PRISTINE OR POLLUTED?

Pollutants are contaminating the Arctic. Climate change could make it worse

CARRIE ARNOLD, SPECIAL TO C&EN

Bears in Svalbard, Norway, may look like they live in a pristine world far from human influence, but human-made pollutants have found their way into their diet.

CREDIT: ASSOCIATED PRESS

For the 300 polar bears that call Svalbard, Norway, home, the rocky archipelago between the top of Norway and the North Pole is a relative oasis. Because Svalbard is the only scrap of solid ground for hundreds of kilometers, polar bears rely on it to build their dens and hunt reindeer. At first glance, the bears live in a pristine, seemingly barren world of ice and snow. Aside from occasional run-ins with the roughly 3,000 people who call the islands home, the bears seem far removed from the world of humans.

In brief

Polar regions have long acted as a chemical sink for the planet—locking away pollutants. Understanding how pollutants travel from temperate regions to the poles is a priority of environmental chemists, especially as climate change intensifies the problem of pollution. Answers will be key to creating a livable Arctic.

So when William Frederik Hartz and other environmental chemists from the University of Oxford found sky-high levels of per- and polyfluoroalkyl substances (PFAS) in Svalbard's ice and snow, the researchers were alarmed (*Sci. Total Environ.* 2023, DOI: 10.1016/j.scitotenv.2023.161830). Those chemicals pose a direct threat to polar bears—and humans.

"The levels in Svalbard polar bears are actually equivalent to [those of] people living near fluorochemical factories in China," says Hartz, now at the Climate and Environmental Research Institute "It's really [unbelievable] to me that something living in a remote Arctic environment can be as contaminated as some of the most-exposed people on earth. It really demonstrates how far PFAS problems travel."

Svalbard hosts only a small amount of coal mining and an airport, so the chemicals have to be coming from elsewhere. Crispin Halsall, an environmental chemist at Lancaster University who wasn't involved with the Svalbard study, has a pretty good idea where: everywhere.

Over the past several decades, scientists have found that the Arctic acts as a chemical sink for many persistent organic pollutants (POPs), as well as other contaminants, such as mercury and microplastics. Ocean currents and atmospheric patterns transport these pollutants from lower latitudes to the poles and trap them there.

But as scientists learned about the long-range transport of chemicals to the Arctic, climate change began to shift the environmental dynamics. When long-frozen permafrost, glaciers, and sea ice melt, they release compounds that have been locked away for decades into marine and terrestrial environments. Reductions in the environmental concentrations of these chemicals have stalled and, in some cases, reversed.

Researchers predict that the Arctic could experience ice-free summers as soon as 2030 (*Nat. Commun.* 2023, DOI: 10.1038/s41467-023-38511-8). Understanding the future of the Arctic, Halsall says, will require chemists to untangle the interactions between the transport of pollutants to the poles and climate change. But as global climate change accelerates, some scientists are asking whether they can learn in time to halt disaster.

POLAR POLLUTION

Pollution in the Arctic isn't a novel phenomenon. In 1883, geologist Adolf Erik Nordenskiöld led an expedition to Greenland. Writing later in the journal *Science*, he recounts his observations (1883, DOI: 10.1126/science.ns-2.44.732). He notes that on July 22 at 2:30 a.m., the sky was covered with a haze that "descended to the surface of the ice, and hid the view over the expanse."

In the article, Nordenskiöld hypothesizes that the haze was metallic soot from space, falling continuously to Earth. But the source of the haze was far more prosaic. Nordenskiöld was seeing metal-tinged particles from industrial processes, such as smelting, happening thousands of kilometers away from Greenland. Not until the Cold War did US Air Force meteorologists determine that the haze was actually pollution. Chemists identified mercury as a component of Arctic haze, a concern because it can persist in the environment for decades. Mercury also bioaccumulates in the Arctic food chain. Small organisms like plants and algae take up mercury from the environment; they then get eaten by fish and seabirds, in whose bodies the mercury builds up. Large predators like seals and polar bears eat the smaller, mercury-tainted prey, an act that concentrates the contaminants even further.

