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Modelling the spread of oil under fast sea ice using three-dimensional multibeam sonar data

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[1] A substantial portion of the world's remaining oil and gas reserves are found in the Arctic. Exploration pressure will intensify as sea ice thinning and retreat continue, and the subsequent production could involve spills or blowouts under various kinds of sea ice. Existing models for the spread of oil under ice are inadequate because they are unable to replicate the complexity or uniqueness of different ice regimes. Through the novel combination of 3-D under-ice imagery from an autonomous under water vehicle (AUV) and oil-trajectory modelling we demonstrate that it is possible to overcome these deficiencies. Results suggest that we are presently underestimating the spread of oil under sea ice by an order of magnitude. This is an important result with wide ranging ramifications as it suggests that our present ability to contain and recover oil under ice is limited. **Citation:** Wilkinson, J. P., P. Wadhams, and N. E. Hughes (2007), Modelling the spread of oil under fast sea ice using three-dimensional multibeam sonar data, *Geophys. Res. Lett.*, 34, L22506, doi:10.1029/2007GL031754.

1. Introduction

[2] Some of the world's largest oil and gas reserves are located in the Arctic [*International Union for Conservation and Natural Resources*, 1993; *Arctic Climate Impact Assessment*, 2005] and the pressure to exploit these reserves will continue to grow when one considers, (1) the increasing demand for these products, (2) the unstable political situation in some oil producing countries, (3) the diminishing oil reserves in more accessible regions, and more importantly (4) the predicted disappearance of summer sea ice extent by 2040 [*Holland et al.*, 2006].

[3] Any increase in human activity in the ice-covered waters could magnify the potential for an oil spill. At present we have no means to remotely detect oil under sea ice [*Emergency Prevention, Preparedness and Response Working Group*, 1998; *Arctic Monitoring Assessment Programme*, 1998; *Dickins and Buist*, 1999; *Dickins*, 2000; *U.S. Arctic Research Commission (USARC)*, 2004; *DeCola et al.*, 2006]. This is a critical deficiency affecting all aspects of a response to an oil spill under ice [*USARC*, 2004]; consequently research and development projects continue to focus on technologies and methods to improve oil spill response in ice-infested waters [*DeCola et al.*, 2006].

[4] Much of the existing oil production in ice-covered seas is situated very close to the shore and often lies within an area of transient land-fast. Land-fast ice is sea ice that is in contact with the shore but is immobilised due to the geometry of the coastline or by anchoring points such as small islands or grounded sea ice ridges and icebergs. Fast ice grows thermodynamically and because it is not mobile it is usually in an undeformed state, although there are irregular undulations on the bottom of the ice due to spatial variations in snow loading [*Wadhams and Martin*, 1990; *Wadhams et al.*, 2006]. Snow acts as an insulator, reducing the heat exchange between the atmosphere and ice-ocean interface, thus reducing the thermodynamic growth in regions with a thicker snow cover. This produces natural undulations in the under-ice topography which can provide many effective catchments to contain any spilled oil [*Barnes et al.*, 1979; *Kovacs et al.*, 1981].

2. State of Knowledge

[5] Experiments performed by deliberately spilling oil underneath sea ice have determined that oil is highly mobile and spreads readily along the bottom of an ice sheet as a gravity driven flow [*Wadhams*, 1976; *Wadhams*, 1980; *Malcom*, 1979]. On a perfectly smooth and level ice surface the oil will form droplets, lenses or slicks whose thickness, H , depends on the balance of surface tension versus buoyancy forces around the rim of the lens. In laboratory tests most types of crude had H in the range 0.5 to 1 cm [*Keevil and Ramseier*, 1975]. A slightly thicker equilibrium thickness of about 2 cm was suggested by *Kovacs et al.* [1981], whilst *Greene et al.* [1977] found a minimum thickness of between 0.5 and 2 cm.

