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The Fate of Dispersed Oil Under Ice: Results of JIP Phase 1 Program

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ABSTRACT 299989:

Ice infested waters pose unique challenges to preparedness and response for potential oil spills. An international team of researchers are working together to create a model to aid in evaluating use of dispersants in ice. The model will be designed to evaluate whether or not dispersed oil droplets formed under continuous or concentrated ice could resurface under the ice to form a significant accumulation within two days. The goal is to develop a tool to support contingency planning decisions with respect to dispersant use.

Phase I of the project was to perform a literature review to develop recommendations to fill data gaps in the ice, current, and turbulence data needed to run a model. Phase II will include field work to collect data and model development and testing. The model will require information about the oil and dispersed oil droplet size distribution and water column information to predict mixing energy that could keep the oil droplets suspended. Droplet size distributions can be easily measured. The challenge is to provide representative information about the water column. We are evaluating several types of oceanographic observational technologies to collect data on under ice mixing energy such as fluorescent dyes, Turbulent Instrument Clusters (TICs), Autonomous Underwater Vehicles (UAVs), and Acoustic Doppler Current Profilers (ADCPs). From our review, we expect to be able to collect the required environmental parameters within reasonable cost and time.

There are a variety of ice formation mechanisms and ice types in the Arctic and Antarctic. Bottom roughness and ice concentration play keys rolls controlling the amount of mixing energy available under the ice. Heavier ice concentrations absorb surface wave energy, which provides the mixing energy for open water dispersant operations. The literature review indicates that good measurements and a good turbulence closure model are key to obtaining good predictions.

We are interested in feedback from the IOSC audience regarding our vision of framing the predictive model as an appropriate decision support tool for the Planning and Response Communities.

INTRODUCTION TO THE JOINT INDUSTRY PROJECT (JIP) FATE OF DISPERSED OIL UNDER ICE:

Increasing interest in hydrocarbon (oil and gas) development in the Arctic is long discussed (Meneley 1984, Gautier et al. 2009). Responsible development includes evaluation and advancement of response options for a potential oil spill. Among response options are chemical or mechanical oil dispersion, which are intended to break up surface or subsurface oil into smaller droplets. Dispersing oil into the water column is a trade-off between oil at the surface where birds, marine mammals, and shoreline ecosystems can come into contact with the oil, vs. subsurface oil and dissolved oil components that could affect sensitive subsurface species. Oil dispersed as small droplets biodegrades faster, due to the larger surface to volume ratio (see, for example, Lessard and DeMarco (2000)) and oil will biodegrade in ice, as shown in Faksness et al. (2011).

Chemical dispersant was used both at the surface and in the subsurface during the Deepwater Horizon oil spill. As a mechanism for scientific review of the decision, a meeting was organized by the National Oceanic and Atmospheric Administration (NOAA) and the University of New Hampshire Coastal Response Research Center (UNH/CRRC) during the Deepwater Horizon oil spill. The workshop participants came to the following conclusion[1] (CRRC 2010):

> *"It is the consensus of this group that up to this point, use of dispersants and the effects of dispersing oil into the water column has generally been less environmentally harmful than allowing the oil to migrate on the surface into the sensitive wetlands and near shore coastal habitats."*

A recent Joint Industry Project (JIP) on response options for oil in ice was awarded to SINTEF and completed in 2009. Through field work with oil in ice, this JIP demonstrated that response options, such as chemical dispersion, have a longer time window in the cold conditions of the arctic than in warmer climates (Sørstrøm and Brandvik 2010). In 2012, another JIP was begun to evaluate the effectiveness of oil spill response options in cold and ice-prone environments. One component of this research was study of chemical dispersion under ice:

> *"The primary objective is to develop a detailed numerical model that predicts the potential for a dispersed oil plume to resurface and re-form a new slick under the ice. Ideally, dispersed oil plumes will remain in the water column indefinitely while biodegradation proceeds."*[2]

The key time period for model prediction is two days, considering that any oil that does not surface within two days is sufficiently dispersed to remain subsurface. Turbulence, or mixing, distributes the oil droplets within the water column as they rise toward the surface.

These are important projects, as there is high public concern related to oil development in the Arctic and concerns related to spill response measures, particularly the addition of chemical dispersants. Decision Makers during an oil spill evaluate tradeoffs among response options, including: no response, mechanical recovery, *in situ* burning and chemical dispersant application. Models can be used to evaluate these different response options, and are part of the evaluation process throughout planning / preparedness and response. The quality of these models, and laboratory to field scale verification are all keys to acceptance of the model's results. This paper describes the efforts completed thus far and future research plans for the ongoing project to model the fate of dispersed oil under ice.

