APP4SEA
Recommendations for best technological and operational practices for oil spill response in the NPA region

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APP4SEA
ARCTIC PREPAREDNESS PLATFORM
FOR OIL SPILL AND OTHER ENVIRONMENTAL ACCIDENTS

Recommendations for best technological and operational practices for oil spill response in the NPA region

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November 2020

APP4SEA Report T.1.1.1

Northern Periphery and Arctic Programme 2014–2020
EUROPEAN UNION
Investing in your future
European Regional Development Fund

APP4SEA

The 21st century brought unprecedented interest in the Arctic resources, turning the region from the world's unknown periphery into the center of global attention.

Within the next 50 years, local coastal communities, their habitual environment and traditional lifestyle will undergo severe changes, starting from climatic perturbations and ending with petroleum industrial intervention and increased shipping presence.

The APP4SEA project, financed by the Northern Periphery and Arctic Programme will contribute to environmental protection of the Arctic waters and saving the habitual lifestyle of the local communities. It will improve oil spill preparedness of local authorities and public awareness about potential oil tanker accidents at sea.

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Summary

This report is one of the outcomes of the project Arctic Preparedness Platform for Oil Spill and Other Environmental Accidents (APP4SEA), funded by the EU Northern Periphery and Arctic Programme. The aim of this report is to describe the use of suitable oil spill response (OSR) methods for the Arctic Area with a primary focus on the open water environment. Coastal protection and activities in shallow water have been not included.

The three most promising tools for OSR in the Arctic are mechanical recovery, in-situ burning and the use of dispersants. The report uses and references the latest data and scientific literature in discussing these tools' pros and cons. The data published by the Arctic Council's Emergency Prevention, Preparedness and Response (EPPR) Working Group in particular has been an excellent source for determining the use of OSR tools in different environmental conditions. Remote sensing and monitoring tools are also briefly discussed.

- Share knowledge on oil behavior on sea, oil spill response methods, experience with tools and models;
- Introduce cutting edge technologies;
- Provide local authorities and general public with access to the knowledge bank.

Contents

Introduction

The Arctic is an area in the Northern hemisphere defined here as where the climate is cold and harsh, where ice often occurs and where there is a lack of light for many months of the year. The Arctic is also remote with limited infrastructure, often creating logistics problems. Because most conventional response technologies require prompt action, they have a limited potential in the Arctic. Since 1920 there have been sporadic oil and gas activities in the Arctic, and the activities will probably increase in the future with more accessible areas created by higher temperatures and the melting of ice. In addition, more activities related to tanker traffic are expected, so the increase in activities related to the handling of oil will increase the risk of oil spills. When oil is spilt at sea, the oil is weathered and the composition is changed depending on the environmental conditions and the oil type. An oil spill may cause serious damage to the pristine Arctic environment. To counteract the negative effects of an oil spill, it is important to improve the operational capability for handling oil spills in Arctic areas with proper oil spill contingency planning.

This report is part of the work carried out within the project "Arctic Preparedness Platform for Oil Spill and Other Environmental Damages" (APP4SEA), funded by the EU Northern Periphery and Arctic (NPA) Programme. The main goal of APP4SEA was to improve oil spill response (OSR) preparedness in the NPA region. This was to be achieved through the following actions:

- Pooling oil spill response competencies across the region;
- Upskilling local authorities in charge of oil spill response through transfer of best practices and tools;
- Raising awareness in coastal communities about the risks associated with increased marine traffic.

Protecting natural and cultural heritage, marine bird species and the livelihood of coastal communities was set as the overall goals of the project.

Project objectives covered a set of important items where the most vital goals were:
- to introduce local coastal authorities to state-of-the-art technologies to improve their organizational knowledge and operational performance;
- to make sure that internationally/locally discovered know-how is recognized and used;

- to form a transnational expert pool to share knowledge on oil behavior on sea, oil spill response methods, experience with tools and models;
- to provide local authorities and communities with an open access knowledge bank;
- to offer a decision-making tool that can be used to improve efficient response and thus minimise ecological impacts and
- to offer interactive educational material for educational institutions.

This report is one of the outcomes of the APP4SEA. Other themes considered the development of the interactive smart map tool with the selected data layers and tools and toolkits for OSR professionals. See: https://app4sea.interreg-npa.eu/outputs-and-results/

The report concentrates mainly on three OSR methods seen as suitable in the Arctic area: mechanical response, in-situ burning and the use of dispersants. Natural oil biodegradation – attenuation – is also discussed shortly. The description of the harsh nature and special vulnerable Arctic conditions are only mentioned briefly in this report, and the reader is encouraged to seek out detailed data from the reports of the Arctic Councils AMAP (Arctic Monitoring and Assessment Programme) Working Group (https://www.amap.no/). The latest data of the Council's Emergency Prevention, Preparedness and Response (EPPR) form a solid data bank for evaluating best OSR practices in the Arctic area.

Other important factors handled in this report are the use of remote sensing, satellites, use of UAVs (drones) and other tools suitable for detecting oil. The modelling of oil spill trajectories is also discussed and several known models and their basic features are covered.

During the execution phase, the APP4SEA project also interacted with specialists and oil-combating authorities of the Arctic area through involvement with the large-scale oil in ice trial arrangements in 2016 in Oulu, Finland. The objective of the MOSPA Agreement (Agreement on Cooperation on Marine Oil Pollution Preparedness and Response in the Arctic) is to strengthen cooperation, coordination and mutual assistance among the Parties on oil pollution preparedness and response in the Arctic in order to protect the marine environment from oil pollution. The MOSPA Agreement was signed in Kiruna on May 15th, 2013 by all eight Arctic states and entered into force in 2016.

Basic features of the Arctic

From the environmental point of view, the Arctic forms a unique and sensitive environment, where any oil spill may cause severe damage. A typical feature for the Arctic is the extreme seasonal variations which reflects the ecological sensitivity of the area. The short summer season is an important mating season for many waterfowl and other animals, and various species crowd certain Arctic areas during the short summer seasons. Cold water forms a rich environment for aquatic life where whales and other mammals feed themselves and have certain areas as their playground. Fish species are numerous, and there are important spawning areas where any oil spill may endanger fish stocks and cause long-term decline. Bottom animals and all species living close to coastlines and in shallow water are the kinds of animals to be targeted for protection.

The Arctic area is a very large area with different geological formations, islands and rocks and deep-water basins. There are numerous types of shorelines, which greatly affects oil recovery options or coastal protection operations against drifting oil slick. Oceanographic and coastal seasonal variations have significant impact on nature and the air temperature variations and winds create rapidly changing conditions where all operations could be difficult and time consuming.

Ice is a chief characteristic of Arctic conditions. Open water has the freezing phase with different ice forms all with their own behavior with spilled oil. Once the sea area is frozen, conditions are often stable, but winds may cause the formation of ice ridges and form dynamic drifting ice conditions. Operations can be carried out on the ice in winter. Finally, spring is the melting season with the ice breakup, after which it is again an open water area.

The cold climate also means that the spilled oil will usually have a slower oil alteration process with slower weathering and persistence of spilled oil. The cold air temperature in turn affects the personnel and all equipment. Cold temperatures, high wind and poor visibility are risk factors affecting safety. The high viscosity of oil, for example, may block pumps and hoses and stop recovery operations.

From the operational point of view, perhaps the main challenge for the OSR operations is the long distances and remoteness of the Arctic area. There is no infrastructure or logistical support to conduct operations. In the case of an oil spill, the resources to dealing with the oil may be very limited and the deployment time for necessary equipment and other resources may be long. It is very likely that the first responders will be forced to improvise countermeasures. There might also be environmental conditions that make any operation too risky for the responders or equipment, and even finding out the oil's location could be a challenge, especially in severe ice conditions.

Seasonal daylight variability is also a special feature in the High North. The long dark season during the winter affects safety issues and makes it difficult to find the oil to be collected. There are also a lot of days when fog will reduce the visibility and produce extra difficulties for responders. Poor visibility or icing phenomena may endanger aircraft operations and significantly affect marine operations.

Seasonal variation also affects clean-up operations in shallow water and close to the shorelines. There are a lot of different shore types, some open and some covered by ice, where certain recovery tools will not be favourable. Seasonal variation will greatly affect the conditions met at certain shorelines. There are also land areas where permafrost is an issue and needs to be considered, especially if some support stations or logistic centers are established in summer.

The safety of the responders and other staff is central to Arctic OSR operations. Guidelines and occupational heathy concerns have been listed for example in EPPR (2017a) and in many guidelines made for personnel working within the oil and gas industry In the Arctic area (https://www.seapro.org/toolbox.html).

Conditions must be safe if a response is to be attempted. Monitors must be used to safeguard the health and safety of response personnel. An explosive, toxic atmosphere can develop in spills of high-sulfur crude oils and volatile oils (EPPR 2017a). It is likely, however, that in the case of a remote oil spill in the Arctic, the significant parts of the volatile have evaporated before any significant countermeasures or equipment are transported to the area under operation. This occupational health concern is anyhow an important issue for first responders and for crew surveying the area to build up the situational awareness view for the command center.

It is primarily the cold weather and extreme weather conditions which may be concerns for responders in the Arctic. Seasonal daylight variations may also bring extra challenges especially in winter when the amount of daylight is minimal. The wind-chill effect is also a factor to consider with regard to good clothing and support stations. It is likely that the extreme environmental conditions may considerably reduce operational efficiency: icing of the equipment, failures due to the extreme cold and problems of water and food supplies are typical failures that accompany typical challenges with electric supplies and batteries in the cold.

For coastal protection work, cleaning efforts and working on the ice, another concern is bears. Sea mammals and their feeding and reproduction sites are special areas to be taken into account, too.

Fate of oil in ice-infested waters

The fate of oil in ice depends significantly on the ice concentration and on the processes and possible encapsulation rate of oil around ice. Various ice formations from stable columnar ice to pack ice formation will significantly affect the selection of the optimal countermeasure. Usually the mid-winter conditions form stable conditions for the countermeasures, and some recovery efforts may be possible based on the ice field. The freezing season and the ice break up conditions with moving ice makes even the surveillance of oil difficult and can block all effective countermeasures. Sometimes the only effective way to deal with oil is oil detection in the ice and then to wait for spring for real countermeasures. Oil can also be trapped under ice, partly inside the ice blocks, and can penetrate through the brine channels of the ice up to the ice surface. Thus, oil-ice interaction can be very complex, as illustrated in Figure 1.

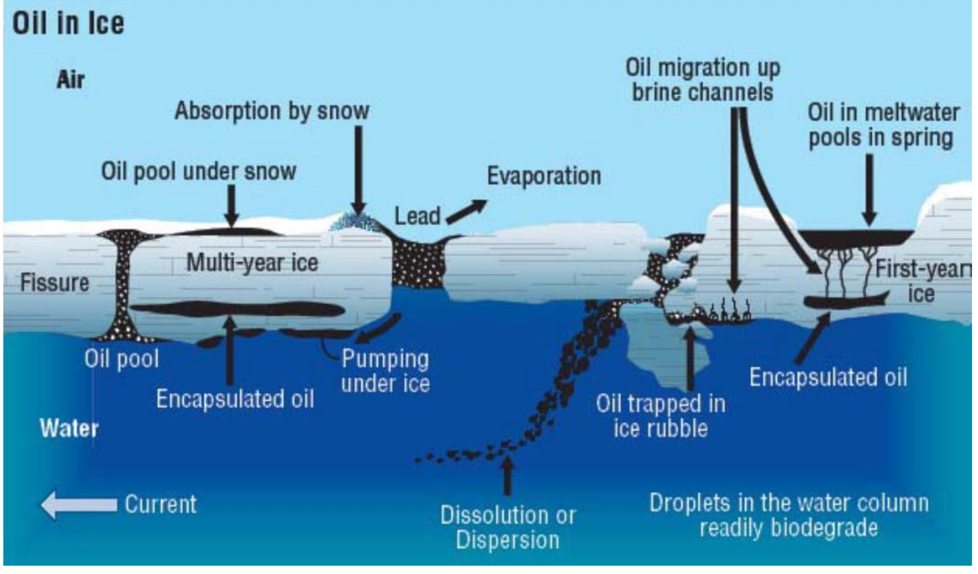

Figure 1. Illustration of oil and ice processes (adapted from Bobra, A.M. and Fingas, M. 1986) (Source: ExxonMobil).

Evaporation is the major weathering process that occurs for spills on ice or in pack ice. Oil evaporation rates on ice, in leads and among pack ice are generally slower than for spills on open water. This is because the temperatures are lower in ice situations, and the oil slicks are much thicker. The presence of a snow cover also greatly reduces the evaporation rate of oil.

Ultimately, spills on or in ice will reach the same final degree of evaporation as spills on water (Buist I. A. et al. 2013).

Oil characteristics

There are a lot of different oil types available and used in the marine industry for fuel for ships. Typical oils are bunker oils, which have a variety of viscosities and thus different behavior in the water if spilled out at sea. Of growing importance is marine diesels, with the low sulphur content. Most important, however, is still the transportation of crude oil, which usually poses the most significant risk for the environment due to the large transport units of the oil. Bunker oil spills usually have the size of a few hundred tons of oil, but the ruptured tank releases of an oil tanker may be in the order of several thousand tons.

The chemical composition of crude oils from different producing regions, and even from within a particular formation, can vary tremendously. Crude oils contain thousands of different chemical compounds. Hydrocarbons are the most abundant compounds in crude oils, accounting for up to 98% of the total composition. While carbon (80-87% by weight) and hydrogen (10-15%) are the main elements in petroleum, sulfur (0-10%), nitrogen (0-1%), and oxygen (0-5%) are important minor constituents. Crude oils also contain widely varying concentrations of trace metals (Buist, I.A. et. al 2013).

The essential feature of crude oil with regard to the ISB is the high amount of volatiles, i.e. light hydrocarbons. These hydrocarbons, C1 – C12, have the tendency to evaporate quickly and most of the crude oils usually will lose a significant amount of their mass by evaporation once spilled into the sea. Technically these lighter hydrocarbons are alkane alkanes, and the whole oil mixture contains a lot of other hydrocarbons such as cycloalkanes, aromatics, asphaltenes and more. More detailed descriptions of crude oils and the properties of various types of crude oil can be found from the literature.

Most crude oils are insoluble in water and will spread via wind and currents. They also usually float on water, except for some more rare types w a higher amount of asphaltenes and other heavy hydrocarbon fractions. Crude oils also form emulsions, which depends significantly on the wave energy and environmental conditions. This tendency to form emulsions with evaporation, dissolution and more is generally called oil alteration. Generally fresh oil is easier to ignite due to the high amount of volatiles. The more altered the oil is, the more difficult it is to use ISB as a countermeasure. The time period between the initial accident point and the point where the oil is too altered to ignite is called the window of opportunity.

The tendency of oil to form emulsions, for example. a mousse type of mixture (water-in-oil), requires wave energy and is thus rather unlikely in the case of oil in ice interaction. Wind waves are effectively reduced due to the ice floes or pack ice, thus the oil alteration process is more dependent on evaporation only. Ice also restricts the spread of oil, thus the oil can be found in higher thicknesses, reducing evaporation compared to free spreading in open water conditions. Lower temperatures also decrease the evaporation rate.

Spills of some crude oils (generally those with higher concentrations of asphaltenes) will start to form an emulsion within a few minutes of being spilled and will form a highly viscous and stable emulsion within hours. Other crude oils must lose some of their lighter components through evaporation before the concentrations of their asphaltenes and resins are raised to the levels required to stabilise emulsions. Most distilled petroleum products do not easily emulsify at all.

There are a few test results available on the degree of emulsification with ice conditions. Most of them were conducted as tank tests or in wave flumes. If no wave energy was present and the temperature was cold, practically no emulsification was noted. Adding wave energy and temperature led to significant emulsification. Payne, J. R. et al. (1987), for example, reports an increase of water content up to 50% in a six-day test for one type of crude oil in open water conditions. The same oil for first year ice in the break up dynamic situation resulted in the water content increasing rapidly by 64%, staying stable six days in the test conditions! For multi-year ice, the emulsification noted was slower, and during the six-day test period 28% of the water content was achieved.

Similar results were achieved in Finland after the Antonio Gramsci oil accident in 1987, where practically no emulsification took place during the first 20 days in stable winter conditions. Then spring came and swell movements started to emit energy to the system resulting in close to 28% water content during a 34-day of period. The observations were also supported by tank and flume tests, which showed up to 75% emulsion rates due to the waves in beach conditions already in short periods (Hirvi, J. P. et al 1992). The oil type was the Soviet Blend, known nowadays as the Russian Blend.

Emulsification as a process may be the unexpected factor which can endanger the response options: even if the evaporation causes a significant loss of oil during the first days, the rapid emulsification may increase the total amount of the mass to be recovered rapidly. As a consequence, there might be significantly larger mass of oil to be recovered than was expected based on the data related to the initial amount of spilled oil. Modern oil spill models use the empirical data of various oils to estimate the fate of oil and give estimates for the oil spreading as sk. oil trajectories.

