The potential transport of pollutants by Arctic sea ice

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Abstract

Drifting sea ice in the Arctic may transport contaminants from coastal areas across the pole and release them during melting far from the source areas. Arctic sea ice often contains sediments entrained on the Siberian shelves and receives atmospheric deposition from Arctic haze. Elevated levels of some heavy metals (e.g. lead, iron, copper and cadmium) and organochlorines (e.g. PCBs and DDTs) have been observed in ice sampled in the Siberian seas, north of Svalbard, and in Baffin Bay. In order to determine the relative importance of sea ice transport in comparison with air/sea and oceanic processes, more data is required on pollutant entrainment and distribution in the Arctic ice pack.

Keywords: Arctic; Sea ice; Pollution; Contamination; Ecosystem; Transport

1. Introduction

Growing concern about Arctic pollution has led to speculation about the relative roles of the atmosphere and ocean in Arctic-wide transport of contaminants. Sea ice, one of the defining characteristics of the Arctic, is usually ignored as a potential transport medium. This paper explores the mechanisms by which ice formation and drift could influence the redistribution of contaminants, such as heavy metals, radionuclides and organochlorines, in the Arctic (Weeks, 1994).

Payne et al. (1991) and Sydnes (1991) discuss processes involved in oil leakage in ice-influenced waters.

A major fraction of the sea ice formed during winter over shallow marginal shelves is advected and introduced into the large-scale drift patterns of the central Arctic pack. Unique to the Arctic are the large amounts of fine-grained particulate material incorporated in and transported by sea ice formed on the shelves. Estimates from expeditions across the eastern Arctic and Barents Sea (Pfirman et al., 1990; Nürnberg et al., 1994) indicate that, regionally, from 10 to 50% of the ice cover can be discolored by accumulations of lithogenic and biogenic material (Fig. 1). Many
pollutants, including radionuclides, tend to sorb onto fine-grained particles and/or organic material (Stumm and Morgan, 1981), and may therefore be attached to the particles incorporated into the ice. During several years of transport, pollutants concentrated in the oceanic surface microlayer may also be incorporated in drifting ice (Gaul, in press), while pollutants deposited from the atmosphere accumulate on the snow and ice surface. Ice melts most extensively along the marginal ice zone. Because this is a region of intense biological activity, pollutants, often transported far from entrainment areas, are released directly into surface water where they may easily enter the food chain. As a result of these processes, drifting sea ice may play a role in long-range redistribution of contaminants in the Arctic.

2. Shelf processes

Recently, concern about potential releases of radioactive contaminants has focused attention on the Kara and Barents seas where nuclear materials have been dumped since 1959 (Yablokov et al., 1993). However, as highlighted by the Arctic Environmental Protection Strategy

Fig. 1. Photograph showing surface sediment distribution on multi-year sea ice. Sediment is often formed into pellets and accumulates in pits on the ice surface called cryoconite holes.
(adopted in June 1991 by the eight Arctic-rim countries), there are also circumpolar concerns about contamination from radioactive reservoirs and groundwater, pesticides, oil, heavy metals and other agricultural and industrial byproducts. Ice may incorporate these contaminants when it forms in rivers, at river mouths and on shelf areas influenced by river discharge and dumped or leaked material (Weeks, 1994).

2.1. River ice

Every fall Siberian rivers freeze over, dramatically reducing water discharge but not completely stopping the flow of major rivers (Fig. 2). River ice incorporates particles when it freezes to the bottom, as well as during anchor and frazil ice formation. Anchor ice forms when the entire water column is supercooled and ice nucleates on particles on the bed of the river (Pfirman et al., 1990; Reimnitz et al., 1992). A change in river temperature or turbulence, or accumulated buoyancy resulting from the build-up of ice can eventually dislodge the combined ice and sediment mass, rafting it to the surface. Here it is included in the overlying ice cover. Rocks as heavy as 30 kg have been incorporated in river ice by this mechanism (Martin, 1981). Frazil ice also forms when the water column is supercooled. While actively growing, frazil crystals tend to collect particles which can subsequently be incorporated into the ice cover. Ice formed in this way appears turbid, with patchy discolorations due to entrained material (Reimnitz et al., 1992). In addition, wind-blown dust and dirty snow accumulate locally on the surface of the frozen rivers. As a result of these processes, river ice often contains large amounts of sediment (Zubov, 1943).

