) mentions that over fifty models existed in the mid 1990s. Typically these models would include wind-induced drift based on winds from observations and/or stochastic model simulations with some combination of spreading and weathering processes. Ice was usually not considered, however several models implement the work of Cox *et al*. (1980) and Cox and Shultz (1981a) to simulate the movement of oil under ice (Wotherspoon *et al*., 1985; Shen and Yapa, 1988; Anderson *et al*., 1993) as mentioned by ASCE (1997). Another approach particularly applicable in the broken drifting ice, was simply to assume a different wind factor for oil in ice (1%) and in water (3%) (Trites *et al*., 1986).

This review focuses on more recent and well-known developments, in particular, on spill models that employ 3D hydrodynamics and account for the presence of ice. For recent detailed reviews of modelling oil spills in ice see Khelifa (2010) and Yapa and Dasanayaka, (2006).

The Oil Spill Contingency And Response (OSCAR) is a commercial model developed at SINTEF (www.sintef.no/static/ch/environment/oscar.htm; Aamo *et al*., 1997; Reed *et al*., 1995). OSCAR includes a 3D advection model, data-based oil weathering, a chemical fates model, an oil spill combat model and a biological exposure model for fish and other species. The oil is modelled as particles. OSCAR addresses the following surface processes: surface spreading and advection, entrainment in the water column, emulsification (mousse formation), and volatilisation (dissolution). Particles entrained in the water column are modelled with horizontal and vertical advection and dispersion. The interaction between ice and oil is included by assigning a state to the oil particles and by defining probabilities for the particle to go from one state to another. Possible states include trapped under ice, on ice floes, and surface-oil. The model also treats shoreline interactions.

Another popular commercially-available model is OILMAPTM (www.asascience.com; Applied Science Associates, 2009; Gjosteen, 2003; SL Ross, 2010). This is an oil spill trajectory, fate and countermeasures model developed by Applied Science Associates (ASA). Features included are instantaneous or continuous oil release scenarios, algorithms for spreading, evaporation, emulsification, entrainment, oil-shoreline interaction, and oil-ice interaction. To aid response, the system can assimilate observed locations for oil spills and include the effects of response measures, such as booms and dispersants (Applied Science Associates, 2003). The oil is modelled as spillets.

OILMAP was used by Reed and Aamo (1994) to predict oil trajectories for SINTEF's 1993 experiment in the Barents Sea. They report that it performed well in the first 72 hours, during which wind speeds were low and off-ice, and the ice concentration was 60-90%. The approach for incorporating ice is to assume that open water oil spreading and weathering processes apply for ice concentrations less than 30%, are modified for the ice concentrations above 30%, and for concentrations above 80% the oil is assumed to be trapped under ice and to move with it. An Ekman veering angle of 15^{o} to the right is applied.

Petit (1997) presents a model of oil behaviour in ice-infested waters with application to the Weddell Sea in the Antarctic. The model includes drift, spreading, weathering and under ice storage of oil and is coupled to a sea ice model (see Demuth and van Ypersele, 1989 and Petit and Demuth, 1993). This model was also mentioned in the reviews of SL Ross (2010), Gjosteen (2003), and Khelifa (2010). The oil is treated with the spillet approach. The oil drift is regarded as having two regimes. If the ice concentration is low (below 30%) then the ice will have no effect on the oil drift. At high concentrations the oil is assumed to be trapped in leads and the oil drifts with the ice. There is a continuous transition between the two regimes. A horizontal dispersion coefficient was applied, following Venkatesh *et al*. (1990). The dispersion coefficient is taken to be zero for ice concentration above 0.8, and linearly increasing to a maximum value at ice concentration of 0.3 to 0.0 (open water). The under ice storage capacity is assumed to be proportional to the ice thickness. The model also considers the transfer between surface and the encapsulated oil as a function of changes in the ice concentration. The oil properties at ambient temperature and winds are calculated using standard correlations (e.g., Whiticar *et al*., 1993) and take into account the lesser wave energy in an ice field.

Environment Canada developed the OILBRICE oil spill spreading and drift model in the 1980's (El-Tahan and Warbanski, 1987; Venkatesh *et al*., 1990), which treats oil spilled in ice. Their efforts focused on medium to high ice concentrations using a 3 category approach: low (ice coverage less than 30), medium (30% - 80%) or high (greater than 80%). Each regime used a different oil thickness algorithm derived from empirical results. The underlying assumption was that the oil moves with ice for concentrations greater than 30%. Information on the variability of ice was obtained from Environment Canada's Regional Ice Model (RIM; Nerrala *et al*., 1988). The oil was modelled as tracer on a finite difference, 1-km grid. Oil encapsulation and under-ice oil holding capacity was also considered. No recent literature references for the application or development of OILBRICE were found.

A spill model developed with heavy emphasis on near-shore interactions is the Coastal Zone Oil Spill Model, COZOIL, developed for the US Minerals Management Service (MMS) for use in Alaskan waters (Howlett and Jayko, 1998). It models movement and weathering of oil in open water and in the surf zone and includes effects of spreading, evaporation, entrainment, emulsification and shoreline interactions. A database describing the Alaskan coastline was compiled to serve as an input.

5.2 Potential Applications

The accuracy of the oil spill trajectories computed by these models depends on more than simply the features of the oil spill models themselves. The accuracy depends on the quality of the winds, ocean currents and sea ice fields that are used as inputs to the oil spill models. Thus any evaluation of oil spill trajectory models for application in the Beaufort Sea must consider both the properties of the oil spill model and the quality of the ice-ocean hydrodynamics used to provide the ocean currents and sea ice fields for the oil spill model.

For short term trajectory modelling, predictions for 1 to 7 days in the future, the purpose of the oil-ice interaction models is to determine what fraction of the oil drifts with the ocean currents and what fraction drifts with the sea ice. Once this is known then the tracking is straightforward. The simple parameterizations based on sea ice concentration which are commonly used (as described above) seem appropriate for short term forecasting where the goal is provide advice on where to dispatch resources (people and equipment) to clean up the oil. The utility of this approach was demonstrated by Reed and Aamo (1994).

A practical reason for favouring simple approaches to modelling oil-ice interactions is the mismatch in scale between the ice-oil interactions and the existing sea ice and ocean models. The interactions between ice and oil take place at the scale of cracks in the ice, floes, leads, ridges, etc. These typically have scales of 1 m to 100 m. On the other hand, an ice-ocean model of the Arctic Ocean with a resolution of 5 to 10 km would be considered a high resolution model. More typically the models have grid resolutions of 10 km to 100 km. The standard sea ice models were designed to work at these same scales. From an operational perspective, there is no point in developing an ice-oil interaction model that assumes knowledge of the structure of the sea ice field at 1 m scales if the sea ice information is only available at 10 km scales.

Given the expectation that oil spill response will be more protracted than at southern latitudes models will be expected to predict trajectories for much longer than 1 to 7 days. A key question that arises is: What are the key sources of error limiting the prediction of oil spill trajectories of 6 months duration in the Canadian Arctic? An answer to this question would guide future research and development. Is the most pressing need for higher resolution ocean circulation models, more detailed sea ice models and observations, or sophisticated oil-ice interaction models?

