Contaminants in the Arctic and the Antarctic: a comparison of sources, impacts, and remediation options

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ABSTRACT. Contaminants, in freezing ground or elsewhere in the world, are of concern not simply because of their presence but because of their potential for detrimental effects on human health, the biota, or other valued aspects of the environment. Understanding these effects is central to any attempt to manage or remediate contaminated land. The polar regions are different from other parts of the world, and it would be naïve to assume that the mass of information developed in temperate regions can be applied without modification to the polar regions. Despite their obvious environmental similarities, there are important differences between the Arctic and Antarctic. The landmass of the Arctic is much warmer than that of the Antarctic and as a result has a much greater diversity and abundance of flora. Because of its proximity to industrial areas in the Northern Hemisphere, the Arctic also experiences a higher input of contaminants via long-range aerial transport. In addition, the Arctic, with its indigenous population and generally undisputed territorial claims, has long been the subject of resource utilisation, including harvesting of living resources, mineral extraction, and the construction of military infrastructure. The history of human activity in Antarctica is relatively brief, but in this time there has been a series of quite distinct phases, culminating in the Antarctic now holding a unique position in the world. Activities in the Antarctic are governed by the Antarctic Treaty, which contains provisions dealing with environmental matters. The differences between the polar regions and the rest of the world, and between the Arctic and the Antarctic, significantly affect scientific and engineering approaches to the remediation of contamination in polar regions. This paper compares and contrasts the Arctic and Antarctic with respect to geography, configuration, habitation, logistics, environmental guidelines, regulations, and remediation protocols. Chemical contamination is also discussed in terms of its origin and major concerns and interests, particularly with reference to current remediation activities and site-restoration methodology.

Contents

Introduction

This paper is concerned specifically with contaminants introduced by human activity into the polar regions and focuses on the terrestrial environment. It examines localized sources that can be remediated rather than long-range sources that can only be controlled in countries that are outside of the polar regions. While both polar regions are less contaminated than other parts of the world, the Antarctic is almost certainly the least contaminated part of the planet and is often referred to, in scientific jargon, as a clean laboratory. The Arctic has permanent communities that by themselves contribute to environmental contamination; the only permanent settlements in the Antarctic are the stations established by national programs to support their research. The Arctic also contains military bases and has active mining operations that can be significant point sources of contamination. In contrast, neither military operations nor mining activities are permitted in the Antarctic Treaty area. In addition, the Arctic is affected to a much greater extent than the Antarctic by long-range transport of contaminants, due to its closer proximity to industrial activity and landmasses. However, it should be noted that most of the Arctic landmass is not contaminated relative to more populated parts of the world.

The regulatory regimes relevant to contaminated sites in the Antarctic and Arctic are significantly different. All activities in Antarctica are governed by the Antarctic Treaty and its instruments, such as the Protocol on Environmental Protection to the Antarctic Treaty. All were developed by consensus, have been approved by all Parties to the Treaty, and are given legal effect by the domestic legislation of each Party. The Protocol on Environmental Protection commits all Parties to comprehensive protection of the Antarctic environment and establishes a set of environmental principles that ensure protection of the environment is a fundamental consideration in planning and conducting all activities in Antarctica. The Protocol also establishes a framework for environmental management processes, which should ensure common standards for all Antarctic activities, and is specific in banning some materials, such as pesticides and polystyrene chips, from the region. However, there are no overall remediation guidelines for chemical contamination or clean-up protocols in Antarctica.

The situation is very different in the Arctic. The magnitude of the contamination at Arctic sites is much larger than in Antarctica, and much more has been done with respect to remediation in some countries. Greater advances in the development of clean up, guidelines, protocols, and methodology have, therefore, been made, but this has been achieved through the initiatives of individual countries rather than as a result of international agreement. There are no controls on substances going to the Arctic.

The actions of the Antarctic Treaty nations come under scrutiny by a number of non-government organisations that are concerned about environmental issues. Principal among these is the Antarctic and Southern Ocean Coalition (ASOC), which was formed in 1977 and consists of an alliance of 230 conservation organisations from 50 countries. ASOC representatives attend Antarctic Treaty Consultative Meetings as official observers and have served on the national delegations of several countries. ASOC representatives have prepared information papers to the Antarctic Treaty System, have contributed to environmental impact assessments and have participated in inspections of facilities in Antarctica. The Arctic has received less attention, and there is not yet a clear process for involving the wider public in Arctic environmental debate.

The Antarctic is an isolated landmass surrounded by the Southern Ocean and is therefore relatively easy to delineate. It is here defined as all landmasses, ice shelves, and seas in the area south of 60°S. The geographic boundary of the Arctic is more difficult to define because the area consists of a cluster of separate landmasses encircling the Arctic Ocean, many of which extend into temperate regions; there are, therefore, several generally accepted definitions. This article defines the Arctic as the land areas north of the tree-line that are in continuous permafrost, together with the intervening water bodies. This area has been chosen as it represents the area to which the subject matter of this paper is most applicable and the area that is most comparable to Antarctica. It includes the northern coastlines of Alaska, Canada, and Russia, all of Greenland, and Svalbard, but it excludes Iceland and mainland Scandinavia.

One of the main differences between the Arctic and Antarctic is the temperature (McGonigal and Woodworth 2001). The Arctic is much warmer because of its proximity to warmer continental landmasses and warmer surrounding waters, while the Antarctic landmass is colder and is mostly covered with a thick ice cap that has a much higher elevation. This difference greatly affects the flora of the regions. Much of the Arctic is covered with vegetation in the summer months, when most of the land is free from ice. The exceptions are most of Greenland, which is of higher elevation and covered with a permanent ice cap, and some high Arctic locations where extreme climatic conditions limit the diversity and growth of plants. In contrast, only the coastal areas and some mountain ranges in Antarctica become free of snow cover each year, and the few plant species that live there have adapted to an extreme environment. These differences affect the ways in which chemical contamination impacts the polar regions and may lead to different clean-up criteria and protocols.

While developing the criteria and protocols for the clean up of military bases in Canada, the term 'Think North' was developed. This was made in reference to engineers and scientists working on the project who failed to recognize that working in the Arctic often requires adaptation of methods and technology used in temperate climates, and that a different way of approaching problems — particularly with respect to logistics, permafrost, and cold temperatures — was needed. This paper addresses many of the ideas related to 'Think North' or, for Antarctica, 'Think South.'

Habitation and population

The Antarctic

The Antarctic has no permanent human population; the inhabitants are temporary visitors, either scientists or support staff working for one of the national Antarctic research programs or tourists and tour staff in operations that range in size from large cruise liners carrying several hundred people to small, private yacht-based adventures. The Council of Managers of National Antarctic Programs (COMNAP) currently lists 82 national research facilities operated by 27 countries, including 45 designed to be occupied year-round and 37 that are summer only. Of these, several are not currently used and may remain unoccupied for the foreseeable future. There are also a number of stations, such as Wilkes in East Antarctica, that were abandoned many years ago and are therefore not included in current COMNAP lists. In addition, there are many sites of past field camps on the continent. The total capacity of the accommodation established for national Antarctic research programs is about 4000, and much of this is occupied during the busy summer period when most of the science is done. In winter there are typically approximately 1000 people in Antarctica maintaining station facilities and undertaking the science activity that occurs during this time of year.