Recently some Table Top evaluations were made in the Gulf of Finland for ten different oil spill scenarios (Laine, V. et al. 2018). One of the scenarios consisted of 20,000 tons of light crude oil release, and several model tools were used to predict the fate of the oil. The scope of this study was to test the local preparedness of the authorities to alert and mobilize resources in all of these scenarios. Using sophisticated tools like ALOHA, SpillMod (Ivchenko, A. 2011), and ADIOS (ARCOPOL 2013) it was noted that depending on the model and the wave and current data used in the analyses, the initial 20,000 tons of oil spill will enlarge significantly in spite of the high tendency of evaporation which already after the first day (open water conditions) will reduce the oil on the water by 6,000 tons. Wave energy rapidly increased the amount of oil on the water resulting in volumes in the range of 70,000–120,000 tons depending on the model used (Rytkönen, J. et al 2018). Here only three days of drifting were modelled in a variety of environmental conditions. It is likely also that in heavy wave conditions the light crude will gradually loose volatiles, absorb more water in and sink under the water surface, thus escaping all OSR actions (Figure 2).

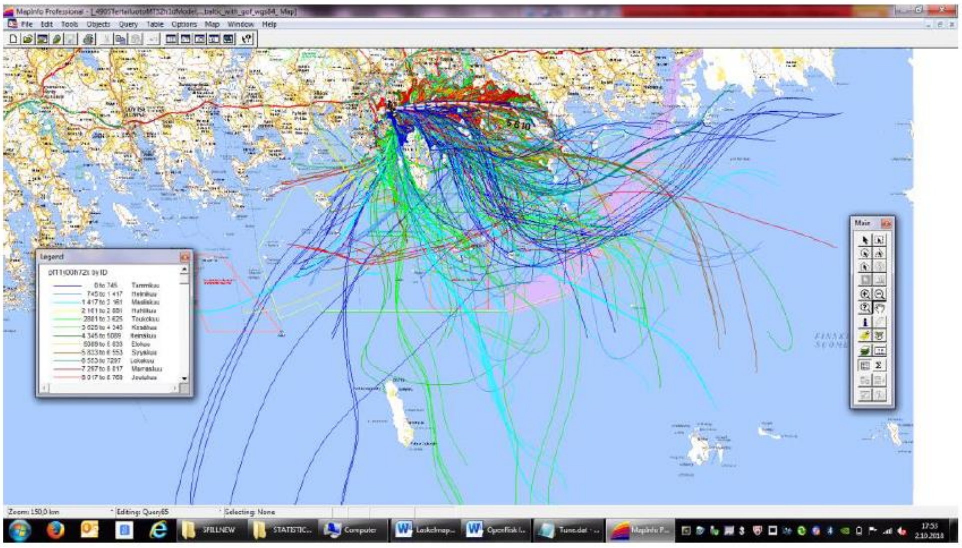

Figure 2. An example of the modelled oil spill trajectory in the Gulf of Finland using SpillMod model. All curves represent the possible oil spill trajectories based on several years wave and current statistical data. Different colors represent the different months of the year (Rytkönen J et al 2018).

Crude oil is a raw material for refined oil products; these are products in general use for humans in various sectors of the economy. Marine fuel oils usually consist of Heavy Fuel Oils (HFO), Intermediate Fuel Oils (IFO) and Marine Diesel Oils (MDO). Some of the HFO types are denser than water and will sink to the bottom if poured into the sea. Some of the IFO types, once spilled into the sea, may alter and sink under the water surface but still continue drifting in the water column and again rise to the surface or beach line depending on the density differences of oil and water in certain environmental conditions. These refined oil types form the largest parts of the ship's own fuel oil and they are also transported by the product tankers, thus forming a risk for a significant oil spill if any of the cargo tanks were to be damaged. There are also other types of refined oil products transported by ships such as kerosines, jet fuels, by-products of crude oil and some new oil types like tar oil, pine oil, bio fuels and gasoline.

Oil on ice

In icy conditions, oil may also exist on the ice. If oil is spilled into the sea and has time to spread, it may end up on the ice if the weather conditions suddenly shift toward frozen conditions. Oil can also be trapped on the ice floes in dynamic pack ice conditions. Some of the oil trapped under ice floes may also seep through the ice especially in the spring, forming melting pools where oil will float on the water. Oil spilled on ice spreads much more slowly than on water and covers a smaller final area, thus slicks on ice tend to be much thicker: The roughness of ice is the key factor for the oil spreading – the more roughness, the less the oil will spread. Smooth first year ice has roughness typically between 3 and 30 mm. Ice ridges, pressurized conditions and ice ridges may increase the roughness and even stop the oil spreading on the ice. Snow on the ice also acts as an absorbent, thus reducing the oil spreading effectively.

Oil under ice

The maximum average oil layer thickness under sea ice can range from several centimeters for spills in early winter to tens of centimeters in April for a spill under ice at the end of the ice growth cycle. The maximum oil thickness in the deepest pools could vary from 10 to over 30 cm, respectively. Actual values will depend on the local ice conditions at the time of the spill (Buist I. A. et al. 2013).

Even large spills (thousands of cubic meters) of crude oil underneath solid (or fast) ice will usually be contained within short distances from the spill source, depending on under-ice currents and ice roughness. Natural variations in first-year ice thickness provide huge natural "reservoirs" to effectively contain oil spilled underneath the ice within a relatively small area.

Table 1. Comparison of crude oil spreading (volume 10,000 bbl) in open water, under solid ice and on smooth ice (Buist I . et al. 2013).

	Open Water*	Under Solid Ice		On Smooth Ice	
		December	April	Ice	Snow
Final avg. thickness (mm)	0.016	10	100.0	3	40
Final area (ha)	10,000.0	15	1.5	50	4

* Assumes a fluid oil spreading on quiescent water

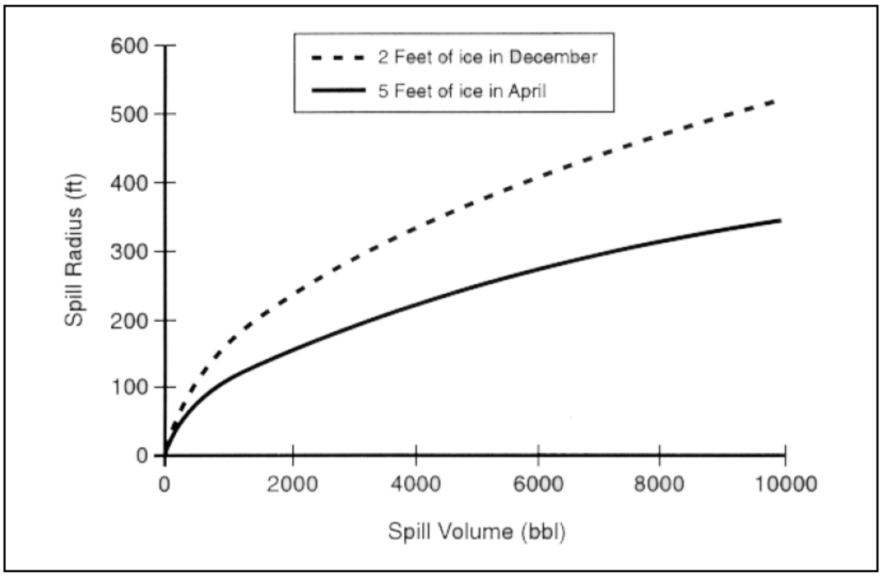

Figure 3. Illustration of oil spreading under and fast smooth ice (Dickins, D. F. & Glover, N. 1996).

There are a lot of formulas available concerning oil spreading in open water conditions and empirical data on how these formulas can also be used for ice-infested waters. Figure 4 below shows one of those diagrams developed for oil spills in open water conditions. The estimated spill radius rate can further be estimated for ice conditions using empirical coefficient, smaller than one, found from the literature: The more severe the ice conditions and the higher ratio for the ice/open water relationship, the less spreading will exists. Studies show that when the pack ice ratio is higher than 60-70%, the ice blocks the spreading and oil and the ice moves together due to currents and winds. For lower ice concentrations, i.e. from 30 to 60%, the oil and the ice will move at different rates under the influence of wind.

The generally accepted factor for the influence on wind to the oil is in the order of 3.5%, while ice floes move downwind at 2-3 % of the wind speed. Due to the Coriolis force, the oil and ice have the tendency in Arctic conditions to turn 10º to 20º to the right of the wind.

There are also studies where the initial threshold conditions for oil movement under ice have been investigated. Depending on the oil type a spectrum of threshold values have been found. As a rule of thumb, however, the oil starts to move if the velocity under the ice exceed 15-20 cm/s. Even though there are much faster sea currents in the Arctic area, most of the current velocities in Arctic near shore areas generally are not sufficient to move oil under ice. Exceptions may be in narrow straits and fjord-type areas. Thus, from the response engineering point of view, a good estimation is that the oil will move with the dense pack ice and, if under ice, the first assumption is that the oil will remain under the ice if the ice field starts to move.

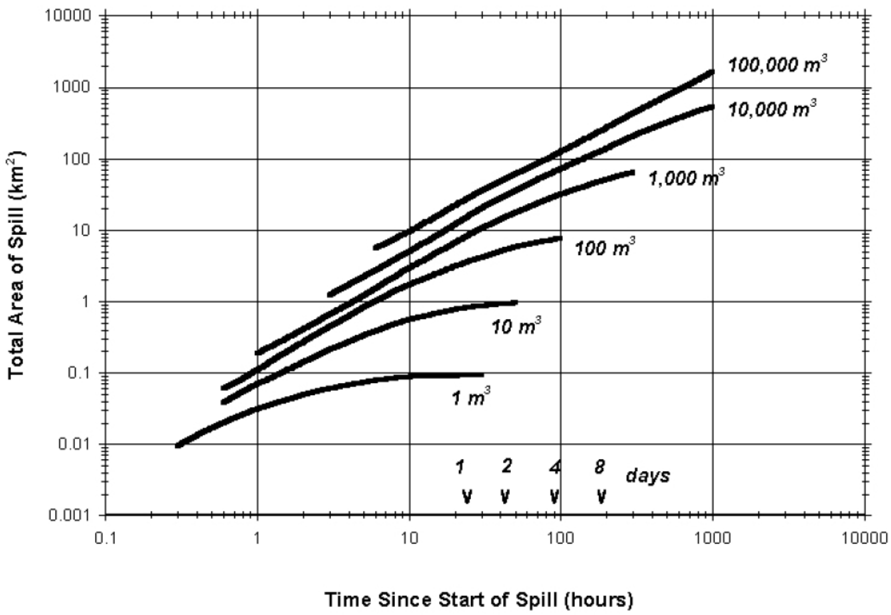

Figure 4. Predicted spreading of oil spill on open water (SL Ross Environmental Research).

With regard to winter-time shipping and the normal tendency to sail along the secured fairway with the assistance of ice breakers, possible damage includes:

- grounding of the ship, if the whole ice field is moving and the ship is jammed into the ice. The ice may transport the ship to the shoal resulting in grounding;
- contact between the merchant ship and the ice breaker, a common failure especially when assisting ships in convoys: ships in the line after the ice breaker, and if some of the ships get stuck and stopped, the ship behind will collide;

- collision of the ship in the ice channel: narrow ice channel will lead to the collision, and ships may hit sideways or partly bow-to-bow;
- icing: the ship is gradually covered by spray ice and will lose stability and capsize;
- ice pressure: the ship is jammed to the ice. Moving ice will break the hull and cause massive damage and even sinking of the ship.

Mechanical Recovery

Mechanical recovery has been understood as a method to contain and collect oil from the water's surface for disposal. This approach requires storage of recovered fluids until they can be properly managed. The following operational sub-systems for this approach were in this report:

- mechanical recovery with two vessels with a boom;
- mechanical recovery with a single vessel with an outrigger (sweeping arms and inbuilt oil lifting system to the recovery tank);
- three vessels with Vessel of Opportunity (VOO) with boom and
- single vessel in ice.

VOO may be a local commercial or recreational vessel identified to assist in responding to large oil spills. Employing VOO and boat crews to assist in emergency response can help the local communities recover during a period of disruption. The advantage here is to use local crew and operators which have the best knowledge of the local circumstances and environmental conditions. The system is used in Alaska (for example https://www.seapro.org/), and similar preparedness in using local fishermen in emergency operations exists in Norway.

The three vessels system is also used in the Baltic Sea, where two smaller boats or tugboats may tow a U-shaped boom with an opening in the top of the U form. The third vessel, having the inbuilt recovery system with sweeping arms, has her position just in the opening and collects all the oil forced to spill out when towing the boom with a velocity of 1-2 knots.

Unlike other remediation technologies, skimmers can be used to recover oils across a wide range of viscosities. Skimmers exist that can effectively recover oil across all of the ASTM viscosity categories (I through V).

Many “rules of thumb” about the selection of oil spill skimmers are based on performance tests conducted in the 1970s through the 1990s. Because skimming technology has not changed appreciably since that time, the standing rules of thumb are probably applicable to commercially available skimmers today. Emerging skimmer technologies are being developed in academic settings to improve the oil recovery capabilities of oleophilic skimmers. Ongoing research includes the development of grooved patterns on drum skimmers, novel oleophilic surface coatings, and the application of nanotechnology to novel oleophilic surfaces.

Work by the Norwegian research organization SINTEF led to the development of highly effective skimmers for oil recovery in ice conditions (Federici & Mintz 2014).

Figure 5. Finnish oil recovery ship HALLI with the inbuilt oil recovery system, inbuilt storage chamber for recovered oil and sweeping arms on both side of the hull (Photo: SYKE).

The effectiveness of mechanical containment and recovery at sea largely depends on the sea and wind conditions at the spill site. Containment and recovery are likely not possible, and are probably unsafe to attempt, in wave heights exceeding 2 m or in winds of more than 10 m/s. Many recovery ships have their practical wave height limitation at 0.5 m, but there are ships with inbuilt wave dampening systems which may still recover oil with a wave height of 2.1 m. Practically this means the sea state where the maximum wave height can be close to 4 - 4.5 m.

Containment booms and skimmers should be deployed downdrift from, and as near as possible to, the release point to minimize spreading. Containment of submerged oil might be possible near or at the source using an oil trawl boom (EPPR 2017a). Booms' limitations depend on the sea state and wind speed. There are also a lot of various types of booms to be used. Heavier booms with the higher skirt are used in open sea conditions, while lighter booms can be used in sheltered locations. Booms are typically used anchored to the site for shoreline protection (stopping spreading or re-diverting the slick) or trapping the oil for skimming purposes. Booms can also be used when towed by two vessels, where the U-form boom will trap the oil for recovery purposes. In open water, booms can be used in U, V or J configurations. Interception of free-floating, thin slicks is not as effective as containment and removal of oil at source.

Skimmers are typically used to recover oil from the boomed area, or an opening is left to the top of the U-form boom from where the recovery ship will take the oil into her storage tanks.

Storage options include barges, towable tanks, tankers and/or other means that are appropriate for the type and volume of oil being recovered. For Arctic incidents in remote locations, the lack of storage and disposal options can quickly become a serious impediment to the success of continuous mechanical oil recovery (EPPR 2017a).

Short period breaking waves decrease significantly the effectiveness of the countermeasure – larger parts of the oil will be mixed to the upper water column, thus reducing the mechanical containment and recovery, ISB or the use of dispersants.

At present, the only viable countermeasure to deal with oil layers trapped beneath or within the ice involves waiting for the oil to surface in spring melt. Monitoring the spill in the interim may be the only practical option (EPPR 2017a). In river conditions, however, open ice slots can be sawn through the ice, and oil moving with the current will carry oil into these slots. In Finland, special saw machines have been constructed to saw slots to the ice. The initial purpose of sawing slots is to more easily allow the ice break up in the rivers in the spring-time and to avoid ice jams causing local flooding problems. Ice slots with containment barriers or fabrics can be used if the river flow velocity exceeds the initial threshold velocity of oil under ice.

Ship propulsion, especially with the azimuth type of propulsion system can also be used to sweep oil under ice flows to the surface further to be recovered by mechanical means or dispersed by ship’s spraying system.

Ice creates many problems for mechanical recovery, and depending on the ice form encountered, the main problems can be summarized as:

- limited access to oil: ice slush or small ice cubicles may block the system’s input channels or belts;
- reduced oil flow to the skimmer: the mixture of oil and ice bristles will decrease the total oil pick up ratio. The water/ice content of the recovery tank will be significant;

- icing/freezing/jamming of equipment: moving parts of the system will be stopped due to the freezing. Pumps and hoses will be blocked by the high viscosity oil. Ice and possible debris will boost the formation of blockages;
- separation of oil from ice is difficult: excess hot water or steam is required, causing the water (oil pick up ratio will be higher);
- oiling/cleaning of ice: part of the oil is touched by ice blocks and will remain in the sea. Some modern ice brush skimmers can be used to loosen and recover oil from the surfaces of the ice blocks;
- deflection of oil together with ice: ice and slush will form a kind of barrier between the skimmer and oil to be recovered;
- strength and durability considerations: special high durable steels, and materials tested in cold environment need to be used here;
- detection, monitoring of slick: detection of oil among ice or under ice is difficult.