During the recent Deepwater Horizon oil spill, six ocean models were used to predict oil spill trajectories (Liu *et al.*, 2011). The oil spill extent was updated whenever satellite based observations were available in order to reduce the error in the trajectories due to the accumulation of the errors in the ocean currents. The ability to use remote sensing to detect oil on water in the Arctic is still under development. As discussed in Section 4.2, recent developments allow oil on water to be detected from space using RADARSAT-2 imagery (Zhang *et al.*, 2011), however that methodology has not been tested in the Arctic nor has it been used to try and detect oil between ice floes.

An even greater challenge is that of detecting oil under ice and the technology to detect oil under ice from airplanes and helicopters is still under development. Overall, the ability to use remote sensing (airborne or satellite) to detect oil on water in the presence of ice or under ice is far from perfect. As such the ability to constrain the model-predicted oil spill trajectories using observations of the spilled oil will be substantially lower in the Arctic than that which might be achieved in more southern locations.

Remote sensing can play a key role in the partitioning of the near-surface oil between the water and the ice. Sea ice concentration is routinely estimated from RADARSAT and other satellites and methods are being developed to estimate roughness from RADARSAT imagery (Peterson *et al.*, 2008). Coarse estimates of ice thickness can be made from the new CryoSat satellite and high resolution (horizontal resolution of 20-70 m) estimates of ice thickness can be made from helicopter borne sensors (Peterson *et al.*, 2008). These types of observations could provide the input data for estimating the partitioning of the oil and then the tracking could be done by the ice-ocean model.

There has been an enormous increase in the number of coupled ice-ocean models for the Arctic over the last 10 to 15 years. A brief overview is provided in the next section. The important point for now is that the push to grid resolutions finer than 10 km is relatively recent and the focus has been on the development of the ocean component rather than the sea ice component.

5.3 Summary of Main Points

- Any evaluation of oil spill trajectory models for application in the Canadian Arctic must consider both the properties of the oil spill model and the quality of the ice-ocean dynamics used to provide the ocean currents and sea ice fields for the oil spill model. Model validation is difficult but essential.
- The existing commercial oil spill models seem to provide a suitable basis for short-term prediction of oil spill trajectories.
- The appropriate approach to modelling oil spill trajectories over 6 months or more is not clear. Validation remains an essential component.
- Remote sensing has the potential to provide information on the oil spill extent in open water conditions
- The combination of remote sensing from satellites and air-borne sensors has the potential to provide the information on ice concentration, thickness and roughness that is required for estimating the fraction of the surface oil that drifts with the currents and that moves with the sea ice.

6. Ice-Ocean Models

There are several families of ocean circulation models, each with their own approach and numerical methods to solve the equations of motion. The seven models listed below are commonly used among the oceanographic community:

- POP- Parallel Ocean Program (http://climate.lanl.gov/Models/POP/)
- MOM- GFDL Modular Ocean Model (http://www.gfdl.noaa.gov/ocean-model)
- HYCOM- Hybrid Coordinate Ocean Model (http://www.hycom.org/)
- POM- Princeton Ocean Model (http://www.aos.princeton.edu/WWWPUBLIC/htdocs.pom/)
- NEMO – Nucleus for European Modelling of the Ocean (http://www.nemo-ocean.eu/)
- ROMS – Regional Ocean Modelling System (http://www.myroms.org/)
- MITgcm – MIT general circulation model (http://mitgcm.org/)

These models have substantial institutional support and a broad base of international users. Versions of these models also appear under different names as a particular institution adopts a model, modifies it and then chooses a new name. There are many other models in use and under development. It is likely that ocean models being developed in Russia, China and Japan will enter the international modelling arena in future.

Over the last 10 to 15 years there has been an enormous increase in the number of comprehensive ocean circulation models applied to the Arctic Ocean. A list of 41coupled Arctic ice-ocean models is provided in Table 1 (Appendix A). These models use a variety of approaches and configurations. For each model, Table 1 lists the lead institution, the principal investigators, model type (vertical grid), horizontal resolution, domain covered by the model, and ocean model component. The list is not exhaustive but attempts to include the major contributors and the leading models worldwide.

Arctic Ocean modelling is an area of very active research and development. A detailed review of the models listed in Table 1 would not be useful without explanation of how each model differs in terms of data sources for atmospheric forcing; global or regional configurations; numerical techniques for horizontal and vertical discretization of the equations of motions; and the sea ice model it is coupled with.

In this section, we review an international effort to evaluate Arctic Ocean models, review Canadian modelling efforts, and discuss sea ice models. This sets the stage for a discussion of comprehensive oil spill trajectory models and identification of the gaps.

6.1 Arctic Ocean Model Intercomparison Project

The Arctic Ocean Model Intercomparison Project (AOMIP; www.whoi.edu/projects/AOMIP) provides a framework for model intercomparison in the Arctic for those modelling groups that choose to participate. AOMIP is an international effort to identify systematic errors in Arctic Ocean models and to reduce uncertainties in model results and climate predictions (Proshutinsky *et al*., 2001; Proshutinsky *et al*., 2005; Proshutinsky and Kowalik 2007). The project has published model intercomparisons on the Beaufort Gyre (Steele *et al*., 2001), the heat and freshwater content (Steiner *et al*., 2004), energy diagnostics (Uotila *et al*., 2005); sea level variability (Proshutinsky *et al*., 2007); water properties and circulation (Holloway *et al*., 2007), and sea ice concentration (Johnson *et al*., 2007). The AOMIP website provides a list of publications, participating institutions and models.

The Arctic Ocean is large and the oceanographic observational database for the Arctic Ocean is not sufficient to provide a definitive test of models. The AOMIP results show that different models tend to do better for different processes and/or in different regions. The main result is that no particular modelling group has found the ideal (or even the best) combination of techniques for modelling the Arctic Ocean. It is also important to note that the AOMIP intercomparisons were aimed at understanding changes in the state of the Arctic Ocean as a whole; so that the models tended to have coarse resolution. The horizontal resolution typically ranges from 20 to 100 km. A model with 10 km resolution would be considered high resolution. This resolution is considered coarse relative to the needs of oil spill trajectory simulation.

We now digress to look at the computational expense of running a comprehensive Arctic Ocean model. The group headed by Dr. W. Maslowski at the Naval Postgraduate School (Monterey CA) has been a leading proponent of the need for higher spatial resolution. In 2008 he reported the run times for an 18-km and a 9-km pan Arctic model. The 18-km version took 28 hours to compute 1 year on 64 processors at the Arctic Region Supercomputer Center and the 9-km version took 168 hours to compute 1 year on 128 processors (Maslowski *et al.*, 2008); that is, a factor of 2 decrease in the grid spacing resulted in a 12 fold increase in computing effort. The group is now running a 2.3 km version of the model (www.oc.nps.edu/NAME/name.html). This factor of 4 decrease in grid spacing likely requires a 24 fold increase in computing effort. Running high resolution models of the Arctic Ocean requires access to substantial computer resources. It is not an activity that can be done on a desk top.