The establishment of infrastructure in Antarctica has occurred in phases driven by geopolitical events and perceptions of the potential for exploiting the resources of the region. Today, the attitude towards abandoned buildings and waste depends very much on the era from which they originated. In the early 1900s, the first infrastructure was established by the exploratory expeditions of the 'Heroic' era, driven primarily by the possibility of new territorial claims and for national and personal prestige. All buildings and relics from that time are now commonly viewed as historic items to be preserved *in situ* so that their context is maintained. In the years surrounding World War II, much infrastructure was established, particularly in the disputed territories of the Antarctic Peninsula, in an effort to demonstrate occupation and to substantiate territorial claims. In the late 1950s, internationally cooperative science, which reached a peak in the International Geophysical Year, drove a further wave of construction. The legacy from that era is now being viewed with some nostalgia, and, unless removed in the near future, may soon make the transformation from being an environmental problem to becoming a problem of the conservation of cultural heritage. The most recent round of construction, driven by the perceived potential for exploitation of the region's mineral resources, came to a halt in 1991, when the Protocol on Environmental Protection prohibited any activity relating to mineral resources for at least 50 years. Abandoned structures from this era are recognised as a potential environmental liability.

Tourism in Antarctica is typically ship-based and, as a consequence, very little infrastructure has been created in Antarctica to support the activities of tourists. During 1984–93 the air force hostel at Base Teniente Rodolfo Marsh Martín (Eduardo Frei Base) on King George Island was used as commercial tourist accommodation; however, this was a unique exception, and the facilities were not constructed for this purpose. Numbers of tourists visiting Antarctica have gradually increased through the years. From perhaps a few hundred visitors per year in the 1950s and 1960s, tourism increased to an average of about 1500 per year during the 1970s and 1980s. The big increase in Antarctic tourism occurred in the 1990s, during which time numbers increased every year from nearly 5000 in 1990/91 to nearly 10,000 in 1998/99 (Bauer 2001). The attraction of spending the change of the millennium in Antarctica increased the number of tourists to nearly 15,000 during the 1999/2000 season. However, since then the trend has reverted to the more gradual increase previously seen. The International Association of Antarctica Tourism Operators reported 12,109 sea-based and 139 land-based passengers and staff in the 2000/01 season. Because of the very different nature of the operations, and despite the significantly greater number of people travelling to Antarctica each year as tourists, many more people-days are spent in Antarctica by those working for national research programs than by tourists.

The Arctic

The areas of the countries included in this review all have resident populations in communities ranging from small, isolated villages to large cities. While some areas are still mainly inhabited by indigenous peoples, others have grown by the immigration of workers. Generally the indigenous peoples of the regions did not have any significant impact on the Arctic until the twentieth century. As in the Antarctic there is also a legacy of explorers, and some sites relating to them are preserved. The Arctic also has native-heritage sites containing historical hunting camps, tent rings, fox holes, and artefacts. As communities grew and people imported manufactured materials from the industrialised world, dumpsites were established, and today Arctic communities face the problems found elsewhere in the world, having to decide on such waste-disposal solutions as burial, open burning, or incineration. Shipping garbage to areas with a temperate climate is not carried out for economic reasons, except for hazardous materials. A much greater impact on the environment in the Arctic has been made by mining, oil exploration, and the construction and maintenance of military defence systems. Mining of metal ores and oil has created large communities, with their associated waste-disposal problems, not only from mining or drilling wastes but also community wastes. Many mining operations have been abandoned, leaving an eyesore on the landscape and frequently leaving contamination on the land and in surrounding waters from the extraction processes, chemicals left on site, and fuel spills.

The area of the North American Arctic covered in this article is home to about 50,000 people, more than 80% of whom are indigenous. The population is divided more or less equally between Canada and Alaska, with the largest communities of Iqaluit and Inuvik in Canada and Barrow in Alaska having populations of 4000–6000. The Canadian high Arctic, north of 75°N, contains only the small community of Grise Fiord (population 110) and the military base at Alert, which is currently manned by about 70 personnel in summer and 35 in winter. In the late 1950s, the Distant Early Warning (DEW) Line, a series of radar stations, was constructed across the Arctic, stretching from Barrow to Cape Dyer on eastern Baffin Island and thence to Greenland. The DEW Line stations, which typically needed 20–50 personnel to operate them, were replaced in 1988–93 with a new radar system consisting of essentially unmanned stations. This trend towards automated operations via satellite, particularly in winter, offers considerable cost savings and may well result in many Arctic bases being unmanned in winter. Near the time of the DEW Line construction there was a trend of movement to communities by the native peoples of the Canadian Arctic and Alaska. As in the Antarctic, the number of people in the North American Arctic increases in summer, as researchers conduct studies in the far north; however, tourism is not very developed.

Greenland, being a mountainous island covered with a vast ice cap with only the coastal regions free from permanent snow and ice, resembles Antarctica in geographical terms. The main difference is that there are about 60,000 Greenlanders, of which 80% are Inuit, with the remainder being of Danish origin. Nearly all of the communities — of which the capital, Nuuk, is the largest (14,000) — are to be found on the lower western side of the island. Commercial fishing and hunting are the main occupations, but the weather also allows for agricultural activities such as sheep farming. Svalbard, an archipelago administered by Norway, lies in the high Arctic. It is physically isolated from the large industrial areas of Europe, Asia, and North America, and local development is minimal (Rose and others, in press). It is home to about 2500 non-indigenous people, mostly involved with mining. As with Greenland, none of the communities are connected by road.

The Russian Arctic covers a vast area of land from approximately 30°E to 170°W. Approximately two million people inhabit this area, with less than 1% being indigenous minorities. Most of the northern inhabitants live in large cities and are engaged in industrial activities. For example, almost 300,000 people reside in the mining area of Noril'sk, but most of the landmass is very sparsely populated and is currently experiencing a decrease in population.

Sources of contamination

Contamination in both the Arctic and Antarctic can arise from distant sources and be transported to the region by air or sea, or it can be the result of local activities.

Long-range airborne contamination

Major atmospheric pathways converge in the Arctic, delivering contaminants from remote sources and circulating them within the Arctic. These processes, referred to variously as the grasshopper effect, the global distillation hypothesis, and long-range transport, carry a broad range of organic and metal pollutants, acidifying compounds, and radioactive contaminants north (Arctic Monitoring and Assessment Programme 1997). The atmosphere contains relatively few contaminants compared with the total burden in Arctic soil, sediments, and water. It is nonetheless an important pathway to the Arctic and is the fastest route from the source of pollution, delivering contaminants from locations around the world in days or weeks. The detection of persistent organic pollutants and some metals, such as lead, in snow remote from human activity in the Antarctic (Tanabe and others 1983; Wolff 1992; Rosman 2001) and in the tissues of animals that spend their entire life in the Antarctic (Riseborough and others 1976; Van den Brink 1997) indicates that these global transport mechanisms are also operating in the Southern Hemisphere.

There has been a great deal of research associated with long-range transport of contaminants and airborne levels in the Arctic (Arctic Monitoring and Assessment Programme 1997; Indian Affairs and Northern Development Canada 1997). Levels of many contaminants have been determined in various matrices, including air, snow, ice, soil, sediments, plants, and animals, and can sometimes be readily attributable to anthropogenic or natural sources. As an example, Table 1 gives the levels of polychlorinated biphenyls (PCBs) in various matrices and locations. These analytical results illustrate various trends. The Antarctic levels are lower than those of the Arctic, and western Russia and Svalbard generally have higher levels than North America. Sediments have higher levels than soils, as they focus contaminants through runoff into lakes. The mammal results reflect a variety of accumulation processes depending on the geographic location, habitat, and position in the food chain. The Antarctic species with the highest concentrations, the south polar skua, is a scavenger that migrates from Antarctica during the winter to more populated regions, whereas the polar bear resides within a more contaminated environment for its entire life.