[6] The rate at which oil spreads under ice is determined by a combination of factors. These include: the rate at which it is introduced, the viscosity of the oil, the surface oil-ice interfacial tension, and the under-ice topography. The direction of the flow of oil will be a function of the under-ice topography, ice dynamics and oceanic currents. However the under-ice topography is fundamental in determining both the volume of oil that can be held by fast ice (the pooling capacity) and the direction of flow. Therefore a first step in evaluating the volume and dispersal patterns of oil under fast ice is an accurate knowledge of its bottom topography.

[7] A limited number of experiments in the 1970s and 1980s were performed in the Prudhoe Bay region to quantify the pooling capability of undeformed fast ice. These experiments were aimed at obtaining the three-dimensional underside relief of the ice through a gridded drilling [*Barnes et al.*, 1979] and ground penetrating radar programme [*Kovacs*, 1977; *Kovacs et al.*, 1981], which usually did not extend more than 200 m in length. A

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Table 1. Summary of Ice Characteristics and the Potential Pooling Volume for Oil Released Under Fast^a

Site	Year	Season	Mean Ice Draft, m	Std. Dev. Ice Draft, m	Oil Pooling Capacity, m ³ /km ²	Reference
Prudhoe Bay	1977	Spring	1.75 ^b	N/A	27,500 ^c	<i>Kovacs</i> [1977]
Prudhoe Bay	1978	Spring	1.24	N/A	47,000	<i>Barnes et al.</i> [1979]
Stefansson Sound	1978	Spring	1.50	N/A	25,400	<i>Barnes et al.</i> [1979]
Tidal inlet	1978	Spring	1.40	N/A	36,200	<i>Barnes et al.</i> [1979]
Tigvariak Island	1978	Spring	1.40 ^b	0.03	32,000 ^c	<i>Kovacs et al.</i> [1981]
Reindeer Island	1978	Spring	1.18 ^b	0.01	10,000 ^c (min)	<i>Kovacs et al.</i> [1981]
West Dock site	1979	Spring	1.68 ^b	0.15	60,500 ^c (max)	<i>Kovacs et al.</i> [1981]
Site A	1980	Spring	1.37 ^b	N/A	24,800 ^c	<i>Kovacs et al.</i> [1981]
Site B	1980	Spring	1.44 ^b	N/A	23,900 ^c	<i>Kovacs et al.</i> [1981]
Site C	1980	Spring	1.44 ^b	N/A	51,300 ^c	<i>Kovacs et al.</i> 1981
Mean of above surveys			1.44	0.06	33,860	
NE Greenland	2004	late summer	1.26	0.10	30,171 (Max: 71,859 Min: 20,729)	This paper

^aAll surveys, besides NE Greenland, were performed in the Prudhoe Bay region and the results were obtained using the method that calculates the volume of the under-ice topography which lies above the computed mean draft.

^bThese measurements were originally recorded as ice thickness and not ice draft. *Barnes et al.* [1979] suggests a freeboard of between 0.1–0.2 m can be found in the region and therefore to convert ice thickness to ice draft we assumed a freeboard of 0.15 m.

^cThe oil pooling capacity calculated using total ice thickness measurements rather than ice draft does not account for any isostatic effects. This may result in higher void volumes and hence oil pooling capacity for these measurements.

summary of the potential pooling capacity of oil, as calculated from these programmes, can be seen in Table 1. It has been the convention to define the potential oil-pooling capacity of sea ice as the volume of the under-ice topography which lies above the mean draft [*Kovacs*, 1977; *Barnes et al.*, 1979; *Kovacs et al.*, 1981], but the justification for this definition is unclear.

[8] From Table 1 we see that each site has a unique under-ice topography which results in a different potential pooling capacity for oil, despite the ice having similar drafts. Values range from 10,000 m³/km² to 60,500 m³/km², with a mean value from all surveys of 33,860 m³/km². On the basis of these results the conventional wisdom is that thousands of cubic metres of oil will be confined within relatively small areas of the order of hundreds of metres in diameter [*Dickins*, 2000; *USARC*, 2004].

