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Editorial

Interaction of Air Pollution with Snow and Seasonality Effects

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Interactions with environmental surfaces significantly affect the abundance and distribution of air pollutants. This influence of surface interactions on air pollutants may, in turn, alter environmental and health effects caused by the resulting mix of air pollutants in ways that are still poorly understood. Among the various types of environmental surfaces, snow and ice crystal surfaces have historically attracted comparatively less research attention, in part due to the difficulties of conducting both laboratory and field studies at subfreezing temperatures. However, snow and ice research has intensified during the last few years thanks to newly developed experimental and field approaches. The research activity in snow and ice pollution in the seasonally or permanently colder regions of the world is rapidly increasing, especially in Canada, Chile, China, Denmark, Finland, France, Iceland, Norway, Russia, Sweden, and the United States of America. It is now clear that snow plays an important role in air pollutants' fate, from exhaust-derived contaminants to microplastics.

In this Special Issue of Atmosphere, we collected original research articles on the forefront of scientific inquiry into the processes of air-pollution–snow interactions and the impact of seasonality on air pollution. The articles report on the research into physical and chemical processes taking place when air pollutants come in contact with snow and the implications of the winter-specific environmental factors for ambient air pollution. Field observation, laboratory-experimental, and modeling studies are included, along with environmental monitoring and source apportionment research of local, regional, or global relevance. The fieldwork covered in the articles was conducted in various types of locations: urban sites (e.g., the cities of Chengdu, Gucheng [1], Helsinki [2], Montreal [3], and Moscow [4]); small cities and rural areas (e.g., Yulin, Huimin, and Zhengzhou [1], Tien Shan [5], Valday [6], and "36 sites on a 2800 km submeridional profile from the city of Barnaul to Salekhard" [7]); industrial [6]; remote (e.g., the Arctic, Antarctic [8], and Tibetan Plateau [9]); and other locations (e.g., along highways [10] and in the mountains [11]).

The articles collected in this Special Issue focus on the following aspects of the interaction of air pollution with snow and the effects of seasonality: (1) the impact of deposited air pollutants on the snow albedo [2,11,12], (2) the composition and properties of particulate and volatile air pollutants detected in snow [4,7,8,11], (3) links with the sources and impact assessment, including, more specifically, seasonality of black carbon in the air and snow [1,2,5,9,12], (4) metals and metalloids in snow [4,6], (5) radioactive isotopes in snow [10], (6) snowpack pollution as an indicator of atmospheric pollution [1,6–8,10,12], (7) photochemistry of compounds released due to interactions with anthropogenic particles that became mixed with snow [3], and (8) the effect of snow on greenhouse gas fluxes from the underlying peat [13].

Several articles in the Special Issue highlight the importance of different forms of carbon in determining snow albedo and the potential effects on the climate and the cryosphere. Meinander and colleagues [2] investigated the spatial and temporal variability of atmospheric carbon deposition and the sampling, sample processing, and analysis methodology for snow samples. The authors note that the results of such research will allow measuring of atmospheric carbon deposition across time and space, including long-term monitoring and source apportionment [2]. Beres and colleagues [12] concluded that black carbon deposition in snow can be estimated from the snow albedo and vice versa. Zhang and colleagues [5] and Wang and colleagues [9] explored the seasonality of atmospheric black carbon concentrations and discuss the contributions of different sources to black carbon air pollution across the seasons. They found correlations between black carbon concentrations and meteorology, including wind speed. In their exploration of the seasonality of black carbon concentrations in the ambient air, Guo and colleagues [1] studied the seasonal correlation between black carbon in the aerosol phase and black carbon in the snow. Duan and colleagues [14] explored the seasonality of $PM_{2.5}$, including its chemical speciation, and discussed the changes in $PM_{2.5}$ and individual chemical species within $PM_{2.5}$ depending on the traced source location and seasons.

Shevchenko and colleagues [7] investigated the morphology and sources of biogenic, lithogenic, and anthropogenic particles in snow and their correlations with proximity to cities and areas of active hydrocarbon production. They note sharp differences in the mineralogical composition of particulate matter in snow and explore its association with geography. Nemirovskaya and colleagues [8] investigated the organic chemical speciation of air pollutants in the snow and ice of high-latitude areas of the Arctic and the Antarctic. They highlight the high degree of preservation of the mineral, biogenic, and anthropogenic particles in the upper layer of ice in these regions. Nemirovskaya and colleagues [8] also demonstrated the possibility of source apportionment for organic air pollutants based on their distribution in the snow and ice. They discuss the effects of topography, the phenomena associated with the oases in the regions, and meteorology, particularly winds, the importance of which was also noted by Zhang and colleagues [5] and Wang and colleagues [9].