Seaborne contamination

Contamination of the marine system has been the subject of several reviews (for example, Arctic Monitoring and Assessment Programme 1997; Indian Affairs and Northern Development Canada 1997). Seaborne contamination may arise from spills from oil tankers, offshore oil exploration, ocean dumping, and the sinking of marine vessels. Until the mid-1980s, 'sea-icing' — managing waste by pushing it out onto the sea ice so that it dispersed as the sea ice broke up in summer — was common practice at research stations, military bases, and communities in both polar regions. Environmental laws and protocols now specifically prohibit such disposal.

Large maritime oil spills, which represent the most serious general threat, have occurred both in the Arctic and Antarctic. Many ships involved in re-supply carry sufficient fuel for the annual needs of the stations and communities, as well as their own bunker fuel. Thus, although the Arctic and Southern oceans are not on the route of bulk oil carriers involved with normal trade, ships carrying very large quantities of oil are regularly in Arctic and Antarctic waters. The risks of oil spill in both areas are increased by sea conditions and the presence of sea ice and icebergs. The largest oil spill yet to occur in the Antarctic was 600,000 litres of diesel and aviation fuel released from *Bahia Paraiso*, which grounded in Arthur Harbour near the United States' Palmer Station in January 1989. There have also been two recent large maritime spills on sub-Antarctic islands. In 1987 the Australian Antarctic support ship *Nella Dan* ran aground on Macquarie Island, releasing 270,000 litres of light marine diesel, and a Russian tanker is reported to have lost 850,000 litres on Grande Terre, Iles Kerguelen (Jouventin and others 1984). The Arctic has also seen major spills and, with oil and gas production increasing, more can be expected.

The United States, Canada, Norway, and Russia all began offshore oil exploration and production activities in the late 1950s. At that time, oceans were viewed as a vast resource, and the possibility that they could be harmed by relatively small quantities of waste was slow to gain acceptance. Hence, the convention was to discard drill waste directly into the ocean. Lead and zinc mines in Greenland and heavy industries in Iceland likewise dumped tailings and organic waste into deep coastal fjords (Indian Affairs and Northern Development Canada 1997). The disposal in Canada of waste at offshore sites (Cambridge Bay and Baffin Island) during the 1950s–

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Table 1. Concentrations of PCBs in various matrices in the Arctic and Antarctic.

Matrix	Location	Units	Concentration	Reference/Comment
Soil	Canada	ng g^{-1}	0.9	AMAP 1997
	Antarctica		0.06	Fuoco and Ceccarini 2001: total mean
Lake sediment	Canada	ng g^{-1}	2–25	AMAP 1997
	US		2–>40	
	Russia		<2–25	
	Greenland		<2	
	Svalbard		2–7	
	Antarctica		0.12	Fuoco and Ceccarini 2001: total mean
Snow	Russia	ng l^{-1}	10	AMAP 1997: 1995 average
	Canada		4.1	Indian Affairs and Northern Development Canada 1997: 1991/92 snowpack survey
	Antarctica		0.44–0.73	Fuoco and Ceccarini 2001: range in samples collected at 7 locations 1993–94
Lichens	Canada	ng g^{-1}	0.2–2.0	AMAP 1997
	Russia		4.5–10	
Birds and mammals	Arctic	ng g^{-1} fat	7200	AMAP 1997: Polar bear circumpolar study
	Eastern Russia		5535	Norstrom and others 1998
	Svalbard	ng g^{-1}	12775	Polar bear (female) - adipose
	Greenland	lipid weight	22420	tissue
	Canadian Arctic		3850	
	Antarctic	ng g^{-1} wet weight	32–107	Subramanian and others 1986: Adélie penguins
			406–750	Fuoco and Ceccarini 2001: Weddell seal
			885–1676	Fuoco and Ceccarini 2001: south polar skua, a migratory species

80s was investigated in two separate reports (Reimer and others 1993; Environmental Sciences Group 1994). Both reports suggested that dumping was extensive but had not adversely affected the surrounding marine environment except within a few metres of metal-containing objects. For the protected waters around Cambridge Bay, most of the dumped material was still visible on the sea-bed, whereas at sites off the east coast of Baffin Island, all material had been dispersed through wave action and ice erosion.

During roughly the same period, the Soviet Union dumped large quantities of radioactive and chemical waste at numerous sites in the Barents and Kara seas (Yablokov 1996). The main dumping site for high-level nuclear waste was the shallow water off the coast of Novaya Zemlya. Although reports by Russian, Norwegian, British, and American groups have confirmed that some leakage is occurring from reactors containing spent nuclear fuel and from separate spent fuel containers, contamination again appears to be limited to the immediate area of the dumped objects (Zimmerman and others 1998). There is consensus, however, that risks do exist for the long-term as increased leakage is expected over time as containment materials corrode.

Beyond the disposal of waste generated from Antarctic stations, large-scale ocean dumping in the Southern Ocean near the Antarctic continent was never taken up as a practical method for managing waste generated elsewhere. Ocean dumping in Antarctic waters is even less likely for the foreseeable future, since the Protocol on Environmental Protection added to the general prohibitions preventing dumping of many types of waste from ships in the Antarctic Treaty Area.

Terrestrial contamination from human activities

Human activities in the polar regions have been very different and have led to dissimilar contamination sources and pathways. The most striking area of divergence is with respect to population and industrial activity.

The Antarctic

Research stations are the major land-based activity in the Antarctic, and, as a consequence, are the source of most locally derived pollutants. One of the main causes of contamination, the use of open waste-disposal sites, is no longer permitted; however, seepage and runoff from these sites continue to be sources of contamination spreading to other parts of the environment. Hydrocarbons from fuel and lubricants, and lead, copper, and zinc, are

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the most common contaminants in waste-disposal sites. The principal contemporary sources of contamination are spills of fuel, lubricants, and hydraulic fluids from storage facilities; vehicles and generators; combustion products from incineration and vehicles, including aircraft; and the disposal of sewage effluent. Inevitably, hydrocarbons are the main contaminant from fuel spills and from incomplete combustion.

The Protocol on Environmental Protection includes measures to reduce environmental contamination from all these sources. Most waste now generated in Antarctica must be removed and past waste-disposal sites must be cleaned up, unless doing so would cause greater environmental harm than leaving them in place. Open burning of waste is no longer permitted and incinerators, if used, must be designed to reduce harmful emissions as much as possible. The products of incineration must also be removed from the continent. Fuel-storage facilities generally have containment systems beneath them and operators are required to have contingency plans for responding to incidents with the potential to impact the environment. In recognition of the continued risk, oil-spill response plans have been made a priority. Other, less routine, activities also have the potential to introduce contaminants. Concrete dust from construction work has caused local die-off of plant communities (Adamson and others 1994). Scientific activities, such as the use of radioisotopes for labelling, have the potential to introduce radioactivity, and lubricant fluids, used with ice drills, will inevitably remain in the ice sheet. In the Antarctic there are about 10 deep core holes (1200–3000 m), each of about 20 cm diameter. Based on an average depth of 2000 m, this equates to a total volume of approximately 600 m^3 of drilling fluid, which is commonly butyl acetate or a mixture of kerosene and trichloroethylene. Drilling fluids are locked into the ice for many tens of thousands of years and gradually move towards the coast, where they will eventually be discharged into the sea.