After World War II, researchers set up monitoring stations across Canada's vast polar regions to measure mercury in air pollution. Most of these stations used passive monitoring: sulfur-impregnated carbon filters adsorbed mercury and other metals. After 3 months of the filters adsorbing metal-tinged particles from the howling Arctic wind, researchers would return and collect the filters. The work showed that every year, Earth's atmosphere deposited several hundred metric tons of mercury in the Arctic.

The process at that time was low tech and didn't require a lot of human input, which is a huge advantage in the challenging environs of the Far North, says Alexandra Steffen, lead mercury researcher at Environment and Climate Change Canada. In 1995, Steffen's team wanted to get a more fine-grained view of how pollution accumulated in the Arctic, so the researchers dispatched an active sampler armed with a pump and a gold-lined trap that could measure mercury levels every 5 min. Instead of showing a more-or-less steady deposition of mercury, as Steffen anticipated, the active sampler indicated that mercury levels accumulated at wildly varying rates.

"At first we thought the machine was broken. What the heck? This doesn't happen with mercury," Steffen recalls. But Steffen's machine wasn't broken. Instead, she had discovered a photochemical process in which bromine oxide free radicals—formed from trace bromine salts from sea spray—oxidize elemental mercury.

A research vessel travels through ice floes so researchers aboard can sample the environment for pollution levels.

Zhiyong Xie (left) and Hanna Joerss (right) during a sampling stop in the Arctic

To sample the snow, researchers like Hanna Joerss are set down from the research ship by crane.

CREDIT: HANNA JOERSS (ALL)

It's the first step in a series of reactions that transforms the metal into highly toxic and bioactive methylmercury, which is deposited on snow, sea ice, and the ocean itself. Steffen's sampler was recording the transformation of elemental mercury to methylmercury. The Arctic was chemically dynamic, not a dead end. "It changed our whole thinking," Steffen says.

As Steffen focused on mercury, a woman living on the isolated Alaskan island of Sivuqaq (also called Saint Lawrence Island) was focused on the chemical dynamics of a different type of pollutant, POPs. Alarmed by a sudden increase in cancer among her fellow Yupik people, Annie Aghnaqa (Akeya) Alowa began raising concerns about the Arctic's chemical contamination. It included abandoned drums of polychlorinated biphenyls (PCBs) and other chemicals from US Air Force listening stations on Sivuqaq as well as chemicals blown in from far away.

Like mercury, the POPs that concerned Alowa were long lived and bioaccumulative. For decades, Alowa worried that the people of Sivuqaq were getting a double hit of POPs, both from the abandoned military sites and from the seals, walrus, and whales that continued to form the backbone of the Yupik diet. But the US government did not take her concerns seriously. Studies subsequently confirmed Alowa's fears that the people of Sivuqaq had elevated levels of POPs in their blood.

The Yupik people of Sivuqaq weren't the only Indigenous population showing high levels of POPs. A Canadian health survey published in 1989 showed that milk from Inuit parents living in the country's Far North had elevated levels of PCBs, which were primarily used as coolants and lubricants in electrical equipment. "This was a shocking thing in the 1980s, and it remains a concern to this day," says Derek Muir, an emeritus research scientist at Environment and Climate Change Canada.

Collectively, the data on mercury and

PCBs helped demonstrate that the Arctic was acting as a repository for the world's industrial chemicals. But for many years, scientists couldn't explain what forces transported these compounds to the upper latitudes.

TOXIC TRANSPORT

Researchers now know that, like much of the human travel to the Arctic, POPs and other chemicals arrive at the poles by air or sea. "Which way it travels depends on the properties of the chemical," says Hanna Joerss, an organic environmental chemist at Helmholtz-Zentrum Hereon.

Since most POPs are both lipophilic and hydrophobic, they don't dissolve well in water. This limits their marine transport, so air is the most common route to the North. Researchers studying the air routes to the Arctic quickly found that semivolatile pollutants aren't blown north in a single gust. Instead, the chemicals "hop" north in a series of steps that has become known as the grasshopper effect.

