# Oil Droplet Surfacing Probabilities Under Realistic Low Turbulence in Ice

CJ Beegle-Krause (SINTEF, N-7465, Trondheim,Norway)

Tor Nordam (SINTEF, N-7465, Trondheim, Norway)

Emlyn John Davies (SINTEF, N-7465, Trondheim, Norway)

Alex Nimmo Smith (Reynolds, Drake Circus, Plymouth University, Devon, Pl48AA, UK)

Miles McPhee (McPhee Research, 405 Clover Springs Road, Naches, WA 98937, USA)

Liv-Guri Faksness (SINTEF, N-7465, Trondheim, Norway)

Mark Reed (SINTEF, N-7465, Trondheim, Norway)

Ragnhild Lundmark Daae (SINTEF, N-7465, Trondheim, Norway)

Ephim Golbraikh (Physics Department, Ben Gurion University if the Negev, 84105, P.O. Box 653, Beer Sheva, Israel))

## ABSTRACT

2017-081 Responders need to choose among oil spill response options to combat spills in ice covered waters as effectively as possible. A decision to apply dispersants in remote ice covered waters requires an estimation of whether or not the oil will initially disperse and then remain dispersed. A concern is that an effectively dispersed plume of oil will not remain dispersed under ice because the mixing energy required is insufficient. We are advancing the predictive capability to determine whether small oil droplets will rise in the calmer, more stable conditions that can occur in ice covered waters. The results will be presented as lookup tables that can be used to assess whether or not oil has been successfully dispersed in ice covered waters.

Ice covered waters can have very low vertical turbulence (mixing) energy, so smaller droplets may rise to the surface in ice covered waters than in open water at lower latitudes. Laboratory studies with oil droplets and field experiments to measure the turbulence directly under ice are being used to provide input and validation data to numerically simulate an oil spill in ice. We assumed that oil slicks were effectively dispersed to form plumes in the water column. Dispersion was assumed to be from natural mixing energy or forced by applying the propeller wash from vessels. The numerical simulations will be performed to determine if these dispersed plumes could significantly resurface.

The International Oil and Gas Producers (IOGP) funded the Joint Industry Project (JIP) "Fate of Dispersed Oil Under Ice". Sintef led two field campaigns (2015 and 2016) with fast ice (ice attached to land) in Van Miljenfjorden in Svalbard. These data for realistic water currents and mixing energy (turbulence) were used in model development. In the second field experiment, dye was released and followed under the ice in order to measure dilution of the dye, as a check on our model. Neap tide periods were targeted in order to look at low mixing energy conditions. At the Plymouth University mesoscale laboratory, studies in a 30 m flume allowed oil droplets of known size to be released in water flowing under synthetic ice under controlled water velocity and under ice roughness conditions. In addition, an analytical model is being developed to estimate the magnitude and dissipation rate of prop wash turbulence. This was necessary to give the time zero basis for estimating how quickly droplets produced by prop wash would rise to the surface. Size classes of oil droplets that do not rise in low vertical turbulence will certainly not rise in higher turbulence. This will allow future research to target larger oil droplet size classes in the Marginal Ice Zone (MIZ). This project was led by SINTEF (Norway) with participation by McPhee Research (USA), University of Plymouth (UK), and Ben Gurion University (Israel).

## INTRODUCTION

When considering the potential application of dispersants for marine oil spills, one key question is "Will the application be successful?" In open water, this question can be answered by monitoring dispersant application operations using a method such as the Special Monitoring of Applied Response Technologies (SMART) protocol[1]. In ice-covered waters, direct monitoring is more challenging. A numerical model that includes data on the ambient environmental conditions can accurately predict how rapidly a plume of dispersed oil will rise to an under ice surface. One goal of dispersing oil in the water column is to break the oil into tiny droplets that rapidly dilute. This facilitates more rapid biodegradation of the oil by providing greater surface area for microbial attack and adequate dilution allows biodegradation without exhausting available oxygen or nutrients. For this effort, we wanted to determine if the natural turbulence under ice could keep oil droplets dispersed in the water column for periods of 2 days or more. We believe that this amount of time will allow large amounts of dilution to the point that any surfacing under ice may cause less environmental impacts than the original slick. Further, if the oil undergoes a large amount of dilution over a 2 day period, even if it surfaces, the under ice loadings would be low enough that redispersion in the spring may also have less environmental impacts than the original slick.

