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EDITED BY
Per Fauchald,
Norwegian Institute for Nature Research (NINA), Norway

REVIEWED BY
Andreas Westergaard-Nielsen,
University of Copenhagen, Denmark

*CORRESPONDENCE
Outi Meinander,
outi.meinander@fmi.fi

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Dust in the Arctic: a brief review of feedbacks and interactions between climate change, aeolian dust and ecosystems

Outi Meinander[1]*, Andreas Uppstu[1], Pavla Dagsson-Waldhauserova[2,3], Christine Groot Zwaaftink[4], Christian Juncher Jørgensen[5], Alexander Baklanov[6], Adam Kristensson[7], Andreas Massling[8] and Mikhail Sofiev[1]

[1]Finnish Meteorological Institute, Climate research, Helsinki, Finland, [2]Faculty of Environmental and Forest Sciences, Agricultural University of Iceland, Reykjavík, Iceland, [3]Faculty of Environmental Sciences, Czech University of Life Sciences Prague, Prague, Czechia, [4]Department for Atmosphere and Climate, NILU, Kjeller, Norway, [5]Aarhus University, Department of Ecoscience – Arctic Environment, Aarhus, Denmark, [6]Physics of Ice, Climate and Earth, Niels Bohr Institute, Copenhagen University, Copenhagen, Denmark, [7]Department of Physics, Lund University, Lund, Sweden, [8]Department of Environmental Science, Interdisciplinary Centre for Climate Change (iClimate), Aarhus University, Roskilde, Denmark

Climatic feedbacks and ecosystem impacts related to dust in the Arctic include direct radiative forcing (absorption and scattering), indirect radiative forcing (via clouds and cryosphere), semi-direct effects of dust on meteorological parameters, effects on atmospheric chemistry, as well as impacts on terrestrial, marine, freshwater, and cryospheric ecosystems. This review discusses our recent understanding on dust emissions and their long-range transport routes, deposition, and ecosystem effects in the Arctic. Furthermore, it demonstrates feedback mechanisms and interactions between climate change, atmospheric dust, and Arctic ecosystems.

KEYWORDS

dust, climate, arctic, ecosystem, atmosphere

1 Introduction

During the last 4 decades, the warming in the Arctic has been nearly four times faster than the overall warming in the rest of the Earth (Rantanen et al., 2022), a phenomenon called Arctic amplification (AA) (Ghatak and Miller, 2013; Gong et al., 2017; Gaston, 2020; Rantanen et al., 2022). There are several Arctic-specific feedback processes (Arnold et al., 2016), which are both a consequence and a driver of the observed AA (e.g., Dai et al., 2019; Serreze et al., 2009). However, warming is not homogeneous across the Arctic, but instead dependent on scale, location and season (Westergaard-Nielsen et al., 2018; You et al., 2021). For example, in Greenland, warming has been largest in the west (Abermann et al., 2023), yet many weather stations along the Greenlandic coast show no clear trend in increasing surface temperatures (Cappelen et al., 2021). On a regional scale, areas in the Eurasian sector of the Arctic Ocean have warmed even up to seven times as fast as the globe (Rantanen et al., 2022).

The United Nations (UN) General Assembles and the UN Coalition to Combat Desertification (UNCCD) (UNEP, 2016; UNCCD, 2022) reiterated that the global frequency, intensity, and duration of Sand and Dust Storms (SDS) have increased in