3. New Analysis

[9] In August 2004 the Autosub-II AUV operating off Northeast Greenland obtained the first multibeam sonar measurements under sea ice, showing in unprecedented detail the three-dimensional nature of the under-ice surface [*Wadhams et al.*, 2006]. Multibeam sonar measurements performed from Autosub-II are similar to three-dimensional swath mapping of the sea floor, except that the system is mounted looking upwards towards the underside of the ice rather than downwards towards the seafloor. The swath data obtained represents the first full representation of the three-dimensional underside relief of sea ice.

[10] Autosub-II ran a number of missions under different ice regimes. It was during a portion of mission M365 that Autosub-II ran under a region of undeformed first-year fast ice, producing a swath 23 km in length (from 39.6 km to 62.6 km into the mission) and up to 100 m in width. The swath data were obtained at an across-track resolution of about 1 m and along-track of approximately 2 m. These data were then interpolated to a pixel size of 2 m × 2 m. Ice draft data from a comprehensive drilling campaign were used to calibrate three-dimensional data from the multibeam system

[*Wadhams et al.*, 2006]. A typical three-dimensional under-ice relief of the undeformed fast ice can be seen in Figure 1a and clearly shows that the natural undulations underneath sea ice are able to provide reservoirs to contain oil released under the ice. As these are summer conditions the undulations may have been increased by enhanced melt rates underneath surface meltwater pools. The undeformed nature of the fast ice is clearly evident in the probability density function (PDF), Figure 1b, which reveals a completely undeformed ice sheet, with no ridges or leads present, with a modal ice draft of 1.30 m (standard deviation of 0.1 m).

[11] This dataset is by far the most extensive three-dimensional dataset presently available on the underside of undeformed fast ice and as such is ideal to objectively calculate the pooling capacity of oil with respect to this ice type.

[12] In order to compare the pooling capacity from this first-year fast ice cover with those from earlier experiments (summarised in Table 1) a circular survey area of 2,500 m² (*i.e.* radius $r = 28$ m), with its origin being the centre of the swath, was identified at the start of the dataset. The diameter of the survey area reflects the limited swath width of the multibeam sonar.

[13] Using the conventional method all voids above the mean ice draft, within the survey area, are identified. The model then calculates; the volume of oil held within these voids (m³), the spatial extent of the oil contamination (km²), the fraction of the survey area occupied by oil (%) and the potential pooling capacity (m³/km²). Once this had been performed the centre of the survey area advanced 60 m in the direction of travel of the AUV, thus ensuring no overlap between survey areas, and the process was repeated. By performing this operation over the entire 23 km dataset almost 400 independent survey regions were obtained.

[14] Comparisons between our results and those of previous experiments are also displayed in Table 1. From our ensemble of almost 400 independent survey regions we obtained a mean pooling capacity of 30,102 m³/km², which compares very favourably with the mean value from all previous studies, 33,860 m³/km². This suggests that the

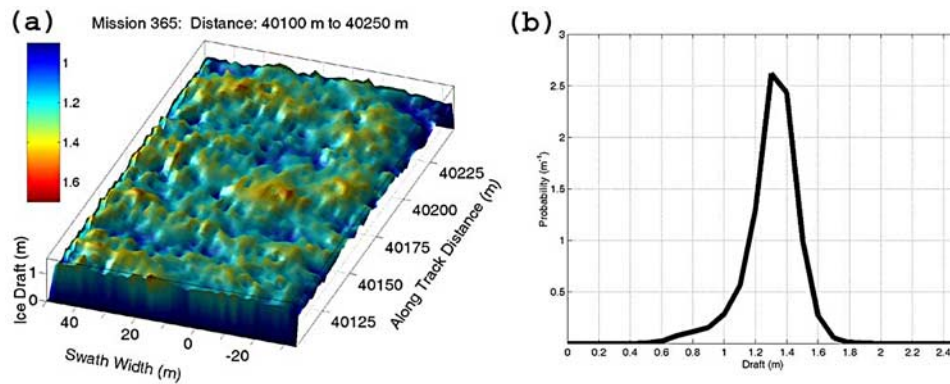


Figure 1. (a) Subset from the multibeam record showing the 3-dimensional detail of the underside first year fast ice. This typical example shows clearly the undulating nature of undeformed first-year sea ice. It is these undulations that hinder the spread of oil under ice. The length of the image is 250 m and has a data aspect ratio of 1:1:0.1. (b) Probability density function of ice draft calculated from the 23 km multibeam dataset obtained under first-year undeformed fast ice. Modal ice draft is 1.30 m.