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[1] http://response.restoration.noaa.gov/sites/default/files/SMART_protocol.pdf

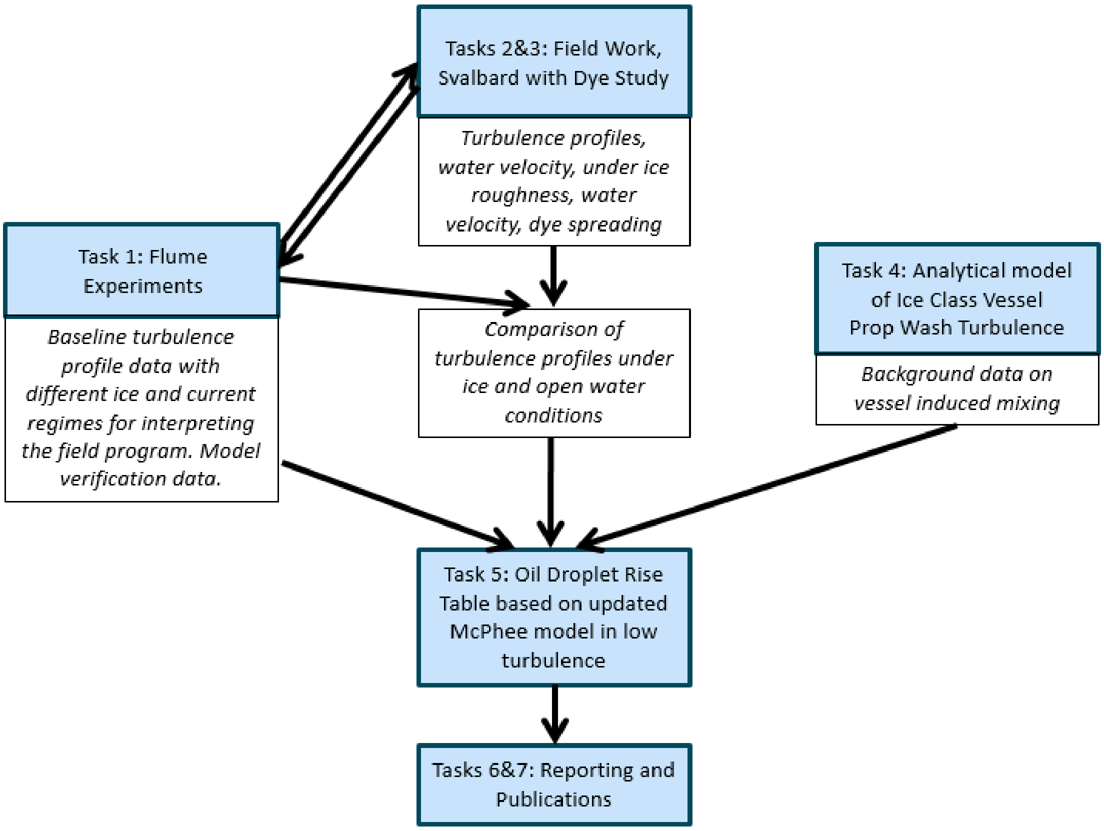

Figure 1. Project flow diagram for the Fate of Dispersed Oil Under Ice, Phase 2 project.

The overall project flow is shown in Figure 1. The goal of this project was to first collect data on under ice turbulence and then input these data into a numerical model to predict how quickly a plume of dispersed oil will resurface under ice. We assume successful dispersion of an oil slick by natural mixing to be as deep as 1-2 m, while icebreaker propeller wash would lead to mixing down to o(10 m) (Spring et al, 2006). The results of the modelling will be placed into lookup tables that provide the time required for various size oil droplets to reach the under ice surface, given different turbulence regimes and oil properties. By using these tables, responders can determine whether or not observed droplet sizes are expected to reach the surface in the next 48 hours. These tables could also be used in planning and drills.