Figure 6. A brush type bucket skimmer designed for oil recovery among ice. (Photo: SYKE)

Figure 7. Robust large-scale ice brushes onboard oil recovery vessel LOUHI during the Oulu Ice Trial in 2016. These ice brushes have been designed for oil recovery in ice. (photo: SYKE)

In-Situ Burning

Oil recovery methods adapted for the Arctic should be simple, low tech, and at the same time also efficient. One of the methods best suited for the Arctic is in-situ burning (ISB), which can be very efficient (> 90 %), with limited logistic demands (Buist 1999, Buist et al 2013). Fresh oil slicks can be initiated very quickly by igniting the oil with devices as simple as an oil-soaked sorbent pad.

In ice conditions, the ice itself often provides natural containment of spilled oil, keeping it thick and slowing weathering processes for extended periods of time, thus allowing oil burning operations to proceed with only helicopters and igniters (Buist et al. 2013). ISB is recognized as a viable alternative for cleaning up oil spills on land and water. It can rapidly reduce the volume of spilled oil and eliminate the need to collect, store, transport, and dispose of recovered oil, and can also shorten the response time to a spill, thus reducing the chances that the spill will spread on the water surface or further into land. However, some precautionary measures are necessary, since there are also a few drawbacks with ISB, such as the smoke production and risk of secondary fires (Fritt-Rasmussen 2010).

ISB is one of the countermeasures available for responding to oil spills in marine but also in ice and snow conditions. Actually, ISB in oil spill response has been utilized since the 1960s and it is the oldest response method. ISB involves the controlled burning of oil that has spilled from a vessel or a facility, at the location of the spill. The main purpose is to reduce the amount of oil beaching and the burning rate of thick (1 cm or more), large (3 m diameter or more) slicks of relatively fresh oil has been measured to be in the range of 3 mm/minute (Buist et al. 2013). When conducted properly, ISB significantly reduces the amount of oil on the water and minimizes the adverse effect of the oil on the environment. Recently, many very extended and detailed studies have been published about ISB in different ice conditions and the applicability of this method in Arctic conditions (e.g. Buist et al. 2013, Federici & Mintz 2014, Fritt-Rasmussen and Petrich 2017, Fingas 2018).

The three factors with the highest influence on the efficiency of ISB are: (1) slick thickness, (2) oil properties (flash point, volatility, API Gravity) and (3) emulsification of oil. Oil slick thickness is the most important factor concerning the success of ISB. Slick thickness should be at least 2–3 mm in order to support burning. Of course, a slick thickness can be maintained by using fire-resistant booms. The oil slick should have a thickness of at least 1 mm to allow the oil to ignite properly and to achieve a reasonable result. If the slick thickness is less than 1 mm, ISB is no longer profitable (Nordvik et al 2003, Fingas 2011).

Slicks, once ignited, will burn until the thickness of the underlying oil reaches about 1 mm. The oil removal efficiency is thus proportional to the thickness of the slick at ignition (Buist et al. 2013). The oil slick must be thick enough to insulate itself from the underlying water: > 2 to 3 mm for weathered crude oils and lighter fuel oils; > 5 mm for light (30% water) emulsions; and > 10 mm for residual fuel oils. Once ignition takes place, sustained burning of the slick requires that sufficient heat be radiated to the slick to maintain the slick at temperatures above the oil's fire point (Buist et al. 2013). Very dense or highly emulsified oil requires a thicker slick (3-10 mm) for the burning (Nordvik et al. 2003).

It is the vapours that burns, not oil, so when igniting a liquid fuel it must be converted to the gaseous form and mixed with air to allow for ignition (Buist 2003). A fuel/oil with a high vapour pressure usually indicates a liquid that easily forms ignitable vapours. The minimum temperature where the vapour/air mixture can ignite is called the flashpoint. The flashpoint increases with increased weathering of the oil, but of course the burning is self-sustained giving a rise in temperature of the fuel to the fire point, which is the lowest liquid temperature where the evaporation rate is sufficient to create flammable vapour-air mixtures (Nordvik et al. 2003).

After the formation of the emulsion, it is difficult to ignite and burn the oil, but by increasing the thickness of the oil, this is possible even if the oil is already well emulsified. If the emulsion has not formed yet, an ignition is possible for any oil with an oil thickness of 2-3 mm, regardless of other properties of the oil (Federici & Mintz 2014). Experimental burns with certain oils emulsified with 50% water or more have shown that effective ISB may be feasible. On the other hand, other oils with as little as 10-20% water have been extremely difficult to ignite with conventional ignition systems. It should be assumed that any oil that has become emulsified to levels of 25% water or more will be difficult to ignite; any oil emulsified to levels in excess of 50% water should be assumed to be unignitable (Buist et al. 2013). Most oil is suitable for ISB but one important exception is very light, refined oil products like gasoline, butane and propane, for which burning poses a safety risk. Oils or chemicals with a flammability point under 37.8°C and vapor pressure under 40 psi should be excluded from ISB (Nordvik et al. 2003). Oils with API gravity of at least 20° will probably burn with high efficiency. In order to burn spilled oil, three elements must be present: fuel, oxygen and a source of ignition. The oil must be heated to a temperature at which sufficient hydrocarbons are vaporized to support combustion in the air above the slick (Fingas 2011).

When less than 30% ice is present, the oil will spread out and the thickness of the slick will reach the minimum required thickness rapidly. Then use of fire-resistant booms will prevent the oil slick from spreading and secure a sufficient oil slick thickness. Using fire-resistant booms to gather the oil for ISB requires less equipment than does collecting the oil for skimmer use (Fingas et al. 1999). The material used varies a lot, and some are manufactured from steel, fire-resistant fabrics and others employing active water cooling (Buist 2000). Also so-called chemical herders can be used to improve the efficiency of ISB. These herder chemicals can be used to gather oil to thicker slicks and it has been shown that they increase the efficiency of ISB in large scale experiments made in tanks as well as in field experiments (Buist et al. 2011a; Buist et al. 2011b). The herding agents work by reducing the surface tension of the surrounding water significantly. When this monolayer of surfactants reaches the thin oil slick, the balance between interfacial forces acting on the slick is changed and the oil is contracted into thicker layers (Buist et al., 2010). Unlike in wind herding, herding agents do not need a boundary to work against and can work well in open waters (Buist et al., 2010).

There is a limited window of opportunity for using ISB and this window is defined by the time it takes the oil slick to emulsify. While most oils are suitable for removal by ISB, there is a limited timeframe after the initial spill in which ISB will be effective. As oil weathers over time, it becomes emulsified with water, and suffers evaporative losses of its volatile compounds. Both emulsification and evaporative loss increase with time and decrease the efficiency of ISB.

The window of opportunity for ISB is a function of oil weathering. ISB was estimated to be a viable response option for up to 72 hours after a spill, depending on the type of oil (heavy oils will have a shorter window of opportunity). For light and medium crude oils, ISB could be performed for 40–60 hours after a spill. For heavy crude oil, however, ISB became almost completely ineffective after just 1–2 hours because of the profound effect of oil weathering on burning efficiency (Nordvik 1995).

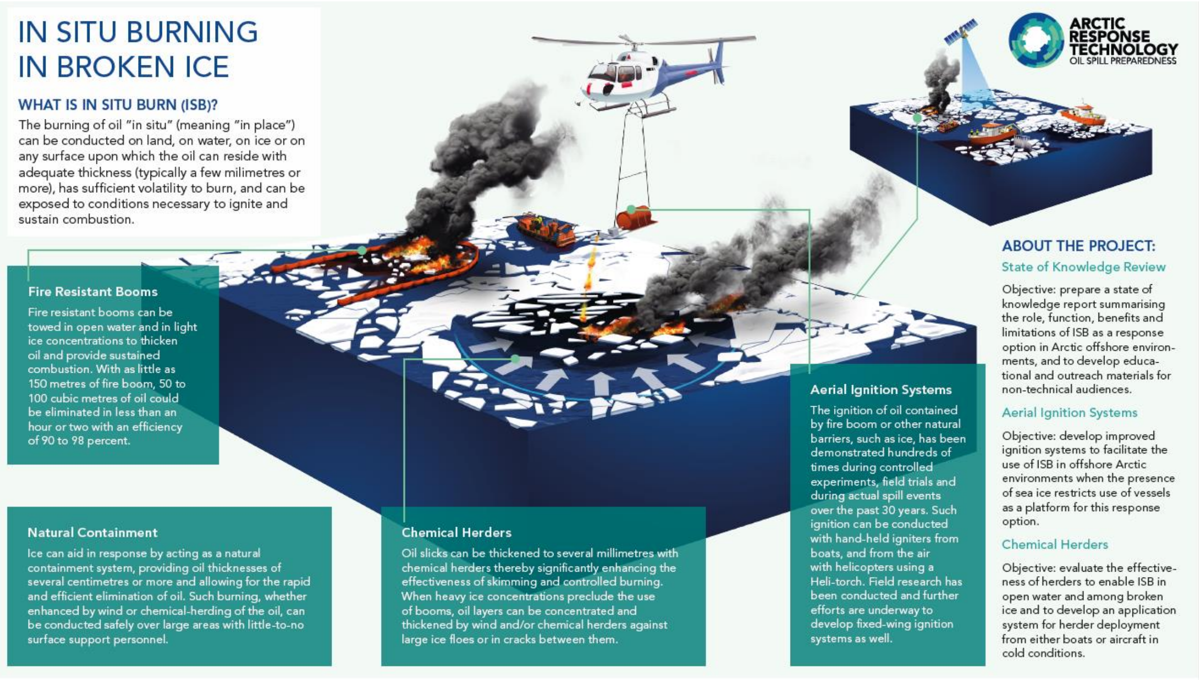

Figure 8. Principle of the in-situ burning in broken ice (Joint Industry Project, www.arcticresponsetechnology.).

In ice conditions, the window of opportunity is greatly extended compared with open water conditions. Ice cover was found to reduce oil weathering, allowing a longer time window for ISB (Fritt-Rasmussen et al. 2012; Fritt-Rasmussen and Brandvik 2011). Of course, conditions are much more complicated in the case of oil spills in ice and oil distribution in different ice conditions may vary a lot (reviewed in e.g. Fritt-Rasmussen 2010; Buist et al. 2013; Fritt-Rasmussen and Petrich 2017).

Usually ISB has been tested in static pack ice conditions while only a few tests have been performed in dynamic ice conditions, indicating that ISB can be sensitive to movements, ice coverage, oil thickness and presence or absence of frazil ice. Burning of oil in broken ice during break-up will be easier than during freeze-up. Oil spilled in dense pack ice will drift with the ice. It has also been shown that the interface between ice and oil is more efficient at transferring heat from the oil to the underlying ice than water.

Figure 9. Burning of oil in a melt pool (Source: D Dickins; in Buist I.A et al. 2013).

Data on ISB efficiency in moving ice is scarce, while data and lessons learned in more stable ice conditions can be found. The older tests have showed some of the following lessons learned (Rasmussen, J.F. & Norut, C.P. 2017):

- **burning oil in solid ice –** tests showed a reduction rate between 1-3 mm/min depending on the test case. Burning efficiencies varied, but reached in some tests 85-96%! Tests conducted for emulsified crude oils, however, showed smaller reduction rates.
- **burning oil in broken ice/pack ice –** there is a variety of test results available made both in laboratory and in field environments. Results show a success rate between 30-90% depending on the test arrangements. The minimum slick thickness obtained for the ISB has been 2.5 mm on cold water. High emulsified oils have also been noted to inhibit the burning, and lower temperatures also to reduce the burning rate. Some of the newer test results, however, indicated also that emulsified oils can be ignited and burned if the correct igniter is used. Brash ice was shown to reduce the burning, and more wind resulted often in a higher regression rate. The field ISB tests in broken ice have generally showed that the ice coverage is of high importance for burning oil in broken ice. With 60-70% to 90% ice cover, the ice will act as natural containment. Up to 30% of the oil will spread as in open water. In between those ranges, the conditions are difficult as the oil can spread to an extent that will make additional containment necessary but not possible.
- **burning oil in snow –** oil can be burned in snow with great success. Tests have shown even more than 90% reduction can be achieved if the contaminated place can be handled

properly. It has also been noted that very low concentrations of oil can be ignited with some additional fuel.

- **burning oil in ice cavities –** There are a number of recent studies looking at the ISB of oil in ice cavities reported in Fritt-Rasmussen, J. & Norut, C.P. (2017). Tests have been carried out in small-scale laboratory experiments and in large-scale field experiments. Generally, if the oil is trapped in small cavities in the ice, the surrounding ice decreases the burning by the ice walls that act as a significant heat sink. Particularly for small cavities, these losses are considerable lateral heat loss. Small-scale studies emphasized that the cavities must have a diameter larger than 4.5 cm; otherwise the heat losses to the surroundings are too high to sustain continuous burning. In the large-scale experiments, significant reduction of oil was noted, and in some tests the reduction rate was close to 85%, corresponding close to 2.5 mm/s of oil regression rate.

It was noted that the heat flux from the flames melts the ice and increases the cavity diameter, hence the larger burning surface of the oil leads to increased mass loss rate. The impact of the wall is, however, found to decrease with an increasing diameter of the hole. A strong coupling between mass loss rate and geometrical changes were thus found (Farahani, H. F. et al. 2015).

It has been demonstrated that higher slick thicknesses are needed to burn oil on ice compared to burning oil on water (reviewed in Fritt-Rasmussen 2010; Buist et al. 2013; Fritt-Rasmussen and Petrich 2017). Both the burning rate and the burning efficiency are also lower for burning oil in ice than on water (Buist and Dickins, 2003). On the other hand, for spills under ice during freeze-up or in winter, the oil can remain burnable for many months until it appears on the ice surface the following spring. Spills in close pack ice will be ignitable for days longer than the equivalent spill in open water. Spills in loose drift ice will likely have a window of opportunity for burning similar to open water conditions (Buist et al. 2013). Burning oil in ice is a standard method for dealing with oil in ice. The natural containment of ice can serve to thicken oil sufficiently for ignition and burning to take place.

ISB was one of the main subjects studied in the Horizon 2020 project GRACE (https://www.grace-oil-project.eu/en-US). This project compiled the lessons learned of past studies and also demonstrated the use of the ISB in the field tests arranged in Greenland.

ISB of oil has been shown to be of high efficiency in controlled field experiments with high ice concentration. Initial field studies from the 1970s and 1980s proved that ignition of crude oil released during melting from land fast ice can be highly effective. These tests also showed that the effective burning and especially the ignition of the oil has a relatively short window of opportunity for the successful reduction of the oil. Most older tests were also conducted as small-scale laboratory tests or in relatively small meso-scale field tests. One of the past large-scale ISB operations were made during the Deepwater Horizon accident in the Gulf of Mexico, where large amounts of oil were burned in more than 400 burns (Mabile, N. 2012).

Table 2. Summary of experiments and operational experience with ISB of different types in various sea conditions (Buist et al. 2013).

ISB TOPIC	Degree of Ice Coverage and Ice Type								
	Ice Free and Open Water *<1/10*	Very Open Drift Ice *1/10 to 3/10*	Open Drift Ice *4/10 to 6/10*	Close Pack Ice *7/10 to 8/10*	Very Close Pack Ice *9/10 to <10/10*	Fast Ice	Leads	Brash and Frazil/Slush Ice	Multi-year Ice
Spill behaviour for ISB	FC, WC, EC, DF, RF	FC, WC, DF	FC	FC, WC, EC, DF, RF	FC, WC, EC, DF, RF	FC, WC, EC, DF	FC	FC, WC, EC, DF	One semi-successful field expt. with FC
Ignition	FC, WC, EC, DF, RF	FC		FC, WC, DF, RF	FC	FC, WC, EC, DF	FC, WC, EC	FC, WC, EC	
Fire boom	FC, WC, EC, DF	FC		□	□	□		□	□
Herders	FC, WC	FC,WC				FC	FC	FC	
Residue	FC, WC, EC, DF	FC			FC	FC, WC, EC, DF	FC, WC	FC, WC, EC	

NA = Not Applicable
FC = fresh crude
WC = evaporated crude
EC = emulsified crude
DF = distillate fuel oil
RF = residual fuel oil

A. USCG experiments near Barrow, AK 1971-1972
B. Experiments by McMinn near Barrow, AK, 1971-1972
C. Experimental spill in Balaena Bay, Canada, 1974-75
D. Experiments in yellowknife, Canada, 1976
E. Experiments by Energetex in Waterloo, Canada, 1977
F. Experiments at McKinley Bay, Canada, 1979-80
G. Experiments by Energetex at McKinley Bay, Canada, 1979-80
H. Experiments at McKinley Bay, Canada, 1981
I. Experiments at Prudhoe Bay, AK, 1982
J. Experiments at McKinley Bay, Canada, 1982
K. Tier II burn tests at Prudhoe Bay, AK, 1983
L. Experiments at OHMSETT, NJ, 1984-86
M. Experiments at Cape Bretton, Canada, 1986
N. Experiments in Calgary, Canada, 1986
O. Experiments at Svalbard, Norway, 1990-94
P. Experiments in Barents Sea, 1993
Q. Experiments at Prudhoe Bay, AK, 2002-03
R. Experiments at Svalbard, Norway, 2006-08
S. Experiments in Barents Sea, 2008-2009

1. Pipeline spill, Near Normal Wells, Mackenzie River, Canada, 1958
2. Tanker *Raphael* spill, Finland, 1969
3. Tank farm accient in Deception Bay, Canada, 1970
4. Tanker *Arrow* spill, Chedabucto Bay, Canada, 1970
5. Collision of *Othello* and *Katelysia*, in Tralhavet Bay, Sweden, 1970
6. Diesel spill in ice choked river, Sweden, 1972
7. *Imperial St. Claire* spill in Lake Huron/Georgian Bay, Canada, 1976
8. Barge *Bouchard* #65 accident in Buzzards Bay, MA, 1977
9. Cargo vessel *Edgar Jourdain* spill, Hall Beach, Canada, 1980
10. Storage tank leak, Warwick Lake, Canada, 1983
11. Tank farm release, ME, 1993

Figure 10. Map showing experimental ISB locations, taken from Buist et al (2013).

