Biological Effects of Oil-in-ice in the Arctic

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1. Abstract

Given the reluctance to conduct large-scale oil spill experiments in ice and the good fortune not to have spills of opportunity to study, it should not be surprising that our knowledge of the fate of oil in ice is limited, and our understanding of the effects of the oil on the epontic (sea ice) biota is even more restricted. Many questions remain about transport rates of various hydrocarbon components through sea ice. Results to date on the effects on the microbial communities are mixed. Biodiversity has been found to increase and decrease, cell counts have increased and decreased, and photosynthetic rates increase and decrease. Some of the conflicting results may be due to the findings coming from a mixture of laboratory and in-situ results. The impact of oil-in-ice on zooplankton appears to depend on the species, the characteristics of the oil, and environmental factors. Recent work has focused on standardizing tests to ensure results between experiments are comparable. The complexities of the winter ice habitat are difficult to recreate and need to be considered when interpreting the results.

2. Background

This review focuses on the effects of oil-in-ice on the biology of the Arctic. It includes some information about the effects of oil on or below ice, but does not include the effects in cold marine waters. This review concentrates on what we know rather than what we might be able to infer. Much of the research was conducted in the 1970s and 1980s and published in grey literature, which is becoming difficult to access. With increasing transportation, exploration, and development of oil on the Arctic Sea shelf area there is a potential for a spill to occur at any stage of ice development from the early stages of ice growth, to its maturation into first-year and multi-year ice, and to the melt season with its associated decay of ice. Yet, if a spill were to occur, what would be our knowledge of the effects on the biological systems?

There are a few good reviews of the effects of oil on Arctic biological systems (Duval et al., 1985; Englehardt, 1985; Ikävalko, 2005). After reading these, it is obvious little is known about the effects of hydrocarbons on the biology of the Arctic, and less is known about the effects of oil-in-ice. There have been some studies that examine the fate of oil in the freezing environment and in ice, but they are limited, and have focused on the transport of bulk oil in the ice. There is considerably less information regarding the effects on biology because the basic transport questions needed to be addressed first to have some understanding of the biological exposure. There is also limited knowledge of the biological communities that might be at risk. The heterogeneous distribution of most biological components means that large-scale experiments and spills of opportunity are the most likely ways to observe the effects on the biological communities. For microscopic organisms laboratory experiments may provide valuable insight into the effects of oil on the ecosystem. As well, laboratory experiments are currently being conducted to examine the effects of the water soluble components of oil on amphipods and cod (Camus and Dahle, 2007).

While there has been extremely little research done on the effects of oil-in-ice on Arctic biology, there is more information available on the effects of oil in Arctic waters (e.g. see volumes 31 and 40 of the journal Arctic) and even more information from sub-Arctic and temperate waters. The lack of direct information on the effects of oil-in-ice on biology means that the effects must be inferred from studies outside of ice. It has been shown that Arctic organisms may respond differently then temperate organisms to the presence of oil because of the differences in metabolism (Chapman and Riddle, 2005). It is important to remember that the ice environment is very different from a marine environment so care must be taken when extrapolating effects to the ice environment. Even work from the Antarctic must be transferred to the Arctic with care. There are significant differences in the sea ice formed in the Antarctic and Arctic because of the relative degree of open water around the edges of the sea ice. The Antarctic ice tends to be more porous and has less columnar ice than in the Arctic. Differences in biological communities in the two Polar Regions may also change the impacts of oil on the biological community.

This document relies heavily on previously published literature reviews. The primary sources of information include Fingas and Hollebone (2003) for physical transport, and Duval (1985) and Ikävalko (2005) for effects on biology. This report addresses the fate of oil-in-ice, the microbial community, and eponic biota such as amphipods. The microbial community is the only one that is likely to be directly affected once the oil is encapsulated. Other organisms are most likely going to be affected only after the encapsulated oil is released, or indirectly through feeding on contaminated organisms.

3. Fate of oil-in-ice

To understand the effects of oil-in-ice on biology it is important to know the fate and behavior of oil-in-ice. As might be expected, the majority of research examining oil-in-ice has focused on its fate and behavior. Fingas and Hollebone (2003) completed a recent review of the findings from research on the behavior of oil in freezing environments. The work to date has focused on bulk oil and has only recently begun to examine how components may be differentially transported (Faksness and Brandvik, 2005). Because of differences in solubility and toxicology of the different components, the transport of different fractions remains an important area of study.