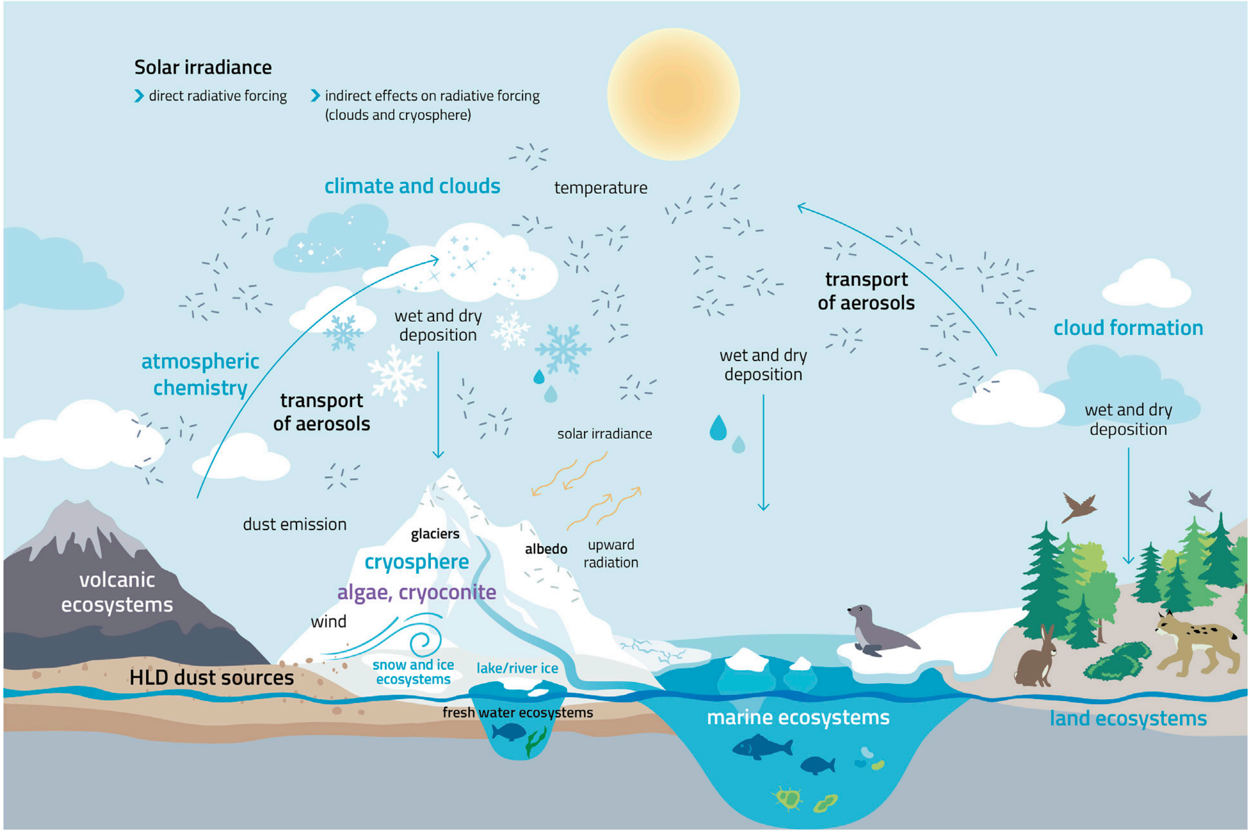

FIGURE 1
Climate and ecosystem related interactions of aeolian dust in the Arctic. These include direct radiative forcing (absorption and scattering), indirect radiative forcing (clouds and cryosphere), and effects on atmospheric chemistry and on terrestrial, marine, fresh water, and cryospheric ecosystems. In addition, semi-direct effects of dust on meteorological parameters (e.g., atmospheric pressure, temperature profile and cloudiness) affect the radiative balance in the atmosphere. Dust deposition can supply ecosystems with macro and micronutrients, acid-neutralizing capacity, heavy metals, microbes and other biota, synthetic materials, and light-absorbing particles.

the last decade and that SDS have natural and human causes that can be exacerbated by desertification, land degradation, drought, biodiversity loss, and climate change. UNCCD and FAO (2024) also highlighted that emerging SDS source areas have been associated with the warming of the Arctic and high latitude regions, the seasonal or permanent drying of inland waters and river deltas, or are following large-scale deforestation and wildfires, or even the ploughing of a single field. Loss of snow cover, retreat of glaciers, and increase in drought intensity due to climate change can lead to surface conditions that increase the likelihood of creation, continuation and expansion of SDS source areas.