Dispersants

Chemical dispersants enhance natural dispersion by reducing the surface tension at the oil/water interface, making it easier for waves to create small oil droplets that remain in suspension for long periods and are rapidly diluted in the water column. The main reason to use dispersants is to reduce the amount of oil drifting to shorelines in the case of a very large oil spill. In addition, the aim is to reduce the exposure of birds and mammals to oil on the water surface (e.g. Prince 2015). Furthermore, it has been thought that the use of dispersants may increase the biodegradation of oil in the water column (e.g. Brakstad et al. 2017). In addition, the use of dispersants may decrease evaporation of volatile organic compounds (VOC) when there is less surface oil (Curd 2011). The effectiveness of the method is a very important issue for its rational use. It has varied in laboratory conditions between 5-35%, while in large-scale tank tests the efficiency of dispersants has been great, ranging at their best from 82 to 99% even in cold conditions (Fingas 2008, Belore, et al. 2009). However, the opposite research results occur where the efficiency has fallen to a low level (e.g. Lewis and Daling 2007). Dispersants' ability to increase biodegradation of oil still needs to be tested, as some studies show that dispersants reduce biodegradation while other studies show that dispersants have very little effect on biodegradation (Fingas 2008). It has also been shown that many of the commercial dispersants may have lower effectiveness in waters like the Baltic Sea with low salinity, but these problems can be avoided by modifying the dispersants to be more suitable in these conditions (Lewis and Daling 2007).

It has been shown that dispersants can be effective even in ice-covered waters, but of course the energy of breaking waves has a positive effect on the effectiveness of dispersants. Chemical treatments are most effective during the first few hours after the oil spill. Oil viscosity is a reasonable indicator of the effectiveness of chemical dispersion. Oils are most dispersible when their viscosity is low (less than 2,000 cSt), and they become undispersible when their viscosity is high (Federici and Mintz 2014). Actually, most oils remain dispersible until they are cooled well below their "pour point" i.e. the temperature at which the oil behaves like a semisolid. The pour point for many Arctic crude oils is well below the freezing point of seawater. The increase in viscosity related to cold temperatures in the Arctic is not nearly as severe as the rapid increase in viscosity of oil affected by evaporation and emulsification processes in open water (JIP 2017). In addition, research has shown that the motion and interaction of broken ice pieces actually enhances the dispersion process by providing surface turbulence at higher levels than would occur naturally with non-breaking waves in open water

(Owens and Belore 2004). It seems that cold temperatures do not much affect the dispersibility of oils or their potential for biodegradation by indigenous microorganisms (JIP 2017). Many large-scale tank and basin tests as well as field experiments have shown that cold temperatures do not reduce the dispersibility of many oils or the activity of the dispersant (Brandvik et al. 1995; Brown and Goodman 1996; Owens and Belore 2004). The effectiveness of the dispersants has been at their best between 82-99% in cold water conditions and dispersants can be effective in partly ice-covered waters (Fingas 2008; Belore et al. 2009). As stated also in EPPR (2017a) dispersants are effective in a wide range of ice conditions and actually the slower oil weathering processes in the presence of ice can expand the window of opportunity for dispersant application. As energy levels in the upper water column tend to diminish in very high ice concentrations (>60%) supplemental mixing energy may however be required. Dispersants are not applicable in solid ice; however, they have been tested successfully with oil between floes in high ice concentrations (70 to 80%). CRRC (2017) stated in their review that there are many open questions still; for example, while some of the major environmental factors affecting dispersant effectiveness have been well studied, the influences of other variables have not. For example, the general trends for low salinity and hyper-saline waters and oils with viscosities above 2000 centipoise are less well known. Furthermore, the degree of dispersion effectiveness for non-Corexit dispersants over a broad range of oils and environmental conditions has been less studied and therefore is uncertain (CRRC 2017).

For spreading dispersants, vessels with spray arms can be utilized, and helicopter spray buckets can cover small areas or, if broader area coverage is required, fixed-wing aircraft can be utilized (EPPR 2017b). Aerial application of dispersants is a response strategy commonly used in many areas of the world. This tool has applications for incidents during the Arctic summer open water period and during periods of open drift ice in non-freezing temperatures. Basically, the dispersion of the oil at near freezing temperature occurs as long as the oil remains fluid. Furthermore, a new controllable applicator arm was developed to deliver dispersant more effectively to isolated oil pockets in the ice (Daling et al. 2010). Of course, the low winter temperatures, the long periods of darkness during the winter, the long distance as well as the presence of ice pose challenges to the operational use of dispersants. For dispersant application, cold can impede proper spray and dosing of different dispersant products. If there is not enough mixing energy, dispersion may not be effective (EPPR 2017b). The shearing, caused by the motion of small pieces of ice in non-breaking waves, may enhance dispersion by providing additional near surface mixing energy that would otherwise not be present in the absence of ice (Owens & Belore 2004). Prop wash provides additional energy to enable dispersion of dispersant-treated oil in ice-free, ice-infested, and full ice cover waters (broken by an ice breaker) when available mixing energy is insufficient. The advantages of using azimuthal stern drive (ASD) ice-capable vessels or jet drives from small support boats to add mechanical mixing energy to support oil dispersion were well known from basin tests (Daling et al. 2010).

In the case of subsea application, it is important to notice that subsea conditions in Arctic are the same as elsewhere. For example, water temperatures at depth in the Gulf of Mexico approach temperatures in the lower water column in the Arctic within a few degrees. However, NRC (2014) concluded that more work was needed to understand the effectiveness, systems design, and short- and long-term impacts of subsea dispersant delivery in Arctic waters (NRC, 2014).

Debate about toxicity

Nowadays the major active components in oil dispersants are surfactants. Surfactants are surface-active agents which possess both hydrophilic and hydrophobic properties causing dispersants to be both water and oil compatible. When oil slick is disturbed e.g. by waves, the surfactants form a film at the water-oil boundary and the oil is dispersed as smaller droplets and surfactants prevents the oil recombining back to oil slick (Hemmer et al. 2011). Some studies have shown that oil-degrading microbes may colonize the droplets within a few days. There are also studies showing that dispersants themselves are less toxic than both naturally dispersed and dispersant-treated oil (NRC 2005). Also, laboratory experiments have demonstrated that indigenous Arctic microorganisms effectively degraded both fresh and weathered oil regardless of whether it was dispersed naturally or with the addition of dispersants (McFarlin et al. 2014). NRC (2014) concluded that naturally available levels of nutrients and oxygen could sustain effective microbial degradation, in Arctic as well as temperate waters. So at least in theory, when the oil breaks into small droplets the surface-to-volume ratio of the oil increases making them more vulnerable to hydrocarbon degrading bacteria which can degrade oil at the water-oil interface (Hamdan & Fulmer 2011).

However, the effect of dispersants on biodegradation is still a matter of dispute. Some papers state that dispersants inhibit biodegradation others indicate that dispersants have little effect on biodegradation (Fingas 2008). Xia et al. (2009) demonstrated, however, that dispersants had positive influence on biodegradation of oil. The biodegration was most efficient when oil dispersants were at a 2:10 ratio, followed by 3:10, 1:10 and 4:10. The test also showed that the biodegration had the highest effect in high temperatures and in waters having high salinities (33 ppt) (Xia et al. 2009). Also, a study by Brakstad et al. (2017) showed that a common oil spill dispersant did not inhibit biodegradation of oil at dispersant concentrations relevant for response operations. In contrast, however, some papers stated that inhibition is a matter of the surfactant in the dispersant itself and the factors of environmental conditions. It is clear on the basis of current literature that the surfactants in some of the current dispersant formulations can inhibit biodegradation (Fingas 2008). The study of Hamdan & Fulmer (2011) showed that even if dispersants may enhance the availability of hydrocarbons to biodegrading bacteria, the dispersant also kill those bacteria causing negative biodegradation results.

The LC50 values of dispersants used in the early 1970s ranged from about 5 to 50 mg/L to the rainbow trout in 96-hour exposures. In contrast, LC50 values for dispersants commercially available today vary from 200 to 500 mg/L and contain a mixture of surfactants and less toxic solvents. The results of dispersant toxicity testing show that dispersants vary in their toxicity to various species, but dispersant toxicity is less than the toxicity of dispersed oil. Of the recent toxicity studies of dispersed oil, some researchers found that chemically-dispersed oil was more toxic than physically-dispersed oil. Most of these found that the cause for this was the increased PAHs, typically about 5 to 10 times, in the water column. Others noted the increased amount of total oil in the water column. Some noted the damage to fish gills caused by the increased number of droplets. A few researchers noted that the toxicity of chemically-dispersed oil was roughly equivalent to physically-dispersed oil (Fingas 2008).

Wise & Wise (2011) did a large review concerning the ecotoxicity of oil dispersants. They surveyed 38 peer-reviewed articles concerning the toxicity of 35 different chemical dispersants. It was notable that most studies examined only the lethality of the dispersants. However, also nonlethal end points were studied including predator/prey recognition, enzyme activity changes and success of hatchability. The animals studied included Daphnia (small planktonic crustaceans), anemones, corals, crustaceans, starfish, mollusks, fish, birds, and rats. Studies in birds and mammals are noticeably lacking. The variety of chemical dispersants, the variability in test methods, and the lack of distinct species overlap between studies make it difficult to compare and deduce which dispersant is most toxic and which is least.

One of the most reliable studies was conducted by The United States Environmental Protection Agency (EPA) and they used altogether eight of the dispersants they allow to be used commercially. The tests studied the toxicity of dispersants alone, dispersants with oil, and oil alone. The toxicity tests were carried out on the minnow Menidia beryllina (96-hour test) and the crustacean Mysidopsis bahia (48-hour test) and also with human cell lines. According to their tests, dispersants had no significant estrogenic or androgenic activity in human cell line assays. Cytotoxicity was only observed at concentrations above 10 ppm. The results of the ecotoxicity tests showed low toxicity of all 8 dispersants (3 to >5000 ppm). Lousiana Crude oil toxicity was 4.4 mg/L LC50 for mysid and 2.9 mg/L Menidia. When dispersants and crude oil were mixed, then LC50s varied between 0.4 and 13.1 mg/L and these mixtures classified as slightly to highly toxic. With mysid it was observed that oil alone had similar toxicity when compared to dispersant-oil mixtures. All 8 dispersants alone were less toxic than dispersant-oil mixtures (Hemmer et al. 2010).

The JIP (2014) made a literature review and based on their findings the existing laboratory data, experimental field studies and monitoring following actual spills show that dispersed oil may potentially cause environmental impacts but only to organisms in the vicinity of dispersed oil and/or in cases when the rate of dilution of the dispersed oil plume is slow (e.g. sensitive areas close to shore). Even though the impact exists, the sessile organisms would most probably be impacted. The toxicity of oil/dispersant mixtures is related to the oil in the mixture and not the dispersant. There is no evidence that Arctic species are more or less sensitive than other temperate climate species that have been tested with dispersed oil. Prince (2015) concluded that the potential environmental costs of adding these chemicals to a polluted area are likely outweighed by the much shorter residence time, and hence integrated environmental impact, of the spilled oil in the environment.

A thorough state-of-the-art report reviewing ecotoxicity of dispersant and dispersed oil was made by Coastal Response Research Center (CRRC 2018) summarizing the very complex issue as follows: Environmental conditions in the Arctic (e.g., low temperatures, extreme light cycles, sea ice) may affect the behavior, distribution, and fate of spilled oil, dispersant, and dispersed oil, the extent to which marine biota are exposed to oil and to dispersants, and the effects of those exposures. Based on this very extensive study, dispersants change exposures to oil in several ways, e.g. the amount of oil in water and water surface, droplet size and fraction of dissolved oil as well as the array and relative concentrations of petroleum hydrocarbons that are bioavailable to aquatic species. The CRRC (2018) report stated that there are actual differences between the physiology of Arctic and temperate species. The limited numbers of studies on Arctic species show that they respond similarly to temperate species when exposed to toxicants. Data about oil and dispersed oil toxicity to Arctic species is limited which leads to uncertainty in predicting impacts, particularly because of the shifting baseline due to changes in Arctic environments. Compared to more temperate regions, the unique ecosystems and aspects of biology/aggregation due to time of year and life history in the Arctic create uncertainty in assessments related to dispersed and undispersed oil.

Economic discussion

Tegeback and Hasselström (2012) estimated in their study that if 10,000 tons of oil contaminated a coastline of the Baltic Sea, the costs would be 100–400 million euros including direct (e.g. clean-up), market (e.g. tourism and fisheries industry) and non-market costs (i.e. environmental and other impacts that are not easily measured in a market). Similarly, Halonen (2007) stated that in the case of a spill of 30,000 tons of oil, the estimated costs of clean-up could reach 1.5 billion euros. According to ITOPF (2012), the most expensive oil spill in history is the EXXON VALDEZ (Alaska, 1989). Clean-up alone cost approximately 2.5 billion USD and total costs (including fines, penalties and claims settlements) have been estimated to be as much as 7 billion USD.

The only source in which the costs of different recovery methods are compared seems to be Etkins (2000). The use of dispersants is the cheapest method and the cost reduction is due to the lower labour costs, i.e. fewer personnel for a shorter period of time and even lower overall equipment costs that are required with dispersant application compared to mechanical containment and recovery operations.

Etkins (2000) showed the analysis of clean-up costs from 97 spills in the oil spill intelligence report (OSIR). This analysis showed that clean-up responses in which dispersants were the only or primary method were less expensive than spills involving other response measures. The costs of use of dispersants only were almost 6-fold cheaper than if only other methods were used, and 6.5-fold cheaper if dispersants were used as a secondary or tertiary method. When comparing dispersants only to the cases where dispersants were used as the primary method, the costs did not differ markedly. One of the reasons for limited costs when dispersants are used is the mitigation of shoreline impact, which reduces the need of expensive shoreline clean-up.

Allen & Ferek (1993) reported field effectiveness of different recovery methods at their best and claimed that ISB had best field effectiveness (90-98%), followed by dispersants (80-90%) and mechanical recovery (10-20%). Natural remediation also has high effectiveness, up to 90%, but of course it takes a long time and has a tremendous environmental impact. The actual effectiveness of any clean-up methodology depends, of course, on the actual application methods, the individual circumstances of the spill (location, oil type, amount of oil), and unpredictable variables such as weather.

The Deepwater Horizon oil spill released an estimated 4.9 million barrels of Lousiana sweet crude oil into the Gulf of Mexico. Of the quantities of oil removed from surface waters, 17% were from the direct capture of oil from well head, 3% from the skimming of oil from the surface, 5% from booming and burning and 8% using dispersants (Hemmer et al. 2011).

Bioremediation and natural attenuation

In addition to active recovery methods, there are also passive option, i.e. natural attenuation or bioremediation. In case of the Exxon Valdez spill in Prince William Sound, Alaska, and the Deepwater Horizon oil spill in the Gulf of Mexico, only 15 to 25% of the oil was effectively removed by mechanical methods. Despite numerous clean-up efforts, including mechanical recovery and ISB, bacteria in the water carried out the bulk of the clean-up operation (Vergeynst et al. 2018). In the case of the Deepwater Horizon incident in 2010, ca. 780,000 m3 of light crude oil were released into the marine environment from the seabed. It has been found that the oil dispersed in the water column was degraded by naturally occurring microorganisms in deep water (1,000 m) at temperatures of 4-5°C, which are not far from Arctic sea temperatures. In the case of the tanker Exxon Valdez, the biodegradation was enhanced by adding nutrients to the spilled oil. Despite intensive oil combat and clean-up, a portion of the spilled oil was buried in the shoreline sediment and oil is still being released from some pockets 25 years after the incident (Wegeberg et al. 2018).