6.2 Canadian Activity

Dr. Greg Holloway (DFO) provided important leadership in Canadian Arctic Ocean modelling by implementing a coarse resolution Arctic Ocean model (Holloway and Sou, 2002; Holloway and Proshutinsky, 2007; Holloway *et al.*, 2007) and making major contributions to the community through AOMIP. Dr. Holloway's modelling was necessarily at coarse resolution because of limited computer power. Dr. Holloway has continued to contribute through the DFO component of the CONCEPTS project described below (Holloway and Wang, 2009).

The current sustained effort in Arctic Ocean modelling in Canada started with the creation of an interagency project called CONCEPTS, the Canadian Operational Network of Coupled Environmental PredicTion Systems. The agencies involved are Environmental Canada (EC), Fisheries and Oceans Canada (DFO) and the Department of

National Defence (DND). The overall goal of the project is the development of a coupled environmental prediction system (atmosphere, ocean, sea ice, waves) for operational forecasts (weather and ocean forecasting). As part of this project the decision was made to use the NEMO modelling system (www.nemo-ocean.eu) as the ocean model component of the coupled system.

As part of CONCEPTS, a DFO project to implement NEMO for the Arctic Ocean (led by Dr. Youyu Lu, DFO) was started to serve a variety of needs. The project has been funded by internal DFO funds (Centre for Ocean Model Development for Application or COMDA), the Program for Energy Research and Development (PERD) and two Environmental Studies Research Fund (ESRF) projects. The goal of the first ESRF project, '*Tracking oil-spills and ice hazards of the Canadian Beaufort Sea with sub-grid ice ocean forecast model*', is to develop an Arctic version of NEMO to the point where the modelled ocean currents and sea ice are sufficiently credible that they can be used to provide potential oil spill drift pathways for locations in the Beaufort Sea. Early results of the ice-ocean model were published by Lu *et al.* (2010). The second project, '*Improving the accuracy of short-term ice and ocean forecasts in the Beaufort Sea*', is a joint project between DFO and EC. The goal is to improve the short-term forecasts through improvements to the ice-ocean model and through the development of data assimilation methods. These model improvements will be integrated into the operational modelling stream at Environment Canada.

The need for high quality operational models for the atmosphere, ocean, ice and waves in the Arctic Ocean has become a high priority because Canada has formally become responsible for providing meteorological and navigation information for two of the five international METNAV areas in the Arctic Ocean. It is reasonable to expect that the CONCEPTS partnership will result in a Canadian operational ocean modelling capacity for the Arctic Ocean within 3 to 5 years.

Two important domestic models are the Canadian Ice Ocean Model (CIOM; Yao *et al.*, 2000) and its successor, the Canadian East Coast Ocean Model (CECOM; Tang *et al.*, 2008; Wu *et al*., 2010) which is the current operational ice-ocean forecast model used by the Canadian Ice Service (CIS). The model domain extends along the east coast of Canada from northern Baffin Bay to Cape Cod. The model is based on the Princeton Ocean Model (Table 1, Appendix A). CECOM has the capacity to input ice thickness data from digitized ice charts, or more specifically, the concentration of various ice types which are assumed to have a certain ice thickness. CECOM could provide an operational model basis for an oil spill model in Baffin Bay if one were required on short notice. It is expected that the CONCEPTS models will replace CECOM for operational sea ice forecasting on the East Coast within 2 to 3 years.

A separate Arctic modelling stream was initiated by Dr. William Perrie (DFO) as part of the International Polar Year (IPY). The goal of the project (entitled '*Impacts of Severe Arctic Storms and Climate Change on Arctic Coastal Oceanographic Processes'*) was, in part, to investigate how the changing ice regime would affect the wind and wave climate and how these changes would impact the coastal zone (Long *et al.*, 2010; Mulligan *et al*., 2010). The ice-ocean model was based on CIOM (mentioned above).

This IPY work has made two important contributions for the purposes of this review. The first is the systematic consideration of the ocean, atmosphere, sea ice and waves as a single, coupled system. The second is serious consideration of the details of the coastal zone processes in the coupled system. Results/conclusions include:

- Wave modelling in the shallow waters off the Mackenzie Delta requires that standard wave model formulations be modified in order to work well.
- The Mackenzie River plume influences the surface waters extending several 100s of km from the mouth of the river.
- Arctic storm intensification can be influenced by the amount of open water available during the summer/early autumn season.

6.3 Coastal Models

The discussion so far has implicitly focussed on large-scale oceanographic models. However the coastal zone is where oil spills generally have their greatest impact. There are many complex processes in the coastal zone which have the potential to be important for oil spill trajectory modelling: complex coastline, narrow channels in the Archipelago, inundation (or flooding) of low lying areas during storms, strong tidal currents, waves changing the current patterns, suspended sediment interacting with the oil to form oil-mineral aggregates that change the properties of the oil, and river runoff creating plumes of freshwater (e.g. the Mackenzie River).

An important feature of the coastal ocean in the Beaufort are the Stamukhi, or rubble ice fields, that form at the edge of the land fast ice zone (Carmack and Macdonald, 2002). The rubble field is formed where the pack ice pushes against the land fast ice and causes the land fast ice to breakup and form a field of broken ice (Figure 4). This generally occurs at about the 20 m isobath in the southern Beaufort Sea. An important feature of Stamukhi is that they extend down into the water column and form an inverted dam which may extend to the bottom. By extending deep into the water column the Stamukhi act as a dam trapping the fresh water from the Mackenzie River on the shelf. Seaward of the Stamukhi is the flaw lead, an area of intermittently open water between the pack ice and the land fast ice.

Given that Stamukhi inhibit the spread of the fresh water from the shelf to the deep ocean, it seems clear that they will also influence the spreading of any oil in the water or ice. There is the potential that during the ice season the Stamukhi could prevent oil in the offshore waters from reaching the coastal zone. However oil that gets incorporated into the Stamukhi and the land fast ice would then be released during the melt season and be available to impact the coastal zone at that time.