We focus on low vertical turbulence regimes: (1) to identify droplet sizes that would not rise in realistic low turbulence, and so could be neglected in subsequent examination of higher turbulence levels, and (2) to provide guidance for potential Arctic chemical dispersant operations. Instrumentation included a Turbulence Instrument Cluster (TIC) and a free rising micro-structure profiler (MSS90) to measure the turbulence. The low turbulence values from Svalbard are similar to earlier unpublished measurements by McPhee in Greenland, so the Greenland data was included in extending the MePhee (2008) model to low turbulence. We do not address the Marginal Ice Zone (MIZ), which is transition region between wave and ice dominated turbulence regimes, since ice can shift rapidly.

## FIELD CAMPAIGNS IN VAN MIJENFJORDEN, SVALBARD 2015 AND 2016

In February of 2015 and April of 2016, researchers from SINTEF and Plymouth University traveled to Van Milenfjorden, in the Svalbard Archipelago (Figure 2). The fieldwork was timed for low tidal exchange periods to obtain measurements of minimum turbulence levels. The following measurements were made: (a) turbulence measurements with a Turbulence Instrument Cluster (McPhee Research), (b) additional turbulence measurements with a free-rising micro-structure profiler (MSS90) equipped with velocity shear probes, (3) water column temperature and salinity profiles using a portable CTD, (4) water current profiles using an Acoustic Doppler Current Profiler (ADCP), and (5) under-ice roughness using a high-resolution acoustic scanner and mini-ROV. During the 2016 campaign, an under ice dye release study was conducted using rhodamine MT to estimate potential dilution of dispersed oil and as model calibration. The weather during first campaign was cold enough that ice was forming, so instrumentation in the water column generated frazil ice. The 2016 field experiment was conducted later in the year, as the fluorimeter to measure dye concentrations does not tolerate frazil ice in the samples.

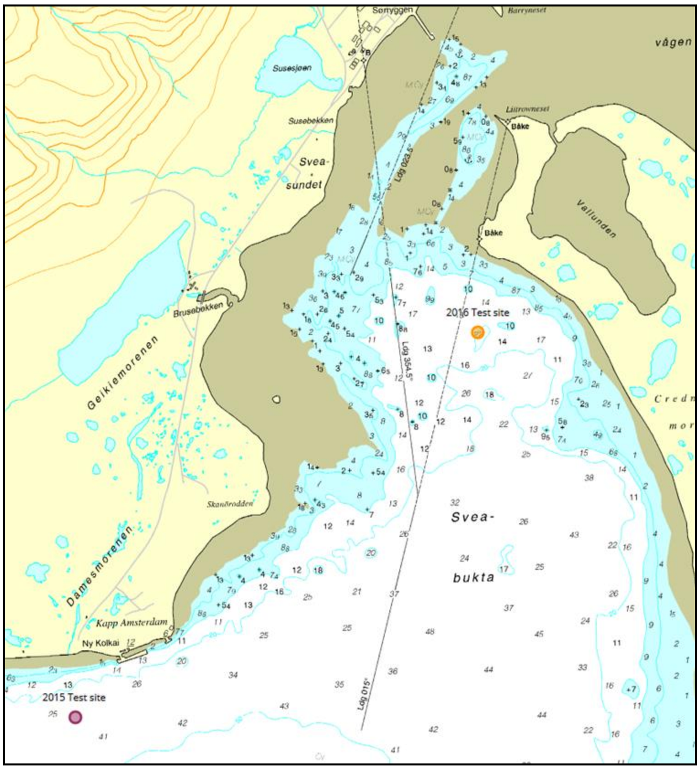

Figure 2. Map showing the 2015 and 2016 field locations. For February 2015 (lower left) and April 2016 (upper right). The difference indicates how rapidly ice melts as the sun returns.