The Arctic

Small towns and hamlets in the Arctic have fuel tanks that are used primarily for power generation and industrial operations. Inevitably there are fuel spills, both large and small. These same communities also created garbage dumps containing all their generated waste. Many now separate some items, such as appliances and batteries, but others still engage in open burning. Larger cities and mining operations create much larger amounts of contaminants and are significant point sources of contamination in the Arctic. As is the case in the Antarctic, environmental-protection plans and fuel-spill contingency planning, and associated documentation, protocols, and enforcement, are now becoming the norm, although in some countries progress is slow.

As part of the modernisation of the DEW Line and its replacement by a new satellite-linked system, an extensive environmental assessment of the old stations in Canada was undertaken and remediation work has developed around this program. The DEW Line required the generation of a large amount of electricity for its operation and therefore utilized many large transformers and capacitors. These contained PCBs, resulting in widespread PCB contamination in and around the sites. The buildings were also coated with paint to which a PCB additive was mixed, and this further added to the PCB problem. The paint used in stations that were abandoned after only a few years' operation, and therefore have not been repainted, contains as much as 7% PCBs (Analytical Services Unit 1997). The other major contaminants at these sites are copper, lead, zinc, and petroleum products.

Sewage disposal

Sewage disposal in Antarctica is generally into the sea below the high-water mark after maceration. Disposal to ice-free areas of land or fresh-water systems is specifically prohibited. At similarly sized facilities or communities in the Arctic, sewage is generally discharged to the land or to sewage lagoons.

Sewage effluent from research stations contains high levels of nutrients and pathogens, and may contain elevated concentrations of metals, such as copper, because the low pH of melt water or lake water used for domestic purposes can strip copper from plumbing pipes. In Antarctica, sewage effluent and domestic grey water cannot be disposed of to ice-free land but can be discharged to the sea or put in deep ice pits if on the ice sheet away from the coast. The prohibition on discharging of effluent to ice-free land areas is because they are very nutrient-poor environments and would be markedly changed by the addition of nutrient-rich effluent. In the Arctic, the addition of nutrients is not viewed as being detrimental to the environment, and therefore discharge to the land at small research stations is seen as the best alternative, as natural bioremediation can then take place. For larger discharges, sewage lagoons are employed. Major cities and industries require sewage treatment before discharge into rivers or large water bodies. Unfortunately, treatment systems, particularly in Russia, are often rudimentary and inefficient.

Petroleum products

Exploration for petroleum products has had profound effects on the Arctic environment, as this area is home to some of the world's largest petroleum reserves, located both onshore and on continental shelves (Bay 1997; Englehart 1985). Catastrophic large-scale oil spills can occur even with the use of modern utilities, and chronic spills and leakage due to outdated equipment and technologies contribute significantly to hydrocarbon contamination. For these reasons, countries have adopted better technologies and have shown that contamination from routine operations can be controlled. Yet accidental spills due to human error and technology failure are still commonplace. According to the Alaska Department of Environmental Conservation, an average of 407 spills occurred annually in the state between 1996 and 1999. These spills involved more than 1.2 million gallons of oil, diesel fuel, and other contaminants associated with the industry. In Canada an average of 12 spills per day was reported in 1995, although the majority were too small to attract media attention.

Hydrocarbon contamination is not the only impact on the Arctic ecosystem from the petroleum industry. The industry also discharges large amounts of organic contaminants and heavy metals (Arctic Monitoring and Assessment Programme 1997). The contaminants of greatest environmental concern are polycyclic aromatic hydrocarbons (PAHs). Crude oils are composed of up to 10% PAHs, whereas shale oils and coal products can be as high as 15%. PAHs are also introduced into the environment from the large volume of water produced by oil and gas platforms, by the incomplete combustion of wood and fossil fuels, and the incineration of garbage, steel, and coal.

The Soviet Union is the world's principal producer of oil and gas. Its northern production alone is comparable to the total output of the United States, which ranks as the world's second largest producer. One of the largest crude oil spills in history occurred in 1994 in the Usinsk region of the Komi Republic of Russia. As a result of accidental leakage from a pipeline, thousands of tons of oil were reportedly spilled. Permafrost in the area is highly water-saturated, causing contamination to spread over a large area. The Usinsk disaster resulted in a spill eight times greater than the *Exxon Valdez* marine oil spill in 1989. Contamination from routine operations is another significant source of hydrocarbon pollution in the Arctic. Poorly maintained pipelines in Russia cause 5–15% of the total annual oil production to be lost through leakage. The most highly contaminated areas in the Arctic are found in Russia at the mouths of rivers adjacent to human settlements, military and industrial areas, and in terrestrial areas where spills such as the Usinsk pipeline rupture have occurred (Fingas 1995).

Persistent organic pollutants

Among the persistent organic pollutants found in the Arctic, the most prevalent in air and snow are pesticides such as dichlorodiphenyltrichloroethane (DDT), hexachlorocyclohexanes (HCH), and chlordane, and technical products such as PCB mixtures and chlorobenzenes. These are most likely to have travelled from the mid-latitudes of the Northern Hemisphere via air currents. The Canada basin and Canadian Arctic archipelago have the highest HCH concentrations among the world's oceans. These are attributed mainly to remote sources. The highest PCB and DDT concentrations in Arctic biota and sea water occur near Svalbard, the southern Barents Sea, and eastern Greenland. A significant contribution to these comes from Russian rivers carrying compounds into Arctic waters from sources farther south (Arctic Monitoring and Assessment Programme 1997).

Mining and heavy metals

Heavy-metal contamination is associated primarily with the combustion of fossil fuels, mining and smelting, and manufacturing industries. Volcanic activity, forest fires, rock-weathering, and other natural processes contribute to contaminant levels in the Arctic but are less significant than anthropogenic releases. Heavy-metal emissions in the Urals, Kol'skiy Poluostrov, Noril'sk, and central and eastern Europe contribute more than half of the air pollution in the Arctic. The most severe effects from heavy metals result from local sources such as the nickel-copper smelters on Kol'skiy Poluostrov and at Noril'sk, which have severely polluted nearby terrestrial and fresh-water environments. Although most of the smelter emissions are deposited close by, they still represent a major source of circumpolar contamination.

Other significant contaminants in the Arctic are acidifying sulphur dioxide and nitrogen oxides from global sources associated with industry and energy production. The impacts attributed to acidification on Kol'skiy Poluostrov include damage to forests, fish, and invertebrates. Extensive vegetation damage is evident in a region surrounding the smelter of Noril'sk. In some areas that are particularly sensitive, such as where soil is acid and shallow, the effects of acidification from long-range transported pollutants can also be found. Both the Canadian and Russian landscape have been affected by contaminants from distant sources; most of the northern part of Kol'skiy Poluostrov and parts of the Canadian Shield are vulnerable.

Radioactivity

Radioactive contamination comes from three main sources: past atmospheric nuclear weapons testing, releases from European nuclear reprocessing, and fallout from the Chernobyl accident. Arctic sources, such as dumped nuclear waste, nuclear storage sites, accidents, and underground explosions, have led to localized contamination (Office of Technology Assessment 1995). The greatest concerns about radioactive contamination in the Arctic arise from the consequences in the event of an accident. Radioactive sources, including numerous operating and decommissioned nuclear reactors, are highly concentrated in northwestern Russia, and represent a potential for the release of considerable quantities of radioactive contamination. With the exception of a nuclear reactor operated by the United States at McMurdo Station, 1962–72, the only local sources of radioactivity used in the Antarctic are those for medical purposes and for labelling experiments. The Antarctic Treaty, which entered into force in 1961, specifically prohibits both nuclear explosions in Antarctica and the disposal there of radioactive waste. As a consequence of the lack of local contamination, the Antarctic has been used for monitoring global background levels of radiation for many years.