Aeolian dust refers to particles that originate from the Earth's surface and are light enough to be suspended by wind and turbulence in the atmosphere, carried by the wind for significant distances, but heavy enough to be deposited by sedimentation. Additionally to air quality impacts, dust affects both weather and climate, but is also driven by those: dust life cycle, i.e., emissions, atmospheric transport, and deposition, are dependent on soil properties, weather and climatic conditions. Long-range transport (LRT) of dust to the Arctic and impacts of high-latitude and Arctic dust emissions is an emerging topic, also recognized as an important climate driver in the Polar Regions (IPCC, 2019; AMAP Arctic climate change update 2021; IPCC, 2021; IPCC, 2023). Each component of the dust cycle is influenced by natural processes (e.g., desertification, permafrost thaw, glacier melt and retreating snow-covered surfaces in general) and anthropogenic activities (e.g., degradation of agricultural and eroded lands, deforestation, construction, mining, and landfills). The dust cycle facilitates the exchange of particles among Earth's major systems, e.g., atmosphere, lithosphere, hydrosphere, cryosphere, and biosphere, enabling dust to traverse ecosystems. A well-known example is Saharan dust fertilizing Amazonia by providing annually about 22,000 tonnes of phosphorus and other nutrients for the area (Yu et al., 2015). Even Greenland's ice-free areas have long been identified as locally important dust sources (Hobbs, 1942; Wientjes et al., 2011; Bullard and Mockford, 2018).

Aeolian dust, depending on the disciplinary context, can refer to all primary emitted particles to the atmosphere from the Earth's surface, or only to the inorganic (mineral) fraction of dust. Dust can also contain organic (e.g., soil organic matter, bacteria, fungi, fungi, algae, pollens, spores, insect and plant fragments), synthetic substances (e.g., fertilizers and microplastics), and adsorbed nutrients and heavy metals. During the transport of dust particles in the atmosphere, they can also undergo chemical and physical transformations, whereas labile fractions of nutrients and metals can be found within the organic fractions (Brahney et al., 2024). For clarity, dust is defined here as a terrestrial sediment, sized <100 µm which is transported in aeolian suspension.

We focus here on interactions between climate, the life-cycle of dust, and ecosystems (flora and fauna), in the northern high-latitudes ≥50°N and Arctic ≥60°N (Figure 1). Climate and ecosystem relevant feedbacks include direct radiative forcing (absorption and scattering) and indirect radiative forcing (modified cloud properties through seeding cloud droplets and ice crystals) and any kind of dust impact by dry and wet deposition on snow- and ice-covered surfaces. Atmospheric chemistry is affected since dust can serve as a sink for radiatively important atmospheric trace gases. Terrestrial, marine, freshwater, and cryospheric ecosystems can show increased productivity and carbon uptake through deposition of dust delivering nutrients like iron and phosphorus. Scattering of solar shortwave (SW) radiation cools the climate, whereas SW absorption warms the climate. Both the scattering and absorption of terrestrial longwave (LW) radiation warm the climate as both decrease the transparency of the atmosphere to terrestrial LW radiation (Kok et al., 2023). The semi-direct effect (Hansen et al., 1997) represents the thermodynamic effect of dust, absorbing solar radiation, on meteorological parameters (e.g., atmospheric pressure, temperature profile and cloudiness) which in turn affects the radiative balance in the atmosphere. It tends to increase the static stability of the atmospheric boundary layer and suppress convection and cloud formation, so as a result allows more solar radiation to penetrate to the surface and counteracts the direct effect.

Dust provides a positive radiative forcing on the order of a few tens of Wm-2 at the top of the atmosphere through the shortwave and longwave scattering and absorption, and the albedo decreases of snow and ice surfaces. High-latitude dust contributes significantly to this forcing, especially during summer and autumn (Kylling et al., 2018; Markowicz et al., 2022). High-latitude emissions thus lead to highly effective regional climate forcing (Kylling et al., 2018). In contrast, high-latitude dust constitutes a negative forcing on the order of a few tenths of Wm-2 due to depletion of the liquid water path and change of cloud phase of lower level mixed-phase clouds (Shi et al., 2022; Kawai et al., 2023). Clouds at high latitudes frequently persist in a supercooled state (Murray et al., 2021). *In-situ* observations and models have shown that HLD serving as a highly potential INP converts cloud droplets to ice crystals, leading to dramatic reduction of a cloud's liquid water content while reducing its albedo and exposing the surface underneath. Increased downward longwave radiation results in positive climate feedback. HLD has been shown to be highly effective biogenic ice-nucleating material while dust from the most prominent low latitudes is abiotic (Tobo et al., 2019; Meinander et al., 2022). During transport, dust scatters and absorbs SW and LW radiation, modifies cloud properties, mixes with other aerosols and serves as a sink for radiatively important atmospheric trace gases (Kok et al., 2023; Mahowald, 2011). When deposited, dust darkens snow and ice and stimulates ecosystem productivity and carbon dioxide drawdown through the delivery of iron and phosphorus. These mechanisms both cool and warm the climate system, the net effect of which is uncertain and accordingly, the sign and magnitude of radiative perturbations arising from increases in dust since the pre-industrial era are also uncertain. This means that it is unknown whether global dust changes have enhanced or opposed anthropogenic warming (Kok et al., 2023).

