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2017 State-of-the Science of Dispersants and Dispersed Oil (DDO) in U.S. Arctic Waters: Physical Transport and Chemical Behavior

Coastal Response Research Center (CRRC)

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Coastal Response Research Center

State-of-the-Science of Dispersants and Dispersed Oil (DDO) in U.S Arctic Waters

1.0 Introduction

Chemical dispersants were employed on an unprecedented scale during the Deepwater Horizon oil spill in the Gulf of Mexico, and could be a response option should a large spill occur in Arctic waters. The use of dispersants in response to that spill raised concerns regarding the need for chemical dispersants, the fate of the oil and dispersants, and their potential impacts on human health and the environment. Concerns remain that would be more evident in the Arctic, where the remoteness and harsh environmental conditions would make a response to any oil spill very difficult. An outcome of a 2013 Arctic oil spill exercise for senior federal agency leadership identified the need for an evaluation of the state-of-the-science of dispersants and dispersed oil (DDO), and a clear delineation of the associated uncertainties that remain, particularly as they apply to Arctic waters.

The National Oceanic and Atmospheric Administration (NOAA), in partnership with the Coastal Response Research Center (CRRC), and in consultation with the U.S. Environmental Protection Agency (EPA) embarked on a project to seek expert review and evaluation of the state-of-the-science and the uncertainties involving DDO. The project focused on five areas and how they might be affected by Arctic conditions: dispersant effectiveness, distribution and fate, transport and chemical behavior, environmental impacts, and public health and safety.

2.0 Objectives

The objectives of the State-of-the-Science of DDO in U.S. Arctic Waters project were to:

- Identify the primary research/reference documents on DDO,
- Determine what is known about the state-of-the-science regarding DDO,
- Determine what uncertainties, knowledge gaps or inconsistencies remain regarding DDO science, and
- Provide recommendations on outreach/education materials needed for senior leadership to be prepared for communicating science regarding dispersant use in spill response.

3.0 Dispersant and Dispersed Oil Databases of Scientific Literature

CRRC created a database that compiled relevant research from 2008 through December 31, 2015. Research documents not published in peer-reviewed scientific publications were included as part of this project, if CRRC determined those references were subject to the appropriate review standards for each organization. The CRRC database was continually updated during the project as new research was identified by the expert scientific panels. The database, which is searchable, is available to the public through CRRC along with the subject area documents

developed by each of the scientific panels. This effort also looked at the Louisiana University Marine Consortium (LUMCON) database that captured relevant literature prior to June 2008.

4.0 Project Process

The CRRC coordinated a discussion among scientists with dispersant research expertise, as well as those with Arctic expertise, to determine the state-of-the-science (knowns and uncertainties) regarding DDO, as it applies to Arctic waters. Scientific panels for each subject area were selected for their knowledge and expertise in that field. The Project Steering Committee, including the NOAA and EPA Project Liaisons, assisted CRRC in identifying individuals with dispersants and/or Arctic expertise. In developing each of the documents these panels reviewed relevant literature and, based on their expertise, developed statements of knowns and uncertainties regarding each focal topic.

The Steering Committee identified five general subject areas that were deemed important to understanding the State-of-the-Science of DDO. Separate scientific panels convened to focus on each of the following topics:

- Efficacy and Effectiveness;
- Physical Transport and Chemical Behavior;
- Degradation and Fate;
- Eco-Toxicity and Sublethal Impacts; and
- Public Health and Food Safety.

The process was initiated in January 2015 with a five-day workshop being conducted, one day for each subject area. Once established, each scientific panel continued to have regular conference calls over the next two years to continue the literature review and develop the knowns and uncertainties documents for each subject area. Dispersant use policies, including operational issues are not within the scope of this project and are not addressed in these documents.

5.0 Public Input Process

Each of the five subject area draft documents was released for a thirty-day public input period. Reviewers were asked to document their comments or recommend changes, substantiated by a citation of a peer-reviewed research paper. Each scientific panel considered all relevant public input received on the draft documents, and when deemed appropriate, amended the original wording. The final subject review documents were released along with the database for each topic. (A sample public input form can be found here http://crrc.unh.edu/dispersant_science).

6.0 Scientific Panel

The scientific panels consisted of a broad spectrum of national and international experts. Their names are listed at the end of each document.