Spring break-up of river ice is a violent event.

### Siberian River Runoff

Fig. 2. Total inflow of the Siberian rivers to the Arctic Ocean (%/month) for characteristic years (Shiklomanov and Skakalsky, 1994). Note the dramatic increase in river discharge in June.
Ice dams form and are then destroyed with massive discharges of water and ice. River beds are gouged by tumbling ice and eroded by torrential water flow. Polluted sediments and waste container on the river bed may be disturbed by these events. In the lower reaches of the Yenisey and Lena rivers, the water level rises > 20 m (Antonov, 1970). Siberian rivers discharging into the Kara, Laptev and East Siberian seas have a huge combined drainage area of 9 × 10^6 km^2 extending far to the south (Shiklomanov and Skakalsky 1994), encompassing many industrial and agricultural regions. The river Ob and its tributaries originate as far south as 45°N (Futsaeter et al., 1991). Pollutants accumulated in these watersheds during the winter may contaminate the river flow during spring and summer.

River ice discharged at the river mouth most likely melts and deposits its particle load in the nearshore zone (Reimnitz and Bruder, 1972). This happens because the main period of discharge is during June (Fig. 2) when the Arctic summer begins and ice in the marginal seas is just beginning to melt. If river break-up occurs before there is much melting of the shorefast ice, river water may flow out over the ice, depositing its sediment load on the surface (Reimnitz and Bruder, 1972). Because the presence of this surficial sediment effectively lowers the albedo of this ice, it melts rapidly in early summer. In part because of the discharge of river water and ice, river estuaries are usually centers of initial ice melting (Zubov, 1943). The river water is warmer than the < 0°C shelf water, and rapidly melts sea ice in a region near the river mouth (Antonov, 1970). Also, particle-laden river ice has a lower albedo and therefore melts more quickly than cleaner ice.

Another factor contributing to the retention of river ice in the nearshore zone is the extensive fast ice cover that forms along the Siberian margin each winter (Fig. 3). This ice is anchored both to the coast and to shallow offshore banks, forming a barrier to offshore transport for floating material (i.e. ice) that is released behind it. Particle-laden river ice, as well as ice influenced by bluff slumping and bottom adfreezing is retained near shore in this way.

Some river and shorefast ice does make its way past these barriers, survives transport across the shelf and is incorporated in the large-scale drift of the Arctic ice pack. A distinguishing characteristic of river ice is that it has low Δ^18O values: Ob River water is ~ −16.2‰, Yenisey River water is ~ −17.9‰ (Brezgunov et al., 1982), and Lena River water is ~ −21‰, while Eurasian Arctic surface water tends to be between 0 and −2.9‰ (Bauch et al., in press). At present, there is not enough information on this transport pathway to actually quantify the amount of river ice that is incorporated in the Arctic ice pack.

Although river ice itself may be retained nearshore, river discharge can influence the ice pack on the shelf in other ways. First, sediments deposited from the river on the shelf are resuspended during fall and winter storms and are incorporated in the developing ice cover — as described below. Secondly, the large river water discharge is primarily in June and July (Fig. 2). At this time there is still extensive ice cover in parts of the marginal seas and the river water (including sediment and contaminants) will flow under the ice cover, potentially freezing on the ice underside. Finally, although river discharge declines in winter it does not cease, so some water may be contributed to ice forming during the rest of the year as well.

2.2. Sea ice

Ice crystals growing in the sea exclude salt, resulting in ice with a lower bulk salinity than the water from which it forms. In this way, soluble salts (Weeks and Ackley, 1986) and some contaminants that are dissolved in the water column are likely to be excluded from the ice (Weeks, 1994). However, Arctic ice forming over shallow Siberian seas often includes sediments and organic material. Some pollutants tend to sorb onto this material and many radionuclides are very particle-reactive (Stumm and Morgan, 1981).