In the case of an acute oil spill, decisions on which methods to use for combating the oil spill must be taken, and the choice of oil spill response technique(s) should be carefully balanced with the presence of marine organisms in the sea and on the sea surface in a Net Environmental Benefit Analysis (NEBA) (Wegeberg et al. 2018). A NEBA is a process that formalizes the evaluation and comparison of the expected response effectiveness versus the potential environmental impacts of the oil spill, as well as impacts from response options (Camus and Smit 2018). Knowledge of the biology and ecology of the specific region is key to the application of a NEBA in a meaningful manner. The output from the NEBA process is the selection of response technique(s) that minimize the overall impacts of a potential spill on the environment, and promote the most rapid and effective recovery as well as restoration of the affected area (IPIECA-IOGP 2015). A NEBA provides a protocol for weighing the advantages and disadvantages of various spill responses with regard to flora and fauna and their habitats within the specific area of concern, compared with no response (Camus and Smit 2018).

Bioremediation is natural biodegrading of spilled oil, which to a certain extent can be accelerated through the addition of nutrients, oil-degrading bacteria, or both. Nutrient and bacteria addition have been tested, and some positive effects have been observed. Many compounds in crude oil are environmentally benign, but significant amounts are toxigenic or mutagenic. The latter are the ones we are most interested in removing or destroying in an oil spill. Bioremediation is a technology that provides an opportunity to convert the toxigenic compounds to nontoxic products without further disruption to the local environment. Generalizing based on two excellent and very detailed reviews (Vergeynst et al. 2018 and Wegeberg et al. 2018) for biodegradation of oil in the marine environment, several factors have to be met and there are certain limitations in Arctic conditions for this process. First, the presence of a microbial organism capable of degrading the oil is required. The number of oil-degrading bacteria constitutes only a fraction of the total number of bacteria in seawater. Although the number of oil-degrading bacteria is low in pristine water, the number may increase following an oil spill. The absence of specific oil-degrading bacteria may, however, limit oil degradation in pristine Arctic waters. For biodegradation, sufficient nutrients are needed. The Arctic is generally an environment with very low amounts of nutrients such as nitrogen and phosphorus. These nutrients feed algae and bacteria in the water and without them, the bacteria cannot grow. A microbial flora may be adapted to low temperatures, but the general expectation is that low temperatures will lead to lower degradation rates. In cold waters the oil is more viscous and this prevents it from being broken up into small droplets in the sea. Biodegradation happens at the water-oil interface and oil-eating microbes can only consume and breakdown oil when it is dispersed into small droplets. The speed of microbial utilization of oil is primarily related to the amount of surface area exposed to aerobic processes. Thick layers of oil, physically weathered oil, or oil isolated to less aerobic environments undergo biodegradation more slowly than dispersed oil. During the Arctic spring and summer, massive phytoplankton blooms occur and glaciers release suspended mineral particles which will stick to the oil droplet and together sink to the seafloor. Microbial degradation of oil on the seafloor occurs much slower than in the water column. Arctic summers with all-day sunlight may help the microbes to break up oil molecules into smaller pieces. However, it may also make the oil compounds more toxic for aquatic organisms.

The knowledge presently available regarding natural degradation of oil under Arctic conditions shows a complex picture depending on oil type (light/heavy) and ambient conditions: temperature, nutrients, time of year, and more. Wegeberg et al. (2018) stated that PAH degraders were found and in very low densities from Arctic waters. It is highly likely that also more complex PAH degraders occur naturally in Arctic seawater, but in extremely low densities. On the other hand, the review of JIP (2014) stated that the microbial communities rapidly adapt to increasing abundance of hydrocarbon utilizers in all aquatic environments that have been studied. Microbial communities in the Arctic are adapted to life in this extreme environment and rapidly respond to carbon-rich but nitrogen-poor petroleum resources. Even though many of the organisms are unique, there are also similar bacteria known to respond to oil in other sea areas.

Nonetheless, it should be noted that bioremediation especially in ice conditions is a slow process that very seldom, if ever, can be considered as the primary countermeasure. Most likely, the most beneficial use of bioremediation is as a secondary combating method that completes the recovery result after application of some other clean-up method. It should be remembered that using natural attenuation or bioremediation as an option requires a long-term and very active environmental monitoring program, so it is not really a passive, do-nothing option.

Some recent guidelines

COSRVA report

One of the most recent guidelines for the best practices and selection of the optimal oil spill recovery means in the Arctic is the Circumpolar Oil Spill Viability Analyses (COSRVA), prepared by the EPPR Working Group of the Arctic Council (EPPR 2017b). It gives estimates for the percentage of time the environmental conditions may be favorable, marginal or not favorable for a certain oil spill countermeasure selected. Generally, the open water season in the Arctic offers more favorable conditions for OSR than in the winter. Also, conditions for response are usually better in autumn than in spring The geographical coverage of the COSRVA is shown below in Figure 11. It can be noted that the Northern Baltic Sea has been excluded, but the area practically covers the North Atlantic, the Bering Sea, Barents Sea, Norwegian Sea, Baffin Bay and the Hudson Bay. Thus, the AMAP map covers the area of the intersecting national waters of Denmark (Faroe Islands), Canada, Greenland, Iceland, Norway, Russia, and the United States.

Another valuable report on Arctic oil spill recovery is the “Guide to Oil Spill Response in Snow and Ice Conditions in the Arctic” prepared by the EPPR Working Group (EPPR 2015). Practical information on the tactics and usage of various response techniques is also given in an updated version of the past Field Guide for Oil Spill Response in Arctic Waters (EPPR 2017a).

The environmental conditions and attributes to describe the metocean conditions are: wind speed, wave height, air temperature, sea surface temperature, sea ice coverage, visibility (horizontal) and daylight or darkness. The main response options handled in this analysis were mechanical recovery, dispersants and ISB.

The general approach of the COSRVA report was to compare a set of metocean conditions listed above for a given location to information about the limitations on oil spill response systems. The limitations of the selected response options were identified against all selected metocean attributes. Then these “combined data” sets were used for selected sea areas for different time periods to determine whether conditions during that time would be favorable, marginal, or not favorable for a response. The results of the COSRVA analyses in fact estimate the percentage of time that environmental conditions may be suitable for a given countermeasure, or not. The description of the methodology is given in EPPR (2017b).

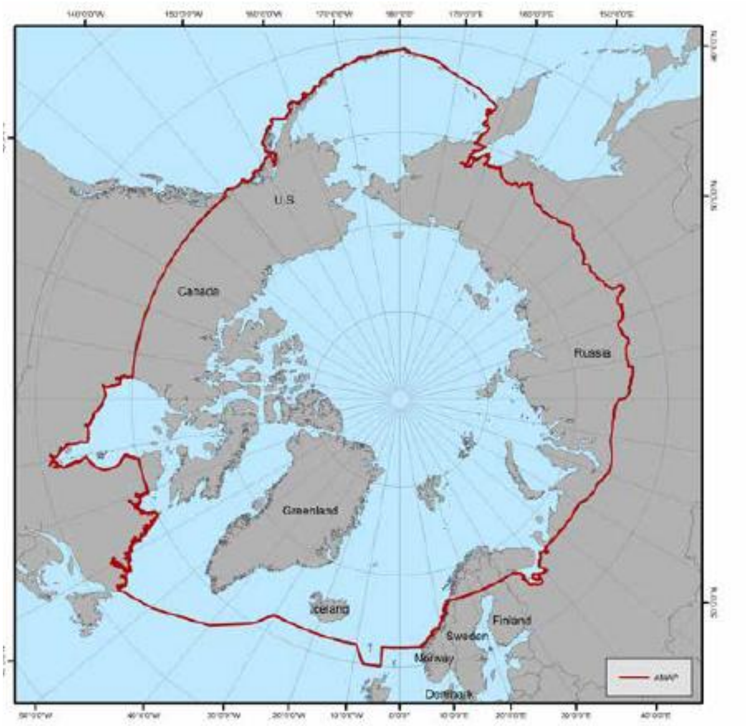

Figure 11. Study area of the COSRVA assessment based on the AMAPS's definition for the boundary (EPPR 2017b).

Table 3. Design conditions and parameters for viable response analyses (EPPR 2017b).

Metocean Conditions	Parameters Potentially Impacting Oil Spill Response
Wind	Wind speed (m/s)
Sea state (waves)	Significant wave height (m) Average wave period (s)
Sea ice	Ice coverage (%)
Air and sea temperature	Air temperature (°C) Superstructure icing (cm/hr)* Wind chill (w/m^2)
Visibility	Daylight/darkness Horizontal visibility (m) Cloud ceiling (m)**

* included for vessels, not aircraft
** not included in quantitative analysis due to lack of data

Gap analyses for COSRVA report

The viable response analyses do not include the overall operational picture or data on the certain response tools available in the area. For example, if the conditions have been analyzed to be favorable for a certain response tool, the lack of this equipment in the response area is not included in the analysis. Also, the possible deployment time from the depots or any transport time is not included, but need to be planned separately. The same holds for other resources supporting the operations like crew onboard, necessary service or logistic solutions.

COSRVA uses a 25 x 25 km^2 grid for the analyses, which may not be suitable for coastal areas with a lot of shallow embankments, rocks, islands and curvy coastal lines. For a closer look of certain restricted areas, other means are need for surveillance and final analyses for the recovery options. For some restricted sheltered areas, the overall analyses may give a false estimation as not favorable or marginal when in fact, due to the good shelter or micro climate of the area under surveillance, the selected countermeasure would fit this area well.

Thus, a parallel to the COSRVA tool is needed to use all available surveillance means to get a fresh situational awareness view of the target area. Satellite pictures and SAR images taken from the surveillance air crafts are needed to ensure the proper tactics are used. Novel drone concepts, especially the fixed wing aircrafts, have a long range and can be used as support tools for the surveillance team trying to map the oil-infested area and to get an idea of whether certain areas can be protected by booms, or certain recovery tools could be directed to the focus areas.

In a remote area and over long distances, the local environmental conditions may vary a lot from the original point made for decision up to the final environmental conditions when the recovery tools have been transported to the site. Even if the COSRVA analyses estimate that a certain main option would be favorable or not favorable, there could still be a window of opportunity to use certain tools or tactics.

The response effectiveness of certain response tools may differ a lot from those given in the literature or in the sales catalog. Most of the mechanical recovery tools have been tested in laboratory conditions, and often the announced oil pick up ratios describe theoretical maximum recovery capacities for a given system. Mechanical means have been used a long time, and there is a certain understanding on their limitations for given wave and wind conditions. Cold air temperatures, however, will often pose additional difficulties for the systems. For example, some mechanical skimmers may still work well partly submerged in the water, but the cold air may easily freeze the hoses or oil scraping systems which in turn will block the work of the whole system. Cold temperatures may also move the oil from the Newtonian fluid more toward a pseodoplastic type increasing the viscosity so much that conventional pumping systems will no longer work without any additional heating by hot water or steam. There are mechanical recovery systems available designed for the winter conditions with modern heating systems for the key parts of the systems. However, if one component of these system would fail by freezing, usually it means the whole oil recovery efficiency will remain practically close to zero.

The same holds for the use of dispersants. Even if the first ideas for the use of dispersants are favorable, the sudden change of the air temperatures or wind velocities will endanger the success. A water surface that is too calm will not produce enough energy for dispersants to speed up the oil dispersion unless some energy (ships' wake or water cannons) can be used. If the distance of the oil spill site is too far to be reached by ships with dispersant spraying units, the use of aircrafts requires sufficient wave energy at the operation site.

The COSRVA analyses do not take into consideration the oil type and/or weathering for the response effectiveness. They do give an estimation of the usefulness of certain response methods in the area, but the final decision-making requires additional information about the spreading, wave dynamics on the oil slick and oil type to understand if some of the main oil alteration characteristics have taken the most favorable option out and if some other alternative solution needs to be used.

The COSRVA analyses contain only three main response methods (with modifications, altogether ten methods!), which may be limited in dealing with the real situation. The optimal the response toolbox may have alternative methods and tactical innovations which are not analyzed here, and may enable a better response when assessed in light of the specific scenario.

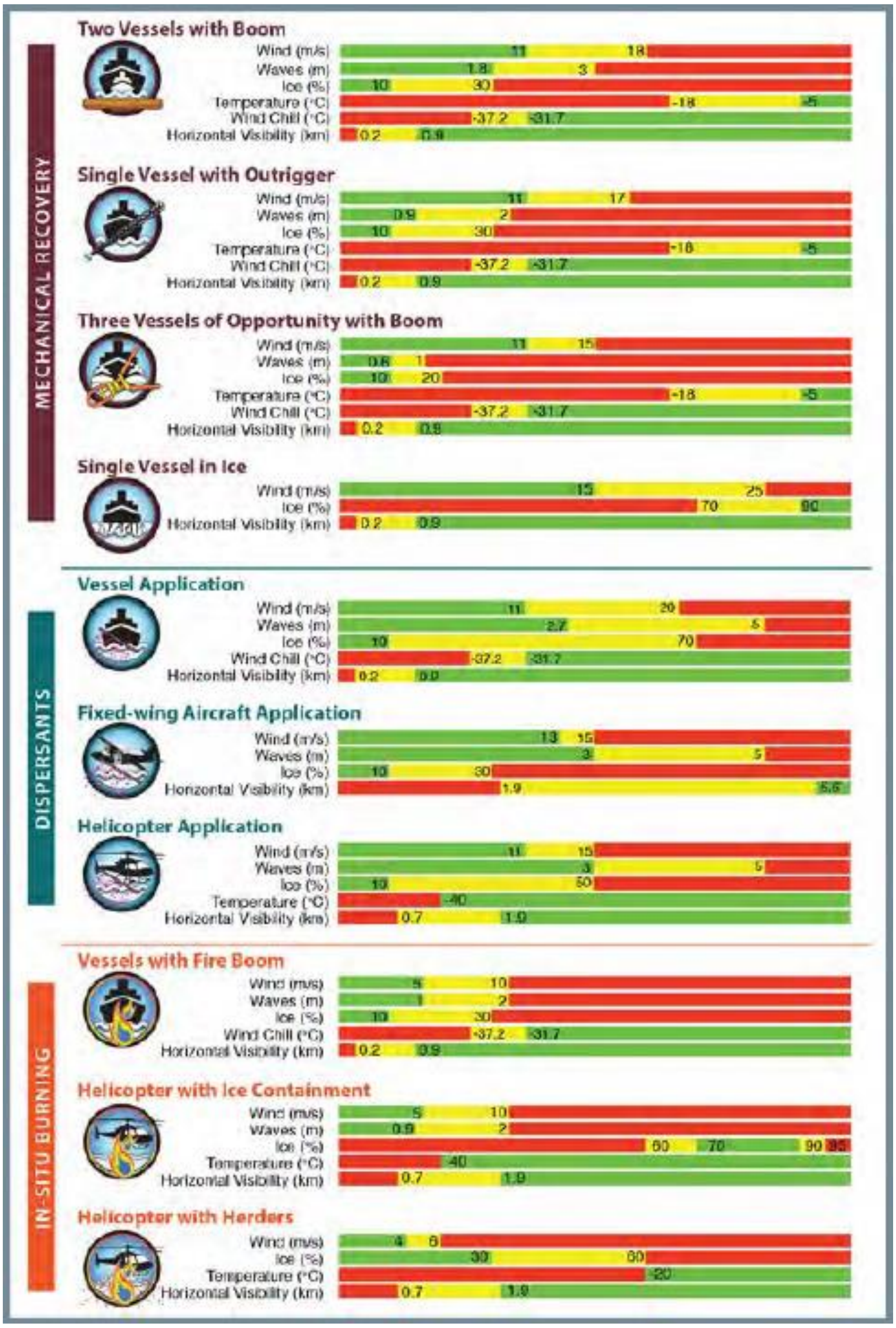

Figure 12. A comparison of the all response options; structural icing and daylight/darkness impact not included. Colors: green – favorable, yellow - marginal, red – not favorable. EPPR 2017b.

Results - examples

The following Figures 13 and 14 represents the reporting for analyzed main countermeasures, i.e. mechanical recovery, ISB or the use of dispersants.

