SEA ICE CONTAMINATION: A REVIEW

Manfred A. Lange

ABSTRACT
The awareness of significant levels of contamination in arctic terrestrial and marine ecosystems has led to increasing research activities addressing this issue. This has resulted in the realization that most of the contaminants are extant to the Arctic and originate in the industrial centers of North America, East Asia, and Central Europe. Besides marine, fluvial, and atmospheric transports, sea ice plays an important role as a transport medium of contaminants. Because of the ever-increasing importance of offshore hydrocarbon deposits in arctic coastal waters, there is a growing threat of oil being spilled or seeped onto land or the ocean. The removal of oil in arctic waters is particularly difficult because of oil entering the sea ice pore spaces. Once entrapped, the oil will be transported through the Arctic Basin and will likely enter the water column either during seasonal melt events or upon the ice being melted entirely in the North Atlantic. In this paper, we review some of the important processes and conditions governing the fate of oil contamination in arctic sea ice.

INTRODUCTION
The Arctic has always been considered to be a pristine place, which is mostly untouched by human interference and largely devoid of contamination. Throughout this paper, we will adopt the UN's Group of Experts on Scientific Aspects of Marine Environmental Protection (GESAMP) terminology for contamination, which is defined as a statistically significant increase in the level of a substance over background levels and for pollution, which is defined as a measurable effect of such contamination on biota. In fact, the Arctic has, for a long time, been seen as something like a “natural clean room”. This view was held, because of the extremely low population density in the Circumpolar North and the limited human activities at high latitudes. It is only during the last few decades and through the onset of systematic investigations that we have started to realize the inadequacy of this picture (AMAP, 1998; Arctic-Centre, 1991; Twitchell, 1991).

Investigations over the last 10 to 20 years have centered on the nature, sources, pathways and effects of contaminants found in arctic ecosystems (see below). The drift
of contaminant-laden sea ice has been identified as a particularly important pathway whose exact role, however, remains to be determined.

In the following, we will briefly describe the nature and characteristics of contaminants found in the Arctic. A review on earlier research will specifically relate to the known effects and possible impacts on arctic ecosystems including local residents. The major part of the paper will focus on sea ice contamination by hydrocarbons as an increasingly important threat to arctic nature and communities.

**TYPES AND SOURCES OF CONTAMINANTS IN THE MARINE ENVIRONMENT**

Following the review by Barrie et al. (1992), we distinguish six major classes of contaminants that may be found in arctic sea ice (for further details see, Lange and Pfirman, 1998):

1. **Chlorinated industrial organic compounds**: Chlorobenzenes (CBZs), Polychlorinated benzenes (PCBs), Dioxins/furans;
2. **Organic pesticides**: Polychlorinated camphenes (PCCs or toxaphene), Hexachlorocyclohexanes (HCHs), Chlordane, Chlorinated hydrocarbons and metabolites (DDT/DDE);
3. **Polycyclic aromatic hydrocarbons**: e.g., Benzo (a) pyrene (B(a)P);
4. **Metals**: Mercury (Hg), Cadmium (Cd), Lead (Pb), Arsenic (As);
5. **Acids**: Sulfur oxides, Nitrogen oxides and
6. **Radio nuclides**: 1950s/1960s bomb test products, Chernobyl products (e.g. 137Cs), radioactive waste and decommissioned reactors from nuclear submarines and/or nuclear ice breakers, potential runoff from land-based sources.

This list of contaminants is also reflected in the priority list of substances to be investigated by the *Arctic Monitoring and Assessment Programme* (AMAP), which includes:

- a) Persistent organic pollutants (POPs)
- b) Heavy metals
- c) Radio nuclides
- d) Acidic compounds

Barrie et al. (1992) give detailed descriptions on the sources and the nature of the various contaminants listed above (see Tables 2 to 5 in Barrie et al., 1992). More recently, Pacyna (1995) published a review on the origin of Arctic air pollutants, which covers most of the compounds listed under 1. to 6. above.