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[1] For more information please see the full report

[2] http://www.arcticresponsetechnology.org/research-projects/fate-of-dispersed-oil-under-ice/at-a-glance , accessed 27 December 2013.

Project Description:

Turbulence is chaotic movement within any fluid, such as the ocean or atmosphere. For oil droplet movement, turbulence affects smaller oceanic scales on the order of 10s of meters or less. This turbulence is the energy in the ocean that can make oil droplets take longer to reach the surface or keep the oil droplets submerged within the water column. Accurate understanding of the turbulence immediately beneath a solid ice layer is critical to modeling the behavior of dispersed oil under ice. In Phase I of the project, the team performed a literature review to select an appropriate numerical algorithm to model the fate of dispersed oil under ice and to determine if data sets already exist describing under-ice turbulence needed for modeling.

Figure 1. Photograph showing the Marginal Ice Zone transition to open water.

Ice Types and Ice Cycle:

The ice cycle and the environmental factors controlling ice motion also control the surface water layer or "mixed layer" that the ice is in. The thickness of this layer is important, as it determines how much water any oil droplets or dissolved oil components can dilute into; a thicker mixed layer means more potential dilution. The mixed layer is shallowest (thinnest) in ice melting and summer seasons. Conversely, the layer is deepest in winter, when surface cooling leads the surface water to become denser, and stronger winds stir deeper into the upper ocean. In some areas, winds lead to further evaporation, increasing the density of local surface water by increasing the salinity, which, in turn deepens the connection of the surface water into the ocean interior.

The seasonal changes to the surface ocean in the Arctic are more complex than the changes that cause freezing in freshwater. The freshwater ice freezing cycle of cooling water leading to ice formation at the top of a freshwater lake is shown in Figure 2. Freshwater has a maximum density at 4°C. Any surface water that cools sinks until the entire water body reaches 4°C. Once this happens, any additional cooling of the surface water results in water that is lower in density and it remains at the surface allowing for rapid cooling of a surface layer and ice formation. However, in the ocean, sea ice formation occurs at a lower temperature of about -1.9°C due to freezing point depression. Also, seawater (above 24.7 ppt salinity) does not have a density maximum above the freezing point. Surface cooling causes the surface water to sink until freezing occurs. In the Arctic Ocean, the top 100 – 150 m is composed of water with different properties than the denser water below. Thus, the upper water column to a depth between 100-150 *m* must fully cool in order for sea ice to form. The lower temperature and perhaps greater depth of cooling leads to sea ice to forming later than lake ice in similar climatic conditions.

The ice formation from salt water leads to brine rejection and accompanying increasing salinity in the layer directly under the ice. Then, during the melting season, a fresh water layer is created over the higher salinity water as ice melts, and wind mixing leads to homogenization of the summer layer during open water season (see Figure 3). This seasonal flux of either brine or freshwater into the surface mixed layer makes the discussion of sea ice formation and changes in the water column more challenging than in the freshwater lake, particularly when one considers that sea ice may not form and melt in the same location in the ocean.