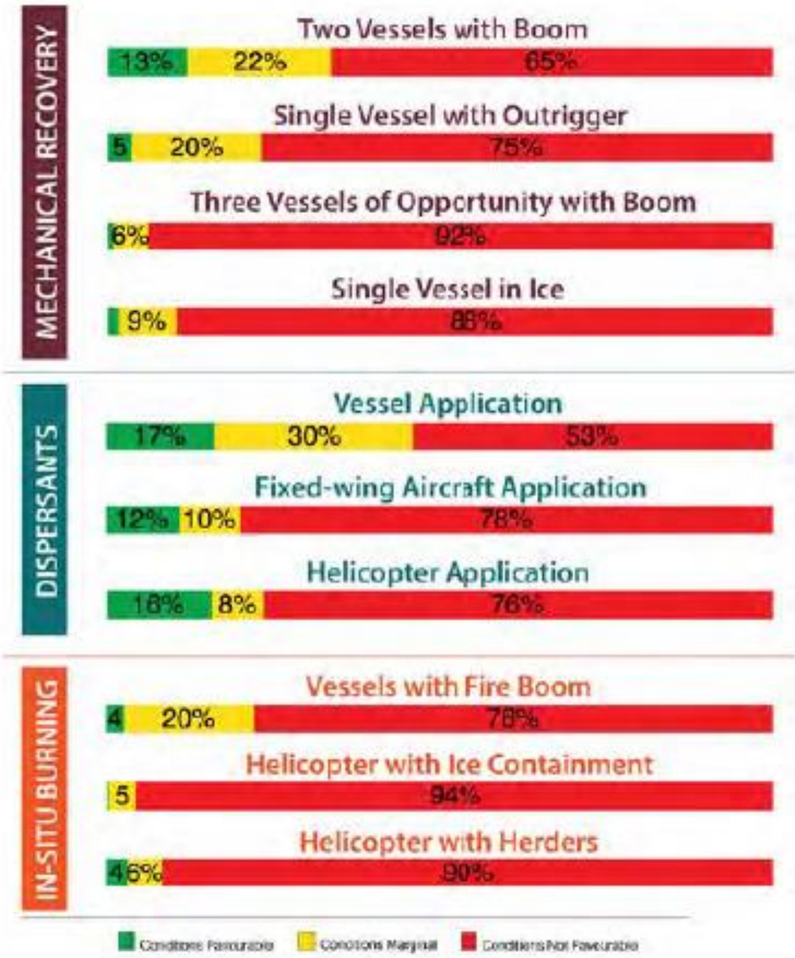

Figure 13. Annual percentage of time for conditions being favorable (green), marginal (yellow) or not favorable (red). EPPR 2017b.

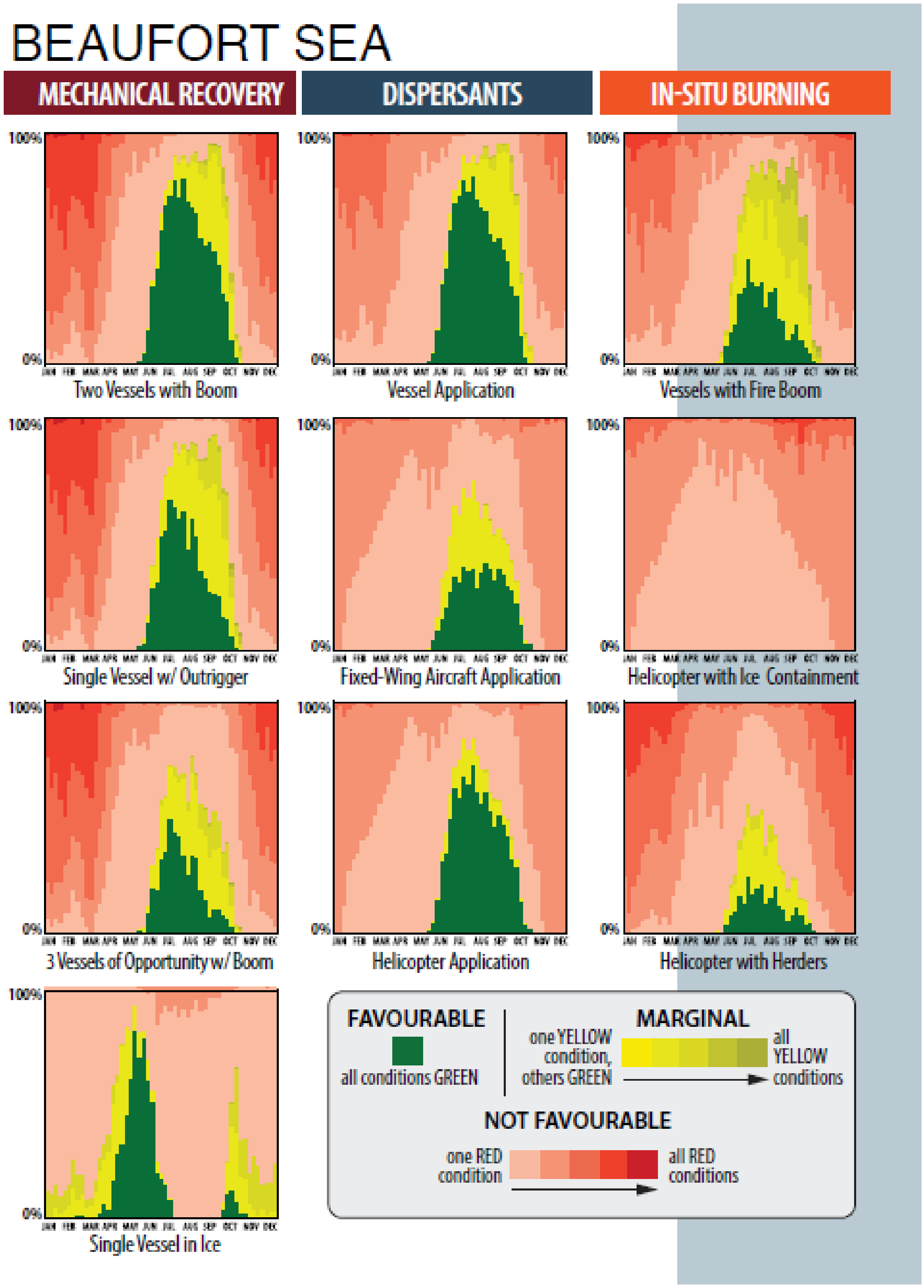

Figure 14. An example of the COSRVA results for the Beaufort Sea. Similar figures gave been published for all Arctic sea areas in EPPR 2017b.

Some general observations can be made:

- the mechanical recovery systems are designed primarily for the open water conditions and suitable also for the low ice concentration. Thus, their usage in mid-winter or in the High Arctic is restricted, sk. not favorable;
- the single vessel in ice system is designed for much higher concentrations of ice. This concept may then be usable when the open water concepts fail due to excessive ice. The new Finnish type of heavy-duty ice brush systems may have potential also for heavier ice conditions, but their oil pick up ratios have not been tested in real conditions yet. Small-scale studies and laboratory tests have confirmed their potential;
- in the Arctic during the summer, a lot of areas are ice-free, which means the mechanical response may be a good response option. However, wind and wave height limit the use of additional booms, trawling systems and the oil pick up of the sweeping arms (outriggers) of the vessels, thus reducing the theoretical value of the oil pick up ratio. Some new recovery vessels with the inbuilt wave attenuation systems may still work in the sea state of a wave height up to 2.1 m. Usually the booms and outrigger systems of the vessels will start to reach their limits when the wave height exceeds 0.6 m or when the recovery speed exceeds 2 knots. It should be noted that the ice brushes of modern recovery vessels may also be used in the open water: the bucket-type recovery brushes with the long arm can be used in the same way as skimmers, jointly with booms to enrich the oil being recovered.
- visibility conditions may reduce the operational response of any of the selected systems. Visibility conditions are typically worse in summer than in winter in the Arctic;
- the dispersant systems mounted onboard the vessels seem to have higher ice tolerance than the concept with two vessels and the boom: the ice floes will easily fill the boomed area and disturb the oil recovery operation;
- conditions for all dispersant systems studied seem to be favorable or at least marginal in the summer period, while being not favorable in winter;
- wind and visibility conditions are not favorable for dispersant systems based on aircrafts, while cold (icing) may significantly affect systems mounted onboard the vessels;
- for ISB, conditions are more likely to be favorable or marginal for the vessels with fire booms than the other two options analyzed (chopper in ice conditions/chopper with herders);
- as with dispersants, ISB may be carried out with a vessel or an aircraft. For ISB / helicopter with ice, ice coverage must be large enough to maintain the oil thickness for ignition;
- ISB with helicopters and herders would be viable at least some of the time year-round at all locations except the High Arctic.

When looking at the overall viability of all systems analyzed, all systems seem to meet the conditions “not favourable” more than 50% of the time over the whole area, some of them over 75% of the time (EPPR 2017b). Figure 14 above gives a good idea of the general viability of the systems analyzed.

General observations

The following general observations can be made:

Conditions were favorable at least 10% of the time for the following systems:

- Dispersant – Vessel Application (17%),
- Dispersant – Helicopter Application (16%),
- Mechanical Recovery – Two Vessels with Boom (13%), and
- Dispersant – Fixed-wing Application (12%).

Conditions were either favorable or marginal at least 25% of the time (combined) for the following systems:

- Dispersant – Vessel Application (47%),
- Mechanical Recovery – Two Vessels with Boom (35%), and
- Mechanical Recovery – Single Vessel with Outrigger (25%)

Finally, conditions were found to be not favorable at least 90% of the time for:

- In-situ Burning – Helicopter with Ice Containment (94%),
- Mechanical Recovery – Three Vessels of Opportunity with Boom (92%),
- and
- In-situ Burning – Helicopter with Herder (90%)

Other guidelines

Currently there are two main guidelines available for oil spill response specifically for Arctic conditions: The Field Guide Response in Arctic Waters (hereafter, “Field Guide”) was recently updated (EPPR 2017a) and is mainly focused on supporting the response and operations. The other guidebook, “Guide to Oil Spill Response in Snow and Ice Conditions” (EPPR 2015), in turn focuses on planning and decision-making processes. The EPPR 2015 version has also later been published by the IMO (International Maritime Organization) in 2017 for more global usage. This guidebook has generic, strategic ang global objectives and focuses on ice and snow oiled from potential marine sources as well as ice and snow in the marine coastal environment oiled from potential terrestrial sources. The key areas are planning, preparation, response, and implementation.

The Field Guide contains updated material and is reorganized to remove repetitions found in the first edition from 1998. It focuses on practical oil spill response strategies and tools for application in open water, ice and snow conditions in remote areas during cold weather. It also provides information relevant to the marine offshore and coastal environments, and to large rivers and lakes where oil is transported and where spills pose a threat to the environment and public health.

Some of the baseline lessons learned of these two guidebooks for the oil spill recovery in the Arctic have also been reviewed and discussed in this report.

The extended Field Guide applies to any cold regions with ice and snow, not just the Arctic. The Field Guide also has a large application range with oil types: they have been grouped into three main categories to make the application easier. Globally there are many different crude oil types, various refined oils and the behavior of all these oil types differ a lot. Here the oil types have been mainly characterized by viscosity which, from the point of view of recovery ability, is perhaps the most critical feature of oil in ice and cold conditions.

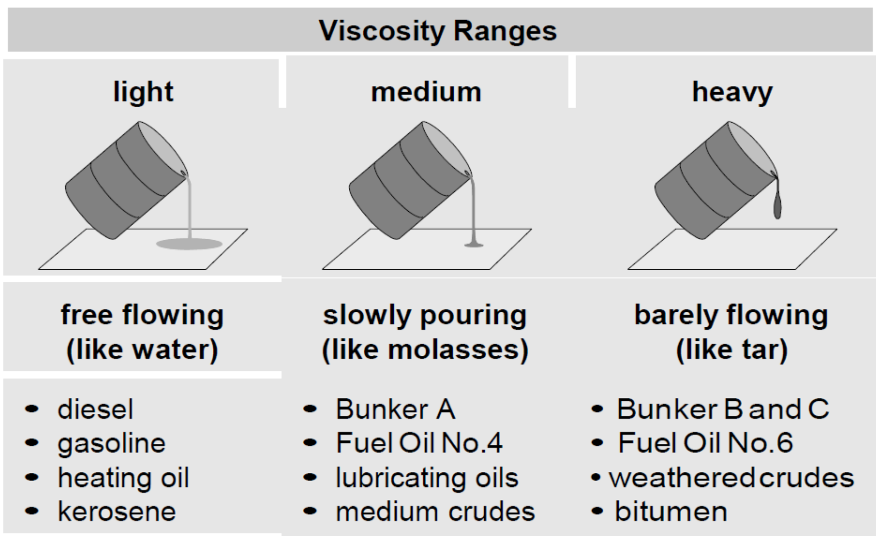

Figure 15. The oil viscosity types used in the Field Guide (EPPR 2017a).

Modelling of oil spill movements

To successfully respond to oil spills, a reliable mathematical model to predict oil movement as well as the weathering of the oil is needed. Calculations help responders focus the response efforts on the right places, i.e. where oil actually exists. This is even more important in ice conditions, when the poor visibility and darkness make visual observations of oil movements difficult. An oil and ice model is normally based on a 3D oceanographic water circulation model and uses the sea currents from this circulation model.

The OILMAP software suite, developed by Applied Science Associates (Figure 16), is the most widely used model for predicting oil spill trajectories in the presence of ice. OILMAP provides rapid predictions of the movement of spilled oil. It includes simple graphical procedures for entering both wind and hydrodynamic data and specifying a spill scenario. More information can be found at http://www.asascience.com/software/oilmap/. OILMAP is a Lagrangian particle-tracking model in which each particle is given an additional degree of freedom to simulate the gravitational spreading of oil into a thin slick. The model calculates particle trajectories using inputs of ocean currents, winds, and ice conditions from observations or circulation models. It also takes into account changes in oil density and viscosity due to weathering by evaporation and emulsification. Oil-ice interaction is parameterized by assuming that the oil moves with the ice at concentrations >30% and with ocean surface currents at concentrations <30% (Blanken et al 2016). Another very similar and much-used model is the SIMAP, which contains the same trajectory calculation algorithms as OILMAP. SIMAP provides detailed predictions of the three-dimensional trajectory, fate, biological effects, and other impacts of spilled oil and fuels. More information can be found at http://asascience.com/software/simap/. OILMAP is a simplified version of SIMAP designed for operational use and for contingency planning. OILMAP uses a reduced number of pseudo-components to represent the oil and so requires less data than SIMAP to define the oil composition (French-McCay et al. 2017).

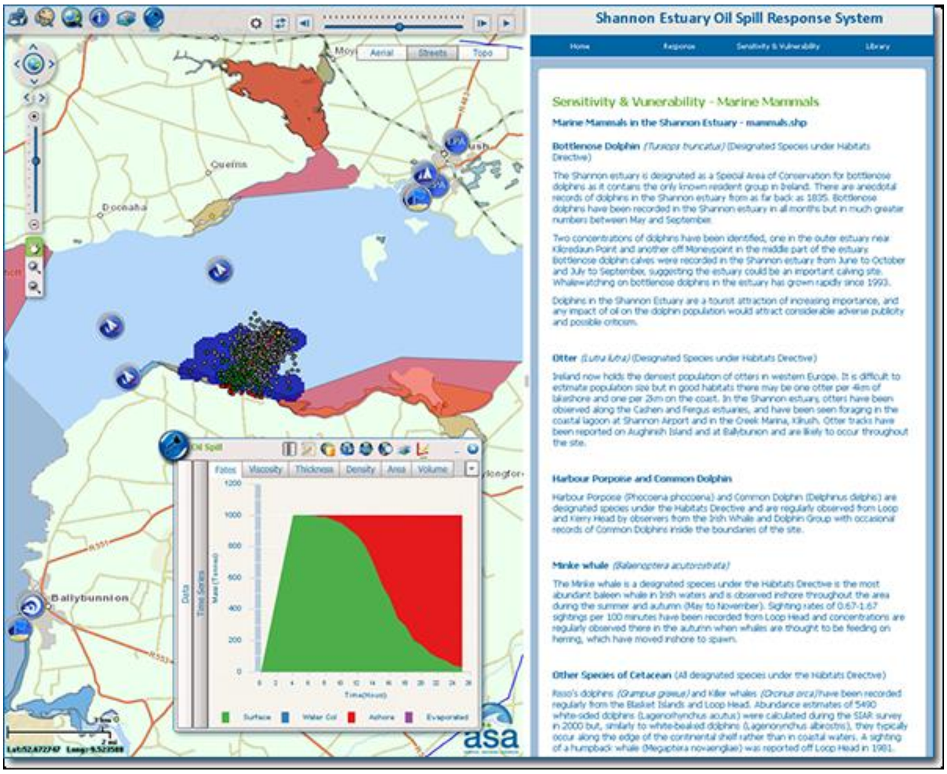

Figure 16. A snapshot showing some features of the OilmapWeb tool.
http://staging.asascience.com/software/oilmap/oilmapweb.shtml

There are several sea ice models for the Arctic Ocean that are formed from operational global ocean (hydrodynamic) models (French McKay et al 2017):

- European Global Ocean Observing System (EUROGOOS) website (http://eurogoos.eu/models/) provides a catalogue of, and links to, existing global, regional, and coastal ocean models generated from the GOOS Regional Alliances (GRAs).