Studies have examined the fate of bulk oil in margins with grease, brash, and pancake ice (Martin et al., 1977; Wilson and Mackay, 1987; Fingas, 1993). Depending on environmental conditions the oil may be incorporated into the ice structure as the ice congeals or is washed to the surface of the ice where it is trapped and weathers. Oil trapped in ice will remain near the surface of the ocean until the next melt season when it will be quickly be released to the ice surface.

Oil spilled under first-year and multi-year ice can be transported under the ice surface until it reaches a shallow point, or it can be incorporated into the ice (NORCOR Engineering, 1975; Dome Petroleum Ltd., 1981, Buist et al., 1983). The time required to encapsulate the oil into the ice is dependent on growth conditions, such as air-ice-water temperature, ice thickness, and quantity of oil to be encapsulated (Izumiyama et al, 2003). The roughness of the ice-water interface may also play a role in how the oil is incorporated. In the presence of a current the c-axes of the ice crystals align, creating regular striations that the oil can become embedded in.

Once the oil is encapsulated it is transported along the brine channels within the ice (Martin, 1979). Flow through these channels depends on the permeability and remains slow through the winter. As the ice begins to warm the brine channels widen and connect allowing the oil to flow to the surface of the ice. Brine channels begin to connect at ice temperatures above -5°C (Eiken, 2003). Once warmed, the oil can flow through 1.5 m of ice within an hour (NORCOR, 1975). Solar heating of the oil may accelerate its flow towards the surface by allowing it to melt through the ice (Glaeser and Vance, 1971; Chen 1972, NORCOR, 1975). Buist et al. (1983) showed that a water-oil emulsion did not transport through the brine channels in the manner of oil alone. Water soluble components of encapsulated oil can also be transported downward in brine channels through diffusion and during brine rejection (Faksness and Brandvik, 2005). Oil can also surface because of ablation of the surface ice down to the oil layer. Comfort and Purves (1982) showed that the transport through multi-year ice followed a similar pattern to that observed in first-year ice. Transport times in multi-year ice may be longer because of a reduced drainage system in multi-year ice.

It is important to note that the oil encapsulated within the ice is not weathered. The release of oil due to transport through the ice or because of lead formation releasing oil pools brings up the fresh oil which is more toxic than weathered varieties. At this time we cannot predict the routes of exposure, concentration of oil components, or the duration of the oil presence throughout a core of ice, which prevents us from understanding the potential toxicity of encapsulated oil on ice biological communities. The toxicity of oil is not the only means by which the biological communities are affected; they can also be affected by changes in the ice habitat caused by the presence of oil. The fact that the effects of oil-in-ice is dependent on the droplet size of the oil incorporated is assumed in the following section.

4. Effects on microbial organisms

Here we are considering only the epontic (in or under ice) organisms. Within the ice all of the organisms are microscopic in size. Larger life forms live on the top and bottom of the ice. However, the ice bottom is the primary area for microscopic phototrophic algae with lesser amounts contained in the ice. High concentrations of algae can exist on the ice bottom during the spring (Alexander, 1974; Horner et al., 1974). Adams (1975) found an increase in biodiversity in the waters under oiled ice, but it is not clear what changes occurred in the ice. When in direct contact with oil the algae can be killed, and species specific mortality has been observed in the field (Acreman et al., 1980). In that instance there were small, but significant changes, in the mortality of the diatoms *Nitzschia cylindrus, Porosira glacialis, and Coscinodiscus lacustris* compared to the mortality of all diatoms. Cross (1987) did not observe a change in populations in areas surrounding small quantities of oil. Hsiao (1978) did find differences in sensitivity to oil in the in-water phytoplankton community. Ikävalko et al. (2004) conducted an experiment where oil was added to the ice surface and then microbial communities throughout the ice column were followed. They found that the addition of oil decreased the quantity of all organisms, including primary producers, throughout the ice column. When a fertilizer was added to the oil, there was a distinct community shift towards the diatoms. They hypothesize that the silica frustules of the diatoms provides some protection. That aspect and the diatoms' ability to form a resting stage may allow them to recover more rapidly from the presence of hydrocarbons. Interestingly, Adams (1975) reported that large amounts of algae were found on the surface of the ice where oil burn residue had deposited.