Besides being persistent, POPs are volatile, especially at warmer temperatures. They also bind to microscopic particles in the air, both naturally occurring and anthropogenic. As the air heats, the airborne POPs rise into the atmosphere, where they are carried on wind currents. If they rise too far—or when the temperature drops—they condense in the form of rain and return to Earth. The process repeats itself as the POPs move north over a series of days or weeks. In contrast, ocean currents move chemicals over years or decades.

Once POPs get to the Arctic, the ambient climate remains cold enough that they can no longer move into the air, and they remain on the surface of ice and snow. The region's lower levels of heat and ultraviolet radiation slow the chemical degradation of these compounds. "We're finding these really high levels of chemicals in a place where we think it should be pristine," says Liisa Jantunen, an air quality researcher at Environment and Climate Change Canada.

As researchers began looking at the impacts of POPs and other pollutants on the humans and wildlife calling the Arctic home, they saw the effects everywhere. Many POPs are also endocrine disruptors, unbalancing the delicate pas de deux of hormones in the body. Among the Yupik people of Sivuqaq that Alowa championed before her 1999 death from liver cancer, researchers linked POP exposure to cancer, thyroid disease, and diabetes. Studies in Inuit populations have linked the high level of POPs in their traditional diets to immune, metabolic, and cardiovascular diseases, as well as neurobehavioral issues.

A moss bag passive air sampler for microplastics

A passive air sampler

The source of these contaminants was the traditional Arctic diet of large marine mammals, which are rich in energy-dense fats. The lipids provide valuable nutrients for warm-blooded animals trying to survive in the frigid North, but the thick layers of blubber also contain high levels of lipophilic pollutants. Researchers like Todd Atwood, an Arctic wildlife expert at the US Geological Survey, are especially concerned about POPs in polar bears. "What polar bears eat are also what other people in our communities eat," Atwood says.

Researchers found that POP exposures had a biological impact in both human and animal species. Transcriptomic analysis of blood, organs, and blubber obtained via subsistence hunts by Indigenous populations showed problems with immunity, fat metabolism, and reproduction. Given the perilous status of polar bears and other Arctic species, it was a disturbing trend, Atwood says.

Concern over contamination in the Arctic prompted calls by environmental chemists and policymakers to halt the production and emission of certain POPs around the globe. Starting around 2000, Alowa's and other Indigenous people's activism that had begun in the 1970s finally bore fruit. In 2001, 152 nations signed the Stockholm Convention on Persistent Organic Pollutants, which banned the production of what scientists have come to call the dirty dozen, the 12 most-concerning POPs, including DDT, PCBs, and dioxin. One of the major criteria the convention used to identify problematic chemicals was their mobility in the environment, which includes transport to polar regions. The convention was a huge success, Jantunen says.

It didn't take long for Arctic monitoring stations to begin to show a leveling off and even decline of many POPs. Newer pollutants, such as PFAS, although not part of the Stockholm Convention, also stopped increasing so quickly, according to Cora Young, an environmental chemist at York University in Canada. "We can see the response to regulation," Young says.

But that downward trend has not always continued. Almost imperceptibly at first, the leveling stopped. In some areas, levels of legacy pollutants like DDT and PCBs began creeping back up. Since this trend appeared only in the Arctic, researchers knew it wasn't because of new emissions. The answer had to lie in the Arctic itself.

CREDIT: JULIAN AHERN (MOSS BAG); LIISA JANTUNEN (AIR SAMPLER)

A member of Roland Kallenborn's team takes snow and ice samples in the Arctic.

Researchers dig for snow and ice samples in the Arctic.

CREDIT: ROLAND KALLENBORN (BOTH)

A CHANGING CYCLE

The Arctic is changing rapidly. Even the ice that clogs the rivers and fills the sea isn't the same ice as before. Hotter temperatures in the summer mean that this ice is transient, melting as the thermometer climbs. The only multiyear ice remaining in the Arctic is north of Canada's Ellesmere Island and nearby Greenland, and even that is shrinking. Almost all Arctic ice is now first-year ice, Young says. It's still sea ice, but it has subtle yet important differences from the multiyear ice that once predominated.