2 Dust sources

The Earth's largest and most persistent dust sources are known to locate in the Northern Hemisphere, mainly in a broad "dust belt" that extends from the west coast of North Africa, over the Middle East, Central and South Asia, to China (Prospero et al., 2002). A new dust source area appeared recently at the bottom of the Aral Sea that dried out during the last 50 years (Chen et al., 2022). Dust from low latitudes also reaches the Arctic through atmospheric transport. There are, however, important large dust sources also in the Southern Hemisphere, located in Australia, Africa and South America. Dust emission sources located at the northern high latitudes have been added to the discussion more recently (Bullard et al., 2016; Meinander et al., 2022), where the term for northern "high latitude dust" (HLD) has been defined to consider high latitudes as areas ≥50°N (Bullard et al., 2016). "Arctic dust," in turn, has been used for dust emissions from latitudes ≥60°N (e.g., Meinander et al., 2022; Matsui et al., 2024). Moreover, Meinander et al. (2022) have recently presented evidence for a "northern HLD belt", defined as the area north of 50° N, with a "transitional HLD-source area" extending at latitudes 50°–58° N in Eurasia and 50°–55° N in Canada and a "cold HLD-source area" including areas north of 60° N in Eurasia and north of 58° N in Canada, with currently "no dust source" area between the HLD and low-latitude dust (LLD) belt, except for British Columbia.

Bullard et al. (2016) have estimated that high-latitude sources cover >500,000 km^2. Meinander et al. (2022), in turn, presented source intensity (SI) values, which show the potential of soil surfaces to act as sources for dust scaled to values from 0 to 1 concerning globally most productive sources, using the Global Sand and Dust Storms Source Base Map (G-SDS-SBM, Vukovic, 2019). They estimate that northern high-latitude land areas with higher (SI ≥ 0.5), very high (SI ≥ 0.7), and the highest potential (SI ≥ 0.9) for dust emission cover >1,670 000 km^2, >560,000 km^2, and >240,000 km^2, respectively. In the Arctic HLD region (≥60° N), in turn, land area with SI ≥ 0.5 is 5.5% (1,035 059 km^2), area with SI ≥ 0.7 is 2.3% (440,804 km^2), and area with SI ≥ 0.9 is 1.1% (208,701 km^2). Hence, the estimates from Bullard et al. (2016) agree with the estimate of Meinander et al. (2022) of very high potential area for dust emissions, both estimating an area of >500,000 km^2.

Typical high latitude dust emissions originate from ice-proximal areas, including glacier forefields and riverbeds, glacial lake areas, sandy beaches and deserts, and large old pumice areas around volcanoes (Bullard and Austin, 2011; Bullard and Mockford, 2018; van Soest et al., 2022; Bullard et al., 2023; Baddock et a. 2024). For example, a recent study showed that dust emissions occur in the High Arctic desert environment of Peary Land, NE Greenland, indicating that aeolian dust emissions are likely a ubiquitous phenomenon along the majority of proglacial river systems draining the Greenland Ice Sheet (Baddock et al., 2024). In the northern high latitudes, Iceland has been identified as the most active source for dust emissions (Bullard et al., 2016; Meinander et al., 2022). When ice and snow melt or permafrost thaws as a consequence of warming, new land areas will be revealed, and these appear as potential new dust emission sources (Meinander et al., 2022).