Sea ice formed over the Siberian shelves incorporates particles predominantly during suspension freezing and frazil ice formation, but also as a result of anchor ice rafting (Reimnitz et al., 1992). Most particle-laden ice appears to form in water depths < 50 m (Reimnitz et al., 1993). This is because the energy needed to resuspend sea
Fig. 3. Extent of shorefast ice and adjacent polynyas along the Siberian shelf seas during May to June, the period of maximum development of the ice cover (after Buzov, 1991).

Floor sediments through the water column increases with depth. Also, anchor ice growth requires that the entire water column is super-cooled. While particles entrained during frazil ice formation are silt-sized or smaller, as noted above, boulders may be rafted from the sea floor by anchor ice.

Processes associated with frazil ice formation tend to cause elevated levels of suspended particulate matter in the water column (Kempema et al., 1989). Combined with wave activity and scavenging by ice crystals, the initial ice cover may become enriched in particulate matter relative to normal concentrations observed in the underlying ocean water (Ackley, 1982; Garrison et al., 1983, Reimnitz et al., 1990, Shen and Ackermann, 1990). These mechanisms could also contribute to the elevated levels of organic material observed in Arctic sea ice. Concentrations of suspended organic carbon may be two orders of magnitude higher than those of sea water (175–560 µg/l compared with 25–45 µg/l from June to August and ~5 µg/l during the remainder of the year) (Mel’nikov and Pavlov, 1978). According to these
authors, the elevated levels appear to result from infreezing of organic material during ice formation on marginal Arctic seas which have higher biological productivity than the central Arctic Basin. When ice melts in summer, some suspended organic material is contributed to the surface sea water (Mel'nikov and Pavlov, 1978).

Dissolved organic carbon may also be enriched within the ice cover due to adsorption. Because many pollutants are preferentially associated with fine-grained sediment (clay) and/or organic material, incorporation of such material on the shelves provides a process for contaminant enrichment in sea ice formed there. Therefore, while sea ice without incorporated sediments or organic material probably has a lower dissolved pollutant load than the water from which it grew due to exclusion of salts and other impurities (Weeks, 1994), sediment/organic-rich sea ice may tend to have elevated contaminant loads.

In winter and spring, the Arctic atmosphere contains high levels of contaminants from Eurasia, known as Arctic haze. As contaminated particles gradually settle out of the atmosphere, sea ice acts as a lid, or sediment trap, on the surface of the Arctic Ocean. Each year that a floe drifts, contaminants and other materials are deposited on its surface from the atmosphere in the form of snow, rain and dry deposition. Heavy metals accumulating in the snow cover of the central Arctic sea ice can reach values that are characteristic of snow deposits on sea ice near Siberian industrial areas (Melnikov, 1991). Contaminants deposited on sea ice by atmospheric transport could percolate into the ice surface when meltwater refreezes (Fig. 4) and could also be added to the ice underside when meltwater runs off and refreezes there. During drift, contaminants concentrated in the oceanic surface microlayer may also be incorporated in the ice (Gaul, in press). As noted by Zubov (1943), by these processes the sea ice sucks in nutritive matter from the atmosphere on the one hand, and on the other the turbidity and organic matter form the entire water layer which is involved in the mixing process'.

3. Central Arctic pack ice

Melnikov (1991) considers processes related to sea ice formation, drift and ice and snow melting to be one of the main factors governing surface ocean metal concentrations in the Arctic. Similarly, Pavlov and Volkov (1993) and Pavlov and Pfirman (in press) note that sea ice formed in the Kara Sea will incorporate radionuclides from the sea as well as those deposited from the atmosphere and release these contaminants when the ice melts. This means that contaminants accumulated throughout the fall and winter are released during spring snow melt and summer sea ice decay. The melt period coincides with the spring bloom of biological activity, increasing the potential for biological uptake of contaminants (Mel'nikov, 1991). This process can influence shelf ecosystems when first year ice and accumulated snow melt. Organisms feeding on the spring blooms may be subjected to elevated levels of contaminants released from the ice.