Sea ice forms from the bottom up, and the longer it lasts, the thicker it gets as new ice is added. As water freezes, the process traps some of the pollutants in the ice. Pollutants are also trapped when contaminated snow falls on the ice and freezes, which means they should be locked away for millennia. "As long as the glaciers and ice caps remain frozen, the PFAS are locked in," Young says.

First-year ice, however, is briny: veins of near-freezing salty water run through it and circulate with the ocean below. These brine rivulets are even richer in PFAS and other contaminants than the older ice, Lancaster University's Halsall says. "The concentration of some of these chemicals in this brine actually outweighs that in the surrounding seawater," he says.

This means that the capture of these pollutants is only temporary. When the first-year ice melts in spring, it releases its brine, along with the POPs it harbored during the long, dark winter, back into the sea. This sudden surge of contaminants occurs just as many Arctic denizens are awakening from their long hibernation with a desperate need for food.

"It's like popping the cork in the champagne bottle. All of this stuff trapped in the Arctic ice is coming back into the air and sea, and more exposure is happening that way," Jantunen says. "And they're being reintroduced into global circulation." By warming the Arctic, climate change could remobilize POPs and transform the region from a chemical sink into a pollution source.

Sea ice isn't the only thing melting in the Arctic. Permafrost is also thawing, and it's releasing high levels of methane and carbon dioxide—greenhouse gases that are further accelerating climate change. But just as sea ice traps POPs, so does permafrost. Miriam Diamond, an environmental chemist at the University of Toronto, says that researchers shouldn't ignore terrestrial sources of POPs.

The impacts of climate change won't be felt on just contaminants that have already arrived in the Arctic, says Gary Stern, an Arctic expert at the University of Manitoba. The changing climate also has the potential to add new sources of pollution. For example, as Arctic ice coverage declines, the region becomes open to new shipping and mining concerns. "The question isn't if an oil spill will happen; it's when," Stern says. Any spill will also add the solvents and emulsifiers used to disperse the oil, along with the oil itself.

What's more, new classes of pollutants continue to be identified. Besides PFAS, scientists are focusing on microplastics and plasticizers, as well as compounds like organophosphate flame retardants, which replaced toxic polybrominated diphenyl ethers. Chemists are also tracking the hydrochlorofluorocarbons and hydrofluorocarbons that replace ozone-depleting chlorofluorocarbons.

To Roland Kallenborn, an organic analytical chemist at the Norwegian University of Life Sciences, these novel pollutants are another example of history repeating itself. "The regulators and industry, they don't learn because the same problems are coming up again," he says. "The chemists are always 10 years behind," trying to address pollution after it happens.

A NEED FOR SOLUTIONS

In much of the Arctic, concerns about climate change dominate the discourse. "Climate change is happening fast. It's happening faster in the Arctic than anywhere else on the planet," says John Kucklick, a biochemist at the US National Institute of Standards and Technology.

The question has shifted from if the climate will affect Arctic pollution—that answer is a definite yes—to how. The melting ice will release trapped legacy contaminants like DDT from within, exposing a new generation of humans and wildlife to these POPs. And as the frigid temperatures that historically trapped contaminants in snow and ice disappear, the warmer air can keep POPs more volatile and hence more mobile in the environment, opening up a potential for them to recirculate in the global environment.

To Diamond, Arctic pollution exemplifies the need for caution when companies propose using new chemicals. "Once a chemical gets up there and it's dispersed all over the place, what are you going to do? You can't do anything," she says. The challenge for scientists is to move beyond understanding what is going wrong in the Arctic and to start solving the problems that they have identified, Diamond says. "I see a very rich literature documenting problems. I see much less activity on solutions."

Carrie Arnold is a freelance writer based in Virginia.