under-ice characteristics of the fast ice in north east Greenland in 2004 are similar to the conditions at Prudhoe Bay ice, both with respect to ice draft and the potential pooling capacity of the oil, despite the fact that the experiments were performed in different seasons. This suggests that the previous estimates for the potential pooling capacity, which are the accepted standards for undeformed fast ice, are valid.

[15] However it is highly unlikely that all voids above the mean ice draft will contain oil, therefore the values calculated in Table 1 should be regarded as unrealistic maxima. A more likely scenario is that oil spilled under sea ice will preferentially flow towards regions of thinner ice, accumulating in interconnected depressions as it spreads.

[16] In order to address this flaw an under ice oil-transport model has been developed. Within this model a number of assumptions were made. These were; a minimum oil spreading thickness of 1 cm [Keevil and Ramseier, 1975; Greene et al., 1977], no movement of oil due to oceanic currents [Kovacs, 1977; Weeks and Gow, 1979; Mathews, 1980; Cox and Schultz, 1979], and no sea ice forming directly beneath the spreading oil pool because of the continuous flow of oil to the underside of the ice [Dickins, 2000].

[17] The model allows oil to flow under the ice from a single release point at the centre of a multibeam swath. From this release point, of ice draft h , the model calculates the minimum ice draft for all adjacent cells. Oil then flows towards the cell with the minimum ice draft (h_{\min}). An oil thickness of 1 cm, which represents the equilibrium oil thickness (d_{oil}), is added to h_{\min} and its new draft is then equal to $d_{oil} + h_{\min}$. The model continues to identify the minimum ice draft that is adjacent to a cell containing oil,

thus allowing the oil to flow, at an equilibrium thickness of 1 cm, along the line of maximum slope until a local ice draft minimum is reached. This local minimum represents the centre of under-ice depression, and as such allows for the formation of the first oil pool (d_{pool}). Oil continues to gather in d_{pool} in n increments of d_{oil} until its draft is no longer the local minimum (new draft is: $nd_{oil} + h_{\min}$). The model then identifies the lowest ice draft that is adjacent to an oil contaminated cell and the process repeats itself until a new ice draft minimum, d_{pool} , is reached. This procedure continues until the oil affected region flows beyond the edge of the survey area. The model utilised the same survey area as employed previously in Model 1.

[18] Once the flow of oil reaches the edge of the survey area no more oil is added. The model then calculates the same parameters as for Model 1 and advances 60 m in the direction of travel of the AUV and the procedure was repeated until the end of the 23 km dataset was reached.

4. Results

[19] Using the conventional technique to calculate pooling capacity, *i.e.* Model 1, we have shown that the results obtained from multibeam sonar analysis are similar to those obtained by previous authors (see Table 1). Our results also show, predictably, that the assumption that approximately half of the ice within any contaminated area will actually contain oil [Dickins, 2000] emerges directly from this definition of pooling capacity (see Table 2 - Model 1: Percent of survey area covered by oil).

Table 2. The Percent of the Survey Area Covered by Oil and the Potential Pooling Capacity for This Survey Area as Calculated by the Two Different Models^a

	Mode	Mean	Median	Std	Max	Min
Model 1: Volume above mean ice draft						
Percent of survey area covered by oil (%)	49.2	49.7	49.8	2.8	59.3	34.1
Potential pooling capacity (m ³ /km ²)	28,395	30,171	29,443	4,856	71,859	20,729
Model 2: Gravity driven flow						
Percent of survey area covered by oil (%)	4.7	9.0	7.9	4.3	29.5	2.7
Potential pooling capacity (m ³ /km ²)	2,285	4,114	3,366	2,641	16,200	548

^aThese statistics were calculated from almost 400 independent survey areas each occupying an area of 2,500 m².