The scientific panel for *Physical Transport and Chemical Behavior* met initially via face-to-face for 10 hours in January 2015 and then an additional 20+ hours of WebEx meetings (February 2015 to December 2016) reviewing publications, discussing the science, writing/editing the draft

document and reviewing and addressing the public input for accuracy. Numerous additional hours were spent by the panelists in preparation for meetings and their individual reviews of the documents.

Disclaimer - This “State-of-the-Science on Dispersant Use in Arctic Waters: Physical Transport and Chemical Behavior” document presents a compilation of individual opinions of the participants in this session of the State-of-the-Science for Dispersant Use in Arctic Waters initiative. To the extent that the Federal Government requested certain information, it did so on a purely individual basis. Similarly, the information herein was presented to the Federal Government by individual participants and represent the participants’ individual views and policies. Therefore, the statements, positions, and research opinions contained in this document do not reflect any consensus on the part of any of the participants and may not necessarily reflect the views or policies of any individual federal department or agency, including any component of a department or agency that participated in developing this document. No federal endorsement should be inferred.

7.0 Physical Transport and Chemical Behavior Document

State-of-the-Science for Dispersant Use in Arctic Waters Physical Transport and Chemical Behavior

I. Arctic Physical Oceanography

A. General Statements

Knowns:

1. The “*western surface waters*” come from the North Pacific through the Bering Strait into the Chukchi and Beaufort Seas. The “*eastern surface waters*” come from the North Atlantic and the local river systems.
2. There are large river systems which introduce freshwater and suspended and dissolved materials to Arctic Ocean waters. These plume systems may present highly effective horizontal modes of transport for oil and dispersants.
 - Influence of these plume systems can be tens of kilometers offshore. The river influence is greater in the Beaufort Sea than the Chukchi Sea (Weingartner et al., 2013; McClelland et al. 2014, Nghiem et al., 2014).
3. There is seasonal ice formation and melting.
4. Seasonal ice melting and large river systems contribute to low salinity surface waters and create a near-surface pycnocline, which inhibits mixing.
5. The deeper waters in the Arctic Oceans are formed in the Atlantic and enter through the Fram Strait.

6. The Beaufort Gyre circulates water and ice in a clockwise manner around the “western” Arctic Ocean. The coastal circulation can circulate in the opposite direction.
7. In an ice-covered ocean, breaking waves and direct wind-induced mixing are reduced.

Uncertainties:

1. The influence of river plumes on circulation in the Arctic is not well understood.

B. Sea Ice and Mixing

Knowns:

1. For all sea ice types, relative motion between ice floes, due to wave penetration and ice floes moving on the water’s surface caused by the wind, can create mixing. The following need to be taken into consideration:
 - Land Fast Ice: During winter in landfast, stable, or non-moving ice-covered areas, there is very little or no mixing unless there is a tide or current underneath.
 - Pack Ice: Friction of the ice on the water causes mixing.
 - Marginal Ice Zone: The marginal ice zone is the transition area between the pack ice and the open water regimes. In open water the turbulence is wave dominated, while under pack ice the turbulence is dominated by the ice. The marginal ice zone is an area where these two turbulence regimes are frequently in transition.
 - In regions of sea ice, the turbulence regime is very dynamic and transient from waves, wind, swell, and relative motion of ice.
 - In regions of sea ice, there is significant wave damping as ice transitions from frazil ice, to grease and slush ice, and to small ice pancakes.
 - Open Water: Surface turbulence is caused primarily by wind-generated waves.
2. During ice formation, brine that is exuded from the ice is transported to the bottom waters and may make a stable and persistent boundary layer depending on environmental conditions (weeks to months to over winter and this can be particularly relevant in near shore lagoons along the Beaufort Sea coast). This movement of brine creates a transport mechanism for moving dissolved constituents (e.g., aromatic hydrocarbons) to the bottom (Payne et al., 1991a). Water soluble constituents from dispersants would be subject to the same behavior.

3. Dispersant use during ice formation may enhance the transport of the dissolved constituents to the bottom waters where elevated concentrations may persist throughout the winter period (Payne et al., 1991a). Refer back to section I.B.2 above.
4. There are a wide variety of mixing scales in the Arctic, both horizontal and vertical (e.g., McPhee and Stanton, 1996; Skillingstad et al., 2003; McPhee et al., 2008; Marcinko et al., 2015). Ice formation, transport and melting result in additional types of mixing compared to open water (e.g., brine rejection, convergence of ice floes).