Environmental impacts

Environmental impacts are generally assessed scientifically for particular chemicals by using data generated from experiments that demonstrate contaminant levels that cause detrimental biological effects. These data

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have nearly all been generated in temperate climates for temperate biota and may not necessarily be appropriate for polar regions. In addition, relatively low levels of contamination may have a greater impact on cold polar environments than the same levels would have on other environments, as these ecosystems have adapted to harsh conditions in ways that make them more sensitive (Arctic Monitoring and Assessment Programme 1997; Indian Affairs and Northern Development Canada 1997). Adaptation to cold, for example, gives fat a more dominant role in the metabolism of polar animals, resulting in the transfer of larger quantities of lipids and fat-soluble compounds up the food chain. Thus, there is a greater potential for low concentrations of fat-soluble environmental contaminants to accumulate and have effects at the top of the food chain. The rate of biological productivity is limited under polar conditions, affecting attenuation processes such as microbial degradation. This is important, for example, in evaluating the significance of metal and petroleum hydrocarbon contaminants, which are detoxified or degraded by natural processes in more temperate environments. Persistent organic pollutants (POPs), by definition, are unusually resistant to degradation, and they are fat-soluble. Although concentrations of POPs are generally lower in the Arctic, and much lower in Antarctica, than anywhere else, their distribution varies, and high levels may accumulate in some biological species. Food chains provide the biological links for uptake, transfer, and sometimes magnification of contaminants by plants and animals. The more hydrophobic organochlorines partition quickly onto soil and plant surfaces, from which they are assimilated in the food chain through diet. The most persistent are found in predatory birds and mammals high on the food chain, with various compounds dominating in different species, depending on metabolism capabilities. For example, PCBs, chlordane, and DDT reach high concentrations in seals. In polar bears, PCBs and chlordane continue to accumulate but DDT is metabolized, leaving only traces of the original contaminant. In some Arctic species, DDT and dioxin-like compounds are present in concentrations likely to produce harmful effects. In general, animals in the marine system are much more susceptible to biomagnification and bioaccumulation of POPs than those in the terrestrial system.

The term environmental impact may be interpreted to mean the detrimental change caused by contaminants and not just their presence. It follows from this definition that some value, attribute, or resource must suffer detrimental change for an impact to have occurred. Some of the values of the two polar regions are similar, but others are unique to a particular locality. For example, the health of Arctic indigenous people can be affected by contaminants that have accumulated in top predators used for food; in contrast, human health is unlikely to be affected in the same way in Antarctica because, with the exception of some countries that continue whaling, people do not use the top predators as a food resource. Therefore, in considering environmental impacts of contaminants, it is important to consider the resources impacted upon and to distinguish potential impacts from those that actually occur. Pathways for the transfer of contamination also need to be identified.

The Protocol on Environmental Protection establishes Antarctica as a 'natural reserve, devoted to peace and science' and goes on to list the values of the Antarctic that should be protected. These include the natural environment and dependent and associated ecosystems, the intrinsic value of Antarctica including its wilderness and aesthetic values, and its value as an area for the conduct of scientific research, in particular research essential to understanding the global environment. This statement of values is important because it provides a framework for judging whether an impact has occurred. It also makes it clear that impacts on the biota are not the only impacts of concern. Therefore, even if a contaminant is present at concentrations below the threshold for toxic effects, it may still have an impact if it impinges on one of the other values. For example, a contaminant generated by a polar station may be at a concentration that is too low to cause any effect on the biota, but it may detract from the ability to detect subtle changes in the global background levels. However, despite the principle that impacts on biological systems are not the only impacts that should be considered, most reports of the effects of contaminants in the polar regions concentrate on the biota.

Evidence of biological impacts of contaminants

Different types of evidence have been used to infer biological impacts. At the most tenuous level, contaminants may be detected in the environment at levels known to cause impacts elsewhere, and it may be assumed that organisms are exposed. Toxicity tests have been used widely in temperate regions to relate environmental concentrations to biological effects, but very few tests using polar species have been published (King and Riddle 2001). As a consequence, there are few data available to determine whether polar species are more or less sensitive than temperate species and hence whether the relationships between concentration and impacts derived from temperate species can be applied to high latitudes. The development of the DEW Line clean-up criteria (Poland and others 2001) suggests that, for lower Arctic environments, temperate data are appropriate, but this may not be so for high Arctic or Antarctic environments, where flora are growing at the extreme limits of their tolerance.

Slightly stronger evidence of impacts is provided by the measurement of contaminants in animal tissues. These demonstrate that not only is the contaminant present in the physical environment, but that the organism is taking it into its body. Again there are very few data from polar species on the level of contaminants in tissues that are associated with detrimental effects. Most studies that use this approach relate measured body burdens in the polar species with body burdens known to be associated with detrimental effects in a few standard temperate species, such as mink.

A correlation between contaminant concentrations and a detrimental change provides much stronger evidence. The change may be detected at one of several levels of organisation within the biological system, ranging from biochemical changes at the sub-cellular level through physiological changes, to, at the highest level, changes in the composition or structure of biological communities. Of course, correlations do not prove a cause-and-effect relationship. To prove conclusively that the contaminant can cause the impact requires carefully controlled experiments, very few of which have been attempted in polar regions (Stark and Riddle, in press).

Although overall there have been very few toxicological or ecotoxicological studies on polar species, most of those that have been published were carried out in Antarctica rather than in the Arctic. This presumably reflects the different intensity of environmental contamination that has occurred in the two regions. The very significant environmental effects caused by routine discharges and accidental spills associated with many industrial sites in the Arctic may not require subtle experimental proof of impacts, and investigative efforts are better aimed towards development of remediation procedures.

Comparison of biological impacts in the Arctic and Antarctic

No attempt is made here to review environmental impacts in the polar regions comprehensively because, particularly in the Arctic, there is significant chemical contamination at many sites and there is an enormous literature on the subject. Instead, particular examples have been selected to illustrate the levels of impacts in the Arctic, and these are compared with the most significant impacts documented in Antarctica.

Globally dispersed contaminants such as PCBs and DDT have been detected in various Arctic species, such as peregrine falcon, polar bear, and Arctic fox. DDT has been associated with eggshell thinning, causing reproductive failure in the peregrine falcon. In polar bears and Arctic foxes, PCBs have been measured at levels known to affect kit survival in mink. In the Antarctic, various POPs have been recorded in seals, penguins, and seabirds (Hidaka and others 1983; McClurg 1984; Subramanian and others 1986; van den Brink 1997) at levels below those causing effects in other species, and no adverse effects have been recorded.

Marine oil spills have killed seabirds in both the Arctic and Antarctic. More than 35,000 bird carcasses and 1000 sea-otter carcasses were found after the *Exxon Valdez* spill, and these were estimated to represent only 10–30% of the total mortality. In the *Bahia Paraiso* spill, about 300 seabirds died as a direct consequence of oil fouling and reproductive failure of the local population of south polar skua was also attributed to the spill (Eppley 1992), although alternative hypotheses for this have been proposed (Trivelpiece and others 1990).

In some parts of the Arctic, very large areas of terrestrial plant communities have been completely destroyed by contamination from industrial activity. The land around the nickel-copper smelters in Kol'skiy Poluostrov and Noril'sk is described as an industrial desert (Arctic Monitoring and Assessment Programme 1997). On Kol'skiy Poluostrov, moss beds in an area of 10–15 km around the smelter have been changed to dry sandy and stony ground. In contrast, there are very few reports of impacts to Antarctic terrestrial plant communities. Moss and lichen communities within a few hundred metres downwind of a cement mixing site at Casey Station were damaged by alkaline dust that affected morphological integrity and photosynthetic physiology (Adamson and Seppelt 1990; Adamson and others 1994). Mosses recovered within about four years, while lichens showed no recovery and remained entirely bleached (Seppelt 2002).