In the following, we will concentrate on the contamination of sea ice as one component of the Arctic System. Because of its increasing economic importance, we will focus on hydrocarbons and their role as contaminants affecting arctic ecosystems (Lange and Pfirman, 1998; Robertson, 1998; Ruokonen and Lange, 1996). However, before getting into this subject, we will review the current state of knowledge on arctic contamination in general.

**SUMMARY OF PAST INVESTIGATIONS AND REMAINING UNCERTAINTIES**

In tune with the earlier stated contention of the “pristine Arctic”, the problem of contaminants in the Circumpolar North did not attain much attention until recently.
Aside from the points noted above, this was also due to the fact that substantial parts of the land and sea area, most notably those belonging to the former Soviet Union, could not be investigated and/or available data were regarded as sensitive and non-public data. A number of factors contributed to the onset and a steady intensification of research on arctic contamination issues:

- the ‘Arctic Haze’ phenomenon (Shaw, 1995; Soroos, 1992);
- oil and gas explorations in the American and Canadian Arctic and the need to carry out environmental assessment studies; some of this work has been summarized by Futsaeter et al. (1991), Payne et al. (1991) and Sydnes (1991);
- the *Arctic Environmental Protection Strategy* and its *Arctic Monitoring and Assessment Programme* (AMAP, 1998) (now a project under the *Arctic Council*) and
- a liberalization within the former Soviet Union and Russia, which allowed research and its publication in formerly ‘closed regions’ (Mel'nikov and Pavlov, 1978; Mel'nikov, 1991; Mel'nikov et al., 1996).

Extensive reviews on the extent of contamination of the Arctic environment were published by Barrie et al. (1992) and Muir et al. (1992). On the (now) Russian side, it was Mel'nikov and his co-workers who presented abundant results on various aspects of Arctic contamination (Mel'nikov and Pavlov, 1978; Mel'nikov, 1991; Mel'nikov et al., 1996; Yablokov et al., 1993). Muir et al. (1992) and Falk-Petersen et al. (1992) present wide-ranging reviews of contaminant levels in Arctic waters. The most comprehensive investigation on the state of the arctic environment to date has been undertaken by AMAP and has been published as the *First Assessment Report* (AMAP, 1998).

In considering the origin of contamination, data on contaminant species and their abundances demonstrate that metals, organochlorines and other substances that are foreign to the Arctic have been identified in substantial concentrations in various parts of the circumpolar North. Simultaneously, these substances are making their way into the polar marine and terrestrial food chain and affect terrestrial and marine ecosystems as well as arctic residents. For example, polar bears on Svalbard have levels of PCBs (PCB = polychlorinated benzene) high enough to cause reproductive damage (Norheim et al., 1992). Sea birds on Svalbard have been sampled after death with apparently lethal doses of PCBs in their brains (AMAP, 1998). Mercury levels in Inuit in western Greenland increase from south to north, apparently due to an increase in consumption of marine mammals (with high mercury concentrations) by the northern communities (Hansen, 1990). Although mercury, cadmium, and lead — metals known to accumulate in parts of the Arctic ecosystem — may have natural sources, anthropogenic activities affect their distribution as well as that of organochlorines. Given these observations, it is obvious that most of these substances must be derived from emission sources far away from the Circumpolar North. In fact, the origin of these contaminants can in many cases be traced back to their original sources by identifying trace chemical fingerprints of the substances found in the Arctic and comparing them with known emission sources in the south.

Long-range oceanic transport plays a major role in delivering contaminants to the Arctic Ocean. A study tracing Siberian river run-off across the central Arctic towards Fram Strait demonstrates that this water is mixed by only a factor of ten by the time it makes its way from the river mouth, across the shelf and to the central Arctic Ocean (Bauch et
al., 1995). Consequently, potentially highly contaminated water is also being delivered to the North Atlantic, far away from its source area. This may ultimately lead to substantial disturbances to marine biota at northern to mid-latitudes.