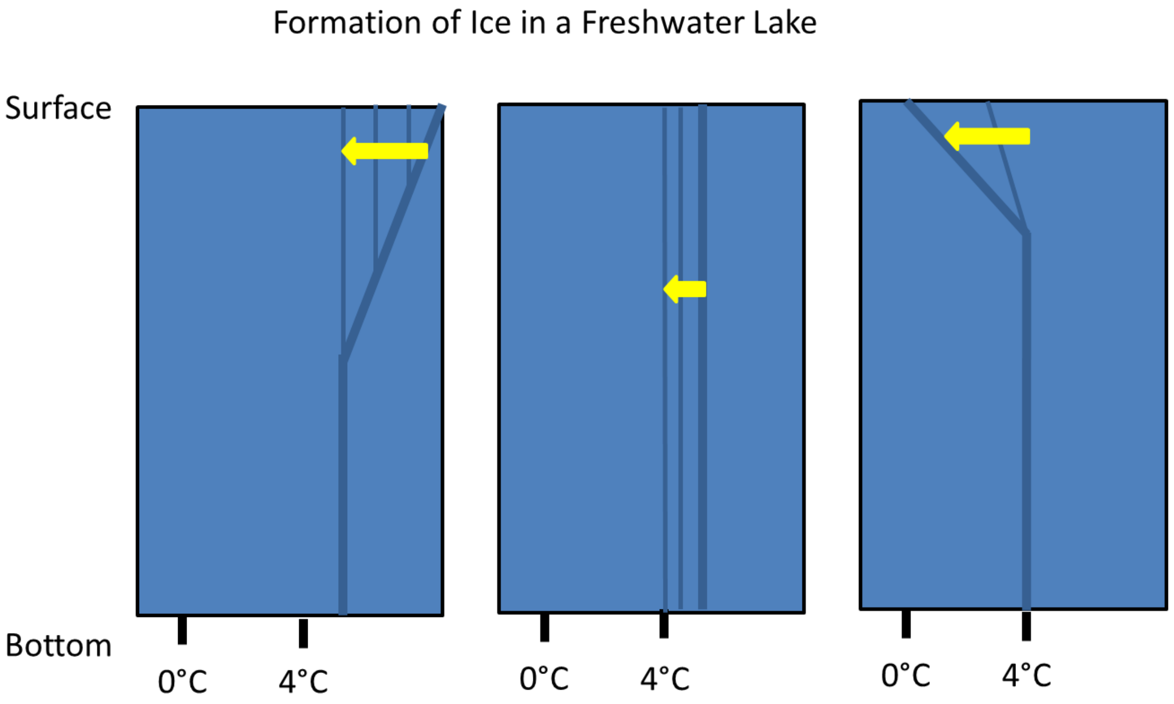

Figure 2. Water column changes leading to ice formation over a freshwater lake. The temperature profile first becomes uniform due to surface water cooling (left panel). Once the temperature profile is uniform, continued cooling lowers the profile temperature to 4°C, which is the point at which freshwater is the most dense, i.e. continued cooling leads to the water becoming lighter (middle panel). Once the lake is uniformly 4°C, the water again becomes stratified, with the coldest water at the surface, leading to ice formation at the lake surface (right panel).

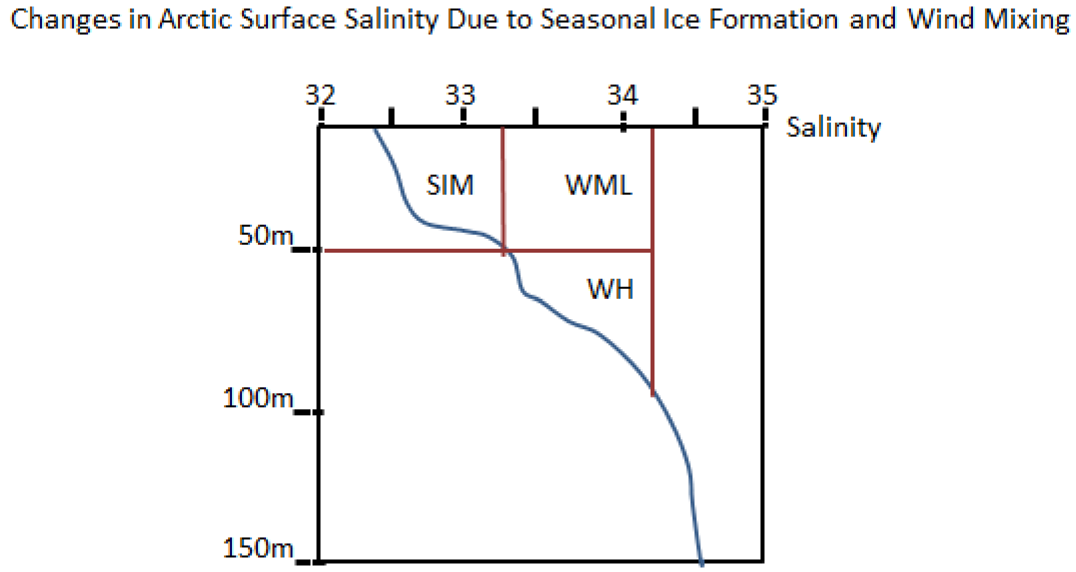

Figure 3. The upper ocean salinity profile (blue line) changes salinity from three factors through the year: Seasonal Ice Melt (SIM), wind induced surface mixing in the Wind Mixed Layer (WML) and seasonal ice freezing creating the Winter Halocline (WH). Diagram after Rudels et al. (1996).

The Arctic Ocean is also a connection between waters from the Pacific Ocean and the Atlantic Ocean. The Pacific Water is fresher than the Atlantic water due to the high freshwater fluxes into the North Pacific as compared to the North Atlantic. The fresher water from the Pacific Ocean is less dense than the saltier water from the Atlantic Ocean so the Pacific Water rides over the Atlantic Water. The Pacific water does not extend completely across the Arctic Ocean, as characteristics are eroded over time due to mixing. The world coldest, densest waters in the world are formed on the Norwegian/Greenland side of the arctic in winter and is called "North Atlantic Deep Water" (NADW) (Dickson and Brown 1994). In the deep Arctic Ocean, influences from the shelf waters of the Barents and Kara Seas can be seen in addition to the NADW as seen in the deep waters of the Canadian Basin (Bauch et al. 1995).