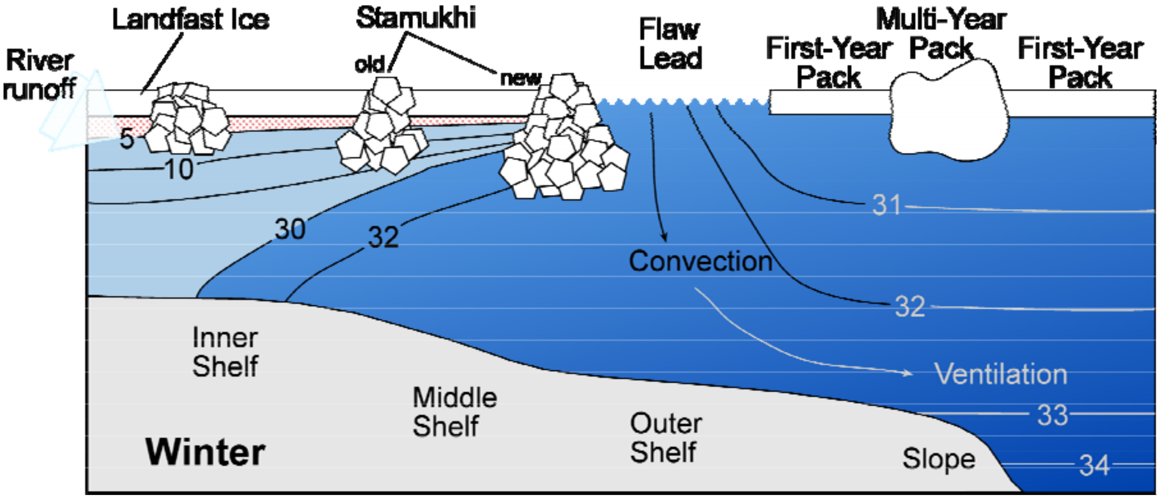


Figure 4 Schematic of the pack ice and oceanographic conditions along the southern Beaufort Sea. The spread of the freshwater from the Mackenzie River is shown to be inhibited by a series of pressure ridges (Stamukhi). The flaw lead is the intermittently open water between the pack ice and the land fast ice. Contours are salinity of the water. This image is based on Figure 10 from Prinsenberg *et al.* (2008).

The differences between an ocean circulation model and a coastal zone model are mostly a matter of which ocean processes are emphasized in developing the code and in the method of application (e.g. horizontal and vertical resolution and whether tides are included). Some of the models listed at the beginning of this section have a history of being used as coastal zone models as well (in particular ROMS and POM). At present DFO has settled on FVCOM (Finite Volume Coastal Ocean Model; http://fvcom.smast.umassd.edu/FVCOM/index.html) for many of its coastal zone applications. The unstructured grid allows the user to have high resolution in the areas of greatest interest. We note that others are using FVCOM as a global ocean model and an Arctic model as well as a coastal zone model.

The details of oil trajectory interaction with the Stamukhi and with the complex currents induced by the coastline, and a definitive answer as to whether the oil reaches the coast are unlikely to be derived from an operational model of the entire Arctic Ocean. Thus one can imagine the need for a high-resolution coastal model for the Beaufort Sea which resolves the small scale processes and can be used to address detailed questions about oil spill trajectories in the coastal zone. Such a model would need the operational model for boundary and initial conditions, or simply be nested within a model such as FVCOM.

6.4 Sea Ice Models

All the ice-ocean models listed in Appendix A incorporate a modern sea ice model. While we have not done a careful survey, it is very likely that all the sea ice models share a common heritage: a description of the sea-ice rheology based on the pioneering formulation of Hibler (1979). Rheology is the mathematical description of how the material responds to compression, shear and tension (the description of how steel is different from glass is different from mud). The sea ice rheology provided by Hibler (1979) assumes that, in a statistical sense, the sea ice looks the same from every direction.

As described by Coon *et al*. (2007), this rheology dates back to the Arctic Ice Dynamics Joint Experiment (AIDJEX; and the pioneering modelling work of Hibler, 1979). Based on images of Arctic sea ice '… it was decided that cracks, ridges, and leads were quite randomly distributed on lengths scales of 100 km, and it would be possible to represent the behaviour by an isotropic model. One can find times when cracks and ridges or leads have preferred directions, and at these times the isotropic model will not be as good.' (Coon, 1980 as quoted by Coon *et al*., 2007). The contact zone between the land fast ice near the coast and the mobile pack ice over the Beaufort Sea (sometimes referred to as the flaw lead) is one example where cracks and leads have a preferred direction.

Scientists have provided improved mathematical descriptions of many processes, systematically tested them, and incorporated them into sea ice models; e.g. improved descriptions of freezing and melting, the albedo (reflectance), melt ponds, the temperature profiles, the effect of snow and many other processes. This has led to many different sea ice models. However the Hibler (1979) rheology has provided the basis for credible sea-ice models with an acceptable computation cost for many years. Within the oceanography modelling community there has not been a big push for improved ice rheology primarily because there were not sufficient observations to test new models and the coarse horizontal resolution of the Arctic models would smear out any improvements.

It is only recently, with the careful analysis of drifting buoy data and the advent of high resolution data from satellites, that the basic assumptions can be tested and they have been found not to be true (Coon *et al*., 2007; Kwok *et al*., 2008). As concluded by Coon *et al*. (2007), ‘The new view of behaviour would lead to a model that directly accounts for velocity (displacement) discontinuities.’ In addition, the enormous increase in computer power over the last two decades has made possible the development of the high resolution ice-ocean models required to investigate where the sea ice models are inadequate (e.g. Kwok *et al*., 2008). In short, new observations and increases in computer power have made it possible for the computational oceanography community to seriously consider alternative sea ice model formulations.

If the details of the leads, fractures, and ridges of a particular part of the ocean are important, then the standard sea ice models are inadequate. One response to this need has been to modify the rheology of Hibler (1979) to improve the simulations of ridges (e.g. Lipscomb *et al*., 2007a,b) and other features. A second approach is to develop a new family of models that starts with the assumption that one needs to account for the structures in the sea ice field. A Canadian contribution here is the model of Savage (2008) which was recently tested against high resolution helicopter-based observations of ice thickness in the southern Gulf of St. Lawrence (Kubat *et al*., 2010). The model did a credible job of simulating the changes in the ice thickness distribution during a ridging event.

A widely used sea ice model is the Los Alamos Sea Ice Model (CICE; www.climate.lanl.gov/Models/CICE; Hunke and Dukowicz, 1997; Hunke and Lipscomb, 2010). The CICE community consists of observationalists and modellers who support the development and testing of the new algorithms, and there is a core group which ensures that the new algorithms get implemented and tested within CICE. Thus CICE generally represents the state of knowledge of the US sea ice community. Other reasons for its wide spread use include:

- the model source code is freely available and is well documented,
- the model has a strong institutional support,
- the development and testing has been going on continuously for many years.

Environment Canada plans to start the transition to the CICE model as its standard operational sea ice model. Therefore over the next few years the CONCEPTS models will move towards implementing CICE version 4.

The model of Savage (2008) and Kubat *et al*. (2010) is still under development and does not have all the features required of an operational sea ice model. However it does show potential as an alternative basis for a sea ice model that more accurately represents the structures present in an ice field. It may also turn out that the core algorithms are too computationally expensive to implement over the entire Arctic Ocean. The practical alternative may be to implement this type of model over the region of interest (e.g. the Beaufort Sea) and provide boundary conditions from an operational model of the entire Arctic Ocean.

6.5 Spatial Variability

An important aspect of tracking oil, or anything else, is the fact that the ocean currents are not the same everywhere; there is important spatial variability. For example, consider the modelled near-surface currents in the southern Beaufort Sea shown in Figure 5. These currents are a snapshot for the month of February in a simulation designed to capture the seasonal evolution of a typical year (they do not represent any particular year). The currents in the central Beaufort Sea are generally to the south and west as part of the Beaufort Gyre (the clockwise circulation in the upper layers in the winter). On the other hand the circulation on the southern shelf is to the east and into the Amundsen Gulf (south of Banks Island). The shelf circulation to the west of Banks Island is weak and disorganized. The transition between the shelf circulation and the Beaufort Gyre is very sharp with a dramatic transition from one to the other. The sea ice drift (Figure 6) shows a spatial structure that is different from the currents. Near the coast and in the Amundsen

Gulf the ice is not moving; it is land fast. Away from the coast the ice is drifting southward and towards the thin ice. Thus there is convergence at the transition zone between the mobile and land fast ice.