Under ice conditions in February 2015 were mostly smooth ice: a flat under ice surface with occasional frazil ice and bubbles up to 12.9 mm in relief. In April 2016, the underside of the ice had smooth undulations with a wavelength of approximately 2 m, with intermittent (less frequent than in winter 2015) specs or pock marks (4 cm diameter, less than 1 cm in depth). Depth averaged currents ranged from 5-10 cm/s in 2015. In 2016, the currents were weaker, with a root mean square value of 2.6 cm/s, which could be due to being further into the fjord. From the microstructure measurements, we were able to estimate mixing efficiency to calibrate eddy diffusivity estimates of 4 x $10^{-4}$ $m^2s^{-1}$ in 2015 and $1.1x10^{-3}$ to $2.1x10^{-3}m/s^2$ in 2016.

## FLUME STUDIES OF DROPLET RISE IN LOW VERTICAL TURBULENCE GENERATED BY SYNTHETIC ICE

The University of Plymouth 35 m linear flume was used for experiments to measure the rise of oil droplets in relevant turbulence flow, combined with three different upper boundary roughnesses. Use of the flume allowed us to do over 100 oil release experiments, which would not be possible to do in the field (Figure 3). Oseberg blend crude oil was released with four different droplet size distributions ($63\mu m$, $88\mu m$, $125\mu m$, $299\mu m$) (see Brandvik et al 2013 and Johansen et al 2013 for information on droplet size control and injection). Plywood with small- and large-grade bubblewrap was used as synthetic ice of three different surface hydraulic roughnesses, most commonly between ($-6.4 < log(Z0) < -3.4$), which extends to slightly higher values than observed in Svalbard. The hydrodynamic profiles of the flume were characterized by an Acoustic Doppler Velocimeter (ADV) at varying distances along the flume. Three different current profiles with peak currents of ~2.5*cm/s*, ~5.5 *cm/s*, and ~12.5 *cm/s*) were used.

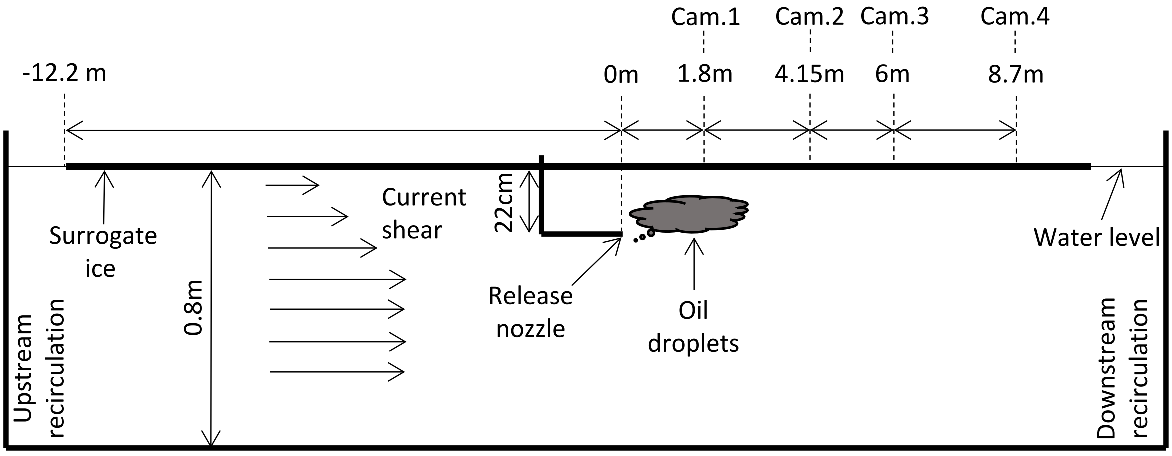

Figure 3. Schematic overview of a single flume experiment showing a "puff" of oil droplets with a known d50 [$63\mu m$, $88\mu m$, $125\mu m$, $299\ \mu m$) into a measured current profile. Four cameras captured the images of the droplet puff, which were used to calculate dispersion.

Figure 4. Example oil droplet "puff" under synthetic ice. The release nozzle on the left side is calibrated such that the amount of oil and the droplet size distribution for the "puff" is known.

