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Editorial: Atmosphere—Cryosphere Interaction in the Arctic, at High Latitudes and Mountains With Focus on Transport, Deposition, and Effects of Dust, Black Carbon, and Other Aerosols

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Editorial on the Research Topic

Atmosphere—Cryosphere Interaction in the Arctic, at High Latitudes and Mountains With Focus on Transport, Deposition, and Effects of Dust, Black Carbon, and Other Aerosols

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Atmosphere and cryosphere are closely linked and therefore need to be investigated as an interdisciplinary subject. Most of the cryospheric areas have undergone severe changes in recent decades, while such areas have been more fragile and less adaptable to global climate change (Boy et al., 2019). Atmospheric air pollutants, in particular black carbon (BC) and dust, are deposited on clean snow, land ice or sea ice surfaces, and decrease their albedo. Due to albedo-feedback, snow and ice are melting faster and seasonal snow cover earlier. Impacts of ice loss include reduction in the Earth's albedo and, as a positive feedback, this leads to further warming (Flanner et al., 2007), as for example in the Arctic region. Albedo is wavelength dependent and typically very high for clean snow, and decreases as a function of snow age, snow grain size, and impurity content (e.g., Warren and Wiscombe, 1980; Aoki et al., 2000; Gardner and Sharp, 2010). It is estimated that Arctic snow albedo is reduced primarily due to BC, but other impurities can also contribute to absorption, such as organic or brown carbon (Doherty et al., 2010). Surface albedo feedback has been found as the second main contributor to Arctic amplification (Pithan and Mauritsen, 2014), and BC deposition to snow and ice can strongly contribute to the darkening via black-carbon-on-snow forcing (Bond et al., 2013). The role of BC in snow and ice has been widely investigated, and detailed scientific assessments have been presented in Bond et al. (2013), Intergovernmental Panel on Climate Change (IPCC) (2013), and AMAP (2015). Seemingly small amounts of BC in snow, of the order of 10–100 parts per billion by mass (ppb), have shown to decrease its albedo by 1–5% (Hadley and Kirchstetter, 2012). A reduction in snow-surface density due to light absorbing impurities has been documented (Meinander et al., 2014; Skiles and Painter, 2017), and BC has also been suggested as disturbing the water holding capacity of snow (Meinander et al., 2014).

Dust has been identified as reducing snow albedo in many parts of the world, for example the Chilean Andes, European Alps, Greenland, Himalaya, Iceland, Caucasus Mountains, North America, and Antarctica (e.g., Painter et al., 2007; Kutuzov et al., 2013; Meinander et al., 2016; Svensson et al., 2018; Bergstrom et al., 2019; Di Mauro et al., 2019; Rowe et al., 2019). In Iceland, dust events have been observed to decrease snow and ice albedo on average by 0.18,

and dust deposition has been estimated to cause an additional 1.1 m w.e. (water equivalent) of snowmelt (or 42% of the 2.8 m w.e. total melt) compared to a hypothetical clean glacier surface (Wittmann et al., 2017). Extreme snow dust storms (Dagsson-Waldhauserova et al., 2015) can lead to insulation effect instead of snow melting (Dragosics et al., 2016; Möller et al., 2016) or to albedo decrease via a clumping mechanism, where small particles form larger particles in snow (Dagsson-Waldhauserova et al., 2015; Peltoniemi et al., 2015; Möller et al., 2019). Experiments have shown that volcanic dust (Iceland) can reduce albedo of snow similarly to BC (Peltoniemi et al., 2015; Zubko et al., 2019). Albedo changes on snow surface can also be caused by pigmented algae (Benning et al., 2014; Lutz et al., 2016), or cryoconite, a mixture of dust, pebbles, soot, and microbes (Di Mauro et al., 2017). All LAI have an important role in enhanced warming via feedback mechanisms. They reduce the albedo of highly reflective surfaces and increase absorption of solar radiation.

The atmosphere, such as over the Arctic, is influenced by air pollution from distant anthropogenic sources, but not all local and foremost natural sources of air pollution are well-known or monitored. For example, anthropogenic pollutants from residential heating (domestic combustion), land transport, industrial production, and biomass burning, accumulate during the winter and spring in the stable Arctic atmosphere resulting in a local phenomenon, Arctic haze. Arctic haze is predominantly caused by sulfate and organic carbon particles and, to a lesser extent, by ammonium, nitrate, BC, and dust (Hyslop, 2009). There are also local anthropogenic sources of air pollution in the Arctic such as shipping, smelters, flaring in the oil and gas industry, air traffic and radioactive waste disposal. BC is the most powerful light absorbing aerosol with climate warming potential of all aerosol types. Significant natural air pollution sources, such as dry riverbeds, volcanoes, high latitude deserts and dust sources, biogenic sources, and oceans, are located at high latitudes. For example, high latitude dust (HLD) sources are estimated to contribute about 3–5% of the global dust budget (Bullard et al., 2016; Groot Zwaaftink et al., 2016). Mineral dust is considered mainly a light-scattering particle in the atmosphere, but a light-absorbing particle when deposited on snow or ice [Intergovernmental Panel on Climate Change (IPCC), 2013]. Volcanic dust is, contrarily, a strongly absorbing particle with a spectral reflectance of 0.03 (Ovadnevaite et al., 2009; Peltoniemi et al., 2015; Zubko et al., 2019). In the Arctic, volcanic dust can reach altitudes of several kilometers and travel distances over 1,000 km (Arnalds et al., 2016; Dagsson-Waldhauserova et al., 2019). Aerosols in cold regions have direct impacts on climate, but their forcing effects can rapidly increase via indirect forcing when aerosols interact with the cryosphere, such as via deposition on snow, ice, sea ice, and other bright surfaces. Dust has been recognized as an important climate driver, causing snow darkening and melting in polar regions [Intergovernmental Panel on Climate Change (IPCC), 2019].