**Sea ice and its role for the transport of contaminants**

Given this observation, the question arises, if similar conclusions can be drawn with regard to contaminants contained in drifting sea ice, i.e., if contaminants entrapped in sea ice that originates in the shallow waters off the Siberian or the Canadian coast may also be transported to the North Atlantic as a consequence of the general drift pattern in the Arctic Ocean. This would imply that these contaminants would be released upon melting of the ice along the marginal ice zone, which is known to be a region of intense biological activity. Consequently, the contaminants could enter most easily into the food chain in this region.

Due to the pioneering work of W. Weeks and S. Pfirman and co-workers the drift of contaminant-laden sea ice has indeed been identified as yet another pathway for contaminant transport in the Arctic Basin (Pfirman et al., 1995; Weeks, 1994)

On the other hand and apparently contradicting this contention, it is known that the formation of sea ice itself acts as a purification process (Weeks, 1994). This is because almost any substance contained in soluble form in the sea water is excluded from the growing sea-ice-crystal lattice except for NH$_4$F, NH$_4$OH, HF and NH$_3$ (Hobbs, 1974). Thus, any chemical contaminant that is introduced into the Arctic Basin in a dissolved state is likely to be less concentrated in sea ice than in the underlying water column from which it was formed.

However, it is also known that Arctic sea ice contains substantial fractions of sediment particles. Based on field observations in the eastern Arctic Basin and the Barents Sea Pfirman (1990) and Nürnberg (1993) estimate that regionally from 10 to 50% of the ice cover is discolored because of high accumulations of lithogenic and biogenic materials. Many pollutants, including radionuclides, tend to sorb onto fine-grained sediment particles and/or organic material that are transported to the arctic coasts by the large Siberian and Canadian rivers (Stumm and Morgan, 1981). Once leaving the estuary, such particles are likely to deposit out of the water column in the near-shore area towards the sea bottom and would therefore be found in much lower concentrations in the sea water by the time the river run-off makes its way to the central Arctic. However, sea ice is known to entrain and transport sediment particles from shelf areas and is a likely candidate for picking up contaminated particles at river mouths through a variety of entrainment mechanisms. Thus, sea ice becomes a potential “accumulator” of and a likely “transport medium” for contaminants adsorbed to sediment particles in the Arctic (Pfirman et al., 1995; Weeks, 1994).

While the role of sea ice in the transport and distribution of contaminants is increasingly acknowledged, we are still far from understanding the exact role of sea ice in this regard. Furthermore, it is even less known to what extent contaminants are chemically modified and what kind of chemical reactions may take place between various chemical compounds. There is virtually no information on the mass balance of certain contaminants for drifting arctic sea ice, e.g., we do not know what fraction of a contaminant has been lost during pack-ice drift and how much has been incorporated as
a result of other processes (e.g., aeolian deposition).

However, this is not to say that there is no information at all. Thus, in the remainder of this paper we attempt to summarize the present state of knowledge on the role of sea ice as a means to facilitate contaminant transport. However, we will not consider the processes briefly described above, but will concentrate on the transport and release of hydrocarbon contamination by/from sea ice in the Arctic Basin.

**HYDROCARBON CONTAMINATION OF SEA ICE**

The discoveries of large deposits of oil and natural gas on-shore and off-shore along the perimeter of the Arctic Basin do not only offer promising prospects for a long-term supply of these resources (Figure 1; Jumppanen et al., 1989), but almost inevitably result in hydrocarbon contamination at varying scales, e.g., through leakage of oil from production platforms or pipelines or be it as a result of a more severe accidental spill of larger proportion. The unique characteristics of the northern seas lead to impacts of hydrocarbon contamination on marine ecosystems that require specific remediation measures compared to the situation at lower latitudes. In addition, and as a consequence of the conditions prevailing in the Arctic (low temperatures, low light levels for long periods of time), the effects of hydrocarbon contamination will prevail for a long time, potentially causing very serious environmental damage.