Besides changes in epontic algae communities, the presence of oil may inhibit primary productivity. In field experiments, Cross (1982) found that photosynthesis was inhibited starting at oil concentrations between 300 and 10,000 mg/L. Cross (1987) found that primary production surrounding small amounts of oil can increase. He hypothesized the effect was due to suppressed grazing, or increased micronutrients from the oil. This is consistent with the results for Beaufort Sea phytoplankton (Hsia et al., 1978). Adams (1975) found increased productivity in the water below oiled ice even though there was less light. In laboratory experiments, Van Baalen and O'Donnell (1984) also observed no change in the photosynthetic rate of *Nitzschi sp.* after a three hour treatment with crude oil (625 mg/L) and fuel oil (250 mg/L). They also found that there was an inhibition in growth rate, and the inhibition increased at lower temperatures.

Besides toxic effects, the presence of oil-in-ice will change the light field and thus the productivity of the primary producers. Primary productivity is directly related to light levels. The amount of light reaching under the ice is dependent on the scattering and absorption that takes place in the atmosphere and ice. Oil is a strong absorber and in large quantities can disrupt the light field. Snow scatters light very effectively, thereby reducing light levels. Moderate amounts of oil do not affect the light field under the ice any more than the natural variations in snow depth and ice thickness (Cross and Martin, 1983).

The presence of oil on the bottom surface of the ice removes habitat used by microorganisms. Once the oil becomes encapsulated this change in the habitat is localized to that portion of the ice column and the impact to habitat is minimized.

Heterotrophic microorganisms are also affected by the presence of oil-in-ice. These are important organisms because of their role in the food web, and more importantly, they are the organisms responsible for biodegradation of oil. Once oil is encapsulated the only degradation that occurs is biodegradation. The toxicity of oil released at later dates is dependent on the response of the microbial community through the winter. Microbial activity has been documented at temperatures down to -20°C in sea ice (Junge et al., 2004) so there is potential for hydrocarbon degradation through the winter.

Research has shown that oil can cause mortality, or have growth and development effects in temperate species. There is a limited amount of research on epontic species, particularly in situ studies. Atlas et al. (1978) found there was a slight increase in oil-degrading bacteria in sea ice, but not nearly the increase seen in the water and sediment communities. They conjecture that the epontic communities are limited by other nutrients. Ikävalko et al. (2004) found that heterotrophic flagellates appeared to migrate downward when oil was added to the upper surface of the ice. The numbers of organisms also decreased in the presence of oil. Gerdes et al. (2005) incubated several bacterial strains isolated from sea ice samples and tested their response to crude oil and their ability to utilize hexadecane and toluene. They found a marked reduction in the diversity of the microbial community after a one-year incubation with crude oil. There was a shift towards three species of γ-proteobacteria, *Marinobacter* spp., *Shewanella* spp., and *Psuedomonas* spp. These species are closely affiliated with known hydocarbonoclastic bacteria in other environments (Gerdes et al., 2005), and are likely to be able to biodegrade hydrocarbons. Their tests showed that these species were able to degrade hexadecane at 1°C. Gerdes and Brinkman (2005), however, reported that there appears to be no biodegradation of crude oil encapsulated in ice at temperature below the freezing point. That result was consistent with the findings of Atlas et al. (1978), who found very little loss of hydrocarbons in samples at both ice surfaces. In a study in Antarctic sea ice, Delille et al. (1997) found that there was a three order of magnitude increase in hydrocarbon-utilizing bacteria, and the elevated population persisted throughout the winter when a fertilizer was present.

5. Effects on meiofauna

A variety of organisms colonize the underside of the ice to feed on the microscopic organisms such as bacteria and phytoplankton. These organisms include, amphipods, copepods nematodes and polychaetes to name a few. Organisms that live on the underside of the ice are at risk from getting mired in the oil, ingesting oil, and ingesting prey that has been exposed to oil. It has been shown that the organisms may not avoid oil slicks (Busdosh and Atlas, 1977; Cross, 1982), which increases their susceptibility to oil. Amphipod movement decreased when they were exposed to oil, even when their appendages were not fouled suggesting neuralmuscular damage had occurred (Percy and Mullin, 1977).