- The Arctic Ocean models include those built off the Nucleus for European Modelling for the Ocean (NEMO) system (used by the Finnish Meteorological Institute, U.K. Met Office, and Mercator Ocean), which is coupled with the thermodynamic–dynamic sea ice model Louvain-la-Neuve Sea Ice Model (LIM) (http://www.elic.ucl.ac.be/repomodx/lim/), the Helsinki Multi-category sea-Ice model (HELMI) developed by the Finnish Meteorological Institute (Haapala et al. 2005; Mårtensson et al. 2012)

- The Towards an Operational Prediction system for the North Atlantic European coastal Zones (TOPAZ) (http://topaz.nersc.no/) was developed by Nansen Environmental and Remote Sensing Centre (NERSC), Bergen, Norway. TOPAZ is currently the Arctic

Ocean forecast platform within the European monitoring and forecast service MyOcean http://eurogoos.eu/modelling_inventory/eurogoos-136/). Forecast products are available at http://eurogoos.eu/roos/arctic-roos/ .

At the moment, operational models have not been implemented with sufficient spatial resolution or skill to define sea ice characteristics and dynamics needed for high resolution oil spill trajectory forecast modelling.

Depending on location and environmental state variables, the ice condition may vary significantly and also change relatively fast. The ice condition is characterized by a wide range of parameters such as multi-year ice or first-year ice, ice type, ice concentration, ice thickness, ice floe size, ice ridges, ice drift and season. The combination of parameters often leads to the use of ice descriptions such as fast ice, pack ice, drift ice, broken ice, brash ice, grease ice, and frazil ice. The spreading of oil is greatly affected by the ice conditions.

With ice concentration of about 40% and a slow drift ice situation the ice may work as a natural barrier. The ice may capture the oil slick between the ice floes and thereby prevent it from spreading. If the spill occurs on top of an ice field, the presence of a snow layer also affects the behavior of the spill as oil may be absorbed and contained by the snow.

Ice concentrations of over 60% can naturally contain oil in relatively thick films (of a millimeter or more). Freeze-up oil/ice interactions are controlled by grease and ice slush. Encapsulation of under-ice spills stops weathering but limits access. The ice drift rate controls the thickness of the oil layer that can accumulate on the surface with an extended release. Spring migration through porous ice exposes fresh oil naturally (Westerberg 2012).

The JIP research program advanced oil spill trajectory modelling by supporting the development of several improved higher-resolution ice drift models that outperform existing models both in pack ice environments with high ice concentrations and more dispersed dynamic ice associated with Marginal Ice Zones (MIZ). Nansen Environmental and Remote Sensing Centre (NERSC) (Ólason et al. 2016) performed the JIP Phase 1 ice modelling efforts, focusing on three model developments: (1) a discrete element (DE) model for the Marginal Ice Zone (MIZ), (2) the Elasto-Brittle (EB) ice rheology model, which is an improvement over the standard (historically used) EVP rheology algorithm for the ice pack, and (3) integration of a wave-in-ice model (WIM) into a high-resolution version of their TOPAZ ocean and ice model. NERSC noticed the DE model was best under MIZ conditions, but it is not suitable for operational use and takes too much time and effort. The newly developed EB model showed significant improvement in performance over the present Elastic-Viscous-Plastic (EVP) modelling approach used in the operational forecast and reanalysis versions of their TOPAZ coupled ice-ocean model. NERSC also integrated a wave-in-ice model (WIM) into a newly updated version of TOPAZ to characterize waves in the Marginal Ice Zone (MIZ). The models OILMAP and SIMAP were updated, integrating the NERSC ice modelling products for use in transport and oil weathering algorithms. Besides the remarkable improvements of the models, while comparing updated models with in-situ data it was noticed that the accuracy of individual oil model trajectories projected weeks to months into the future were expected to be low. This is why in the case of real spill, forecasts should be updated frequently (on a time scale of hours to days) e.g. with satellite data, aerial observations or drifter data (Ólason et al. 2016; French-McKay et al. 2017).

In addition to OILMAP and SIMAP, there are many other software programs used to forecast oil spill drifting in open water conditions. Spill event models operate on comparatively small scales in space and time. During and after the occurrence of a spill event, a spill is distributed in the environment in accordance with the properties of the substance(s) and the environmental conditions. Oil drift modelling has been developed much since the 1980s, and there are now several models available. Differences in forecasting quality are mainly related to externalities, e.g. model set-up. Several commercial or free software programs are available and those listed or described below are just a sample:

<u>ADIOS2</u>

ADIOS® (Automated Data Inquiry for Oil Spills) is NOAA's oil weathering model. It is an oil spill response tool that models how different types of oil weather undergo physical and chemical changes in the marine environment. See more at http://response.restoration.noaa.gov

<u>BSH dmod</u>

The BSH dmod model is described in Dick and Soetje (1990) and applied in e.g. Murawski and Nielsen (2013). The model is able to deal with ship driving fuel oils and a variety of natural crude oils.

<u>CAROCS</u>

The Computer Aided Rescue and Oil Combating System (CAROCS) model is described in Chybicki et al. (2008). It was designed and developed by the Maritime Institute in Gdansk (MIG). Among the processes influencing oil spill dispersion, this model considers 1) advection caused by sea currents and wind, 2) wave height and direction, 3) vertical and horizontal diffusion of oil spill droplets, and 4) vaporization and dispersion. The model also utilizes the High Resolution Operational Model for the Baltic Sea (HIROMB) hydrodynamic operational model designed specifically for the Baltic Sea as well as the WAM4 wave forecast model as input. Together with the POSEIDON model, it is used in the integrative GIS framework presented in Kulawiak et al. (2010).

GNOME

The General NOAA Operational Modeling Environment (GNOME) model (Figure 17) supports the NOAA/National Ocean Service (NOS), Office of Response and Restoration (OR&R), Emergency Response Division (ERD) standard for best guess and minimum regret trajectories by providing information about where the spill is most likely to go (Best Guess Solution) and the uncertainty bound (Minimum Regret Solution). Further information:
http://response.restoration.noaa.gov/ as well as NOAA (2002), Beegle-Krause et al. (2003), Chen et al. (2011), NOAA (2012).

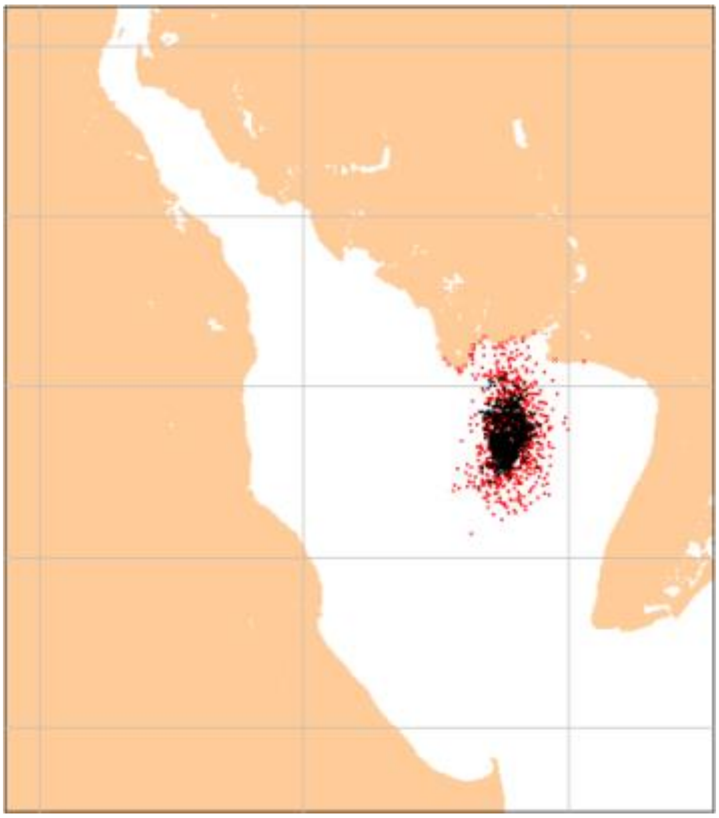

Figure 17. GNOME model output depicting relative distribution of oil. *https://response.restoration.noaa.gov/oil-and-chemical-spills/oil-spills/response-tools/gnome.html .*

MEDSLIK2

The oil drifting model in the Mediterranean area, MEDSLIK2 (De Dominicis et al. 2013a, b), is similar to Seatrack Web, but the backtracking is missing in MEDSLIK2.

MOHID

The Mohid Desktop Spill Simulator has been developed within the ARCOPOL (The Atlantic Regions' Coastal Pollution Response) project (ARCOPOL 2011a). It is a fast oil and inert spill Lagrangian simulator integrating offline metocean forecasts from several different institutions in the Atlantic Area for the regions or ARCOPOL partners. This desktop client application allows end users to have control over model simulations. Parameters such as the date and time of the event, location and oil spill volume are provided to the users; this interactive tool integrates best available metocean forecasts (waves, meteorological, hydrodynamics) from different institutions in the Atlantic Area. Metocean data are continuously gathered from remote servers or ftp sites, and then automatically interpolated and pre-processed to be available for the simulators. This simulation tool can also import initial data and export results from/to remote servers, using OGC WFS services. Simulations are provided to end users in a matter of seconds, and thus can be very useful in emergency situations. The backtracking modelling feature and the possibility of importing spill locations from remote servers with observed data (for example, from flight surveillance or remote sensing) allow the potential for application to evaluate possible contamination sources. The numerical model used to simulate spill fate and behavior in this application is the Lagrangian component of the MOHID water modelling system, including an oil spill module.

MOTHY

MOTHY is a 3D pollutant drift model implemented by Météo-France for the Mediterranean Sea and the Black Sea (also worldwide). Operated since 1994 in the marine forecast section at Météo-France, MOTHY was used extensively for the Erika and the Prestige incidents. The system is operated at the request of CEDRE for support of the oil spill fighting operations and on demands of the Marine Rescue Coordination Centres for support of the search and rescue operations. CEDRE is also developing the MOTHY for HNS spill modelling. A meteorologist on duty is able to run the model around the clock. About 500 interventions each year are conducted with an averaged time response of 30 minutes. Pollutants can be oil or floating objects. Current in the mixed layer is computed using a combination of a shallow water model driven by the wind and the atmospheric pressure, coupled to an analytical turbulent viscosity model, so as to represent vertical current shear, and a background current provided by an oceanic model (MERCATOR or MFS). A continuous profile from surface to bottom describes the water column. The length of the forecast is, for most cases, 2 or 3 days but 10-day

forecasts are available. For specific cases, probabilistic forecasts up to 10 days can be managed. Additional oil spill model capabilities: beaching,
sedimentation, and backtracking. MOTHY predicts each pollutant parcel in size, position coordinates (Lat, Lon), position in the water column (surface, bottom or in the column) or beached. Documents on the Mothy model can be found at:
http://www.meteorologie.eu.org/mothy/english.html and
http://www.meteorologie.eu.org/mothy/references/ .

OD3D

OD3D (Martinsen et al. 1994, Wettre et al. 2001) calculates the drift and chemical evolution of a marine oil spill in the guise of a number of “superparticles,” each of which represents a certain amount of oil or its byproducts. The user may choose from a range of oil types for the spilled oil. The oil slick is modified by advection due to currents and by weathering, evaporation, dispersion, emulsification due to exposure to air, water and waves over time. In addition, the model includes a novel deep blowout sub-model for oil sources below the surface. The core of OD3D has been developed in cooperation with SINTEF (Trondheim, Norway).

OilMARS

The 3D Oil Spill Model for the Arctic Seas (OilMARS) was developed at the Arctic and Antarctic Research Institute (AARI, St Petersburg, Russia). The model simulates the transport and transformation of oil pollution on the sea surface after continuous/instantaneous accidental oil spills from stationary or moving sources, the spreading of the observed oil slicks on the sea surface, and the oil pollution in the water column (Stanovoy et al. 2012).

OILSPILL

The Oil spill Risk Analysis Model of the U.S. Geological Survey is described in Smith et al. (1982).

OSCAR

SINTEF has the OSCAR modelling tool for oil spill drift and spreading estimations. It is scenario-based software. http://www.sintef.no

OSERIT

The Belgian MUMM's OSERIT oil drift and fate model interface (Dulière et al. 2013) is a 24/7 accessible support tool for evaluation of an oil spill report by MUMM duty personnel, Coast Guard Centers and other governmental authorities involved in oil pollution response at sea or the follow-up of (presumed) illegal pollution. The user-friendly interface allows duty personnel of these organizations to automatically obtain a first, quick simulation of the spill drift by entering, at the very least, the spill time and location. When using the oil model interface, a simulation will be generated in near-real time that contains either (1) a forecasting of the drift (simulation of future trajectory up to 4 days), which can be used to evaluate the possible impact of an oil spill on resources at risk, or (2) a backtracking of the drift (simulation of past trajectory up to 4 days), which may facilitate the identification of the alleged polluter or pollution source – e.g. when combined with AIS data. OSERIT development was funded by the Belgian Federal Science Policy Office (BELSPO).

OSIS

Oil Spill Identification System: http://www.osis.biz/ss2.asp

POM-RW

A 3D hybrid flow/transport model to predict the dispersal of oil pollution in coastal waters (Korotenko et al. 2000,2002,2004). The transport module of the model takes predetermined current and turbulent diffusivities and uses Lagrangian tracking to predict the motion of individual particles (droplets), the sum of which constitutes a hypothetical oil spill. The basic processes affecting the fate of the oil spill are taken into account and parameterized in the transport model. Originally a Russian model, extensively applied in the Caspian Sea.

RiskTool

The Russian model RiskTool (Ivchenko 2013a) is a derivative of the spill transport model SPILLMOD (Ovsienko 2002). It utilises historical meteorological and hydrological data from the Baltic Sea region as forcing to facilitate realistic risk assessments for oil stranding. Information about RiskTool, of which documentation is limited, is complicated by the fact that a number of software products with the same or very similar name have been published for a variety of purposes in the realm of risk assessment. An application with a very similar name (DynamicRiskTool) has been developed within the ARCOPOL project in 2011 for marine traffic accidents (ARCOPOL 2011b).

Seatrack Web

Seatrack Web is the de facto official HELCOM oil drift forecasting and hindcasting system hosted by SMHI (Swedish Meteorological and Hydrological Institute), and developed by SMHI and FCOO (Defence Center for Operational Oceanography, Denmark) and BSH (Federal Maritime and Hydrographic Agency, Germany) and FMI (Finnish Meteorological Institute). Seatrack Web (Liungman and Mattsson 2011; SMHI 2012) is a user-friendly system for forecasts and backtracking of drift and spreading of oil, chemicals, algae and substances in water in the Gulf of Bothnia, the Gulf of Finland, the Baltic Sea, the Sounds, Kattegat, Skagerack and eastern part of the North Sea (out to 3° E). Seatrack Web's aim is to provide a tool for authorities in HELCOM countries for oil spill prediction, combating and identification of illegal polluters. STW uses the latest technology, 3D modelling, updated atmospheric and ocean forecasts and observations, satellite information and HELCOM's AIS system to provide a fast and effective service which is used operationally throughout the Baltic region by Coast Guards, Border Guards, Rescue Services and Environmental Institutes. The Seatrack system, including the oil spreading model PADM (Particle Dispersion Model) and graphical user interface, is continually being improved and optimized by a team of experts at SMHI, DCOO, BSH and FMI.

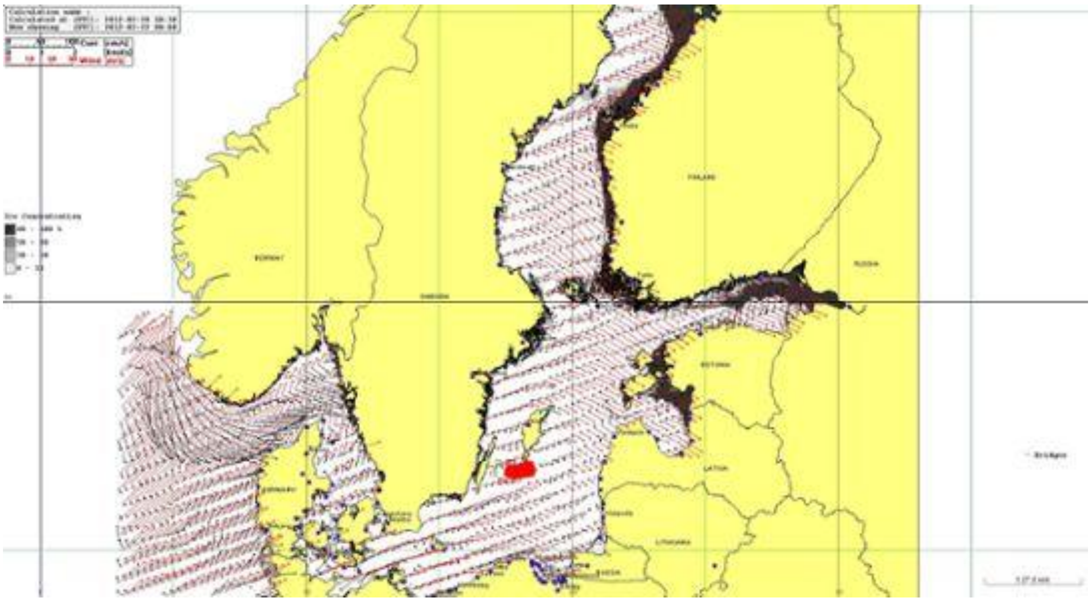

Figure 18. The results in Seatrack Web are presented graphically. The image shows the extent of ice, an oil discharge and a calculation of a fictive oil discharge.
https://www.smhi.se/en/services/professional-services/environment/forecasts-of-oil-spills-1.7624

SPILLMOD

The Russian spill transport model SPILLMOD (Ovsienko 2002; Ivchenko 2013b) was developed by the late S. Ovsienko. It has been applied in the Baltic Sea.