![Figure 1: Location of major (potential) hydrocarbon deposits (shaded areas; numbers in map correspond to the numbers in the adjacent table) in the Arctic (further details, see Jumppanen et al., 1989)](image)

<table>
<thead>
<tr>
<th>No.</th>
<th>BASIN</th>
<th>OIL BILLION BARRELS</th>
<th>GAS TRILLION CUB METERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>FINMARK TROUGH</td>
<td>5.0</td>
<td>3.68</td>
</tr>
<tr>
<td>2</td>
<td>CENTRAL BASIN</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>3</td>
<td>SORMAPP</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>4</td>
<td>OLGIA</td>
<td>0.8</td>
<td>0.25</td>
</tr>
<tr>
<td>5</td>
<td>VICTORIA</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>6</td>
<td>SOUTH BARENTS</td>
<td>4.6</td>
<td>10.0^2</td>
</tr>
<tr>
<td>7</td>
<td>NOWAYA ZEMILYA</td>
<td>0.4</td>
<td>0.42</td>
</tr>
<tr>
<td>8</td>
<td>PECORA OFFSHORE</td>
<td>2.3</td>
<td>1.47</td>
</tr>
<tr>
<td>9</td>
<td>PECORA ONSHORE</td>
<td>4.0</td>
<td>2.10</td>
</tr>
<tr>
<td>10</td>
<td>WEST SIBERIAN OFFSHORE</td>
<td>5.7</td>
<td>30.0^3</td>
</tr>
<tr>
<td>11</td>
<td>WEST SIBERIAN ONSHORE</td>
<td>&gt;30</td>
<td>&gt;26.25</td>
</tr>
<tr>
<td>12</td>
<td>UYDENAYA</td>
<td>1.1</td>
<td>0.63</td>
</tr>
<tr>
<td>13</td>
<td>SHMDT</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>14</td>
<td>YENSEY LENA</td>
<td>7.4</td>
<td>3.33</td>
</tr>
<tr>
<td>15</td>
<td>WEST LAPTEV</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>16</td>
<td>SOUTH LAPTEV</td>
<td>1.0</td>
<td>0.04</td>
</tr>
<tr>
<td>17</td>
<td>LIST LENA</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>18</td>
<td>NORTH WEST LAPTEV</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>19</td>
<td>NOVOSIBIRSK</td>
<td>0.2</td>
<td>0.10</td>
</tr>
<tr>
<td>20</td>
<td>D.E. LONG</td>
<td>0.2</td>
<td>0.10</td>
</tr>
<tr>
<td>21</td>
<td>EAST SIBERIAN</td>
<td>0.0</td>
<td>3.33</td>
</tr>
<tr>
<td>22</td>
<td>CHALIN</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>23</td>
<td>HOPE CHUKCHI</td>
<td>5.96^1</td>
<td>0.70</td>
</tr>
<tr>
<td>24</td>
<td>BEAUFORT OFFSHORE</td>
<td>1.66^1</td>
<td>2.12^1</td>
</tr>
<tr>
<td>25</td>
<td>NORTH SLOPE</td>
<td>28.0^1</td>
<td>1.70</td>
</tr>
<tr>
<td>26</td>
<td>MACKENZIE</td>
<td>11.6</td>
<td>2.30</td>
</tr>
<tr>
<td>27</td>
<td>SVERDRUP</td>
<td>15.0</td>
<td>4.38</td>
</tr>
<tr>
<td>28</td>
<td>NORTHEAST GREENLAND</td>
<td>3.0</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>TOTAL</td>
<td>136.12</td>
<td>93.90</td>
</tr>
</tbody>
</table>

During the initial stages of oil and gas development on the Alaskan North Slope, these problems have been studied extensively and have been summarized by Futsaeter et al. (1991), Payne et al. (1991) and Sydnes (1991). The subject has been reviewed more
Hydrocarbons are introduced into arctic marine ecosystems in various ways. The main sources of hydrocarbons include:

1. **Transport of oil or oil products from outside the Arctic**: marine and atmospheric transport; riverine input.

2. **The oil and gas industry in the Arctic** through: discharges of oil-based drill cuttings; processing water; ballast water from storage tanks; drainage; minor spills/leaks of oil and oil products during normal operation; losses from evaporation; emissions of combustion products; transport by ship; marine oil spills.