There are many examples of rivers and lakes in the Arctic severely polluted by heavy metals from industrial activity. In the Murmansk region, the ecosystems of at least five fresh-water bodies are described as completely destroyed (Arctic Monitoring and Assessment Programme 1997). In the Antarctic, subtle changes to the structure of the simple microbial communities of a lake close to a station have been reported (Ellis-Evans and others 1998).

The marine benthic environment of the Arctic has been contaminated both by accidental spills and by continual discharges at many industrial sites and major seaports. A spill of 1000 tonnes of bunker oil in Arctic Norway caused the death of all macroalgae in some heavily oiled patches (Arctic Monitoring and Assessment Programme 1997). The most contaminated marine site in Antarctica is Winter Quarters Bay, at McMurdo Station on Ross Island, where about 80,000 m^2 of seabed is contaminated with PCBs and hydrocarbons. This has resulted in reduced faunal diversity and the presence of a few opportunistic species (Lenihan 1992). Similar changes have been recorded within a few hundred metres of a disused waste-disposal site on the shoreline near Casey Station, East Antarctica (Stark 2000).

Significance of impacts

It is clear that the Arctic has very seriously polluted sites that are as bad as sites anywhere else in the world. Levels of contamination are such that some indigenous peoples who rely on a traditional diet are among the most exposed in the world to certain contaminants (Dewailly and others 1989). While reductions in production of many POPs have caused a decline in the environmental levels of some Arctic contaminants, lower human exposure is not yet evident for many contaminants. Contamination in Antarctica is unlikely to be a hazard to human health, unless by careless handling of abandoned waste. When compared thus, the impacts of contamination in the Arctic appear to completely overshadow the impacts in Antarctica. Is it then reasonable to dismiss contamination in Antarctica as a minor, local concern? The authors believe not.

The Antarctic continent is almost completely covered in permanent ice, with only 0.4% or about 50,000 km^2, being ice-free exposed rock; this recent estimate is derived from the Antarctic digital database. This is smaller than Tasmania (64,519 km^2). The ice-free areas are the essential habitat for much of the wildlife and plants of Antarctica, in addition to fauna that inhabit Antarctica seasonally. They are also the most attractive sites for the construction of research stations and are the centres for most human activities on the continent; consequently they are the sites of most environmental contamination. Most Antarctic research stations (51 of 73) are located on ice-free areas within 5 km of the coast. This thin coastal strip represents only 0.05% of the total land area of Antarctica or about 6000 km^2; an area smaller than Yellowstone National Park (8,900 km^2). This habitat is globally important as the home for most of the terrestrial flora and fauna of Antarctica, including iconic Antarctic species such as Adélie penguins, which are found nowhere else in the world. Thus, although the absolute level of contamination in Antarctica is much less than in the Arctic, it is spread disproportionately around the continent and is concentrated in areas that are environmentally highly sensitive.

The landmasses of the Arctic are predominately ice-free (84% or 11.2 million km^2) with the small amount of permanent ice cap concentrated in Greenland. Although the Arctic contains numerous point sources of contamination, some of which are extremely high, the area as a whole is far less contaminated than more populated parts of the world. While it is not as free from contamination as the Antarctic, the exposed, ice-free land of the Arctic is vast in comparison with the small area of ice-free Antarctica.

Environmental regulations and guidelines

Environmental regulations and guidelines generally apply to air, water, or land. For air emissions, regulations are generally more applicable to industrial activity and therefore only relevant to those areas of the Arctic where such activity occurs. As mentioned, the mining operations in Kol'skiy Poluostrov and Noril'sk are major sources of aerial contamination arising from within the Arctic region. Air emissions can also arise from landfarming of soils contaminated with petroleum product. Regulations with respect to air emissions are more stringent and more rigorously enforced in Arctic countries other than Russia. Many Arctic communities still open-burn the waste generated by their communities, and whilst this practice is obviously undesirable, it probably does not introduce significant amounts of contaminants to the Arctic ecosystem as a whole. As an example of the major difference between environmental practice and philosophy between the two polar regions, open burning is not permitted in Antarctica.

The London Convention (also known as the Convention on the 'Prevention of Marine Pollution by Dumping of Wastes and Other Matter') of 1972 prohibits the dumping of specified items in the ocean and has grown increasingly restrictive. In 1993, 72 countries of the London Convention agreed to ban the disposal of industrial and low-level radioactive wastes at sea. The so-called 'reverse list,' introduced in 1996, specifies materials that may be considered for disposal at sea, with all others being prohibited. The permitted materials include dredged material, sewage sludge, industrial fish-processing waste, offshore man-made structures at sea, organic material of natural origin, and bulky items made of iron, steel, or concrete. Sewage and industrial outfall effluent, accidental oil spills, and routine discharges from vessels are regulated separately. Most of the eight Arctic countries have passed legislation prohibiting the dumping of hazardous materials, and only Russia has reported the dumping of industrial or radioactive wastes since 1990, a practice that ceased in 1993.

In the Antarctic, there are currently no legislated clean-up regulations or guidelines with respect to contaminated soil. With respect to waste disposal and environmental management, the Protocol on Environmental Protection generally obliges member countries to minimise waste production and to clean-up past and present waste-disposal sites on the continent. This clean up is a matter of discretion; if the process is likely to cause more damage than leaving the site as it is, the parties are not required to carry out this action. The Protocol also seeks to have as much waste as possible returned to the country of origin and gives guidelines for the minimum levels of waste treatment and the disposal of combustible and liquid wastes on the continent or at sea. Some products are specifically prohibited from the Antarctic, such as PCBs, non-sterile soil, polystyrene beads, chips or similar forms of packaging, and pesticides (other than for limited purposes).

Each of the five Arctic countries considered in this paper, and most of the countries that are signatories of the Antarctic Treaty, have their own environmental regulations and remediation criteria. For the clean up of contaminated sites, these generally take the form of soil and water guidelines that are used as the first trigger to determine whether an area may be considered contaminated. These guidelines often have three sets of levels that apply to the three land uses of agricultural, residential or parkland, and industrial or commercial. In this scheme, the Arctic would generally be classified as parkland. There is now a general trend to conduct further studies when guidelines are exceeded, in order to show whether any negative environmental impact is occurring before initiating any clean-up action. For some contaminants, such as PCBs, environmental regulations exist that require remediation regardless of impact assessment and therefore are more easily dealt with.

In the Canadian Arctic, the DEW Line clean-up criteria (DLCU) were primarily based on the experimentally determined levels of contaminants by plants growing in contaminated soils in the Arctic (Poland and others 2001). They were more stringent than the normal Canadian guidelines for PCBs and lead in the early 1990s. This difference was largely a recognition of the cleaner Arctic environment and resulted from the ability to determine analytically the level of these two contaminants at distances of several kilometres from point sources against the Arctic background levels; the measured levels would generally be below background levels in southern Canada. In 1999, the Canadian Council of Ministers of the Environment lowered both the lead and PCB guidelines. For industrialised areas of the Arctic, these levels would not be appropriate and the industrial guidelines would apply.