Now imagine the fate of an oil slick near the transition between the Beaufort Gyre and the shelf to the south. As the slick spreads the oil can go west with the currents in the Beaufort Gyre, east with shelf currents, south and east with the sea ice, or stay in place with the land fast ice. Clearly there are multiple potential pathways that the oil can take, in whole or in part. Eddies and other small scale features will add additional variability and uncertainty. The key point is that any ice-ocean model used for the oil spill trajectory modelling needs to provide a credible representation of the large scale spatial variability in the ocean currents and the sea ice drift in addition to the storm driven variability.

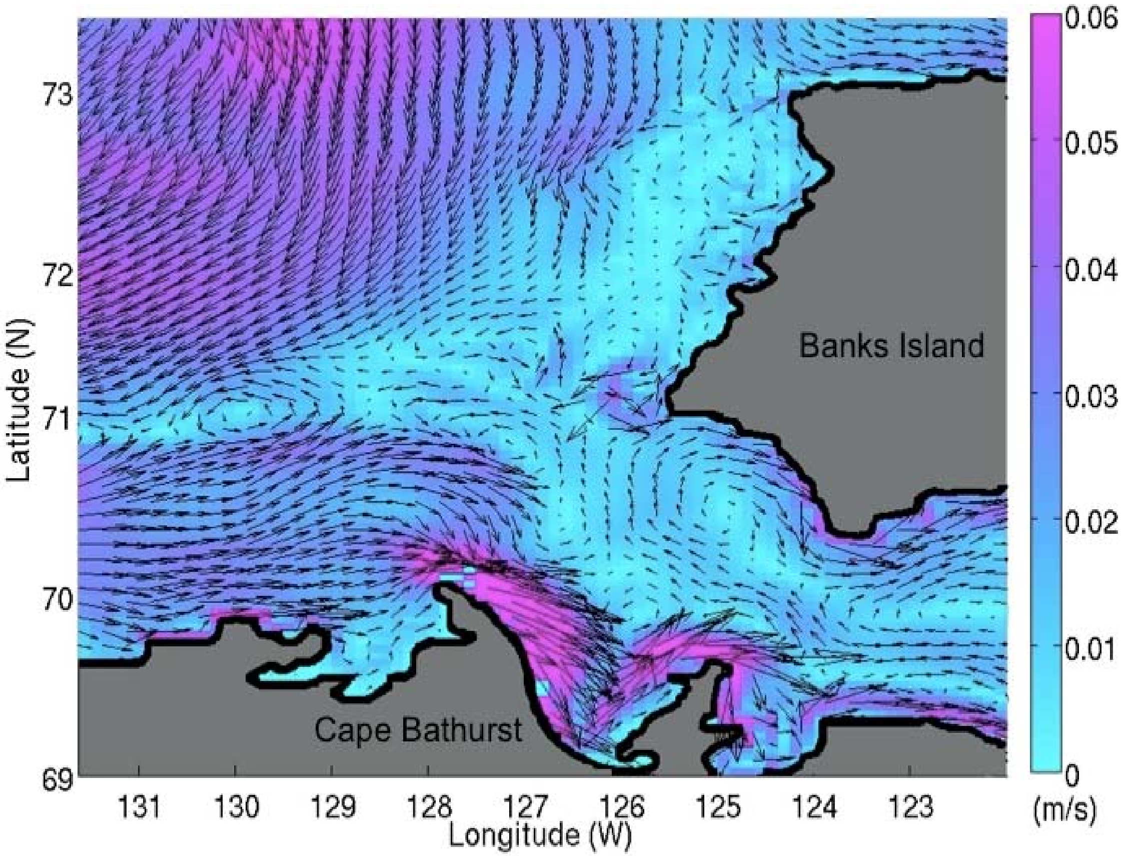


Figure 5 Near-surface (10 m) currents from the 6 km resolution domain for a snapshot in February. Color axis shows the magnitude of the velocity in m/s.

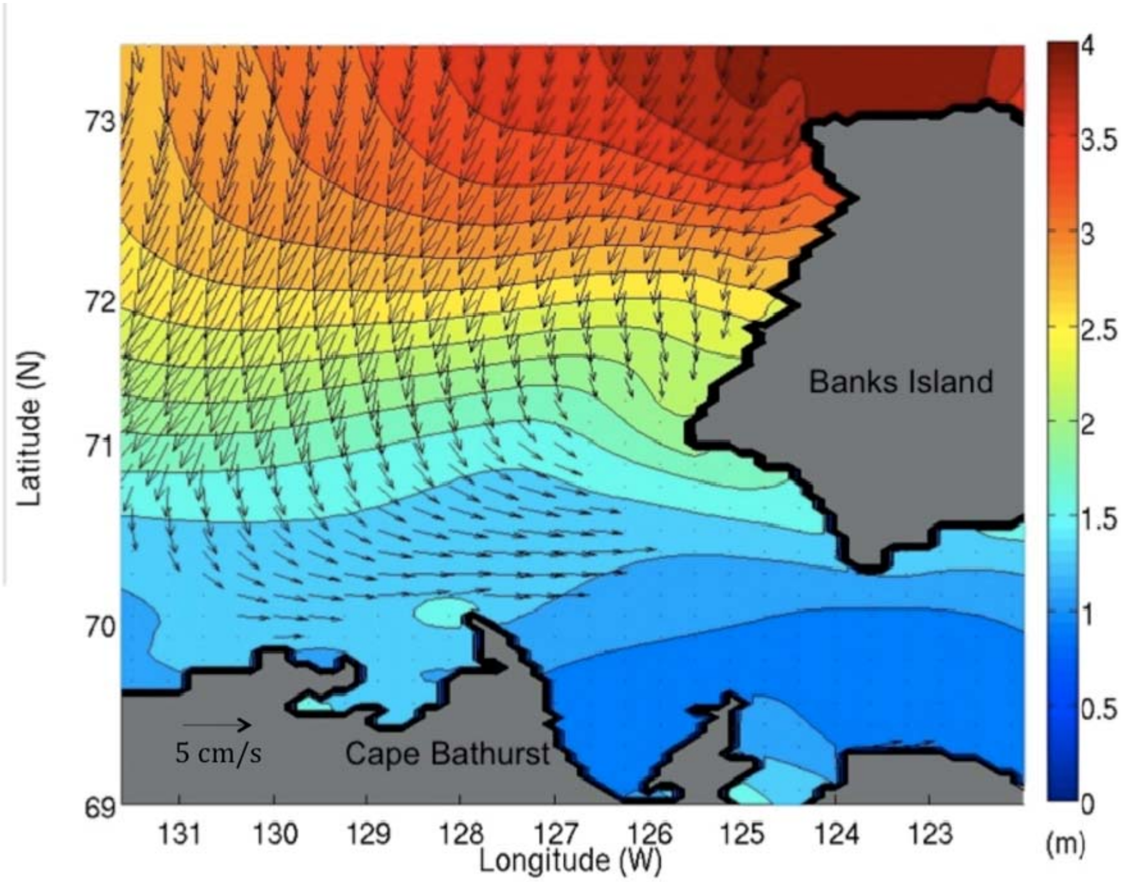


Figure 6 Ice velocity vectors overlaying contours of ice thickness at the same time as the near-surface currents in Figure 5. Color axis indicates the ice thickness in metres.