Boundary layer shear stress dominated the transport of the oil droplet "puff" down the flume. Thus careful characterization of the under ice velocity profile is needed to best predict how oil droplets will travel immediately under the ice. As the main flume velocity increased to 10 cm/sec, the boundary layer did not extend more than 10-20 cm below the ice. Depending on the formulation of the under ice oil spill trajectory model, this oil could be considered "surfaced", thus standard trajectory oil droplet rise calculations may be sufficient for simulation. We next need to consider how to correctly model under ice oil transport in ice-covered waters.

## RESULTING TURBULENCE MODEL

McPhee's (2008) model of the upper ocean boundary layer required extension to naturally occurring low vertical turbulence levels. These lower turbulence conditions would allow us to eliminate smaller size classes of oil droplets from further consideration in higher currents and mixing. The two field programs in Van Mijenfjorden were designed for sampling during neap tidal slack waters in order observe such low turbulence levels. Water currents were mostly less than 6 cm/s, with the most probable 15-min average speeds falling between

1 and 2 cm/s. McPhee used data from this study and an older study in Greenland to improve the model and predict the turbulence profiles.

The *local turbulence closure* (LTC) modeling approach was used, and is based on the ice-ocean boundary layer similarity methodology described by McPhee (1994; 2008), which calculates momentum eddy viscosity (assumed via Reynold's analogy comparable to scalar variable eddy diffusivity) as the product of the local turbulent scale velocity, $u_*$ (square root of the kinematic Reynolds stress magnitude), and mixing length, $\lambda$, i.e., the vertical extent over which local turbulent fluctuations transfer momentum. For Van Mijenfjorden conditions, the model was formulated with $\lambda$ distributed vertically according to the LTC specifications, and friction velocity constrained by Coriolis acceleration to decrease exponentially with depth from its surface value.

Turbulence measurements made during two field campaigns near Svea, Svalbard, in 2015 and 2016 provided quantitative assessment of mixing length[2] in low energy tidal flow under fast ice. The model was configured to consider two adjustable parameters controlling turbulent structure in the upper 10 m, namely the far-field current magnitude, $U_{ff}$, and the hydraulic roughness of the ice under surface, $z_0$. The best match for the 2016 TIC data profiles velocities: 10, constraints was found $U_{ff}$ = 18.5 mm s$^{-1}$ and by specifying these $z_0$ = 5.7 mm, using parameters, of eddy viscosity were computed for three different values: far-field, 30, 50 mm s$^{-1}$. By Reynold's analogy, eddy diffusivity is assumed identical. The resulting three turbulence profiles are shown below (Figure 5). Turbulence is highest near the close to the surface due to the interaction between the ice and water current. These data will be used in the calculation of the droplet rise tables, as propeller turbulence dissipates quickly.

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[2] Mixing length is a description of characteristic distance a fluid parcel will travel with the same momentum.

