AN EVOLVING HISTORY OF ARCTIC AEROSOLS

BY TIMOTHY J. GARRETT AND LISA L. VERZELLA

The Arctic represents the forefront of contemporary climate change, profoundly altered by distant emissions of greenhouse gases. Summer sea-ice cover is shrinking rapidly, while average Arctic temperatures are rising at a rate twice as fast as the global mean. A long legacy of international cooperation in the geophysical sciences has been dedicated to improving understanding of climate in the Arctic. Led by geographer Karl Weyprecht, scientists from 11 nations established a network of Arctic meteorological stations for the first International Polar Year (IPY), held 1881–84. Fifty years later, a second IPY saw 40 nations expanding and solidifying this network. The Third IPY, in 1957–58 (also known as the International Geophysical Year), involved 67 countries and was organized around a solar maximum to focus on the nascent field of space physics.

Currently underway is the Fourth International Polar Year. Between March 2007 and March 2009, scientists will be engaged in over 200 projects, involving 60 nations. The Fourth IPY differs from its predecessors in focusing on how and why Arctic climate is changing, and also by coordinating ground, air, and space-based platforms for the investigation of the transport from midlatitudes of trace aerosol and gas plumes into the Arctic. While anthropogenic climate change did not command greater emphasis in earlier IPYs because it had not yet been confidently predicted or detected, the study of pollution intrusions languished mostly out of misinterpretation and neglect. Arctic atmospheric pollution, once thought to be a late twentieth-century discovery, turns out to have been noticed by our pioneering predecessors of the late 1800s.

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Our study of the research record shows that the remarkable phenomenon of "Arctic Haze" has been a story of repeated discovery and rediscovery. Most studies now recognize the first time Arctic aerosol pollution was noticed to be between the late 1940s and 1950s, when the U.S. Air Force flew at least 3,000 "Ptarmigan" weather reconnaissance missions along a route from Alaska over the Arctic Ocean. As described in 1957 by air force meteorologist J. Murray Mitchell, "Perhaps the most surprising outcome of the 'Ptarmigan' observations has been the high incidence of haze at flight altitudes which restricts horizontal and slant visibility to an estimated range of 3–8 km without impairing vertical visibility to an obvious extent. The color effects in the haze suggest that, like the low-tropospheric haze of middle latitudes, the constituent particles are no larger than about 2 μ. This size is so small that, should the haze be made up of ice, the crystals would be very rudimentary."

At first, these notes went largely unnoticed, at least until decades later when Glenn Shaw of the University of Alaska, Fairbanks, drew greater attention to the phenomenon. As a recent Ph.D. from the University of Arizona, Shaw went to Barrow, Alaska, to measure atmospheric turbidity as part of the 1972 Arctic Ice Dynamics Joint Experiment. Shaw was

FIG. 1. U.S. Air Force meteorologist J. Murray Mitchell Jr. has been credited with the first diagnosis of Arctic haze, in 1957.

alarmed to find the sky was not the deep blue he expected, but that it displayed a whitish haze; two years of sun photometer measurements showed skies sometimes as murky as those seen in cities.

Shaw suspected the haze was pollution from well outside the Arctic, but this hypothesis was met with overwhelming skepticism from colleagues. So, for follow-up work Shaw teamed with University of Rhode Island chemists Kenneth Rahn and Randolph Borys. The first set of results, obtained in spring 1976, showed that background aerosol had unnaturally high vanadium concentrations indicative of heavy oil combustion, and that when it was most hazy, the composition was consistent with plumes of soil dust, blown to the Arctic from the Gobi Desert.

Fig. 2. Polar voyager Adolf Erik Nordenskiöld (1832–1901) believed a metallic soot from space settled "imperceptibly and continuously" over the Arctic.