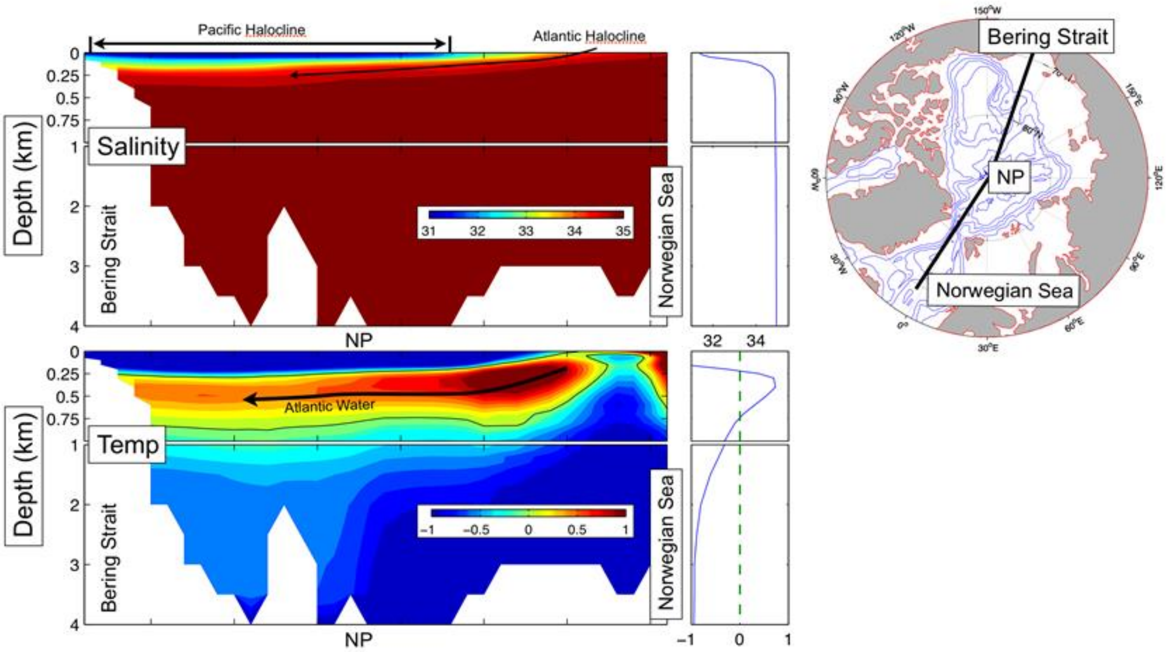

Figure 4. Cross section of temperature and Salinity through the Arctic Ocean. Note how the fresher Pacific Water water rides over the saltier, denser Atlantic Water. The map of the Arctic Ocean on the right shows the sampling path for data used in these sections.

Movement of Ice, Changing Ice Concentrations

Ice occurs in a variety of forms due to formation process and age. Both cycles start with Frazil ice, which is comprised of needle-shaped ice crystals randomly oriented in the surface ocean. The ice moves through stages toward solid ice in the form of ice floes or sheet ice. Both of these types of ice are subject to further aging by seasonal melting, and changes due rafting or pressure ridging.

For oil spills, we consider below the key ice types and stages for oil interaction with ice for modeling:

- During initial freeze-up, oil can freeze into the sea ice, be transported with the ice drift, and be released elsewhere when melting occurs;
- The marginal ice zone, where conditions vary rapidly in both space and time;
- Drifting ice with low ice concentration;
- Medium ice concentrations,
- Pack ice with high ice concentration, where oil is contained/trapped between the ice floes and moves with the ice field

Table 1. Description of the ice growth process

Stage	**Pancake cycle**	**Congelation Growth cycle**
Young ice	Frazil ice Pancake ice rafting	Frazil ice Grease ice Nilas Finger rafting
First-year ice	Cementing and consolidation (ice floes and sheet ice) Rafting and ridging	Congelation ice (sheet ice) Rafting and ridging
Multi-year ice	Weathered from melt Ridging	Weathered from melt Ridging