3 Dust emissions and timing

There has been great interest in understanding the role of aeolian dust emissions in climate by modulating solar radiation and cloud properties (e.g., Barr et al., 2023). Bullard et al. (2016) estimated that HLD sources emit at least 80–100 Tg yr−1 of dust to the atmosphere (~5% of the global dust budget), which they expect to increase under future climate change scenarios. Other model results by Groot Zwaaftink et al. (2016) and Meinander et al. (2022) indicate that Arctic dust emissions amount to roughly 1%–3% of global dust emissions. In addition, it has been estimated that 1.5–31 Tg of dust aerosols are transported from lower latitudes to the Arctic region (Böö, 2023). Moreover, dust emissions have increased in the Arctic during 1981–2020 according to model simulations by Matsui et al. (2024).

The northern hemisphere dust emission rates vary in response to environmental conditions, such as seasonal variation in wind shear, soil moisture content, snow cover and temperature, where, e.g., snow cover can decline dust emissions (Bullard et al., 2016; Di Biagio et al., 2018; Meinander et al., 2022). However, Arctic winter storms and snow-dust storms occur in Iceland (Dagsson-Waldhauserova et al., 2015; Dagsson-Waldhauserova et al., 2019). In 1949–2011, Iceland had on average 34–135 dust days per year (days per year in Iceland with conventionally used synoptic codes for dust observations) with the highest frequency in winter and spring in the southern parts of Iceland, and in May-October in the Northeast Iceland (Dagsson-Waldhauserova et al., 2013; 2014). Similar frequencies as in the NE Iceland have been reported from Alaska and Greenland (Crusius et al., 2011; Bullard et al., 2023). The long-term seasonal variations of local dust storms in Iceland during 1949–2011 (Dagsson-Waldhauserova et al., 2014), reveal that in southern Iceland March, April and May are the months where dust events have been most frequent, while in NE Iceland they occur mainly in summer and early autumn (May–September).

4 Dust transport paths

East Asia and Africa are important sources of dust observed at higher latitudes in the Arctic, as confirmed by analysis of ice cores, aerosol samples, satellite observations and numerical modeling (e.g., Groot Zwaaftink et al., 2016; Đorđević et al., 2019). Dust has been suggested to travel more than 20,000 km from a Chinese origin to the French Alps (Grousset et al., 2003), and over 5,000 km from Africa to Finland with water vapor transport as the driving force (Meinander et al., 2023). In fact, during the last 4 decades, 78% of atmospheric rivers occurring over northwest Africa have been associated with extreme dust events over Europe (Francis et al., 2022). LRT dust in Finland has been found to originate from the Sahara, Aral-Caspian and Middle East (Varga et al., 2023). Records of LRT dust reaching Finland during 1980–2022 (Varga et al., 2023), reveal that March, April and May are the months where dust events have been most frequent. Saharan dust transport across the eastern side of the North Atlantic Ocean towards the Arctic, associated with ice melt over the deposition area in Greenland, was reported by Francis et al. (2018).

Dust from high latitudes is often transported over shorter distances in the Arctic (Groot Zwaaftink et al., 2016), but it can also reach lower latitudes (Crusius et al., 2011; Cvetkovic et al., 2022). In Svalbard, dust emissions from a proglacial river plain (Adventdalen) indicate the presence of a highly emissive source for sediments in such environments (Rasmussen et al., 2023). Iceland receives long-range transported Saharan dust once or twice a year on average (Varga et al., 2021), while local Icelandic dust has been collected, e.g., in Svalbard (Moroni et al., 2018). Long-term model simulations have confirmed large amounts of Icelandic dust transport to the ocean, but also to Greenland, Svalbard and Europe (Groot Zwaaftink et al., 2017). Svalbard, in turn, has been reported to receive LRT dust mostly from Africa, Asia and Eurasia (Groot Zwaaftink et al., 2016; Di Mauro et al., 2023).

5 Dust deposition and impacts on ecosystems

5.1 Deposition

Aeolian dust is deposited on soils, lakes, streams, seas and oceans, on ice and snow, as well as on vegetation, across the Arctic region (Bowen and Vincent, 2021). Ecosystem implications are highly dependent on the dust amounts and specific particle properties, e.g., mineral composition (Baldo et al., 2020; Varga et al., 2021) and nutrient concentrations (Arnalds et al., 2014) and timing of deposition. For wet and dry dust deposition, the ecosystem effects may vary depending on the location, season and geographical scale (e.g., Meinander et al., 2022; 2023). With increasing altitude, contributions from remote sources, especially Africa and Asia, are increasing and LRT dust therefore becomes more important for dust loads in the Arctic (Groot Zwaaftink et al., 2016). Kavan et al. (2024), in turn, have reported a correlation between dust deposition and the altitude of sampled dust in Svalbard stating that with higher altitude lower deposition amounts were found, implying a high probability for LRT.