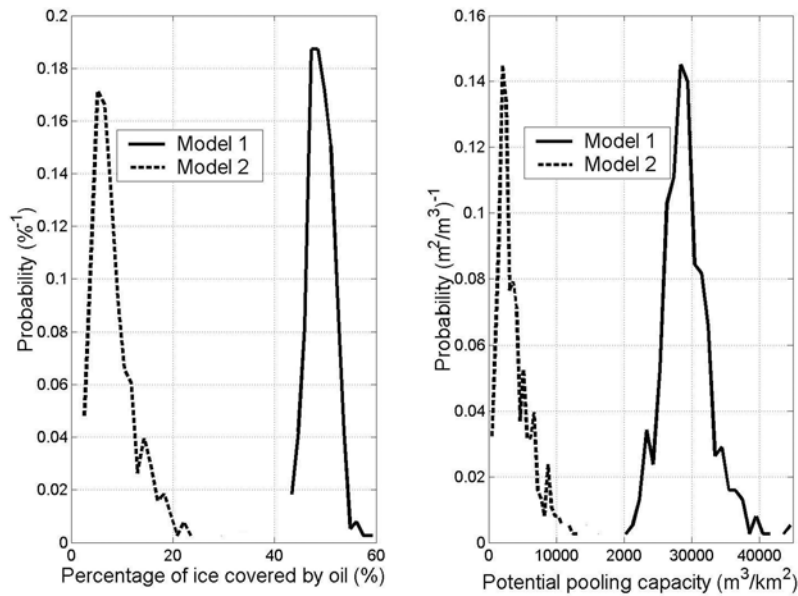


Figure 2. Probability density function for (left) the percentage of ice covered with oil and (right) the potential pooling capacity for each model. The probability density functions were calculated from model results for the almost 400 individual survey sites.

[20] However by using a model that is based on the realistic movement of oil under sea ice we find that the results are significantly different (see Table 2 - Model 2). The gravity driven flow model, Model 2, suggests that only about 5% of the underside of sea ice within the 2,500 m² survey area will be contaminated by oil at any one time, a dramatic difference from the ~50% reported earlier. Furthermore the pooling capacity of sea ice is reduced from a modal value of approximately 28,500 m³/km² to about 2,000 m³/km², over an order of magnitude difference. These differences are clearly visible in Figure 2 which displays the PDFs for both the percentage of ice covered with oil and the potential pooling capacity for each model.

[21] By taking the modal value for the area within the survey region that is contaminated by oil and the modal value for the potential pooling capacity (see Table 2) we can

calculate the probable area and diameter contaminated by an oil spill of differing volumes for both models. Figure 3a shows the probable area occupied by a spill of differing volumes, whilst Figure 3b displays the likely diameter of the contaminated area. From Figures 3a and 3b it is clear to see that under the present scenario of calculating potential pooling capacity (Model 1) we may be significantly underestimating the area covered by an oil spill under sea ice. For example a spill of 5,000 m³ of oil, a reasonable estimate for a single pipeline break, will under the previous version for calculating pooling volume contaminate an area of 0.17 km² and occupy a diameter of 0.47 km. Using the gravity-flow model (Model 2) to calculate pooling volume we find that the diameter of the spill is actually 1.67 km and occupies an area of 2.19 km². The size would be greater still for oil from a blowout, typically emitting 500–1,000 m³ per day for several months with accompanying gas.