Uncertainties:

1. Traditional knowledge indicates the presence of small scale generally offshore currents under land fast ice, but the current structure is uncertain (McPhee et al., 2013).

C. Storms

Knowns:

1. There are frequent large storms in winter in the Bering-Aleutian system.

II. Oil and Dispersed Oil Behavior

A. Droplet Size/Formation

Knowns:

1. Dispersants reduce the interfacial tension between oil and seawater.
2. For a given level of turbulence, a reduction of interfacial tension will result in smaller droplet sizes. Therefore, given sufficient turbulence, dispersants decrease oil droplet size.
3. Increased turbulence leads to decreased droplet sizes.
4. The smaller the oil droplets, the slower their rise velocity. Therefore, the smaller oil droplets remain in the water column longer.
5. The greater the turbulence, the greater length of time the oil droplets will remain in the water column.
6. The greater the turbulence, the larger the oil droplet size that will remain in suspension in the water column.
7. As droplet size gets smaller, the surface area to volume ratio increases.

8. Dispersants do not change the oil chemically. Rather, a dispersant-mediated increase in oil droplet surface-area-to-volume ratio facilitates hydrocarbon dissolution of water soluble constituents. This leads to a rapid increase in oil droplets and dissolved constituents in the water column that will decrease over time with dilution and degradation. The rates of dilution and degradation are location and depth dependent.
9. For a given oil and dispersant combination and set of environmental conditions, chemically-enhanced dispersion decreases with lower dispersant to oil ratio (DOR). However, dispersion effectiveness will not continue to increase indefinitely with increasing the DOR. (Khelifa et al., 2007b, 2011; Khelifa and So, 2009)
10. Surface dispersant application results in the formation of smaller, dispersed oil droplets which results in a higher concentration of soluble hydrocarbons in the surface mixed layer. These dissolved hydrocarbons are subject to volatilization.
11. In a subsea dispersant application, mechanical erosion of dispersed oil droplets is enhanced as they rise in the water column (Van Ganse et al., 2013; Aprin et al., 2015). This can lead to enhanced dissolution, and increases the concentration of dissolved components in the water column.
12. Dispersant applications at depth generate higher concentrations of dissolved constituents. In the deep ocean, with lower turbulence, a layer with higher concentrations of dissolved constituents and small droplets may persist for a long time. The persistence and length-scale of a layer depends on specific subsea or release conditions. There are additional considerations for the Arctic as noted in Section I.B.3 above.
13. Fewer dissolved constituents partition into the water column near the surface than at depth due to competition with evaporation. At both surface and depth, transport and dilution of these dissolved constituents and finite oil droplets are highly location specific.
14. There were a number of temperate-water field studies completed in the 1970's, 1980's and 1990's using older methods that suggested rapid decreases in dispersed oil concentration due to dilution in surface water. More recent temperate-water dye and wave-tank studies and modeling confirm dilution with time. (Cormack and Nichols, 1977; McAuliffe et al., 1980 and 1981; Lunel, 1994; Daling and Indrebo, 1996; Strom-Kristiansen et al., 1997; French McCay and Payne, 2001; IPIECA, 2001; French McCay et al., 2006; Trudel et al., 2009).
15. Dissolution is not reversible; however, the dissolved-phase concentrations will decrease with time depending on the level of dilution, microbial degradation and volatilization (in the surface mix layer).

Uncertainties:

1. Validated models that predict near-surface droplet size distribution of naturally or chemically dispersed oil in ice-infested waters do not yet exist. Confounding factors include ice concentration and type, limited mixing energy due to wave damping caused by ice, temperature, and DOR.
2. Studies aimed at understanding the relationship between mixing energy and droplet size distribution in the laboratory (e.g., Brandvik et al., 2014; Merlin 2014; Aman et al., 2015) may not use conditions that represent those that exist under field conditions. For example, in Aman et al., (2015) the test system allowed the droplet size distribution to come to or approach equilibrium under a constant level of shear. This does not simulate the rapidly decreasing mixing energy oil experiences in a jet released from a point source.
3. There are significant questions about whether the scaling from laboratory to field conditions is appropriate.