Regulations with respect to petroleum product contamination are much more varied and often relate to underground storage tanks and groundwater aquifers. Petroleum product spills are now generally less common and contained more quickly than in the past. Historic minor spills or even major spills on land can be viewed differently in the polar regions than in temperate climates. Drinking water is often obtained from groundwater aquifers in temperate regions and therefore petroleum spills that contaminate groundwater represent a serious problem. In the polar regions, groundwater is essentially absent and drinking water is generally obtained from lakes. On the other hand, biodegradation of petroleum products proceeds more slowly in polar climates, and spills can seriously degrade permafrost, leading to pooling of material at depths greater than the active layer and to possible soil structural instability.

Logistics

Logistics are nearly always a major challenge when working in remote polar regions. Problems are numerous and unpredictable, and greatly affect environmental remediation work.

Weather is a key contributor. Poor weather conditions — such as fog, wind, ice, and snow — can severely disrupt transport operations. Ships may become icebound for weeks, completely disrupting all work associated with their visits, and often resulting in cancellation of planned activities. Aircraft may be unable to land or take-off for several days or occasionally weeks. Poor weather conditions combined with cold temperatures make working at polar sites difficult and often preclude on-site work being conducted for days at a time. The short field season, which is usually only 2–3 months, presents other logistics problems.

All visitors to Antarctica must cross the Southern Ocean, and, as a consequence, access is only possible either by ship or aircraft. Many researchers, and by far the majority of tourists, still use marine transport, and even those operations that have inter-continental air-transport systems to bring people to the Antarctic still rely on the large cargo capacity of ships to carry the bulk of their equipment and supplies. All forms of transport in Antarctica are weather-dependent and unfavourable conditions must be factored in to the planning for all activities.

Although some ships travel directly to Antarctica from countries in the Northern Hemisphere, most operate from ports on the southern extremes of the continents that fringe the Southern Ocean. Ships travelling from the South American ports of Ushuaia and Punta Arenas typically take 2–3 days to reach one of the research stations on the Antarctic Peninsula. In favourable weather and sea-ice conditions, travel from Cape Town, Christchurch, and Hobart, which service most of the stations in continental Antarctica, takes 8–20 days, depending on the destination. Bad weather and heavy sea ice can delay shipping for many days or weeks. Ships suitable for Antarctic activities are generally expensive and are in limited supply, as they must be at least ice-strengthened, although icebreakers are preferred. Ships used in support of national research programs are frequently multi-purpose, being used to carry passengers, deliver fuel and equipment to the station, and undertake marine research. As a consequence, there is often intense competition for ship-time, and it may be difficult to schedule additional tasks associated with clean-up activities if they involve extended calls at stations for loading or additional dedicated voyages.

Many aircraft flying to the continent are at the limits of their flying range and have 'points of no return' beyond which they are committed to landing in Antarctica. The long flying time combined with the changeable nature of Antarctic weather means that many scheduled departures will be delayed and many others will turn back after several hours of flying. Thus, although the actual flying time may be less than 12 hours, the reality is that it may take days for personnel to be delivered to an Antarctic work-site by air. Travel within Antarctica is generally by helicopter or small, fixed-wing aircraft such as the Twin Otter. However, most of the more severely contaminated sites are in close proximity to stations, so long-distance travel is usually not required to gain access to these locations.

The close association of most contaminated sites with research stations has both advantages and disadvantages with respect to the logistics of clean up. The advantage is that in many cases the station will have most of the infrastructure required, such as accommodation for the people involved, heavy vehicles and vehicle workshops, and wharf facilities for back-loading excavated waste. The disadvantage is that these facilities are frequently in high demand to support the activities for which they were established, and competition for space and resources can be intense.

In contrast, some Arctic regions, including parts of Eurasia, Alaska, and the extreme western portion of the Canadian Arctic, can be reached overland. This alleviates the problem of transporting equipment and supplies by sea. Many communities can be reached by scheduled airline. However, many places where contamination is found are remote from the commercial airports or the

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sites where road travel terminates, and so the same logistical problems found in Antarctica are also found in the Arctic. Because the scale of the remediation projects are so much larger, problems noted above are much greater in the Arctic. Since many contaminated sites in the Arctic are abandoned and not near to any current community, clean-up projects have to be mounted by bringing all the equipment needed to the site by sea-lift; for landlocked sites an ice road or large aircraft may be required. Personnel have to be flown in. Even if the clean-up site is reachable from a community, there is rarely surplus equipment available during the summer months, as most equipment is required in the community for the brief construction season. In many countries in the Arctic, there are organizations that coordinate research logistics. Through agreements, these organizations employ people from nearby communities to act as guides and bear monitors, and to supply accommodation and food. Often clean-up projects are required to use local labour when available.

Health and safety

Clean up of contaminated sites is inherently hazardous in any location because of the nature of materials being handled and the heavy equipment required to undertake the task. As a consequence, health-and-safety plans are a necessity for any such operation. Environmental conditions in the polar regions create additional hazards for remediation work programs, making safety plans even more important. In addition, the isolation and limited medical facilities combine to provide further strong incentives to prevent accidents. Recent medical evacuations from Antarctica graphically illustrated the complex logistics required when medical emergencies occur in remote locations in winter. Almost without exception, Antarctic research stations will have a medical officer on site; however, assistance is usually provided by site personnel trained as medical technicians, and in recent years telemedicine has been used increasingly to access specialist expertise.

Fire is an ever-present danger at isolated locations, and emergency shelters and safety procedures are normally put in place. Fire is a particular hazard in sub-zero temperatures because liquid water is at a premium and special facilities must be established to maintain sufficient water to fight a fire. Two recent fires, in the laboratory of the British Antarctic Survey station at Rothera and the abandoned DEW Line site (PIN-3) at Lady Franklin Point, Canada, highlight this hazard. The PIN-3 fire occurred at the active unmanned radar site. The buildings at the site were originally coated with paint amended with PCB additive so that the fire created dioxins (Environmental Sciences Group 2000).

In the Arctic, the presence of polar bears affects accommodation and operations. Personnel require firearms training, and often remediation teams are accompanied by a bear monitor, who is armed and protects the workers in the event of a bear attack.

Remediation activities and options

The scientific and technical knowledge required for successful remediation in cold climates is the same for both polar regions. Clean up of contaminated sites in the developed world has received major funding and resources in the last 25 years, which, as a result, has led to major advances in the understanding of contaminant migration, behaviour, and stability. The development of new techniques, as well as the improvement of traditional ones, has led to the removal, destruction, separation, or confinement of contaminants at many sites in temperate regions. Several major remediation projects have also taken place in the polar regions, with the largest being at McMurdo Station in Antarctica and the DEW Line in the Canadian Arctic. However, relatively little research has been conducted relating to contamination issues in cold climates and the unique situations that exist in the polar regions. On the scientific side, there are information gaps in such areas as bioaccumulation in polar species, toxicity of contaminants to polar species, migration rates of contaminants through permafrost, and the development of risk-assessment models and the information required to generate them. From an engineering point of view, methodology for the construction of buildings and dams, and the supply of services such as water, sewerage, and electricity has developed through the years. Only now has work begun in the challenging areas of landfill construction, contaminant-barrier design, cold-climate bioremediation, and the transfer of other technologies, such as solvent extraction and thermal desorption.

There are also differences between the Arctic and Antarctic to be considered, many of which relate to provisions in the Antarctic Treaty and associated protocols. Also, because of the greater industrial activity and economic circumstances, the situation in Russia is different than elsewhere.