For global dust emissions and their Arctic deposition, Meinander et al. (2022) calculated that when total annual global dust emissions for <30 μm particles are 3,000 Mt (megatonnes), then deposition on Arctic snow is 7.6 Mt, on Arctic Sea ice 4.7 Mt and on Arctic Sea surface 21 Mt. In comparison, Arctic dust with a total emission of 30 Mt has 4 Mt deposition on Arctic snow, 3 Mt on Arctic sea ice, and 12 Mt on Arctic Sea surface. Simulations by Groot Zwaaftink et al. (2016) on the other hand, indicated that over 83% of dust deposited on Arctic sea ice originates from HLD sources, since due to limited convection, larger particle sizes and enhanced efficiency of removal, dust emitted in these source regions is mostly deposited closer to the source. Also, for coarse particles, one could expect an increasing contribution from nearby sources. Moreover, Icelandic top sediments show coarser particle size distributions compared to the high dust-emitting crusts from mid-latitude arid regions (González-Romero et al., 2024).

5.2 Dust contributions to ecosystems

Dust can affect the ecosystems through numerous mechanisms, for example,:

1. *Dust as a light absorbing particle in cryospheric ecosystems.* Dust can impact via an "ice-albedo feedback", which increases cryospheric melt and the effective snow grain size as a result of a darker (low albedo) surface, and may shorten the melt period and influence water availability (Painter et al., 2012; Meinander et al., 2013; Skiles et al., 2018; Boy et al., 2019). In contrast, insulation and prevention of snow and ice from melting is observed with a sufficiently thick layer of particles (Wittmann et al., 2016). Natural debris flows have also prevented large ice masses from melting in Iceland (Ben-Yehoshua et al., 2020; Kavan et al., 2024). The cryosphere also includes cryoconite (Di Mauro et al., 2017), a mixture of mineral and organic material covering glacial ice, playing important roles in biogeochemical cycles and lowering the albedo of a glacier surface formed by dust, small rock particles, soot, and microbes (Piotr et al., 2022).
2. *Dust as a nutrient and factor affecting atmospheric carbon dioxide fixation.* Dust can supply macro- and micronutrients to marine (Gaston, 2020; Meinander et al., 2022), freshwater (Scholz and Brahney, 2022), and terrestrial ecosystems (Aciego et al., 2017; Ponette-González et al., 2018). Dust can enrich surface soils with a wide range of nutrients (P, K, Mg, Na, Ca, Fe, Cu, Mn and Mo) and some elements have an indirect effect on the availability of other elements (McTainsh and Strong, 2006). HLD of volcanic origin, e.g., from Iceland and Alaska, is rich in bioavailable iron with significantly higher solubility (up to 30%) than the typical low latitude dust with low pH (Baldo et al., 2020). This can impact primary productivity and nitrogen fixation in the North Atlantic and Pacific Oceans and lead to additional carbon uptake. Iron deposition on the ocean can be higher around Iceland than west of Africa (Arnalds et al., 2014). Impacts of phosphorus minerals on ice algal blooms have also been documented (McCutcheon et al., 2021). The highest dust deposition rates in Iceland have been found in the areas with the highest densities of bird nests (Gunnarsson et al., 2015).
3. *Dust is a factor affecting acidity.* Dust has been found to contribute to the alkalization of precipitation pH (Grider et al., 2023), and to altering the surface water pH, depending on the chemical composition (Brahney et al., 2024).
4. *Dust as a distributor of biota.* Dust can deliver microorganisms (Dastrup et al., 2018), microfauna (Rivas Jr et al., 2018) and organic material (Field et al., 2010) to the recipient ecosystems. Diatoms and organic material can be transported during snow-dust storms in Iceland (Dagsson-Waldhauserova et al., 2015).
5. *Dust as a provider of toxins.* Dust can bring toxins to the ecosystems (Fubini and Fenoglio, 2007).
6. *Dust as a contributor for soil formation.* Dust can be an important contributor to pedogenesis, i.e., the phenomenon leading to soil formation (Munroe et al., 2024).
7. *Dust as a modifier of atmospheric radiation, clouds and precipitation.* Dust aerosols absorb and scatter solar irradiance (Kok et al., 2023) and act as cloud condensation nuclei (CCN) and ice nucleating particles (INPs) (Creamean et al., 2022; Barr et al., 2023; Kok et al., 2023) having a direct and indirect effect on Arctic climate. Varga et al. (2023) found that during 1980–2022 all winter LRT dust events reaching Finland were associated with freezing rain. Indirect ecosystem effects of dust in the Arctic ecosystems include impacts on the availability of light and water (atmospheric radiation, cloud formation and precipitation).