According to Muir (Pers. Commun.), such release of contaminants during melting in nearshore areas could contaminate shore fisheries, marine mammals and bird feeding areas. Since many of the mammals (e.g. beluga, harp seal) and birds are migratory, local releases – even in river estuaries – could be significant in uptake of contaminants. Therefore, migration of animals to regions influenced by contaminated ice may also represent a pathway for food web contamination. Sea ice transport of contaminants also has the potential to influence other regions if the ice exits the shelf and drifts within the central Arctic pack ice. Much of the ice within the central Arctic ice cover formed initially on the marginal seas (Fig. 5). In particular, the wide, shallow Siberian shelf seas are a major source. The Laptev Sea appears to discharge the most ice each year to the central Arctic, followed by the Kara Sea and, to a lesser degree, the Barents Sea (Zacharov, 1976). The East Siberian Sea imports some ice each year from the Arctic Basin. The combined action of winds and currents cause large seasonal variations in the transport of ice, both onto and off of the shelves. Both the Barents and Kara seas export ice to the Arctic Basin in winter and import ice in summer. In order to assess potential pollutant transport, detailed data is required on both the import and export of ice that is formed in regions where it may entrain contaminants.
Fig. 4. Eight cores obtained in the Barents Sea in May 1989 generally had $\Delta^{18}$O values $< 0 \permil$, indicating that the ice was formed outside of the Barents Sea with influence from river water and/or precipitation (Pfirman et al., in prep.). Less than 20\% of the total 15 m of ice analyzed had $\Delta^{18}$O values $> 0 \permil$, which is typical for ice growth in the Barents Sea. The very low values indicate refreezing of meltwater in the surface layers of some floes. Contaminants originally deposited on the ice surface may be redistributed by such percolating meltwater.

Most of the sea ice exported to the central Arctic from the shelves, forms along the polynya at the edge of the fast ice (Fig. 3) and over the outer parts of the shelf seas. In the Eurasian Arctic, drifting ice is incorporated into the Transpolar Drift Stream, moving west towards the Fram Strait (Fig. 6). Transport from the Laptev Sea to the Fram Strait typically takes $\sim$ 3 years (Fig. 7). Ice in the western Arctic, contributed from the Beaufort, Chukchi and East Siberian seas, is incorporated in the anti-cyclonic Beaufort Gyre. Ice may circulate in this gyre for 5 years (Thorndike, 1986).

During transport, the original ice floe is modified substantially (Pfirman et al., 1990). Each summer, all of the snow and between 32 and 70 g/cm$^2$ of ice melts off the surface (average 40 g/cm$^2$) (Hanson, 1965). Water produced by the melting snow and ice runs off the floe, percolates into the floe surface, accumulates in melt ponds and may refreeze on the ice underside, redistributing some contaminants originally located on the ice surface. Some dissolved and particle-associated contaminants are also lost to the water column with the meltwater. Each winter, more ice is added to the underside of the floe (Fig. 8). As a result, while the floe thickens with time, the original first-year ice section, perhaps 1.5 m thick, eventually melts away. Particles, distributed within the ice during formation on the shelves, eventually melt out and often accumulate on the ice surface. Zubov (1943) states that every particle
frozen into the ice from below will appear on the surface in 2–3 years. Because of their darker color, such particles absorb more solar energy and melt the ice around them, forming accumulations in pits, called cryoconite holes (Fig. 1). This pitting process is important because it concentrates the particles as well as retains much — but not all — of the particle load on the ice surface, even when the meltwater runs off the floe or the floe is tipped or submerged during a rafting event. Therefore, drifting ice that originally contained dispersed contaminant-laden particles tends to form concentrated accumulations at the surface as time progresses (Fig. 8). Maximum surface concentrations from ice melt could be expected within ~3 years, if ~50 cm of the ice melts off the surface each year and the original ice is 1.5 m thick. After this time, no additional contaminants are added to the surface from the melting ice, although atmospheric deposition may continue to add contaminants.

4. Contaminant release in marginal ice zones

4.1. Fram Strait and East Greenland

The main exit for Arctic sea ice is through the Fram Strait. Each year ~2600 km$^3$ of sea ice (representing ~1 million km$^2$) is exported.
Fig. 6 Mean sea ice drift patterns in the Arctic Ocean (Gordienko and Laktionov, 1969). Dashed line indicates the average maximum extent of sea ice.

through this region in the East Greenland Current (Kvambekk and Vinje, 1993) (note earlier estimates had placed the total volume closer to 5000 km³, (Vinje and Finnekåsa, 1986)). For comparison, this volume of ice is similar to the volume of Siberian river discharge (2525 km³ (Zubov, 1943); 2340 km³ (Melnikov, 1991)). Between 50 and 85% of the ice discharge consists of multi-year and second year ice (Vinje and Finnekåsa, 1986), which potentially contains accumulated contaminants. The marginal ice zone extends southward from the Fram Strait, along the eastern slope off Greenland (Figs. 6,7). In winter, ice also continues around the southern tip of Greenland and extends up into Baffin Bay.