3. **Other sources**: natural seepage from sedimentary deposits; sewage; dumped waste.

**Basic characteristics of oil and the fate of spilled oil in the Arctic**
Crude oil is a mixture of organic compounds, which includes saturated hydrocarbons, aromatic hydrocarbons and asphaltenes/resins. The physical and chemical properties of the three groups of oil components are significantly different, and the fate of an oil spill in the marine environment will therefore largely depend on the type of oil under consideration (Sydnes, 1991).

The behavior of hydrocarbons as well as the ultimate effect of oil and oil products on the polar marine environment depend on a large number of factors. From a chemical point of view the most important ones to consider are the intrinsic chemical properties of the hydrocarbons, the consequences of oil-water interaction, the influence of ice on physical and chemical processes, the interactions between oil and light in the course of a highly variable influx of solar energy and, under ice-free conditions during the summer, the partial evaporation of oil (Sydnes, 1991).

Weathering of oil and oil products is largely temperature dependent and under polar conditions a very slow process, even in leads and other areas of open water, and it is extremely slow in oil trapped underneath the ice. After nine months of exposure, oil experimentally spilled in a sea ice field showed only 5% loss of weight and no bio-degradation at all (Futsaeter et al., 1991).

**Hydrocarbon contamination of sea ice**
This brings us to the issue of hydrocarbon contamination of sea ice. In warm and temperate seas, hydrocarbons released into the water column are chemically broken down relatively rapidly into harmless substances. While in the Arctic, continuous summer daylight enhances the breaking down of oil on the one hand, low temperatures hamper chemical and possibly biological degradation, on the other. During winter the oil is fully preserved. An oil spill in sea ice will be trapped between or under the ice floes, and be protected against eroding wave action and light (Figure 2). An oil spill in the Arctic may thus retain its potential harmfulness for a much longer period than in other areas. Furthermore, it will inevitably become trapped in areas of high biological importance such as the sea ice edge region or in the shallow shelf- and coastal areas (Hansson, 1992).

Oil spilled in ice-covered seas will behave differently from oil spilled in the open ocean (Futsaeter et al., 1991). In pack ice, wind and the movement of ice floes lead to a
concentration of oil and oil products in leads and polynyas (i.e., a long-term open water area in an otherwise closed sea ice field), which results in a surface layer of oil in open-water patches (Figure 2, Sydnes, 1991). Oil splashed onto the surface of the ice will form a snow-in-oil sludge that is resistant to burning and chemical dispersion. A layer of oil may become trapped underneath the ice and may be incorporated into the ice during later freezing or due to capillary movement of the oil. This is different from the case of a sea-bed blow-out where rising oil is directly brought into contact with the bottom surface of the ice.

---

In considering the incorporation of hydrocarbons we note that unlike the entrapment of contaminants through suspended sediments (see above), oil and oil products are likely to directly enter the pore space of the sea ice. It is known that oil and oil products which are released underneath the ice cover may migrate up the brine channels due to capillary effects. The hydrocarbons incorporated in this way may contaminate a larger fraction of the ice because sea ice possesses a high absorptivity (ice will absorb up to 25 % of the volume of spilled oil and snow up to 80 %). In addition, though arctic sea ice also is characterized by a relatively large mobility (i.e., through its drifting movement; Brinen and Pyzhin, 1993) and may lead to contamination of the upper ocean far away from the area where the contaminants became incorporated.

This depends to a large extent on possible transport and release processes taking place within the interior of an ice floe. Dominant factors influencing these processes are the structure of the pore space (i.e., the brine channel system), which depends on the ice growth processes and the resultant ice texture. Secondly and even more importantly, it is the hydrologic conductivity of the connected pore space, which is largely controlled by temperature.