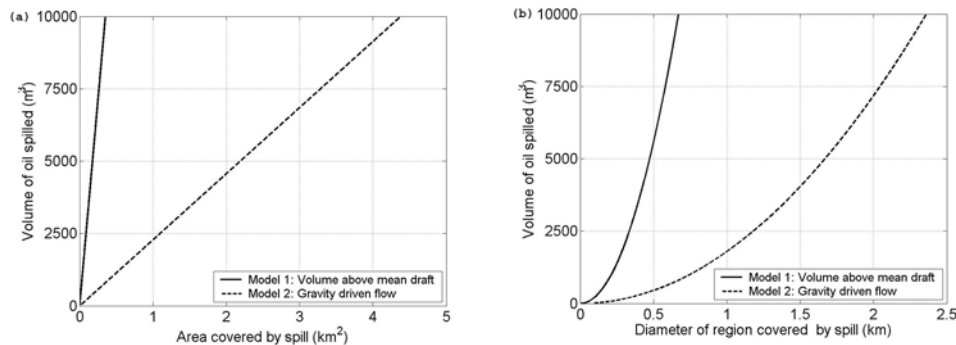


Figure 3. (a) Area of sea ice contaminated by an oil spill of varying volumes as calculated from the modal values shown in Table 2. Dotted line represents values obtained from calculating the pooling capacity of sea ice using the volume above the mean draft method (Model 1), and the model based on gravity flow (Model 2) is shown by the dashed line. (b) Diameter of the region of sea ice contaminated by an oil spill of varying volumes as calculated from the modal values shown in Table 2. Dotted line represents values obtained from calculating the pooling capacity of sea ice using the volume above the mean draft method (Model 1), and the model based on gravity flow (Model 2) is shown by the dashed line.

[22] These differences are considerable and suggest that if there were an oil spill under fast ice we would, at present, seriously underestimate its spatial impact.

5. Summary

[23] It has been suggested by *Fingas and Hollebone* [2003] that existing oil-under-ice models are inadequate because they are unable to replicate the complexity or uniqueness of different ice regimes. We have demonstrated that it is possible to overcome this inadequacy through the use of an upward looking multibeam sonar fitted on to an AUV. Furthermore by combining sonar data with an oil-trajectory model it is possible to determine the potential holding capacity of sea ice and predict the spread of oil at a given location. Our results indicate that we may be underestimating the spread of oil under sea ice by an order of magnitude, though to be certain controlled field tests are required to validate our findings.

[24] Our results also highlight the variability in the potential holding capacity of oil under sea ice, despite the sea ice within our study region having a standard deviation of only 0.1 m over 23 km. Within this region our results suggested that the potential holding capacity varied from 548 m³/km² to 16,200 m³/km² (see Table 2). As the under ice topography is heterogeneous in nature there will always be different stages in the movement of oil that are dependent on a combination of the changing nature of the under ice topography and the absolute amount of oil spilled. As a consequence the process of oil flowing under ice is non-linear and as such there is no simple parameter (volume per unit oiled area) that can be used universally to describe the flow of oil under all ice conditions. Nevertheless, our ensemble approach suggests the most-likely pooling capacity for level first year ice is around 2,000 m³/km².

[25] Accurate knowledge on the topography of the underside of sea ice is essential to predict the flow of oil under fast ice. We have shown that it is possible to obtain this data with an upward looking multibeam sonar mounted on an AUV.

[26] The usage of AUVs is increasing year-on-year, in fact the offshore survey industry has over 100,000 km and 10,000 operational hours experience [*Hagen et al.*, 2006]. In the near future one can envisage AUVs being used routinely to obtain information on both the ice characteristics and the integrity of nearby oil and gas pipelines and installations. The data obtained can be fed routinely into an oil spill model tuned to the area of interest. We will then be in a better position to predict and trace the flow of oil, and thus anticipate the optimal regions where an oil recovery programme should concentrate.

[27] With our results suggesting that only around 5% of the sea ice within an area of 2,500 m² is contaminated, and with no means to remotely detect oil under a sea ice cover, the probability that an oil spill will be detected through the traditional method of drilling holes through the ice is low. Consequently a new technique of combining novel observational techniques and modelling could be the way forward.

[28] **Acknowledgments.** This work was supported through the EU DAMOCLES programme. Data collection by Autosub was supported by the UK Natural Environment Research Council's Autosub-under-Ice Programme.

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