Physical debris

Physical debris may consist of buildings, communication structures, machinery, vehicles, garbage, litter, and barrels and their contents. In the Arctic, physical debris is generally dealt with by burying in a landfill and covering with a layer of clean fill. Any hazardous components — such as batteries, chemicals, and electrical transformers — are normally separated and sent to southern disposal facilities. Household waste is still frequently open-burned and the resulting ash buried in a landfill. Waste petroleum products in North America can be incinerated in the Arctic if they meet the same criteria as permitted in the south, which relate to threshold levels for PCBs, lead, chromium, cadmium, and chlorine. Protocols for testing the contents of barrels have been developed as part of the DEW Line project in Canada. For the barrels themselves, these are generally crushed prior to landfilling. In industrialised areas, metal waste is recycled but in most Arctic locations the cost of transporting wastes is not economically viable; recycling of copper or aluminium, which have a higher value, has taken place from some locations. In Antarctica, burial of waste is not permitted, so all waste must either be shipped north or incinerated. This has led to the greater use of compactors and techniques for dealing with the containment of waste materials on ships.

Chemical contamination

As previously discussed, in Arctic countries there are criteria relating to contaminant clean-up levels for specific elements or chemical compounds, whereas in the Antarctic there currently are not. Contaminated soils can be remediated in several ways. Most commonly they are excavated and either treated or shipped off-site. The DLCU Protocol states that contaminated soils should be removed from contact with the Arctic ecosystem, so the options include shipment to a disposal facility at a non-polar location, as would be done in Antarctica, landfilling on-site, or on-site treatment. Landfills for the disposal of contaminated soils have been designed and constructed at several locations in the Canadian Arctic. The design incorporates the addition of clean fill above the landfill to a sufficient depth to completely freeze the contents of the landfill into the permafrost zone. These landfills have liners that can withstand the Arctic temperatures above and below the landfilled material. All buried material has undergone standard leachate testing to ensure that the contaminants are not mobile. Soils contaminated at very low levels with lead and PCBs are buried under approximately 30 cm of clean fill at stable locations as part of the DLCU criteria in order to prevent aerial migration. On-site treatment to separate, concentrate, or destroy contaminants has been used, for example, in Alaska to concentrate PCBs from soil by solvent extraction, but this treatment method has not been widely used. The main reasons include the difficulty and expense of using complex equipment at remote locations and also because many soils are contaminated with both metals and organic compounds and technology to remove both is not practical or economically viable. Contamination of marine sediments has been found both in the Antarctic (Lenihan 1992; Snape and others 2001) and the Arctic (Muir and others 1995, 1996); however, no clean up has yet been attempted.

The polar environment presents unique challenges for hydrocarbon remediation efforts. In warmer climates, landfarming in conjunction with bioremediation has become the method of choice for remediating light petroleum fractions in soil, whereas heavy oil or tar contamination is treated by extraction, incineration, or burial. Petroleum-degrading microbial activity is known to occur even at low temperature, and can be enhanced by the addition of nutrients. Several promising remedial techniques for terrestrial hydrocarbon contamination, including bioventing, biopiles, and landfarming, are currently being tested at clean-up project sites in the Arctic and Antarctic.

Landfills, dumps, and tips

Landfills, dumps, or tips are collections of waste material on land or ice that may or may not be buried under or together with soil. The term dumps is used to describe them here. Historic dumps present a difficult remediation problem in the polar regions. The reasons for this include permafrost intrusion, health and safety considerations, very high costs, and logistics. The Protocol on Environmental Protection states that remediation should not be carried out if it creates more environment damage than leaving a site as it is. This was used as one of the underlying principles in developing the DLCU Protocol for dumps. Old dumps in which material is frozen into the permafrost may well represent such a case. The environmental assessment of dumps is best conducted not by analysing the dump, which in cold climates is often impractical anyway, but by analysing soils at the toe of a dump and in drainage pathways leading from a dump. If no contaminant leaching is observed, then, in a Canadian Arctic context, the dump can be left intact; normally visible material is compacted, barrels crushed, and fill added so as to permanently cover all the material. If contaminants are found to be leaching from a dump, then clearly some remedial action is required. If the dump is in an unstable location, then it should be removed in both an Antarctic and Arctic situation. Removal can be time-consuming as materials can only be excavated as they become free from adhesion by permafrost. Safety considerations need to be taken into account when deciding on a strategy for removal. Buried items — which could include gas cylinders or barrels full of waste oil — make excavation of frozen material undesirable both from an environmental and safety point of view. Excavations of dumps in the Canadian Arctic have been undertaken. Some have dealt with the frozen material by taking several seasons to complete the task (Analytical Services Unit 1997), whereas at another, many fragile barrels containing waste petroleum products had to be pumped out before excavation could proceed (Analytical Services Unit 2000). At several DEW Line sites, stabilization of dumps has been engineered by placing a liner across the toe of the dump, keying into the bedrock and adding sufficient fill to freeze the dump into the permafrost.

Conclusions

The Arctic and Antarctic are different in many ways; however, they have more in common with each other than they do with other regions of the world. Many of the differences are attributable to the way people have used the two regions in the past and their relationship with the rest of the world. The Arctic is an extension of the developed world, while the Antarctic has maintained a high degree of separation. Most of the similarities are due to the shared environmental conditions and the biological adaptations these have imposed. These adaptations may influence the susceptibility of high-latitude organisms to contamination, and, if so, should be allowed for in environmental guidelines and regulations for these regions. Currently this is not possible because the responses of

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polar species to environmental contamination have not been sufficiently studied.

Localised changes to biological communities have been attributed to contamination in both the Arctic and Antarctic. In general these changes are consistent with those seen elsewhere and typically include reduction in diversity and increased dominance by a few hardy or opportunistic species. There have not been sufficient studies to judge whether, as a general rule, these changes occur at environmental concentrations known to cause similar responses in temperate regions. Because of the variety of contaminants involved, the varying mixtures of contaminants occurring at polluted sites, and the natural variation inherent in biological systems, it is likely to be some time before community-level studies are able to indicate whether biological communities from the polar regions are more or less sensitive than those from temperate areas. The controlled ecotoxicological approach of exposing individual species to a gradient of concentrations of single contaminants offers the promise of providing insights on the relative sensitivities of polar species more quickly. A suite of toxicity tests using species from high latitudes, carefully selected as analogues to temperate species widely used in tests, should indicate if there are fundamental reasons for applying different environmental standards. Surprisingly few data from toxicity tests using high-latitude species are available, and, less surprisingly, the few data that are available tell an inconsistent story. Some of the first studies indicated that Arctic amphipods are tolerant of zinc and lead. More recently, a sub-lethal test using a common Antarctic sea urchin suggests that the slow larval development of many high-latitude/cold-climate invertebrates may make them susceptible to contaminants at lower concentrations than similar temperate species.

Although risks to human health and impacts to biota are the most widely accepted drivers for environmental guidelines, it may be that other criteria, designed to protect specific values of the region, are more appropriate for the Arctic and Antarctic. The starting point for such guidelines should be identification of the uses and values of the regions and the potential for contaminants to degrade them. Historic differences in use of the two areas have a major influence on perceptions of their environmental values. It is also important to recognise the complexity and variability within the Arctic with respect to such topics as climate, population, permafrost, jurisdiction, and environmental sensitivity. Whereas activities in some areas are similar to those in temperate areas, such as the Mackenzie Delta in Canada and Noril'sk in Russia, other areas, such as Ellesmere Island, are more akin to Antarctica.

Levels of many contaminants in the polar regions are likely to remain at or close to existing levels for decades. Much more research is necessary to understand the effects of contaminants on the environment in the polar regions, and to develop engineering solutions to deal with adverse situations. For the most part, local and regional contamination can be reduced through legislation and with adequate financial and technological resources. Where contamination is part of a global process, long-term reductions can only be achieved through continuing global reforms.

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