B. Coalescence and Slick Reformation

Knowns:

1. In the open ocean mixed layer, small dispersed oil droplets (the size depends on the level of turbulence and type of oil) do not form visible slicks.
2. An increase in droplet concentration increases the coalescence of droplets.
3. A particular droplet size distribution is formed under a certain level of mixing energy (Delvigne and Sweeney, 1988; Li and Garrett, 1998; Reed et al., 2009; Zeinstra-Helfrich et al., 2015).
4. If the mixing energy weakens, it is possible for droplets to coalesce, (due to differential settling), but in the case of sufficient dilution, concentrations of larger droplets may not be large enough to reform slicks (Sterling et al., 2004; Zeinstra-Helfrich et al., 2015).

Uncertainties:

1. The turbulence regime under ice is not well understood. Therefore, it is difficult to predict droplet rise under pack ice.
2. While some studies have been conducted (SL Ross, 2006; Merlin, 2014), there remain questions about the extent to which resurfaced chemically-treated oil will be readily amenable to dispersion if mixing energy is reintroduced.

C. Transport

General Statements:

In the Arctic, transport processes are similar to other regions of the world when considering open water conditions and subsea release scenarios. In these cases, local variables such as temperature, salinity, currents, will feed acceptably into existing models. As such, hydrodynamic principles used in other regions can be used for the Arctic.

Once oil is frozen into ice, open ocean transport processes are no longer dominant, and the encapsulated oil will move with the ice.

Knowns:

1. The capacity of ice to pool non-dispersed oil increases with under ice roughness which decreases oil spreading and the resulting area of the spill (Goodman et al., 1987; Wilkinson et al., 2007a).
2. In subsurface releases, differences in rise velocity can cause horizontal separation in droplet size in the presence of a cross current.
3. Dissolved oil and the smallest droplets will move with the water. They will remain in their initial water density layer, which may not stay at a constant depth.
4. Dilution of contaminant concentrations is driven by mixing. In most cases, vertical mixing is of lower magnitude than horizontal mixing in ocean waters.
5. In general, concentrations of oil droplets and dissolved components in the water column decrease over time as the spill expands away from the source in 3-dimensional space.
6. With a continuous or intermittent subsurface release, it is possible that a previously contaminated water mass passing through the rising plume (e.g., through a current reversal) can have an increase in dissolved and particulate hydrocarbon concentrations.

Uncertainties:

1. Pooling capacity and transport of oil trapped under ice are not easy to predict (e.g., characterization of the cavity geometry and capacity, the dynamics of the Kelvin Helmholtz instability, or knowing the current shear structure).
2. Waterborne transport of surface oil in regions with intermediate ice coverage is uncertain (Deslauriers et al., 1977; Deslauriers and Martin, 1978).
3. It is difficult to predict oil transport and mixing in frazil, grease and slush ice.
4. Though we know that oil droplets can rise to the surface during early ice formation stages, we do not know how much these ice forms (frazil, grease, slush) control the

horizontal movement of the oil (Wilkinson et al., 2007a; Wilkinson et al., 2013; Wilkinson et al., 2014).

5. Spreading of dispersant-treated oil in ice-infested water is difficult to predict.

D. Oil in Ice

Knowns:

1. Some examples of oil spills in heavy sea ice include:

Spill Name	Location	Year	Reference
T/V Kurdistan	Nova Scotia	1979	Reimer 1980
Godafoss	Norway	2011	Broström et al., 2011
Runner 4	Gulf of Finland	2006	Wang et al., 2008

2. Experimental field releases have also given information on oil behavior in ice (Dickins, 2011).
3. Spreading and transport of oil-in-ice are two different processes; transport involves the relocation of the oil and ice, while spreading involves the movement of the oil within the ice field.
4. Spreading of oil can be constrained by the presence of ice.
5. Oil in close pack ice will move or be transported with the pack ice.
6. At low concentrations of pack ice, oil will move the same as it would in open water, which may be at a different speed than the pack ice (Khelifa, 2010, Drozdowski et al., 2011).
7. Movement of ice containing entrapped (e.g., frozen-in-place) fresh or weathered oil can result in a secondary release, when the ice melts, at distances far from, and long after, the initial spill.
8. In leads, during early ice formation or refreezing conditions, fresh oil may emulsify due to wave action without appreciable evaporation (Payne et al., 1991b). Depending on the type and percentage of ice coverage and the crude oil involved, water-in-oil emulsions can form and display different responses to treatment with dispersants, ranging from partial to complete dispersion (Brandvik et al., 2010).