In this Research Topic, the main objective was to fill some of the gaps in our understanding of HLD sources, local sources of BC and other air pollutants in high latitudes, as well as long-range transport of air pollution from lower latitudes. The impacts of air pollutants on the cryosphere and the identification of LAI in snow pack are crucial to understand the atmosphere—cryosphere interaction and climate.

WHAT DID WE NOT KNOW BEFORE THIS RESEARCH TOPIC AND WHAT DO WE KNOW NOW?

The main findings of the papers published in this Research Topic include:

BC from cropland burning is entering Arctic snow areas from latitudes as low as 40°N in the spring. Some of these emissions can be deposited beyond 80°N despite the low injection heights associated with cropland burning (Hall and Loboda).

Local emission of BC have been identified from the snow samples in Antarctica. Antarctic BC originates from human activities such as local combustion of fossil fuels as well as regional wildfires from the South American continent (Khan et al.).

A 31-year study of Alpine snow pack showed an occurrence of about 0.75 dust on snow deposition events on average. Saharan dust layers can be defined by snow pH > 5.6 together with a Ca^{2+} concentration >10 μeq/l, with increased Mg^{2+} by 25% and Ca^{2+} by 35% (Greilinger et al.).

What are the light absorbing impurities (LAI)? The story of LAI in snow as a journey of one science field and the remarkable scientist behind it. What was the past and what are the needs in the future? (Warren).

Radon concentrations on the Antarctic Plateau have increased due to subsidence of terrestrially influenced tropospheric air (long distance air pollution) while radon concentrations at coastal Antarctic sites have increased from local radon sources in summer and tropospheric subsidence. An Antarctic and Southern Ocean radon overview is provided by Chambers et al.

Dust storms are frequently occurring in Antarctica's ice-free area where the mean PM_{10} concentrations are similar to those reported from background North-European stations (Kavan et al.).

First study provides an evidence of long range transport of Icelandic volcanic dust toward the High Arctic, >2,000 km. This is also the first documented study on long range transport of HLD inside the Arctic (Moroni et al.).

HLD can be transported toward Europe, traveling over 3,000 km (Dordevic et al.).

There are 128 dust days annually reported in Iceland based on the 60 years SYNOP data analysis (Nakashima and Dagsson-Waldhauserova).

Nepal experiences heavy spring dust loads from north-west reflected in high AOD observations, which can be estimated using linear regression model (Bhattarai et al.).

This Research Topic offers new findings on aerosols and air pollutants such as BC, dust, radon, and ozone. These air constituents were identified as having different origins: BC from low latitude crop burning, combustion of fossil fuels in Antarctica and wild fires in South America; dust from the Sahara and high latitudes such as volcanic dust from Iceland and Antarctic dust. Light absorbing impurities, aerosols and air pollutants were

reported from the Russian Arctic, the European Alps, Svalbard, Antarctica, South America, Southern Ocean, and Himalaya, as well as Icelandic dust detected in Balkan Peninsula in Europe.

The long-range transport of air pollutants toward fragile pristine areas of our planet is the main link between most of the studies in this Research Topic. Transport of HLD as an air pollutant toward inhabited areas of Europe is another transport pathway which needs to be considered. Local sources of air pollution inside the polar and mountain regions as well as their long-range travel capabilities inside such regions need to be taken into account in assessing their various impacts. These studies provide evidence of the presence of BC, dust, radon in previously not known remote locations. Great interest has arisen and a large amount of work has been done to understand the direct and indirect impacts of BC on climate as well as BC source identification. There are, however, great gaps in current understanding of BC, for example in wet and dry deposition rates as well as seasonal and temporal variability of BC in the cryosphere, and of dust (crustal desert dust as well as HLD) sources, (re)suspension/deposition processes, and climate impacts (albedo changes/snow melt, atmospheric chemistry, cloud microphysics, etc.) currently missing in climate models.

Scientific research is a long journey for individuals, institutions, and worldwide networks for better understanding of our planet. Such a scientific journey is full of surprises of great importance and following two sentences from Professor Steve Warren's life and contribution to this Research Topic (Warren), dated decades ago, perfectly describe the meaning of it: "I could hardly imagine anything more boring than atmospheric dust," and "What's that light-absorber you're finding in the atmospheric aerosol? Bob revealed his not-yet-published secret, whispering in our ears: 'It's carbon!'"

AUTHOR CONTRIBUTIONS

PD-W coordinated the writing of the editorial. OM made original plans for the topical conference session and consequently Research Topic and provided large inputs for the editorial.

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