Because of the formation of cryoconites on the ice floe surface, much of its particle load will be released when the entire floe disintegrates during melting. Sediment traps on moorings deployed across the Fram Strait show that traps located in the marginal ice zone accumulated much more ice-rafted debris than traps located underneath the ice stream to the west, where there was a persistent ice cover (Hebbeln and Wefer, 1991). Therefore, the release of contaminant-laden particles is expected to be greatest along the marginal ice zone.

An important point is that the surface accumulation of particles/pollutants will be released to the sea surface when the ice melts. This concept is emphasized by Pavlov and Volkov (1993) and Pavlov and Pfirman (in press) who conclude that drifting ice with contaminants will ‘partially clean’ the area of contaminant incorporation, but will also lead to the contamination of surface sea waters in the region where ice melt occurs. Most melting and therefore particle/pollutant release occurs in the marginal ice zone, where there is a great amount of biological activity in the surface waters. Here fauna associated with the ice form an important link in the food web between primary producers and fish, sea birds and mammals (Futsaeter et al., 1991). In particular, ice fauna form the base of the Arctic food chain. If these fauna are contaminated by association with the ice, the contaminants may be passed on — and accumulate in — the higher trophic levels of the food web.

A mitigating factor that may be important for multi-year ice is that during transport, freeze/thaw cycling tends to aggregate particles into pellets on the ice surface (Barnes and Reimnitz, 1974; Barnes et al., 1990; Goldschmidt et al., 1992). These pellets were also observed in sediment traps located under the marginal ice zone (Berner and Wefer, 1990). Pelletization results in increased settling velocities of the particles and their contaminant load, moving them out of the surface layer much more rapidly than if they were released as single particles. Very little data is available on particle release from sea ice to determine the relative importance of particle aggregation.

4.2. Barents Sea

The Barents Sea is a vulnerable area with extensive fishing activity, a large amount of ice melting and close proximity to pollutant sources in the eastern Barents and Kara seas. It is one of the most highly productive seas in the world.
Fishing focuses on the marginal ice zone, where biological activity is concentrated. Although much of the sea ice in the Barents Sea forms locally, it also receives ice from the Kara Sea and the Arctic Ocean. More than 40% of the ice may be multi-year (Loeng and Vinje, 1979). According to Vinje (1985), who assumed an average ice thickness of 2 m, the Barents Sea imports 37 km$^3$ from the Arctic Ocean and exports 72 km$^3$. Most of the import from the Arctic Ocean is between the months of April and June. Ice import from the Kara Sea in winter is an order of magnitude greater (629 km$^3$ (Vinje, 1987)). During June, July, August and December, the flow reverses and 72 km$^3$ of ice are exported to the Kara Sea. Ice coring in the western Barents Sea in May 1989, confirmed that much of the sea ice sampled was imported from elsewhere. This conclusion is based on the analysis of Δ$^{18}$O values as well as physical characteristics of the ice. Sea ice formed in the Barents Sea should generally have values Δ$^{18}$O > 0‰, while most of the ice sampled was actually < 0‰ (Fig. 4). This suggests that some of the ice could have formed on the Siberian shelf in waters that had river input. Abelmann (1992), based on analysis of sea ice diatom assemblages, also concluded that ice sampled in the east and north of Svalbard in 1987 probably originated in parts of the Kara or Barents seas that had some river influence.

4.3. Other marginal seas
The large-scale circulation of ice in the Arctic generally results in the export of ice from the
shelf seas, transport over the central basin and discharge through the Fram Strait. However, modeling of ice motion (Colony and Thorndike, 1985) indicates that the ice that melts in the shelf regions contains some contribution from the central Arctic (Fig. 9). This is important to remember when considering deposition of contaminants from the atmosphere. For example, sea ice melting in the Beaufort Sea is likely to contain some ice from the north, which may have accumulated deposits of Eurasian atmospheric pollutants.