9. The window of opportunity for surface application of dispersants increases in the presence of high ice coverage and at low air and sea temperatures due to reduction in oil weathering e.g., evaporation (Brandvik and Faksness, 2009).

Uncertainties:

1. A general algorithm for transitioning between ice regimes has been discussed since the late 1970s, however there is not agreement on the transport of oil within ice between about 3/10th and 8/10th ice cover. It is assumed that at about 3/10th ice coverage, the oil moves as though it was in open water, and is controlled by the ice at about 8/10ths ice coverage (El-Tahan et al., 1988). However, there is no specific field calibration for this guidance, though theoretical arguments have been made (El-Tahan et al., 1988; Venkatesh et al., 1990). The presence of frazil or brash ice between larger floes would increase control of the oil as compared to open water.
2. It is uncertain if oil/dispersant mixtures trapped in ice will be readily dispersible when the ice is melted.

E. Temperature Effects on Oil Weathering

Knowns:

1. Aqueous solubility and vapor pressure decrease with decreasing temperature.
2. Lower temperatures also result in higher viscosity and reduced spreading rate when compared to more temperate waters (Khelifa, 2010).
3. During warming temperatures in the spring, oil encapsulated in first-year ice can migrate to the ice surface through brine channels. The surface oil warms due to solar radiation, promoting formation of melt pools. The bulk properties of the oil are essentially the same as when first encapsulated and will be subject to evaporation.
4. Water-soluble constituents in the oil can be released to the brine and be transported to the water underneath the ice during melting.

F. Weathering

Knowns:

1. Field trials verified findings that the weathering process is slowed down in Arctic conditions and that the dispersant window can be as long as seven days in Arctic conditions (Daling et al., 2010).
2. Evaporative weathering increases the oil's viscosity and may decrease dispersibility.
3. Water-in-oil emulsification significantly increases viscosity and may decrease dispersibility.
4. Oil can be found in between ice floes, under the ice, encapsulated in ice as pools, in ice brine channels, and on top of the ice. Each of these has specific implications for weathering.
5. Oil-ice-weather interaction is controlled by ice-specific physiochemical processes (e.g., encapsulation) not observed under ice-free conditions.

Uncertainties:

1. The variation in weathering of oil with ice concentration and type is uncertain. For example:
 - The degree of water-in-oil emulsification, as a function of ice concentration and type, is difficult to predict.
 - There are limited field data on oil weathering in ice-infested waters to improve the prediction of oil evaporation (Sørstrøm et al., 2010; Daae et al., 2011; Brandvik et al., 2013).
 - It is difficult to predict the dissolution of dispersant-treated oil in ice-infested waters (e.g., droplet size influence, role of diffusion within droplets, effects of emulsification).

G. Testing/Monitoring

Knowns:

1. Standardized measurement methods are crucial to acceptable data generation.
2. Laboratory, tank, and flume testing conditions should mimic field conditions to the best of their ability (e.g., various forms of sea ice, not just fresh-water ice blocks purchased from local sources).

3. Testing and monitoring of oil in ice-infested waters have occurred over several decades. (As reviewed in Dickins 2011, Fingas and Hollebone, 2011.)

Uncertainties:

1. It is difficult to extrapolate lab and tank test results on physical transport and chemical behavior to field conditions.
2. The lack of standardized methods for mesoscale tests (e.g., wave tanks) makes comparison of results difficult.
3. Because there is such a wide range of ice conditions in the Arctic and it is so time consuming and expensive to run mesoscale tests with oil and ice, it is uncertain which field conditions are most important to simulate. Field tests can help to resolve uncertainties, but they are difficult to conduct (e.g., permits, controls, safety).