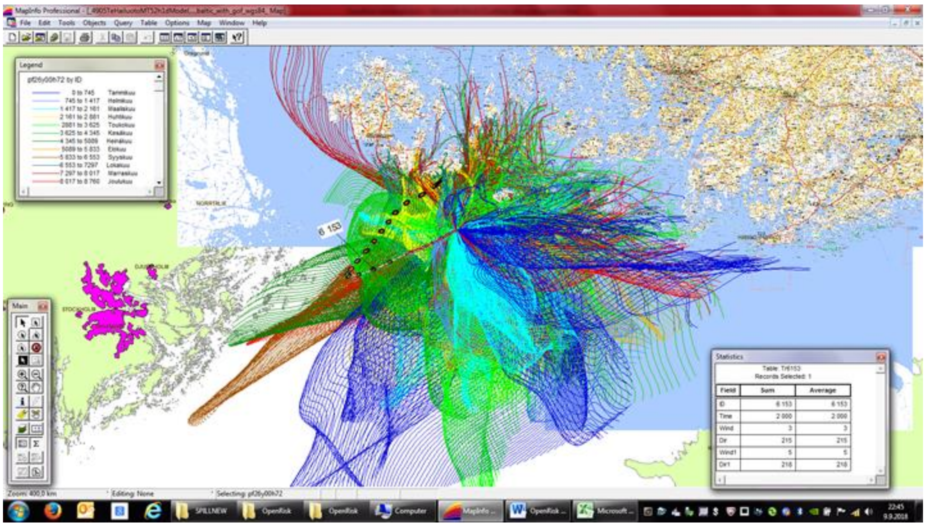

Figure 19. An example of the SPILLMOD calculation where the estimated trajectories of an oil spill have been calculated using statistical long-term wind and current data (Laine, V. et al 2018).

<u>COHERENS</u>

Models developed using the COHERENS (Luyten et al. 1999) modelling tool represent the group of 3D circulation and transport models most commonly used for biogeochemical applications, e.g. phytoplankton dynamics. These are traditionally concerned with dissolved and particular components in the water phase.

There is, however, and increasing interest in using and further developing 3D models also for HNS applications. COHERENS stands for COupled Hydrodynamical Ecological model for REgioNal Shelf seas, and originates from RBINS-MUMM, Belgium. It is a 3D finite difference, s-layer, multi-purpose numerical model designed for application in coastal and shelf seas, estuaries, lakes and reservoirs. The code is open source, available to the public since 2000. It is multi-platform and has an extremely good documentation (1,500+ pages). COHERENS is modular in its design, and very flexible and expandable. It is actively developed and constantly evolving.

<u>DREAM</u>

DREAM (Dose-related Risk and Effects Assessment Model) is a particle model developed by SINTEF. DREAM is part of MEMW (Marine Environmental Modeling Workbench) that also contains OSCAR (Oil Spill Contingency and Response for contingency planning) and ParTrack, for drill muds, cuttings, and associated chemicals. The SINTEF OWM (the Oil Weathering Module), available as a separate model, is also used as the weathering engine in OSCAR. The possibilities of MEMW are comprehensive. Examples:

• Particle model for oil, chemicals and solid material (such as sediments)
• Extensive chemical and oil database that can be extended or adjusted by the user
• Biological module (effect on fish, plankton, etc.)
• Use of GIS (for example to designate ecologically sensitive areas)
• Definition of mechanical recovery systems (like skimmers, dispersants)
• Extensive graphical output (particles, concentrations, concentrations per component, etc.)
• Graphical presentation of flow, wind, etc.
• Definition of habitat and depth grid
• 3D particle behavior
• Allows import of bathymetric database.

A particular feature of DREAM is that oil or chemical products can be fed into the program by specifying the real components. These components are defined in DREAM using many chemical and physical specifications. After a spill, these components behave differently: some evaporate, some dissolve, etc. DREAM is able to give detailed information on behavior and spread for the different phases and components of the spill (Jong 2004). DREAM is not publicly available, but SINTEF may run the model for a substantial fee.

Monitoring

Successful countermeasures against oil spill require an adequate preparedness, a large toolbox of oil recovery methods, trained personnel and excellent communication and surveillance means. When an accident takes place and results in an oil spill outflow from a ship or from a drilling platform, it is of primary importance to have tools to locate the spill, to follow the spill and to have tools to follow effectiveness of the selected countermeasures. The fresh data describing the fate of an oil spill is crucial knowledge for the on-scene commander of the responders to form a situational awareness view of the case.

There is a large set of sensors and tools available for oil spill detection and tracking. The usual way to initiate countermeasures against detected oil spill is based on the first alert made by the ship(s) in distress, some other party close the accident or a third party getting data based on remote-controlled means. Typical remote-controlled party is a surveillance aircraft or helicopter flying over the oil spill and detecting a spill and giving the first warning to authorities. Another option is to get an alert via satellite images, for example as a part of the EMSA’s CleanSeaNet service. After receiving the initial information about the oil spill, the combatting authority needs on-line information about the expected size, position, drift velocity and direction to mobilize the required countermeasures and to have time to localize special sensitive areas to be protected by booms or other relevant ways (Rytkönen, J. et al 2018).

Oil spill detection

There are basically three main reasons why crude oil and refined oils are detectable with optical sensors, i.e. based on the visible spectrum:

- in optical terms the refraction index is greater than for the water,
- the light absorption coefficient is stronger than for water and
- oil tends to be fluorescent when subjected to bright natural light.

The above-mentioned properties make it possible also to measure the thickness of the oil slick. Additionally, classification into the basic oil categories can be made, i.e. whether or not the oil may belong to crude oil, refined light oils, or heavy oils.

Typically, the information required both for satellite and airborne surveillance tasks includes

- the area of the oil slick and its position,
- estimated oil type and physical properties,
- estimated oil slick thickness: very often 80% of the amount of oil will stay in 20% of the total area of the oil slick, making this information of perhaps the greatest importance from the countermeasures point of view,
- oil alteration, dispersed oil extension and
- confidence level of the oil detected (or possible other source of pollutant or algae blooming. Information about the confidence level is more accurate if the visual observations can be confirmed by thermal images.

The most common sensor types for remote monitoring are infrared sensors, sensors using microwaves (both active and passive). The most common active sensor type is the Synthetic Aperture Radar (SAR) which probes variations of the short gravity-capillary waves.

Satellites currently offer reliable images for oil combating authorities to determine if a certain sea area is affected by oil spills or not. In an operative situation, there is a need to get more detailed data, confirmation of the slick size and type and of the oil slick spreading phenomenon, so various surveillance means are needed to receive a sufficiently accurate view of the situation.

SAR satellite images cannot provide information on the nature of a spill (for instance whether it is mineral oil, fish or vegetable oil, or other), but spills from vessels often appear as long, linear dark lines (indicating a substance discharging as the vessel is moving), with a bright spot (the vessel) at the tip. Vessel detection is also available through the CleanSeaNet service. CleanSeaNet is a satellite-based oil spill surveillance and vessel detection service which analyzes SAR images from satellites to detect possible oil spills on the sea surface. If a vessel is detected in a satellite image, its identity can often be determined by correlating the satellite data with vessel positioning reports from the European monitoring systems operated at EMSA, such as SafeSeaNet. http://www.emsa.europa.eu/ssn-main.html Even though SAR satellites may be the most advanced satellite-sensor combination, optical satellites are also used for spill detection. Due to the many constraints, however, the optical satellite images are often used as secondary remote monitoring options as SAR satellites will give a better response for oil slick detection. Table 4 shows a set of optical satellite types available.

Table 4. Operational optical satellites (Puestow, T, 2013).

Instrument	Resolution (m)	Swath (km)	Revisit (days)
LANDSAT 5, 7, 8	15 - 30 (MS) and 120 (TIR)	185	16
MODIS	250 to 1000	2330	1-2
MISR	275 to 1100	360	2-9
DMC	20 to 30	600	Near daily
SENTINEL-2	10 to 60	290	Near daily; to be launched 2014
QuickBird	0.6-2.4	16.4	1-3.5 days
Worldview-1/2	0.5-1.8	16.4	Near daily
Geoeye	0.41-1.35(MS)	15.2	2.1 days

Other means for oil spill detection

The choice of sensors or platform used to carry out detection or surveillance tasks depends heavily on the each case: environmental conditions and season, as well the spill characteristics, may vary case by case. For open water oil spill detection, the optimal devices might be different than for ice conditions. To get an understanding of the suitable means available, the remote surveillance task can be divided into two main categories: deployment platforms and sensors/systems onboard those platforms. The third category is then the integrated use of the set of sensors and devices to fulfil the oil detection task to support the operative countermeasures and to improve the operational situational view over the accidental and surrounding area.

Many of the recent guidelines available are concentrated on the oil-in-ice characteristics and the various environmental conditions where oil and ice can interact. Oil slicks in ice conditions can be met in:

- freezing conditions,
- early stages of ice formation (frazil ice, pancake ice), where oil can also be trapped in a horizontal layer over the forming ice layer,
- between the ice floes where the ice and water coverage ratio will vary between 0 and 100
- moving ice and

- in the conditions where oil may lie partly or totally under ice, covered by snow (Rytkönen, J. 2018).

There are three main activities related to management of oil spills in the marine environment in which satellite remote sensing has a role: contingency planning, emergency response and monitoring:

- Contingency planning for oil spills involves gathering baseline data, identifying economically and environmentally sensitive areas and assessing the availability of facilities and equipment to be used in clean-up efforts should an oil spill occur.
- Emergency response to a specific oil spill incident involves identification of the location and extent of a spill and short-term monitoring of the spill.
- A monitoring program involves frequent imaging of areas where spills or illegal dumping are likely to occur (Northwest Pacific Action Plan [NOWPAP]).

Satellites have regular orbit runs over oceans and coastal areas; thus they can be used effectively for gathering statistical information. Oil slicks can be found all over the world.

The advantages of using satellites for oil spill detection are the following:

- They can cover a large area in a short period of time
- Data may be transmitted via the internet almost immediately
- Many radar satellites are useful in detecting large offshore spills and spotting anomalies
- Some operational commercial satellites can be tasked to respond to emergencies within a range of 90 minutes to 4 hours.

Disadvantages include the following:

- The timing and frequency of overpasses by satellite systems may not be optimal for the situation
- Clear skies are needed to perform optical work
- The probability of detecting oil may be low
- Developing algorithms to highlight oil slicks is difficult
- Extensive time may be required to convert data into actionable information.

Extensive studies conducted by SINTEF in Oil In Ice – JIP and in Arctic Oil Spill Response Technology Joint Industry Programme (JIP) and recent R&D Finland in sensor technology have also listed a set of modern sensors and their suitability areas as follows:

•Passive optical sensors: cameras and multispectral imaging systems, ultraviolet (UV) and Near-InfraRed (NIR) sensors, hyperspectral sensors
•Passive Thermal InfraRed sensors (TIRs) and Micro-Wave Radiometer (MWR) systems
•Active radar sensors: Side-Looking Airborne Radar (SLAR) and Synthetic Aperture Radar (SAR) systems, Marine Radar, Ground Penetrating Radar (GPR)
•Active Laser and fluorosensors: fluorosensors, Tunable Diode Laser Spectroscopy (TDLS), Laser-Ultrasonic Remote Sensing of Oil Thickness (LURSOT), Light Detection and Ranging LiDAR
•Experimental sensors: Acoustic Sensors, Nuclear Magnetic Resonance (NMR) Spectroscopy, trained dogs.

Monitoring onboard vessels and offshore structures

Common systems for oil spill detection onboard vessels are visual observations using the naked eye, binoculars, cameras and video cameras. It is also common knowledge that skippers of response vessels have outdoor observers on the deck (or keep the bridged door open) to notice any oil smell, for example in dark situations where the poor visibility makes it not possible to use optical means to detect oil.

There are also numerous, more sophisticated tools for oil detection such as:

- oil radars, which use of the ship’s existing X-band radar. They have options also for wave monitoring algorithms, radar with horizontal and vertical polarization and often support for the ship’s IR censor system;
- infrared camera systems;
- UAVs (unmanned aerial vehicle) (drones)
- AUVs (autonomous underwater vehicle) and
- tethered balloon systems.

UAVs may also offer solutions for surveillance close to the vessel or offshore platform (copter type solutions) or remote operations with fixed wing solutions. There are commercially available solutions where UAVs can be launched from the ship deck and also various means to get the UAV back after a surveillance flight.

Figure 20. Tekever AR5 – a fixed wing UAS for oil spill surveillance (Rees, M. 2017).

Autonomous drifting buoys, drifters

Autonomous drifting buoys for oil spill monitoring are specially designed buoys to be used to follow oil spill movement. During the oil spill, these buoys will be carried out to the spill site, deployed in the water and left to move with the oil. The system will send position data and thus give on-line information about the drift and current position of the oil slick.

A typical drift buoy uses Iridium telemetry which is the most cost-effective means of transmitting data for environmental applications. The Iridium modem provides the end users with lower transmission costs and an increase in data throughput.

Drifters are also used in Finland for operative oil combating. The competent oil combating authority, the Finnish Environment Institute (SYKE), has a joint agreement with the Finnish Meteorological Institute (FMI) and Finnish Border Guard to use drifters in accident situations: In the case of a detected large-scale oil spill, the Finnish Border Guard will deploy drifters using a patrol boat, ship or helicopter. Data sent by the drifter will be received by FMI and be transferred to SYKE where the trajectories will be analyzed using SeaTrack Web numerical analyses. Similar procedures could also be used in Arctic conditions, where drifters can be deployed from helicopter, aircraft or larger UAV.

Table 5. Remote sensing technologies – sensors and their application range (Watkins, R 2016).

Sensor	Sensor Abbreviation	Deployment Platform	Detection	Application
Visual / Optical	VIS / OPT	Stable ice surface, offshore platform, airborne, Unmanned Aerial Vehicle (UAV), shipborne, Autonomous Underwater Vehicle (AUV), Remotely Operated Vehicle (ROV)	Reflected visible light contrast between oil and water	Detection of oil extent and estimated layer thickness (e.g. BAOAC)
Thermal Infrared / Forward-looking Infrared	TIR / FLIR	Stable ice surface, offshore platform, airborne, shipborne	Thermal emissivity differences between oil and surrounding ice/water	Detection of oil extent and possibly distinguish between thin and thick oil slicks
Ultraviolet	UV	Airborne, UAV	Reflected ultraviolet contrast between oil and water	Detection of oil extent and detection of thin oil slicks and sheens
Laser Fluorosensor / Light Detecting and Ranging System	LFS / LIDAR	Airborne and under ice platforms	Fluoresced light emissions from aromatic components of oil	Detection of oil on or just below the sea surface and estimated layer thickness
Sonar (multi-beam, broadband and narrowband, single beam)	Sonar	AUV, ROV	Reflected acoustic signals to image oil below the ice or oil on water surfaces	3D under ice mapping and detection of potential oil layers under ice or minimally encapsulated
Marine Radar (x-band)	Marine Radar	Offshore platform, shipborne	Variations of the reflected radar backscatter signals from oil and surrounding water	Detection of oil and extent on the sea surface within operating range limits
Side-looking Airborne Radar	SLAR	Fixed-wing aircraft	Differences in the backscatter signals from waves dampened by oil and surrounding water surfaces	Detection of oil and extent on the sea surface
Synthetic Aperture Radar	SAR	Satellite, airborne	Differences in the backscatter signals from waves dampened by oil and surrounding water surfaces	Detection of oil and extent on the sea surface
Ground-penetrating Radar	GPR	Stable ice surface, helicopter (oil on ice under snow)	Electromagnetic backscatter signals imaging oil and ice	Detection of oil through snow and ice
Dogs	Dogs	Stable ice surface	Olfactory hydrocarbon recognition	Detection of oil on, in and under snow and ice

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APP4SEA is funded under the European Regional Development Fund (ERDF)
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