5. Sea ice contaminant data

Pollutants of primary concern in the Arctic are organochlorines, heavy metals, radionuclides and oil (Payne et al. (1991) and Sydnes (1991) discuss the fate of oil leaked in ice influenced waters). Data on actual contaminant levels in Arctic sea ice are sparse and we have not been able to locate any information on radionuclide concentrations in sea ice. The most comprehensive information available to date on sea ice contaminants is from Melnikov and Vlasov, 1992 (Fig. 10).

These data, reported as average values for various Siberian seas in 1990, indicate that the ice generally has intermediate levels of contaminants compared with the snow above and the water below. Total PCB concentrations in the ice, typically, were equal to or greater than those in the overlying snow and underlying water (ice: 1500–2500 pg/l; sea water: 1000 pg/l; snow: 1500 pg/l). Dethleff et al. (1993) found values ranging between 100 and 3000 pg/l in sea ice and water of the Laptev Sea.

Near the Fram Strait, Gaul (in press) observed concentrations in drifting, porous sea ice of 1200–1600 pg/l for DDT and 15,500–20,300 pg/l for PCB 138 at a station located just north of Svalbard at 80°48'N and 8°46'E (Fig. 10). Gaul notes that the ice contained 'fecal pellets' (probably actually sediment pellets; Gaul, pers. commun., 1993) which he notes may explain the 'amazing' amounts of DDT and PCB 138. Two stations further south in the Greenland Sea had lower levels of organochlorines and did not contain notable amounts of particulates. Levels of DDT and PCBs in these samples were elevated in
the ice relative to surface sea water (Fig. 10), but in one case the amount of HCH was higher in the water than in the ice. The ice may have accumulated the pollutants during formation and/or drift. Analyses of the origin, drift path and age of the ice are required to determine the reasons for the elevated concentrations.

In contrast, first year sea ice with a low particle content at the Canadian Ice Island (81°N, 97°W) contained generally low levels of organochlorines (Hargrave et al., 1988). Concentrations of HCH in ice meltwater were up to one order of magnitude lower than those in sea water (Fig. 10). Interestingly, dieldrin concentrations in the ice were 3 times higher than in sea water. No detectable concentrations of HCB, chlordane, isomers of DDT and DDE and congeners of PCBs were observed in the ice samples, however, detectable amounts were observed in particulate matter collected from the bottom 10 cm of the ice (Muir et al., 1992). Low contaminant values would be expected to be found in this ice that formed from fairly clean water, had a generally low particle content and had not drifted for very long and so did not have much opportunity to pick up contaminants from either the surface microlayer of the ocean or from the atmosphere.

According to Russian observations, Pb, Fe, Cu and Cd, typically, are elevated in sea ice/snow compared with surface ocean water (Melnikov,
Fig. 10. Organochlorine levels in Arctic snow, sea ice and surface water for the Chukchi, East Siberian, Laptev and Kara seas in 1990 (Melnikov and Vlasov, 1992); north of Svalbard in 1979 and two stations on the east Greenland shelf in 1985 (Gaul, in press); Canadian Ice Island (81°N, 97°W) in 1986 (Hargrave et al., 1988). The 100-m bathymetric contour is shown to indicate the extreme shallowness of the eastern Kara, Laptev, East Siberian and Chukchi seas.
In 1991), perhaps due to atmospheric deposition and
infreezing of particulate matter. Under-ice obser-
vations in the Laptev Sea indicate that starting in
March, Pb, Fe and Cu are released from the ice,
apparently due to brine migration, resulting in
concentrations in the surface water that are 2–3
times higher than the initial values (Pb increased
from 0.1 µg/kg to > 0.2 µg/kg, Fe from < 0.5
µg/kg to > 1.0 µg/kg, and Cu from < 0.1 µg/kg
to > 0.2 µg/kg, (Melnikov, 1991)). Campbell
and Yeats (1982) concluded that ice contributed
Fe, Cu and Cd to surface waters during melting in
northwest Baffin Bay. In their study, sea ice, with
notably high particulate concentrations (4.75
mg/l), collected off Bylot Island yielded concen-
trations of these metals significantly in excess of
the levels observed in surface waters (Table 1).