H. OMA/OSA

(OMA (oil-mineral-aggregates) or OSA (Oil-Suspended Particulate Matter Aggregation))

Knowns:

1. There are several general reviews of this topic: (Lee, 2002; Khelifa et al., 2005a, 2008a; Sun and Zheng, 2009; Gong et al., 2014).
2. OMA/OSA production is a natural process that occurs when oil comes in contact with organic and inorganic material.
3. OMA/OSA formation depends on the concentration of and type of suspended particulate matter and the type of oil spilled (Khelifa et al., 2008a).
4. In the DWH oil spill, deep water OMA/OSA production and sedimentation near the well was affected by varying uses of drilling mud injection in the well control efforts (OSAT, 2010).
5. In the Arctic, river outputs and glacial till could be significant. OMA/OSA is known to occur in cold waters and in the presence of ice (Khelifa et al., 2005b; Lee et al., 2009).
6. The effect of adding dispersants to oil in the presence of high enough concentrations of suspended particulate material and mixing energy will increase the rate of formation of OMA/OSA (Khelifa et al., 2008a; Khelifa et al., 2008b; Zhang et al., 2010; Fu et al., 2014). Lab studies on negatively buoyant OMA/OSA showed that application of chemical dispersants enhanced their formation. (Khelifa et al., 2008a; Khelifa et al., 2008b).

- Temperatures in some of the studies ranged from 0°C to 25°C.
7. The buoyancy of OMAs/OSAs depend on the oil to mineral ratio (Stoffyn-Egli and Lee, 2002).
- Once formed OMAs/OSAs are very stable structures.
 - Individual OMAs/OSAs can sink, float, or be neutrally buoyant.
 - Lab studies on negatively buoyant OMA/OSA showed that their sinking rate is similar to those of sediment flocs.
 - Mixing energy is a major factor in controlling sedimentation of OMAs/OSAs.
 - Coagulation and flocculation can cause individual OMAs/OSAs to aggregate, causing them to sink.
8. In general, oil sedimentation in offshore areas is less likely to occur because sediment/particulate matter concentrations are typically low in that environment (Brandvik et al., 2010).
9. Field and laboratory observations have shown:
- Particle fines less than ~10 microns are likely to promote OMA/OSA formation (Khelifa et al., 2008a).
 - OMA/OSA formation has been observed at sediment concentrations as low as 50 – 100 mg/L (Khelifa et al., 2007a; Khelifa et al., 2008a).
 - Dispersed oil, because of its smaller droplet size, has a higher surface area making it more likely to aggregate with fine particles, possibly promoting sinking of this oil (Khelifa et al., 2008a).
 - For a given mixing energy, OMA/OSA formation increases with lower viscosity oils (Khelifa et al., 2002).
 - OMA/OSA formation decreases with decreasing temperature (Khelifa et al., 2002).
 - OMA/OSA buoyancy depends on the oil-sediment-dispersant mixture, oil and sediment size distribution and density, and the mixing energy. OMAs/OSAs can be negatively, neutrally or positively buoyant (Stoffyn-Egli and Lee, 2002; Khelifa et al., 2008a; Khelifa et al., 2008b; Khelifa et al., 2008c).
 - OMA/OSA formation increases with water salinity (Khelifa et al., 2005c).

Uncertainties:

1. There are uncertainties about the formation, behavior and fate of OMAs/OSAs in ice-infested water (e.g., possibilities of sinking, effects on microbial degradation, in-ice and under-ice turbulence regimes).
2. There are limited data on the effects of ice on OMA/OSA formation. (Lee et al., 2011).

I. Mathematical/Computer Modeling

Knowns:

1. Mathematical models are only as good as the assumptions upon which they are founded.
2. State-of-the-art oil in ice models use coupled ice-ocean models for ice concentration and ice flux between grid cells. This allows calculation of the movement of oil in ice-infested waters. These models continue to use individual implementations of the general algorithm regarding percentage ice cover described in the Uncertainties Section II.D.1. above.
3. Present day coupled atmosphere-ice-ocean models provide dynamically consistent fields as opposed to using disparate sources of winds, ice fields and currents (Gearon et al., 2014). If using a coupled ice-ocean model, then the winds that were used to drive the coupled ice-ocean model should be used in the oil spill model for dynamically consistent fields.
4. Models have been proposed to predict oil transport and spreading of oil under ice and in ice-infested waters (As reviewed in Reed et al., 1999; Khelifa, 2010; Drozdowski et al., 2011; NAS, 2014).
5. Recent mathematical models of deep water well blowouts and their response options have become more sophisticated, but still have limitations (Brandvik and Faksness, 2009; Faksness et al., 2011; Beegle-Krause et al., 2013; Afenyo et al., 2015)
6. Laboratory studies and field measurements were used to develop a weathering model which includes a prediction of mixing within the marginal ice zone in Arctic waters which affects the resurfacing of physically- or chemically-enhanced entrained oil droplets in the water column (e.g., Downing et al., 1997).
7. Oil spill models can use output from coupled ice-ocean models that use an Elastic Viscous Plastic (EVP) or an Elastic Brittle (EB) ice rheology.
8. Discrete element models address individual pieces of ice and can be used at a much finer scale than continuum formulated models, and include processes such as ridging, rafting and fast ice which are important in oil transport in ice-covered waters (Hopkins, 1998; Hopkins and Thorndike, 2006; Khelifa, 2010).