The topic of source apportionment, in the context of metal and metalloid pollutants in urban snow, was investigated by Vlasov and colleagues [4]. In addition to finding a broad range of toxic metals in urban snow, Vlasov and colleagues found specific associations of metal and metalloid co-occurrence clusters with urban sources such as road dust and wind blowing of soil particles, the wear of metal parts of cars, the abrasion of tires and roadway surfaces, vehicle exhaust, and heat power plants. Dinu and colleagues [6] identified a range of geochemical, biological, and anthropogenic factors impacting the accumulation of heavy metal pollutants and selected anions in snow. They discuss the impact of vegetation on the underlying snow cover pollution. As shipping, mining, and industry develop in the Arctic in the future, Vlasov and colleagues' and Dinu and colleagues' methodologies could also become valuable for environmental pollution research in remote high-latitude regions.

Pey and colleagues [11] explored the aerosol deposition from the atmosphere to the snowpack in the Spanish Pyrenees and examined its impact on the optical properties of snow and the snow melting processes. They found the impact on the snow albedo significant enough to be considered in modeling distributed energy balance and snowmelt predictions. Viru and colleagues [13] investigated the impact of snow cover on the greenhouse gas emissions from hemiboreal drained peatlands. As the winters are becoming milder in the northern regions, understanding the impact of snow cover on greenhouse gas emissions from various underlying systems is emerging as a critical topic of future research.

Hall and colleagues [3] explored the source and seasonality of photolabile chlorine species (e.g., Cl_2, HOCl, $ClNO_2$, $ClNO_3$, and BrCl) and the impact of salt application during snow removal operations on the presence of photolabile chlorine species in the ambient air. They examined the association of the photolabile chlorine species in the ambient air with the abundance of chloride ions in $PM_{2.5}$ particles based on a decadal analysis (2010–2019) in the city of Montreal. Their field observations were confirmed in laboratory photochemical experiments. Hall and colleagues showed that anthropogenic salt application to paved surfaces for snow and ice removal produces atmospheric photoactive chlorine species. This newly discovered phenomenon has implications for future modeling of atmospheric photochemical oxidation processes and snow–air interactions to achieve a better understanding of boundary layer meteorology.

Finally, Mezina and colleagues [10] investigated the deposition of three radioactive isotopes (^{7}Be, $^{210}Pb_{atm}$, and ^{137}Cs) in the snow as indicators of precipitation and atmospheric aerosol deposition across seasons. They found that the distribution of radioactive isotopes across different size fractions of particulate matter in the snow is important for determining the degree of regional anthropogenic impact.

The articles in this Special Issue have not explored the impact of air-pollution–snow interactions and seasonality on health effects. However, air pollution has been shown to cause a broad range of adverse environmental and health effects [15,16]. The alteration of air pollution due to snow interactions and seasonality is believed to influence the health impact of air pollution. Numerous studies have linked air pollution exposure not only with cardiovascular and pulmonary disease [17,18] but also neurological disorders [19], reduced IQ [20], impaired athletic performance [21], diabetes [22], and carcinogenesis [23]. Therefore, understanding the physical and chemical processes involved in the snow–air-pollutant interactions will help us determine how the presence of snow and seasonality impacts the harm of air pollution to human health.

Air pollutants in gaseous and particulate forms can undergo various physical and chemical transformations between the time when air pollutants are released and when exposure occurs. Air pollutants interact with environmental surfaces such as vegetation, soil, exposed rock, water surfaces, and snow. Snow specifically is an important determiner of air pollutants' fate. The interactions of some air pollutants with snow lead to their temporary or permanent extraction from the atmosphere. Conversely, snow–air-pollutant interactions also result in the introduction of pollutants into the air. The time scale, conditions and the nature of this two-way air pollutant flux present a significant knowledge gap.

Upon melting, refreezing, evaporation, and sublimation, snow pollutants can be transformed and transferred to the atmosphere, the hydrosphere, the lithosphere, and the biosphere. Such transformation processes may alter the chemical nature and distribution of air pollutants across the gas and particulate phases within a broad range of aerosol particle sizes [24–26]. A new research field dedicated to investigating these transformations is emerging. This future research should address the remaining knowledge gaps in our understanding of snow-air-pollutant interactions and their impacts, which preclude answering multiple questions regarding the impact of snow and seasonality on gas-phase atmospheric chemistry, cold temperature photochemistry, photochemical and photophysical processes in snow and ice, snow–ice–air–water–soil interactions, aerosol dynamics, and the resulting alterations of the environmental and health impact of air pollutants. We hope that the selected phenomena explored by the authors of the articles in this Special Issue and the findings inspire and inform future research into snow–air-pollution interactions and the impact of seasonality on air pollution.

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