Later studies of winter haze confirmed a clear anthropogenic signature, revealing high levels of such heavy metals as titanium, chromium, manganese, iron, and nickel, principally from Eurasia. Rahn and Shaw concluded that "Arctic haze is the end product of massive transport of air pollution from various midlatitude sources to the northern polar regions, on a scale that could have never been imagined, even by the most pessimistic observer."

While the work of Shaw, Borys, and Rahn has laid the foundation for the current IPY Arctic pollution studies, it has a distant and underappreciated precedent. Like Shaw, late 1800s Arctic explorers and scientists were also astonished by Arctic aerosols—so much so that in a 1906 lecture, British scientist George C. Simpson remarked, "All who have traveled in Arctic regions know the peculiar haze which fills the air when the temperature falls very low and gives the 'cold' aspect to Arctic scenes. Such a haze, which is not a mist or fog, was frequent during the winter in Karasjok [69°N in Norway]. On the other hand, at the end of the summer the air reached a degree of transparency which I have never seen equaled in any other place."

Even the First IPY appears to support indications of a seasonal haze. Under the command of Lt. P. H. Ray, the U. S. Army organized a formal IPY expedition to Alaska's northernmost point, Point Barrow, arriving by sail in September 1881. A permanent site was established, and from 18 October 1881 to 27 August 1883, hourly meteorological data were recorded. Among these detailed records, a "light" or "dense" haze is often mentioned. While it is not entirely clear from these qualitative indicators whether the "haze" was aerosol or rather tenuous ice crystal precipitation, precipitation was not noted concurrently, and the haze was noted under both clear and cloudy conditions. It was not a fog, either, as this was noted only during summer and fall. The haze events occurred regularly in stretches of several days between November and April. This seasonality observed by Ray in Barrow, and also by Simpson in Karasjok, is a telltale sign of Arctic haze, and one that continues to be echoed in quantitative measurements at these sites today, such as reported in a paper by Quinn et al. in *Tellus* last year.

However, it is perhaps Swedish geologist (Nils) Adolf Erik Nordenskiöld who was first to explicitly draw attention to the haze phenomenon. Nordenskiöld earned renown for his extensive Arctic explorations, in particular for being the first to successfully navigate the Northeast Passage to Asia from the Atlantic. His 1883 expedition to Greenland is described in a fascinating article from an 1883 issue of *Science*. His notes from 22 July at 2:30 a.m. contain this description: "The sky was covered with a thin veil of clouds, through which the sun shone warmly, at times even scorchingly. From time to time this veil of clouds, or haze, descended to the surface of the ice, and hid the view over the expanse; but it was, remarkably enough, not wet, but dry—yes, so dry that our wet clothes absolutely dried in it."

Nordenskiöld also described a "kryokonite" (cryoconite or ice-dust), something he had observed during an earlier 1870 Greenland expedition: "Everywhere where the snow from last winter has melted away, a fine dust, gray in color, and, when wet, black or dark

brown, is distributed over the inland ice in a layer which I should estimate at from 0.1 to 1 millimetre." By absorbing sunlight, the cryoconite created narrow cavities that ranged from millimeters to a meter across, and up to a meter deep. The holes frequently trapped the explorer's feet, frustrating his party's progress across the ice sheet.

Nordenskiöld found in the cryoconite a mixture of communities of microscopic plants and a sooty substance that contained "metallic iron, which could be drawn out by the magnet, and which, under the blowpipe, gave a reaction of cobalt and nickel." The cryoconite showed no topographical preference, indicating to Nordenskiöld that it had not washed down from mountains. Nor did it appear to have blown inland from the coast; it was seen equally at the ice border as it was a hundred kilometers into the ice-sheet interior. When a colleague returned from the Arctic with a large variety of similar samples, Nordenskiöld inferred the dust to be a "signature of these Polar Regions." Nordenskiöld found similarly composed particles within hail fallen at Stockholm, and this solidified in his mind a hypothesis he had been developing since his 1870 Greenland voyage: "I consider it proven by these observations the existence of a cosmic dust which falls imperceptibly and continuously, which may have immense importance not only for geophysics but also for the field of geology and practical questions, for example in agriculture."