9. Oil spill models can use output from coupled ice ocean models that use common continuum grids, but they cannot use output from Discrete Element Models (DEM).
10. There are very few validation studies of present day models to predict transport of oil spills in ice-infested waters (e.g., Reed and Aamo, 1994; Daae et al., 2011).
11. For spreading (see uncertainties section II, D, 1. on oil in ice), most existing models were developed using limited sets of data and are not applicable to all possible ice regimes (e.g., Yapa and Belaskas, 1993; Yapa and Weerasuriya, 1997; Gjøsteen, 2004; Gjøsteen and Løset, 2004; Yapa et al., 2006; Wilkinson et al., 2007a,b; Fingas and Hollebone, 2013; Gearon et al., 2014).
12. Existing oil spill models do not include algorithms to model all of the effects of processes that control oil-ice interaction at small scales ranging from less than a meter to tens of meters (e.g., oil encapsulation in growing sea ice, oil migration in brine channels affecting pooling and ice melting, water-in-oil emulsification in frazil ice, mixing by ice-ice interaction, mixing caused by the movement of floes).
13. Overall, there is a conceptual understanding, but limited empirical data to develop improved predictive models for processes such as dispersed oil droplet sizes, dissolution, OMA/OSA formation, and water-in-oil emulsification during oil spills in ice.

Uncertainties:

1. There are no peer-reviewed numerical models for turbulence in the Marginal Ice Zone (MIZ). We have good models for wave-generated turbulence and for turbulence under pack ice. The MIZ is a transition zone, where the water column is likely transitioning between wave-dominated turbulence and under-ice turbulence regimes. This is important for predicting whether or not dispersed oil will remain subsurface.
2. Modeling of how oil moves under ice is not mature (e.g., limited knowledge of critical shear stress).
3. Modeling of migration of oil through brine channels is not mature (e.g., limited knowledge of oil flow rate).
4. There are limited measurements of interfacial tension reduction with DOR in cold conditions, limiting our ability to model droplet size distribution.
5. Most data access, visualization and analysis tools do not include polar projections (e.g., polar stereographic) and thus are not as suitable for the Arctic. Some newer tools that use polar projections are available (Arctic Collaborative Environment (ACE), next version NOAA ERMA (released May, 2017)).

6. Several oil spill models have implemented algorithms with higher concentrations of ice increasingly controlling oil movement, but there is not community consensus on how this should be done.

J. Subsea Release

Knowns:

1. For the nearfield, many aspects of subsea releases in Arctic, temperate, or tropical waters are expected to be equivalent given the same prevailing conditions at depth. Subsea conditions (temperature, salinity, pressure) may not be unique to the deeper waters of the Arctic.
2. In shallow waters, the force from the rising gas of a blowout could break the ice. (Dickins et al., 1981, Brandvik et al., 2013; Johansen et al., 2013).

Uncertainties:

1. In a subsea release, the degree to which the presence of gas bubbles (including gas-to-oil (GOR) ratio), high pressure, and hydrate formation alters the droplet size distribution is uncertain.
2. Laboratory studies have been done on the change in droplet size distribution simulating a small subsurface release (Brandvik et al., 2013; Johansen et al., 2013). There is uncertainty about the droplet size distribution in a plume of oil from a subsea release with dispersant application in the field.
3. Although this is an area of active research, there is uncertainty about droplet and dissolved constituent intrusion in the water column associated with a subsea release (e.g., where it happens, droplet size, extent of down-current advection).
4. The extent to which the heat of the oil-water plume will melt ice is uncertain.

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