6.6 Summary of Main Points

- Arctic Ocean modelling is an area of very active research and development. There are many different coupled ice-ocean models for the Arctic Ocean.
- The results of the Arctic Ocean Model Intercomparison Project (AOMIP) show that different models do better for different processes and/or different regions and no particular model is ideal for modelling the Arctic.
- Canada (DFO, EC and DND) plays a lead in the implementation of NEMO (Nucleus for European Modelling of the Ocean) for the Arctic Ocean as part of the Canadian Operational Network of Coupled Environmental PredicTion Systems (CONCEPTS). An operational system is planned.

- The Canadian East Coast Ocean Model (CECOM) is currently being used operationally by the Canadian Ice Service (CIS) for the east coast of Canada including Baffin Bay.
- Coastal processes are an important consideration for oil spill tracking. Unstructured grids, such as FVCOM (Finite Volume Coastal Ocean Model) allow for the very high resolution in coastal water.
- Long, continuous, sea ice features, such as Stamukhi, which extend deep into the water column are not well represented by the current generation of ice-ocean models and this will limit the reliability of oil-spill trajectories in the vicinity of such features.
- Until recently, most sea-ice models were based on a rheology formulation which assumes that sea ice is, in essence, a smooth field. More complex sea-ice models are being developed, however, integration of these models into coupled ice-ocean models is still in the early stages.
- Any ice-ocean model used for the oil spill trajectory modelling needs to provide a credible representation of the large scale spatial variability in the ocean currents and the sea ice drift in addition to the storm driven variability.
- Comprehensive ice-ocean models of the entire Arctic Ocean require substantial computer power and can not be run on a desktop computer.

7. Gap Analysis

A comprehensive oil spill trajectory modelling system should include a high resolution ice-ocean model to provide information on ocean currents and sea ice. The quality of ice-ocean model output will be a function of the quality of the implementation of the ice-ocean model for the area of interest, the suitability of the boundary conditions and atmospheric forcing, and the effort spent on calibration and validation. The choice of the particular ice-ocean model is less important as many high-quality models are available.

The acceptance of the ice-ocean model output for use as an input to the oil spill trajectory model (by regulators, industry, NGOs, academia, and the local communities) will depend on the ability to demonstrate the reliability of the ice-ocean model simulations for this application. The paucity of ocean observations will be a limiting factor for this demonstration.

For blowouts in deep water, the plume model is crucial to estimating how the oil will be distributed in the water column (how much of it reaches the surface versus how much remains at depth). Analysis of the simulations for the *Deepwater Horizon* spill suggests that, for depths greater than 1000 m, the existing models are not yet reliable. As well the plume models need to be tested in Arctic (cold water) conditions. If chemical dispersants are used at the well head, as was done for the *Deepwater Horizon* spill, then observations will be required to determine the distribution of the oil in the water column.

The tracking of virtual drifters in the ocean currents and the sea ice without an oil spill model is a useful tool for understanding where oil may go as part of a scenario planning exercise (e.g. Nielsen *et al,* 2008; Wang *et al*., 2010). However, processes like weathering and evaporation tend to limit the long distance transport of oil. Thus failure to account for these processes will tend to overestimate how far the oil gets transported. Understanding weathering and evaporation in Arctic conditions (cold water and sea ice) will be important to generating reliable estimates of how far an oil slick can be expected to travel in the environment.

The current generation of oil spill trajectory models seems well-matched with the current generation of models for the other elements of the comprehensive system. For example, the oil spill models are designed to make use of the information that the sea ice models can provide (i.e. ice concentration and thickness at large scales). As such, all the components required for a comprehensive oil spill trajectory model exist and seem suited to the task. The gap in development is the integration of all the components (ice-ocean model, wave model, oil spill model, atmospheric model) into a system that can be activated immediately in the event of an oil spill. Potential problems with the plume (blowout) model should not delay the integration of all the components.

Such an integrated system can be expected to provide reasonable oil spill trajectories for short term prediction, perhaps several days to a week. The limit of several days to a week is based simply on the observations that 1) Reed and Aamo (1994) reported that OILMAP performed well over 3 days in a Barents Sea experiment that included sea ice, and 2) in their simulations of the *Deepwater Horizon* spill, Lui *et al*. (2011) chose to use satellite-based observations to update the oil slick location whenever observations were available in order to reduce concerns related to the accumulation of errors. The gap here is the testing of the limits of predictability for such an integrated system.

The picture for oil spill trajectory modelling for the long term, say 6 months, is less clear. The multiple pathways for oil movement and the uncertainty in the ocean currents, sea ice drift and the oil-ice interactions means that deterministic model predictions (i.e. a definite prediction of where the oil will go) become unreliable, and that probabilistic predictions (i.e. the model assigns probabilities that the oil will be found at any particular location) are required. A careful analysis of the sources of error is required to understand how each component of the oil spill trajectory modelling system (ocean currents, sea ice, ice-oil interactions, etc) contributes to the overall uncertainty. This would then guide the need for improvements to the components. It is likely that improvements will be needed to all the components in all the models. However the small spatial scales of the oil-ice interactions strongly indicate the need for higher resolution in the ice-ocean models and that the next generation of sea ice models must account for the detailed spatial structures in the sea ice fields. Features such as the flaw lead and Stamukhi (rubble fields) potentially have a significant impact on the exchange of water (and oil) between the shelf and the deep ocean.

High-resolution modelling of the entire Arctic makes substantial demands on computer resources. A possible way forward is to implement a high-resolution regional Beaufort Sea model for oil spill trajectory modelling. This model would take its boundary conditions, initial conditions and atmospheric forcing from the operational models of Environment Canada. The Government of Canada is developing an operational ice-ocean model for the Arctic Ocean through the interagency project CONCEPTS. The regional model approach would allow the systematic development of novel sea ice models and integrated oil spill trajectory models that could be nested within the operational system.

In trajectory modelling, the errors in ocean currents accumulate and thus the uncertainty in the trajectories increases with time. The standard technique for controlling the uncertainty is to use observations of the oil slick size and location to constrain the simulations. However in the Arctic such observations will be difficult to obtain. Developing and using remote sensing techniques for detecting oil in and under ice may help improve simulated trajectories. Further development of the method of Zhang et al. (2010) for detecting oil-on-water seems particularly attractive given the extensive RADARSAT-2 coverage in the Arctic.