6. Ice-related processes

6.1 The ice ‘cap’

The presence of sea ice in the Arctic generally
inhibits ocean-atmosphere exchange. This is im-
portant because many pollutants, such as
organochlorines, are semi-volatile, i.e. they parti-
tion preferentially into the atmosphere. Sea ice
acts like a lid, keeping volatiles introduced below
it from entering into the atmosphere. For exam-
ple, pollutants discharged in river water that are
frozen into the sea ice may not be released until
the ice breaks up and melts. Polynyas and leads —
places where there are breaks in the ice cover —
may also represent regions for the exchange of
volatiles, including organochlorines (Barrie et al.,

Because volatility increases with temperature,
some chemicals deposited on the ice surface in winter, are released back
into the atmosphere in the summer when the
surface warms and the snow melts (Barrie et al.,
1992). If deposition occurs on drifting sea ice,
release may occur far from the original incorp-
oration location.

6.2 Shelf brines

Another way that sea ice may influence pollu-
tant distribution is by the transport of shelf brines
associated with ice formation. Salt excluded dur-
ing crystal growth is added to the underlying
water column (Fig. 11). Highly saline water is
formed in this way in many shelf regions, particu-
larly where the water depth is shallow — allowing
surface to bottom convection — and where large
amounts of ice are formed: e.g. the polynya along
the Siberian fast ice zone (Fig. 3). According to
Pavlov and Pfirman (in press), such vertical con-
vection associated with ice formation redis-
tributes the concentration of radioactive sub-
stances. Payne et al. (1991) observed that this
process could also redistribute dissolved aromatic
hydrocarbons.

Shelf brines run off the banks and flow into
neighboring depressions, probably carrying sedi-
ments and associated contaminants with them
along the way. On shelves with complicated to-
pography, such as the Barents and Kara seas, it is
likely that the brines will accumulate in enclosed
depressions. When brines accumulate sufficiently
to overtop and overflow shelf depressions and
where shelf troughs extend across the shelf to the
edge, the brines will run off and sink to their
density level (Fig. 11) and then flow along the
slope.

6.3 Ice gouging

Another process that affects materials on the
sea floor is gouging by sea ice pressure ridges and

| Table 1 |
|---|---|---|---|---|---|
| Mn  | Fe  | Ni  | Cu  | Cd (µg/l) |
| Ice | 1.43–1.47 | 25.28–59.90 | 0.37 | 8.22–7.29 | 0.31 |
| Water | 0.10–0.56 | 0.60–3.07 | 0.17–0.28 | 0.18–0.60 | 0.020–0.075 |
Fig. 11. Brine rejection during sea ice formation leads to vertical convection over the shallow Arctic shelves (Anderson and Dyrssen, 1989). Where convection extends from the sea surface to the sea floor and breaks down the stability of the water column, it is also easier for sea floor sediments to be resuspended higher in the water column. Also the dense shelf brines formed in this way may eventually run off the shelf, potentially carrying with them contaminated shelf sediments along the slope.

icebergs (Weeks, 1994). Sea ice pressure ridges on the Siberian shelves often have drafts of 25 m (Zubov, 1943) and have been documented in the Eurasian Arctic extending down to 43 m (Wadhams, 1986). While recent iceberg gouging in the Barents Sca affects the sea floor down to 120–130 m water depth (Elverhøi et al., 1989) due to calving from glaciers on Nordaustlandet (Svalbard) and Frans Josef Land, most icebergs observed today are generally <100 m thick (Vinje, 1985). Some glaciers on the northern island of Novaya Zemlya calve into the sea. The icebergs documented by Pavlov (1993) to the east of this region may come from here, although according to Zubov (1943) most of the Novaya Zemlya icebergs are trapped in shallow fiords. Severnaya Zemlya is also a source of icebergs to the Siberian seas. Icebergs in the Laptev Sea reportedly ground in water depths up to 183 m (600 ft (Kovacs, 1972)). While ice gouges may penetrate > 5 m into the sea floor, in the Barents Sea typical plough mark relief is 2–5 m deep and 10–50 m wide (Elverhøi et al., 1989).