However, in the quantities Nordenskiöld would have been able to detect, the metallic iron, cobalt, and nickel Nordenskiöld noted was almost certainly not meteoric in origin, nor even from terrestrial dust. Most probably it was airborne fly-ash caused by smelting and coal combustion—the industrial revolution was well underway. Perhaps considering his long and arduous voyage, Nordenskiöld might be forgiven if he felt Greenland simply too remote to be plausibly contaminated from human activity!

Another Scandinavian, oceanographer and diplomat Fridtjof Nansen, was also puzzled by the "ice dust," but came to a more sober conclusion on its origins. In 1882, as a young man of 21, he joined the *Viking* for a six-month sealing expedition along the southeast coast of Greenland. As the *Viking* drifted with the ice floes, Nansen explored from the vessel by foot. On 5 July, he noted that "Something which hit me as especially peculiar was that the surface of the larger sheets of this gigantic chunk of ice were not completely clean and white, but often had a dirty, grayish, or even brownish hue. How could this be explained? Was it dust? But only a very small number of these ice floes could have been so close to a coastline that dust could have been blown out onto them. Or is it more likely that everywhere, even across the Arctic Sea, there is dust in the air, and that it is taken down onto the ice with every snowfall?"

Under later microscopic analysis, Nansen found 16 different diatomaceous breeds of algae, most known only to the seas North of East Siberia. Nansen suspected that the biota drifted, frozen within the ice, and later thrived under solar ablation. Mixed with the algae were particles of unevaluated mineral composition "which most likely came from the air with the falling snow, and which most likely originated from the lands around the Polar Sea, and maybe also from Siberia."

Today, during the current IPY, intrusions of aerosol pollution into the Arctic are attracting renewed interest because of their possible role in changing the climate of the Arctic. At midlatitudes it is normally thought that pollution aerosol cool local climates by enhancing reflection of sunlight. In the Arctic it is more likely that the net effect is warming. Aerosol pollution can increase absorption of radiation across the solar and terrestrial wavelength spectrum. Where soot has deposited on snow, it makes the surface darker and accelerates solar ablation; and in the troposphere, it adds to solar diabatic heating. Soluble haze aerosol can contribute to Arctic warming by altering cloud properties, in particular by increasing droplet number and decreasing droplet size. It is believed this augments

Fig. 3. Fridtjof Nansen (1861–1930), right, shown with Captain Axel Krefting and the *Viking* during an 1882 sealing expedition to the Greenland Sea. Nansen observed dark stains on the ice sheet that he hypothesized were from dust transported by air from more southern lands.

cloud downwelling thermal emission in winter and spring, when longwave radiation tightly couples Arctic sea ice and clouds.

The history of how aerosol perturbs Arctic climate appears to be long, and is likely still evolving. In general, as regional economies develop, fossil-fuel consumption escalates exponentially while particulate emissions pass through a "dirty" phase. GCM studies by Koch and Hansen (2005) suggest that regional soot transport to the Arctic attained a series of temporary maxima: in 1920 from North America, and in 1960 from Europe. Similarly, recent Greenland ice cores show a rapid rise in anthropogenic soot and sulfate that began in the late 1800s, but with peak sulfate levels in the 1970s, and peak soot between 1906 and 1910.

This recent work adds weight to what had been noted incidentally over a century before: that as early as the late 1800s, the Arctic had been significantly disturbed by aerosols from midlatitudes. In fact, this may well have been the dominant anthropogenic climate signature at the time. In recent years, the Arctic has been relatively clean, but as East Asia develops, it appears that the Arctic may pass through a new dirty phase. Evaluation of the future evolution of aerosol contributions to Arctic climate will require long-term maintenance of observation networks developed during the Fourth International Polar Year. Aerosol intrusions into the Arctic should not again be sampled and then forgotten for decades at a time, as they were in the last century.

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