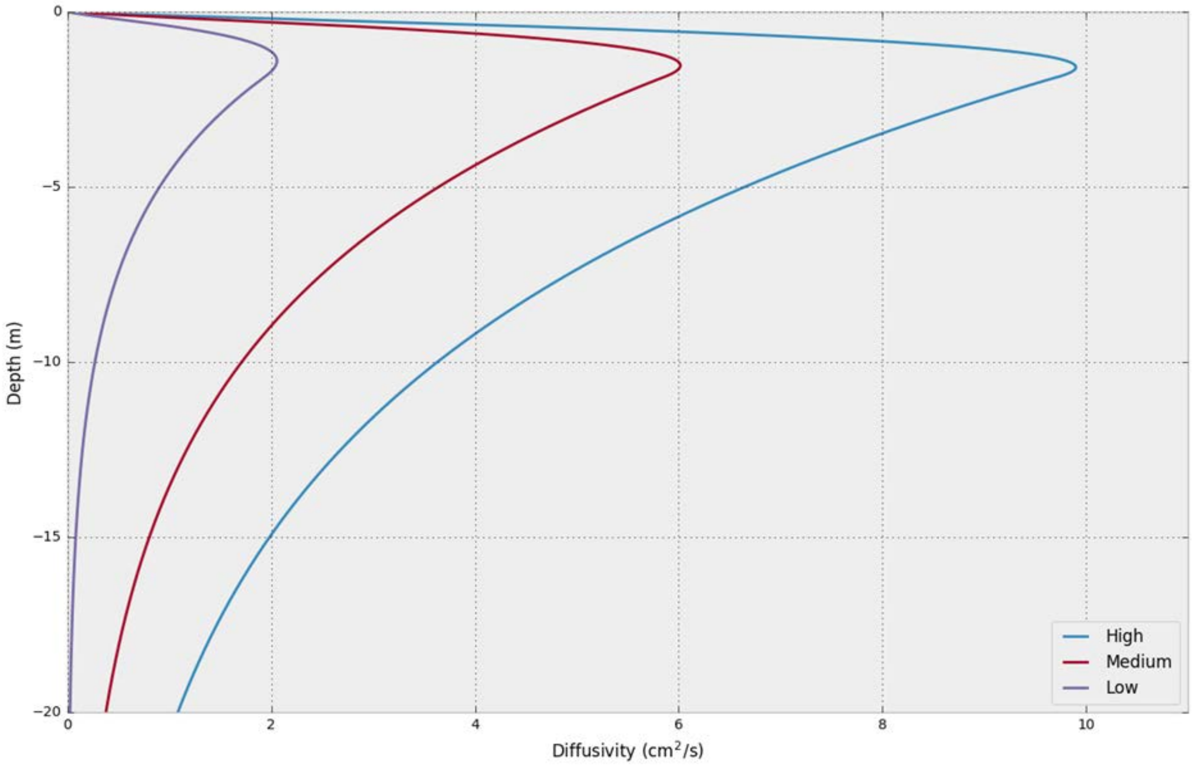


Figure 5. Low turbulence profiles based updated McPhee model using the Svalbard 2015 and 2016 field work.