Oil that has been incorporated and rises to the water-ice interface forms sessile drops. This sessile behavior is a result of the non-wetting properties of hydrocarbons on ice in water. The drops are thus quite mobile until they are frozen into the growing ice. These
lenses of encapsulated oil are likely to remain intact until spring when the opening of brine channels provides an access route to the surface or to the underlying water column. Oil and oil products are subsequently observed to pool with the melt water on the ice surfaces well before the integrity of the ice sheet is destroyed (Mackay, 1985). The biological community on the ice surface, including birds, seals and polar bears are then exposed to the oil-water mixture. In contrast to Antarctic sea ice, the sea-ice community in the Arctic Ocean resides mainly within the lower tens of centimeters (Spindler, 1990) and may thus be less vulnerable to surface accumulations of contaminants.

Returning briefly to the question related to the fate of oil entrapped in the sea ice pore space, there are a number of questions that have yet to be solved:

- to what extent enters oil the sea ice pore spaces after being introduced to the water column;
- what is the fate of the oil once entered into sea ice and what are possible chemical alteration processes;
- when and where is oil released into the water column after being transported throughout the Arctic Basin through the prevailing drift paths.

While this is by no means a complete list, significant progress has been made recently, particularly with regard to a better understanding of the microstructure of the sea ice pore space (e.g., Callaghan et al., 1999; Eicken et al., 2000; Weissenberger, 1992) and the possible movement of oil contamination in individual brine channels (Menzel, 2002; Menzel et al., 2000). Such understanding is essential for the construction of brine/contaminant transport models in sea ice. Thus, understanding details of some of the processes that take place on the micro- to intermediate scale (i.e., from sub-millimeters to tens of meters) allows the quantification of physical processes and a quantitative risk assessment related to the introduction of oil into arctic waters.

DISCUSSION AND CONCLUSIONS

The contamination of arctic land and sea areas is a well-proven fact. This has been reviewed extensively by the Arctic Monitoring and Assessment Programme (AMAP, 1998). It is also known that most of the contaminants found in the Arctic originate outside the circumpolar North and are transported northwards through various atmospheric and oceanic processes. The role of sea ice as a transport medium and the large-scale sea ice drift patterns in the Arctic Basin as a contaminant pathway have been identified more recently.

While the formation of sea ice can be considered as somewhat of a cleansing mechanism for soluble contaminants in the water column, the introduction of contaminants through an entrapment of suspended or re-mobilized sediment particles during sea ice growth has been demonstrated as an effective contaminant incorporation mechanism.

In contrast, hydrocarbons released into the water column as a result of increasing exploitation and transport of oil and oil products in arctic shelf areas will enter the sea ice through its highly absorptive brine-channel/pore space. Once incorporated, the oil will undergo various — yet still ill-defined — transport and modification processes. Similar to other, mostly sediment-adsorbed contaminants, hydrocarbons will be released
into the water column either during summer melt events in the interior Arctic Ocean or in the marginal ice zone of the North Atlantic, where most of the sea ice drifts to.

While the impacts of contaminants on arctic marine and terrestrial ecosystems as well as on arctic residents depending on natural resources for their livelihood have been decisively documented, there are still a number of open questions, primarily with regard to hydrocarbon contamination of sea ice.

Thus, we cannot conclude with certainty that oil contamination has to be regarded as a serious problem to the arctic (marine) environment. Consequently, much more research is needed to substantiate such contentions. We suggest that in the absence of more reliable knowledge a precautionary approach to the potential threats of hydrocarbon contamination of arctic ecosystems is taken and exercised.

ACKNOWLEDGEMENT

Over several years, work on the topic of this paper has been supported by grants from the Deutsche Forschungsgemeinschaft and the Internationales Büro des bmb+f. I would also like to acknowledge numerous helpful discussions with Drs. Blümich, Callaghan and Langhorne. Thanks are due to an anonymous reviewer for helpful suggestions.

REFERENCES


Arctic-Centre The State of the Arctic Environment Reports, Arctic Centre Publications 2, Arctic Centre, University of Lapland, Rovaniemi, Finland (1991) 405p.


Ruokonen, M. and Lange, M.A. Environmental Problems Related to Oil on and in Arctic Sea Ice: A Literature Survey and Synopsis, Arctic Centre, University of Lapland, Rovaniemi, Finland (1996) 28p.