Amphipods species within the water were found to have different mortality rates in the presence of crude oil (Budosh and Atlas, 1977). This species difference may explain differences in mortality rates observed by Cross (1982) and Foy (1978, 1979). The toxicity of the oil may also be dependent on the life stage (Cross and Martin, 1983). Budosh and Atlas (1977) found that the amphipods responded differently to different components of the oil and mortality rates increased when the animals were allowed to come in contact with the oil. They did not react to the presence of paraffinic components of the oil and became mired when they contacted the slicks. On the other hand they avoided the aromatic slicks, but died when exposure continued. They showed no toxicity when exposed to the asphaltic fraction; however, their respiration rates decreased. Changes in respiration were observed to be dependent on oil concentration by Percy and Mullins (1975). Low concentrations were found to depress respiration and higher concentrations increased it. There are effects on embryo's (Olsen et al., submitted a) and metabolism (Olsen et al., submitted b). The amphipod *Gammarus wilkitzkii* has been found to be fairly tolerant to the presence of the water soluble components of oil, but did change in appearance and have increased molting (Killie and Gulliksen, 1994; Hatlen, 2007). Killie and Gulliksen (1994) also found that the amphipod accumulated PAHs that could be transferred up the food chain.

Cross and Martin (1987) examined the effects of untreated oil, solidified oil, and three chemically dispersed oils on the underice meiofauna. They provided a single concentration (100 ppm) of oil within each enclosure. The untreated and solidified oil covered less than 10% of the ice within the enclosure and the biology was not sampled in the oiled areas. They found that the copepods and polychaetes populations decreased in the dispersed oil treatments, but were not affected in the untreated and solidified oil areas. The nematode population was not affected by any of the oil treatments. There was some evidence that individual species were affected differently. A higher proportion of adult and higher level copepodites were observed in the untreated oil and solidified oil enclosures compared to the controls. Although there was a decrease in overall copepod populations in the dispersed oil treatments the numbers of cyclopoi and calanoid nauplii remained constant in those enclosures.

While much of the existing literature has been available for some time, there are a number of new laboratory studies underway (Camus and Dahle, 2007). The effects of oil on higher trophic levels was the subject of a recent conference in Norway (Langtidsvirkninger av utslipp til sjø fra petroleumsvirksomheten (PROOF), September 2005). Much of our current knowledge centers on organisms found in shallower waters where the epontic and benthic fauna are often the same organisms. The newer studies are addressing species that are found in the Arctic pack ice.

6. Summary

Our knowledge of the effects of oil-in-ice on the Arctic ecosystem is extremely limited. Not surprisingly, much of the effort to date has focused on the fate of oil in ice, a question that must be answered before the biological effects can be understood. A basic understanding of the transport through ice has begun to be developed. There are still large areas to address regarding transport and fate, particularly in the rates of transport of water soluble components of crude oil. There is a distinct possibility that under-ice biota can be exposed to portions of encapsulated oil, but we do not have enough information to provide rudimentary estimates of exposure.

There have been a few experiments examining the response of the microbes to the presence of oil in ice and the results are not always consistent. There is some evidence that community structure can be altered (both increased and decreased biodiversity), quantity of organisms can increase or decrease, and that primary productivity can be enhanced by the presence of oil at low concentrations and inhibited by high concentrations of oil. Primary productivity generally takes place in the spring as the ice begins to warm and encapsulated oil begins to be transported through the ice. What happens during the colder winter months is less understood. There is some evidence that biodegradation may shut down at temperatures below freezing, but the reasons are not understood. It is not known if this is because of biological processes, nutrient limitation within brine drainage channels, or if the encapsulated oil is at toxic levels.

The inferences on the effects of oil-in-ice on higher trophic levels are covered in the reviews by Duval (1985), Engelhardt (1985), and Ikävalko (2005). The conclusion of Wells and Percy (1985) is that the impact of oil on the epontic community is difficult to predict because so little is known about that ecosystem. This is an area of research that is getting more attention at this time. Several new laboratory and field experiments are underway and more results are expected soon. The effects of the oil is dependent on species, life stage, oil type and concentration, and the use of dispersants. The cold environment of epontic organisms appears to drastically alter their tolerance of the water soluble fraction compared to more temperate species. However, they are more likely to become mired in oil because the biology and oil are concentrated at the ice-water interface.

7. References

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