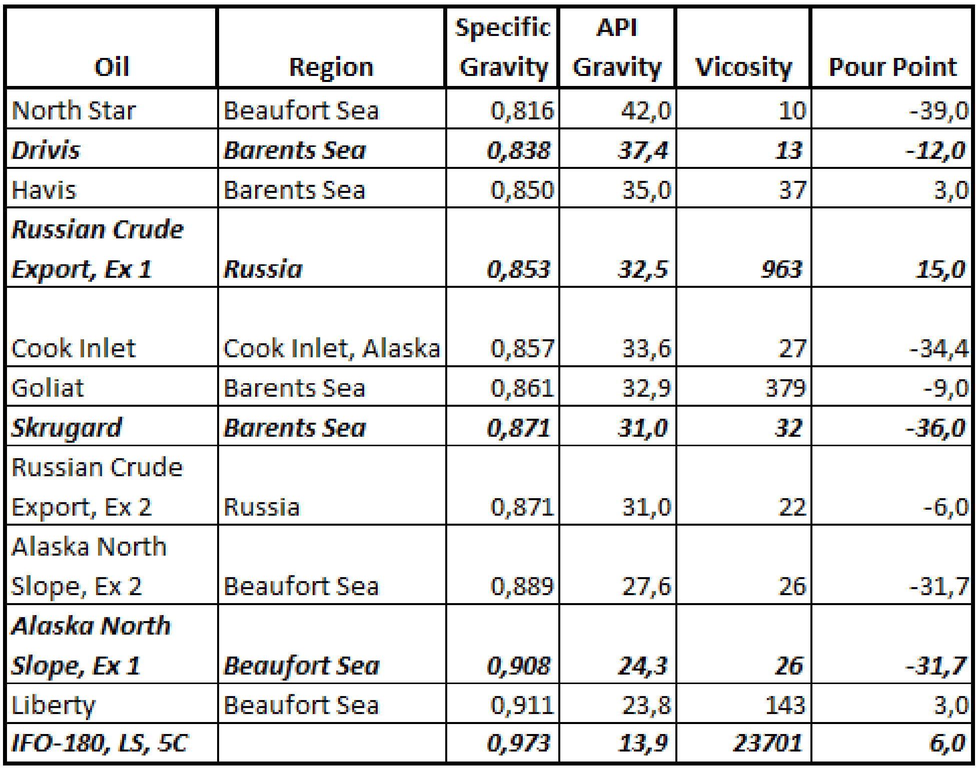
## TURBULENCE IN SHIP WAKES

Ice cover can dampen the mixing energy, which is needed to disperse dispersant-treated oil slicks. The most likely operational configuration for this is an ice class vessel remaining stationary via thrusters, so that the propeller wash could be directed to mix the oil and dispersant. This technique was successful in scale testing in an ice basin (Nedwed et al, 2007, Spring et al., 2006) and in larger scale field tests (Buist et al., 2009). Less likely would be the vessel transiting through the oil, with a large amount of mixing energy provided by the propeller wash and hull displacement of a vessel used to provide mixing energy. Work has been completed on the propulsion mixing model in ice covered waters for a single propeller. What remains is considering the downward water movement between two counter-rotating propellers and dispersing the propeller turbulence (sideways and vertically) due to impingement with ice as in Spring et al (2006).

## DROPLET RISE TABLES

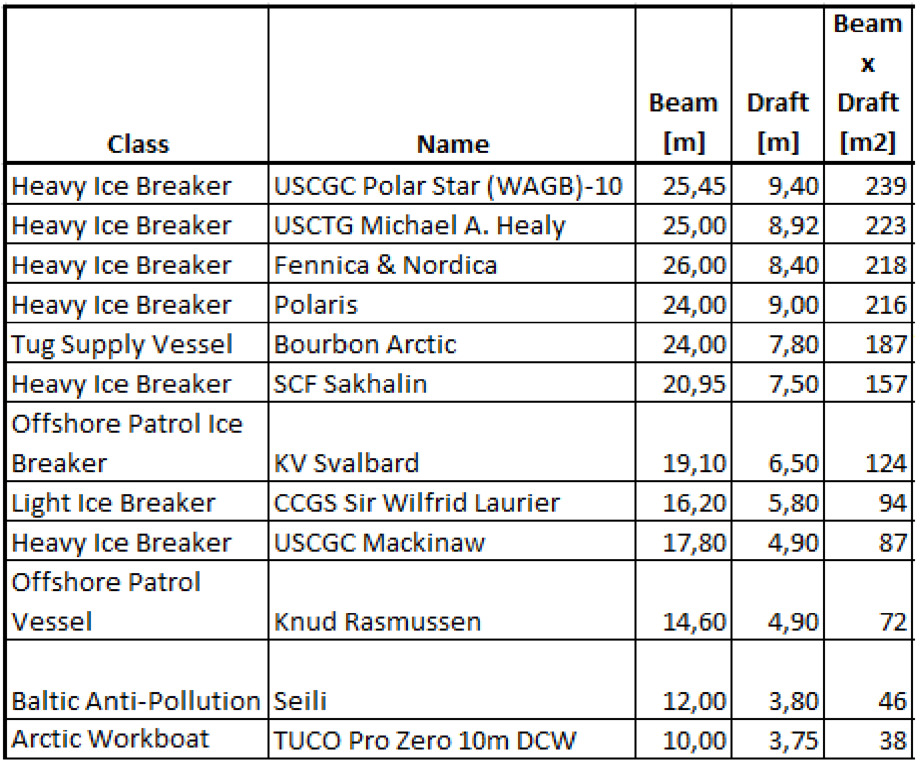
The final deliverable for the project is a report with droplet rise tables for a variety of scenarios including variations in: oil droplet diameter, turbulence profiles, oil types (densities) and mixing scenarios (wave or ship based). The five oils selected were four crude oils and IFO-180 (Table 1). The oils were selected to be from a variety of areas in the Arctic (Barents Sea, Beaufort Sea and Russia) in order to have a wide range of densities and viscosities. Each model will be run for 48 hours of model time. SINTEF will use the updated McPhee Turbulence model and the results of the Ship Dilution model in an offline manor to calculate these tables. At the time of this draft, the configuration of the matrix is tables is being discussed.