Anderson et al. (2017) have stated that dust input to soils and lakes may have substantial ecological impacts in Greenland, while in Iceland, deforestation of large native woodlands by Vikings only up to 120 years after the settlement led to almost total elimination of forests (Aradottir and Arnalds, 2001). Final ecosystem collapse occurred with the arrival of colder climate and massive erosion where the vegetated ecosystem was turned into desert, existing until today in large parts of Iceland and forming a large source of high-latitude dust.

6 Discussion and future perspectives

This brief review examines feedback and interactions between climate change, dust life-cycle, and ecosystems in northern high-latitudes and the Arctic. The multiple mechanisms related to dust emissions, transport and deposition both cool and warm the climate system, with an uncertain net effect. Dust plays a significant role in terrestrial and aquatic ecosystems, e.g., by providing nutrients, and with impacts on the availability of light and water. Due to Arctic warming, HLD dust emissions can be expected to increase. For example, Matsui et al. (2024) found that the globally simulated dust emission flux in the Arctic (>60°N) increased by 20% from 1981 to 1990 to 2011–2020.

Reanalysis data sets, which combine modeling and remote sensing data, estimate that 1.5–31 Tg of dust aerosols are transported from lower latitudes to the Arctic region (Böö, 2023). The contributions of LLD and HLD complicates the interpretation of how much different sources contribute to the dust loadings and corresponding temporal and spatial deposition patterns. Another challenge is that low latitude dust source emissions of road and agricultural dust is barely characterized at all (Kristensson et al., 2024).

In future research, cross-sectional networking of atmospheric high latitude dust experts (measurement, modeling and remote sensing communities) with soil and cryospheric experts should be utilized for identification of current and future dust source locations and particle properties (on the ground, when windlifted, during transport and when deposited). Optical properties of various dust types need to be investigated to estimate their climatic significance. For example, for dark Icelandic dust, the imaginary part of the complex refractive index (i.e., absorption properties) at 660–950 nm has been found 2–8 times higher than most of the northern Africa and eastern Asia dust samples (Baldo et al., 2023), and dust deposition amounts in the Arctic have been estimated larger in terms of mass than those of BC (Meinander et al., 2022), and the absorption potential of Icelandic dust similar to BC (Peltoniemi et al., 2015).

In the future, dust emissions from northern soils are expected to increase, e.g., due to increase of bare ground as a result of glacier retreat, permafrost thaw and melt of snow- and ice-covered surfaces. There is an urgent need also for a better understanding (e.g., Matsui et al., 2024; Romanello et al., 2024) of the complex counterbalancing feedbacks related to Arctic dust, e.g., shortwave and longwave cloud radiative effects (CREs), induced by the increase in temperature (temperature feedback) and by the increase in dust emission flux and atmospheric burden (emission feedback). For example, Matsui et al. (2024) found that an increase in dust emission weakened the sensitivity of ice nucleation in Arctic lower tropospheric clouds to warming by 40%, as compared to the case without Arctic dust emission increase.

Author contributions

OM: Funding acquisition, Visualization, Writing–original draft, Writing–review and editing. AU: Writing–review and editing. PD-W: Funding acquisition, Writing–review and editing. CG: Writing–review and editing. CJ: Writing–review and editing. AB: Writing–review and editing. AK: Writing–review and editing. AM: Writing–review and editing. MS: Writing–review and editing.

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