As part of this review, a potential alternative to an ocean-model based tracking system was identified for cases where the ocean is largely ice covered. The alternative system would be based entirely on remote sensing. Maps of daily ice drift are now produced from satellite remote sensing and ice concentration is routinely estimated from satellite data. The partitioning of the surface oil between the water and the ice is largely based on ice concentration with a secondary contribution from ice thickness. RADARSAT does contain some information on ice roughness (or thickness), but the signal can be confounded by other effects. However helicopter or airplane borne sensors could be used to measure thickness profiles during the spill event and these data could be used to calibrate the RADARSAT signal for the time, location, and conditions around the spill. Given the drift rates and the partitioning of the oil between the water and ice, the oil in the ice could be tracked. The authors are not aware of such a system at present, and the technical difficulties may prove insurmountable. However the idea should be given consideration. This tracking method would not deal with the oil that is not moving with the sea ice and it assumes that there is no movement of oil under land fast ice.

The focus of this review has been the offshore and the continental shelf. Modelling oil spill trajectories in the near-shore zone and the interactions of oil with the coastline have not been reviewed here.

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Appendix A – Ice-Ocean Models

Table 1 (Part 1): Sponsors and Details

Country	Institute	Model Name/Abb.	PI	V-grid	Resolution	Domain	Ocean Model	Publication
Russia	Arctic and Antarctic Research Institute	AARI	A. Makshtas		50 km X 50 km	N. Atl + Arctic + N. Pac		Makshtas *et al*. 2003
Germany	Alfred Wegener Institute	AWI	R. Gerdes C. Koeberle and M. Karcher	-z (33)	26-28 km,	50N Atlantic – Bering Str.	MOM	Koberle and Gerdes 2003
Canada	Bedford Institute of Oceanography	BIO **	Y. Lu	-z (46)	6-18 km	50N Atlantic- Bering Str.	OPA	Lu *et al*. 2010
Canada	Dalhousie University	DAL *	F. Dupont	-z				
USA	Florida State University	FSU	E. Chassignet and D. Dukhovskoy					Dukhovskoy *et al*. 2006
USA	Geophysical Fluid Dynamics Laboratory	GFDL *	S. Griffies and M. Winton					Griffes, 2010
USA	Goddard Space Flight Center	GSFC	S. Hakkinen	-sigma (20)	0.35 - 0.45 deg	16S Atlantic – Bering Str.	POM	
USA	International Arctic Research Center	IARC-1/ COCO	B. Hibler, G. Panteleev, and E. Watanabe	- z-sigma (25)	26-28 km	GIN Sea to Bering Str.	POM	-Wang *et al*. 2002 -Wang *et al*. 2005b
USA	International Arctic Research Center	IARC-2/ COCO	B. Hibler, G. Panteleev, and E. Watanabe	- z-sigma (25)			POM	* varies in horizontal friction and time-step from IARC-1
Russia	Institute of Computational Mathematics and Mathematical Geophysics (RASN)	ICMMG	E. Golubeva and G. Platov	-z (33)	35 km – 1 deg	Atlantic + Arctic	-finite element	
USA	Institute of Marine Sciences	IMS	M. Johnson					

* Participated in AOMIP prior to 2008; ** Not an AOMIP participant (Not included in AOMIP website).

Table 1 (Part 2): Sponsors and Details

Country	**Institute**	**Model Name/Abb.**	**PI**	**V-grid**	**Resolution**	**Domain**	**Ocean Model**	**Publication**
Russia	Institute of Numerical Mathematics (RAS)	INMOM *	N. Diansky	- sigma (27)	¼ deg	20S to Aleutian		
Canada	Institute of Ocean Sciences	IOS	G. Holloway	- z (29)	0.5 deg – 55 km	GIN Sea to Bering Str.	MOM	
USA	Jet Propulsion Laboratory	JPL/ ECCO2	R. Kwok and A. Nguyen	- z-sigma				* differs from ECCO2 (MIT) in vertical grid
France	Laboratoire d'Oceanographie: et du Climat: Experimentations et Approches Numeriques	LOCEAN/ ORCA05	M-N. Houssais/ C. Herbaut	- z with shaved cells (46)	25 – 50 km	30S Atlantic – 50N Pacific		
France	Laboratoire de Physique des Oceans	ORCA025/ DRAKKAR *	C. Lique	- z (46)	3 – 28 km	- global	OPA	
Canada	Laval University	LU *		-z (29)	0.5 deg – 55 km	50N Atlantic – Bering Str.		
USA	Los Alamos National Laboratory	LANL	E. Hunke and B. Wingate	-z (40)	9 – 44 km	- global	POP	
Belgium	Louvin La Neuve	LLN					OPA	
USA	Massachusetts Institute of Technology	MIT/ ECCO2	C. Hill and P. Heimbach	-z (50)	15-22 km	Regional Arctic + GIN Sea		
Canada	McGill University	MCGU *	B. Tremblay and A. Jahn					
Norway	Nansen Environment and Remote Sensing Center	NERSC *	H. Drange	- z	22-270 km	- global	MICOM	
USA	National Center for Atmospheric Research	NCAR *	M. Holland					

* Participated in AOMIP prior to 2008; ** Not an AOMIP participant (Not included in AOMIP website).

Table 1 (Part 3): Sponsors and Details

Country	Institute	Model Name/Abb.	PI	V-grid	Resolution	Domain	Ocean Model	Publication
UK	National Oceanography Centre Southampton	NOCS/ ORCA025	Y. Aksenov and B. de Cuevas	-z (64)	6 km – 28 km	- global		
USA	Naval Postgraduate School	NPS	W. Maslowski	-z (30) -layer	1/6 deg – 18.5 km	50N Atlantic – Bering Str.	MOM	
USA	New York University	NYU-a	D. Holland	-layer (11)	1 deg – 111 km	30N	MICOM	* isopycnic model
USA	New York University	NYU-b	D. Holland	-layer (11)			MOM	
Norway	Norwegian Polar Institute	NPI *	Ole A. Nost					
Germany	Ocean and Atmosphere Systems	OASYS	M. Karcher and F. Kauker					
UK	Proudman Oceanographic Laboratory	POL	M. Maqueda	-z (26)	30- 300 km	- global		
Sweden	Rossby Center, Swedish Meteorological and Hydrographic Institute	RCO/SMHI	M. Meir	-z (59)	0.5 deg – 55 km	50N to Aleutian		
Russia	Russian Academy of Science, Moscow	RASM/ FEMAO1	N. Yakovlev and N. Diansky	-z (16)	1 deg- 111km	65N Atlantic – Bering Str.	- finite element	
Russia	Russian Academy of Science, Moscow	RASM/ FEMAO2	N. Yakovlev and N. Diansky	-z (33)	1/6 deg – 18.5 km	50N Atlantic - 65N Pacific	- finite element	
Russia	Russian Academy of Science, Novoibirsk	RASN	E. Golubeva and G. Platov	-z	35km	Atlantic + Arctic	- finite element	

* Participated in AOMIP prior to 2008; ** Not an AOMIP participant (Not included in AOMIP website).