Table 1. List of oils considered for the Droplet Rise Tables. The five oils were selected for inclusion in the set of tables (bold italics). Highlighted oils were selected for diversity in Arctic oil characteristics.



| Oil | Region | Specific Gravity | API Gravity | Vicosity | Pour Point |
|---|---|---|---|---|---|
| North Star | Beaufort Sea | 0,816 | 42,0 | 10 | -39,0 |
| ***Drivis*** | ***Barents Sea*** | ***0,838*** | ***37,4*** | ***13*** | ***-12,0*** |
| Havis | Barents Sea | 0,850 | 35,0 | 37 | 3,0 |
| ***Russian Crude Export, Ex 1*** | ***Russia*** | ***0,853*** | ***32,5*** | ***963*** | ***15,0*** |
| Cook Inlet | Cook Inlet, Alaska | 0,857 | 33,6 | 27 | -34,4 |
| Goliat | Barents Sea | 0,861 | 32,9 | 379 | -9,0 |
| ***Skrugard*** | ***Barents Sea*** | ***0,871*** | ***31,0*** | ***32*** | ***-36,0*** |
| Russian Crude Export, Ex 2 | Russia | 0,871 | 31,0 | 22 | -6,0 |
| Alaska North Slope, Ex 2 | Beaufort Sea | 0,889 | 27,6 | 26 | -31,7 |
| ***Alaska North Slope, Ex 1*** | ***Beaufort Sea*** | ***0,908*** | ***24,3*** | ***26*** | ***-31,7*** |
| Liberty | Beaufort Sea | 0,911 | 23,8 | 143 | 3,0 |
| ***IFO-180, LS, 5C*** | | ***0,973*** | ***13,9*** | ***23701*** | ***6,0*** |

Table 2. Ice Class Vessels considered for this study. Only rear propellers mixing were considered in this study. The SCF Sakhalin will be the test case.



| Class | Name | Beam [m] | Draft [m] | Beam x Draft [m2] |
|---|---|---|---|---|
| Heavy Ice Breaker | USCGC Polar Star (WAGB)-10 | 25,45 | 9,40 | 239 |
| Heavy Ice Breaker | USCTG Michael A. Healy | 25,00 | 8,92 | 223 |
| Heavy Ice Breaker | Fennica & Nordica | 26,00 | 8,40 | 218 |
| Heavy Ice Breaker | Polaris | 24,00 | 9,00 | 216 |
| Tug Supply Vessel | Bourbon Arctic | 24,00 | 7,80 | 187 |
| Heavy Ice Breaker | SCF Sakhalin | 20,95 | 7,50 | 157 |
| Offshore Patrol Ice Breaker | KV Svalbard | 19,10 | 6,50 | 124 |
| Light Ice Breaker | CCGS Sir Wilfrid Laurier | 16,20 | 5,80 | 94 |
| Heavy Ice Breaker | USCGC Mackinaw | 17,80 | 4,90 | 87 |
| Offshore Patrol Vessel | Knud Rasmussen | 14,60 | 4,90 | 72 |
| Baltic Anti-Pollution | Seili | 12,00 | 3,80 | 46 |
| Arctic Workboat | TUCO Pro Zero 10m DCW | 10,00 | 3,75 | 38 |

The final project deliverable is 525 tables of droplet rise. Droplet diameters will tested range from 30µ to 110µ. Note that as turbulence level increases, the larger the droplet that can remain submerged in that water column.

## CONCLUSIONS

The potential use of chemical dispersants in ice covered waters is a concern, as mixing energy can be very low and the Arctic hosts many sensitive species. By extending the McPhee model to very low turbulence levels, and developing an improved propeller mixing model, we can test scenarios. The final droplet rise tables will provide key information for Decision Makers for evaluating local conditions in order to decide regarding chemical dispersant usage in the Arctic.

This JIP included two field experiments in Svalbard, Norway, linear flume tests using different oil droplet sizes and three different under ice roughnesses at the University of Plymouth and model development at SINTEF, McPhee Research and Ben Gurion University. The field and flume measurements concentrated on lower natural under ice turbulence levels. Realistic low turbulence profiles have been developed. Model development for ship induced mixing of chemical dispersant and oil is in the final stage. The project's final deliverable is a set of calculated droplet rise tables with five different oils, and overall results will be reported in two peer reviewed publications.

## ACKNOWLEDGEMENTS

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