Presumably, the most important effects of ice gouging are (1) the damage that it could do to waste containers resting on the sea floor (Weeks, 1994) and (2) the release of contaminants to the water column when sediments are physically reworked and resuspended by the ice. Materials dumped in the shallow fjords of Novaya Zemlya (Yablokov et al., 1993) could be affected by these processes. Sediment transport via adhering and adfreezing to the ice mass is probably not as important.

7. Conclusions

Because many dissolved contaminants are excluded with salt during the freezing process, sea ice without incorporated sediments or organic material may be less contaminated than the water from which it forms. However, much of the ice formed in shallow regions (< 50 m) of the Siberian seas entrains sediments and organic material and may therefore incorporate associated contaminants. Some of this ice is exported from the shelf and transported over more than a thousand kilometers to the Greenland and Barents seas.

Due to surface melting during transport, particle concentration typically increases in the upper portion of the ice cover, often forming a slurry of mixed sediment and organic material after several years of transport. Contaminants, originally distributed throughout the ice, may become concentrated during drift on the ice surface in this way. Although some contaminants are lost in meltwater runoff, contaminants are also added from atmospheric deposition of Arctic haze, as well as from the surface ocean microlayer.

Most particles and associated contaminants are probably released at the sea surface along the marginal ice zone. Because of the intense biological activity in this region, pollutants released here can easily enter the food chain. Therefore, the biological communities most at risk from long-range pollutant transport by sea ice are those along the marginal ice zones of the Barents and Greenland seas, as well as the Iceland Sea and the west coast of Greenland and Baffin Bay (Weeks, 1994). Sea ice transport could therefore provide a link between pollutant source areas and distant wildlife. Although their origins are not
clear, organochlorines and metals are definitely making their way into the marine food chain in the Arctic. For example, polar bears on Svalbard have levels of PCBs high enough to cause reproductive damage (Norheim et al., 1992).

The process of retaining particle/pollutant concentration during transport and releasing it at the sea surface over a thousand kilometers away makes sea ice a unique and potentially important transport mechanism. Transport of contaminants by wind and oceanic processes tend to result in dispersed and reduced concentrations downstream. Also, due to brine formation and sedimentation of pollutants on the shelves, oceanic processes in the Arctic tend to move contaminants downward, out of the surface water layer. The opposite is true in the case of contaminant transport by sea ice.

8. Future research

As documented in this paper, transport by sea ice is unique, but nearly no data are available to permit an assessment of its relative contribution to pollutant redistribution in the Arctic. Future studies should focus on the entrainment, transport and release of contaminants by sea ice. For example, how are different contaminants incorporated into sea ice growing under various conditions, e.g. with and without entrained sediment or organic matter? Where does river ice melt? Are there regions on the shelves where contaminant incorporation is particularly active? Where and under what conditions are polluted river and/or sea ice transported off the shelves? How are contaminants transformed during transport? What is the relative importance of atmospheric deposition versus infreezing in contributing to the pollutant load of sea ice? What role does volatilization from snow and water play in transport and release of organochlorines by sea ice? How important is seasonal contaminant release during transport? What happens to pollutants released when an entire floe disintegrates? How important is particle aggregation in contaminant release? Are organisms associated with the ice contaminated? Does sea ice contribute contaminants to higher trophic levels in the Arctic food web?

Because many pollutants are likely to be associated with fine-grained sediments and organic material, prime candidates for assessment of long-range pollutant transport are 'dirty' sea ice floes in the Barents Sea and east Greenland marginal sea ice zones. An investigation of ice exchange between the Barents and Kara seas should also have high priority because the Kara Sea — strongly influenced by the polluted Ob and Yenisey rivers — contributes ice to the Barents Sea. Investigations of contaminant load should be coupled with analyses of ice physical characteristics, sediment and organic carbon content and composition (including clay and heavy minerals, diatom assemblages) and tracers such as $\Delta^{18}$O and organochlorine ratios. By carrying out such integrated investigations, pollutant incorporation mechanisms can be reconstructed as well as the origin, development and transport history of individual floes.

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