Table 1 (Part 4): Sponsors and Details

Country	Institute	Model Name/Abb.	PI	V-grid	Resolution	Domain	Ocean Model	Publication
Belgium	Universite Catholique de Louvain	UCL *	H. Goose	-z (31)	47 – 222 km	-global	OPA	
UK	University College London	UCL	S. Laxon			-global	OPA	
Canada	University of Alberta	UOA **	P. Myers	-z (46)	6-18 km	50N Atlantic- Bering Str.		
USA	University of Massachusetts, Dartmouth	UMAS/ FVCOM	C. Chen	- sigma	1-15 km			Chen et al. 2009
USA	University of Washington	UW	M. Steele and J. Zhang	-z (21)	40 X 40 km	- Arctic + GIN Sea	MOM	-Zhang et al. 1998
USA	University of Washington	UW	M. Steele and J. Zhang			- global	POIM	
USA	Woods Hole Oceanographic Institute	WHOI	A. Proshutinsky, and P. Winsor					

* Participated in AOMIP prior to 2008; ** Not an AOMIP participant (Not included in AOMIP website).

Appendix B – Subsurface Plume Modelling Review

To predict the fate of oil from subsurface blowouts, computer models have been used effectively. As reviewed by Spaulding *et al*. (2000), modeling the dynamics of rising oil and gas plumes in shallow water can be traced back to McDougall (1978), Fanneløp and Sjøen (1980), Spauding (1982), Milgram (1983), Kolluru *et al.* (1993), and Rye (1994), Zheng and Yapa (1997; 1998), Yapa and Zheng (1997a), Yapa *et al*. (1999). A brief review of these studies can be found in Yapa and Zheng (1997b). Based on the experimental observation of complicated bubble plumes structure (called double plume) in stratified ambient conditions, McDougall (1978) developed a double plume model to simulate the underwater oil well blowout in a stratified environment. The double plume phenomenon was further investigated by Asaeda and Imberger (1993) both experimentally and theoretically for a wide range of flow conditions. In the study by Fanneløp and Sjøen (1980), both approximated and numerically integrated solutions for the submerged bubble jet/plume and the surface spreading have been derived. Although they neglected the slip velocity between the bubble and the plume fluid, the gas expansion was considered. The effect of slip velocity has been later studied by Milgram (1983) by conducting sensitivity study of a gas plume model to certain key parameters. It was found in the study that the results were not sensitive to the value of slip velocity but the slip velocity can not be totally ignored. The model developed by Milgram (1983) was later modified by Rye (1994) to calculate several scenarios of underwater blowouts including the 1979 IXTOC-1 blowout. The IXTOC-1 incident was also simulated by Kolluru *et al.* (1993) using the subsurface blowout module of the Worldwide Oil Spill Model (WOSM), but no detailed on the model formulation was provided. Yapa and Zheng (1997a) and Zheng and Yapa (1997b) have developed Lagrangian model for buoyant oil jets and smoke plumes with the consideration of stratification and ambient current. Their model has been extensively validated against analytical and theoretical results and laboratory and experimental data (Zheng and Yapa, 1998; and Yapa *et al*., 1999). As concluded by Yapa and Zheng (1997b), the models described here can only be used to simulate oil/gas release from not so deep water (e.g. up to 200m).

One of the main difficulties in modeling deep water (over 1000m) is that the complex physio-chemical phenomena, such as hydrate formation, are not well understood. The thermodynamic models by Nguyen *et al*. (1993) and Jakobsen *et al*. (1996) can be used to predict the hydrate formation but can not be used for deep water blowouts as they do not model the bubble plume and oil/gas plume behaviours. To consider both hydrate formation and plume behaviours, Topham (1984) developed a jet/plume model for deepwater oil/gas releases that includes the kinetics and the thermodynamics of hydrate formation. However, the hydrodynamics of the model was a simplified model which limits its application. The approach used by Zheng and Yapa (1999) has improved hydrodynamics, but they ignored the kinetics of hydrate formation and assume that all hydrates are formed at the very beginning of the release. This method has been later improved by Yapa *et al*. (2001) who coupled the intrinsic kinetics of hydrate formation process developed by Englezos *et al*. (1987) and hydrate decomposition process developed by Kim *et al*. (1987) with the hydrodynamic model. Spaulding *et al*. (2000) also presented an integrated model for the prediction of oil transport from a deepwater blowout. The hydrodynamic model was based on McDougall (1978), Fanneløp and Sjøen (1980), and Spaulding (1982) and the hydrate formation and dissociation was calculated externally using a software package, MEGHA. Johansen (2000) presented a comprehensive deepwater spill model (DeepBlow) capable of simulating of gas hydrate formation and decomposition, gas dissolution and gas separation from the plume and compared the model with field experimental data in Johansen (2003). However, only thermodynamics were considered in the DeepBlow formulation and the kinetics (reaction rates) was ignored. As the Yapa *et al*. (2001) was written during the middle stage of the project, and the complete model formulation was not provided, they reported the complete development of their CDOG model in Zheng *et al*. (2002) and compared the model with large scale and unique field experiments (Johansen and Rye, 2003) conducted in Norway in a companion paper (Chen and Yapa, 2002). More recently, Adcroft *et al*. (2010) have presented a model to simulate the underwater plume from the Deepwater Horizon spill. However, the method they used was a simple embedding of a model of the temperature-dependent biological decay of dissolved oil into an ocean-climate model.

The plume dynamic models, despite its importance as highlighted by Dasanayaka and Yapa (2009), was not considered. The near-field dynamics were also neglected in the modeling of blowouts in South Caspian Sea by Korotenko *et al*. (2002).

The key to obtaining good predictions using these models described above also relies on the suitability of key input parameters, such as droplet size distribution. The oil droplet size distribution is one of the most important parameters that affects the transport of oil is (Li and Garrett, 1998). Droplet size distribution also affects how oil dissolves, and the characteristics of any resulting surface slick (Rygg and Emilsen, 1998; Johansen, 1999). Unfortunately, this is one of the difficulties in existing models due to the limited availability of experimental study and theoretical formulation (Chen and Yapa, 2007). All the available models such as DeepBlow (Johansen, 2000), CDOG (Zheng *et al*., 2002), and OILMAPDEEP (ASA, 2011) use the empirical method described by Johansen *et al*. (2001). The problem with Johansen *et al*. (2001) is that it was based on limited data of physically-dispersed oil; therefore, it tends to predict larger droplets, and as such, its use for cases with subsurface injection (like Deepwater Horizon) may lead to significant errors. Although all these models offer options for user specified droplet size distributions, the near-field plume model must be disabled, and the consequent neglect of near-field plume dynamics may also affect the predicted plume behavior. Furthermore, since the Deepwater Horizon was the first instance of subsurface dispersant application (Thibodeaux *et al*., 2010; Kujawinski *et al*., 2011), no experimental data on droplet size distribution resulting from deep water dispersant injection are available. Neither are there any studies evaluating the same.

In summary, our ability to model the deepwater blowout is still very limited especially in the case of subsurface chemical dispersant injection. Thibodeaux *et al*. (2010) concluded, "*As a consequence, there are no mathematical model tools for predicting oil release aspects tuned to deepwater forecasting blowout oil/chemical fate in the marine environment*".