For this project, we will take an approach of developing a model to simulate ice environments that are at the low end of the energy scale. That is, if we can show by modeling that oil dispersed in these environments remains dispersed for significant periods, than oil dispersed in more energetic environments will remain dispersed for longer periods. Most of the research in under ice turbulence has been done in pack ice, which provides a stable environment for researchers and scientific equipment. Significant research has been done in open water turbulence induced by momentum (wind/wave), heat, moisture or shear fluxes (see example, see review by D'Asaro (2013)). As a first step in our understanding of under ice turbulence, we intend to collect turbulence data under land-fast ice located in a coastal area. If this turbulence is not adequate to keep dispersed oil in the water column, we will consider additional data collection in locations that are more challenging to sample.

shows a summary of the terminology from MANICE (2005), based on the World Meteorological Organization. In rough seas the Pancake cycle occurs, while in calm seas the Congelation Growth cycle occurs. Both cycles start with Frazil ice, which is comprised of needle-shaped ice crystals randomly oriented in the surface ocean. The ice moves through stages toward solid ice in the form of ice floes or sheet ice. Both of these types of ice are subject to further aging by seasonal melting, and changes due rafting or pressure ridging.

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Model Selection:

During the literature review phase of the project, the McPhee (2008) turbulence model was selected as the starting point for further development. This ice-ocean boundary layer model is based on the Local Turbulence Closure (LTC) approach described by McPhee et al. (2008). LTC is a time-dependent, first-order-closure (eddy viscosity) model incorporating velocity and length scales pertinent to turbulent exchange in a rotating (planetary) boundary layer forced by surface stress and buoyancy flux. (Earth's planetary rotation is important in many oceanographic applications, particularly at the poles.) These scales are derived from a substantial body of ice/ocean observations, spanning large ranges in surface stress and buoyancy flux associated with freezing and melting, including conditions encountered in the marginal ice zone (Morison et al. 1987, McPhee and Kantha 1989, Sirevaag 2009)
During an oil spill in ice covered waters, the oil may be dispersed and trapped under ice floes. The fate of this oil depends on several different factors:

- Roughness of the ice bottom.
    - Under-ice roughness will cause increased oil trapping, and increase turbulence.
    - Oil will move more freely beneath a smooth ice bottom, and friction is reduced.
    - Sea ice with a smooth underside will drift more rapidly than very rough or ridged pack ice

  - Depth of ice keels (i.e. very rough ice) will affect the Ekman veering angle relative to the wind direction, and the relative motion of the ice relative to a cloud of droplets underneath.
- Size of the ice floe/cover/sheet, or concentration and consolidation of the ice pack.
  - A more consolidated ice pack reduces wind stress transfer to the upper ocean, reducing turbulence.
- Ice cover concentration.
  - Damping of waves will reduces vertical turbulence, so degree of ice cover as well as distance from the ice edge will be significant parameters in the problem.
- Strength of the under ice current.
  - Stronger currents relative to the ice will produce higher turbulence levels for a given mean roughness measure.
- Freezing and melting processes.
  - Freezing processes may cause oil to be frozen into the ice floe and thus be transported with the drift of the ice, to be eventually released again during breakup.

Note that that above are not directly related to the project, but are background information for the reader on oil in ice.

CONCLUSION AND NEXT STEPS:

In Phase 2, the McPhee (2008) turbulence model will be updated. The model will be modified to include active and passive contaminants, such as oil droplets and dissolved oil components. The model will may also be modified to work in the MIZ, a transition area between open water and pack ice, but tests in lower turbulence regimes will be used to determine the potential need. Also in Phase 2, field work to test, calibrate, and verify the model will be important. Although instrumentation hasn’t been selected, we are considering a well instrumented tracer study, such as a rhodamine dye release, an arrangement of Turbulence Instrument Clusters (TICS), Acoustic Doppler Current Profilers (ADCPs), and/or other Automated Underwater Vehicle (AUV) or Remotely Operated Vehicle (ROV) mounted instrumentation. The dye would simulate the movement of the dispersed oil, and the instrumentation would allow an extensive data set for use with developing the new turbulence closure model.

Phase 2 project could include[3]:

- Designing and conducting a programme to collect data on under-ice turbulence and currents in a low-energy, land-fast ice environment,
- Designing and conducting a programme to conduct dye tracer studies in parallel with the data collection efforts defined above,
- Running the plume model using defined oil droplet sizes and oil densities and the turbulence/current data to predict the behaviour of dispersed oil;
- Preparing a detailed report describing the findings of tasks in Phase 2.

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[3] http://www.arcticresponsetechnology.org/research-projects/fate-of-dispersed-oil-under-ice/scope-of-work Accessed 2 January 2014.

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