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FACULTY OF ENVIRONMENTAL SCIENCES

BACHELOR THESIS

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Department of Water Resources and Environmental Modeling

The optical properties of volcanic dust particles and their effects on the Arctic environment

BACHELOR THESIS

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Objectives of thesis

The overall objective is to better understand the effects of natural dust particles suspended in the atmosphere on the Arctic environment and climate change. By studying the optical properties of volcanic dust particles from high latitude deserts, we can find how they interact with sunlight and how this can affect the areas where such particles are deposited. This thesis focuses on volcanic sand and silt. Such dark particles have been found to affect the melt of snow and ice because they absorb the light radiated by the Sun more than lighter colored particles (Meinander et al., 2022). Volcanic particles can be transported towards the Arctic by, for example, air masses travelling from Iceland to Svalbard and further North. This makes it important to study the effects of the deposited dust particles on these environments, such as changes in albedo and the melting of snow and ice. This thesis focuses on examining the optical properties of the dust particles themselves and subsequently attempts to draw conclusions together with current research on how they may affect the environments in question.

Methodology

Laboratory measurements of the optical properties of volcanic sand and silt samples from Iceland were conducted at the Finnish Geospatial Research Institute (FGI) in Espoo, Finland, using the FGI goniometer. The FGI goniometer is a unique system used for optical measurements, consisting of, among other parts, a spectroradiometer, optics and motors. The volcanic sand and silt samples were measured both sieved and un-sieved. Samples were sieved through a laboratory test sieve with mesh sizes 500 um, 250 um and 125 um, thus resulting in samples with particle sizes above 500 microns, above 250 microns, above 125 microns and below 125 microns. Each sample was measured with the FGI goniometer, results of measurements are represented with graphs of, for example, albedo and bidirectional reflectance of the sample. The results of these measurements were used together with literary research in order to reach the objectives of the thesis mentioned above.

The proposed extent of the thesis

30 pages

Keywords

light-absorbing impurities, dust, air pollution, climate change, Iceland, the Arctic, cryosphere, optical properties of particles, albedo

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Recommended information sources

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Dean

Prague on 20. 03. 2023

Authors statement:

I hereby declare that I have independently elaborated the bachelor thesis with the topic of: “The optical properties of volcanic dust particles and their effects on the Arctic environment” and that I have cited all of the information sources that I used in the thesis as listed at the end of the thesis in the list of used information sources. I am aware that my bachelor thesis is subject to Act No. 121/2000 Coll., on copyright, on rights related to copyright and on amendments of certain acts, as amended by later regulations, particularly the provisions of Section 35(3) of the act on the use of the thesis. I am aware that by submitting the bachelor thesis I agree with its publication under Act No. 111/1998 Coll., on universities and on the change and amendments of certain acts, as amended, regardless of the result of its defense. With my own signature, I also declare that the electronic version is identical to the printed version and the data stated in the thesis has been processed in relation to the GDPR.

In Prague, Czechia on 30.03.2023

Signature: ______________________

Taru Koivusalo

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Abstrakt

Bylo zjištěno, že nečistoty absorbující světlo (LAI) usazené na sněhu a ledu ovlivňují jejich albedo a procesy tání. Snížené albedo sněhu a zvýšené tání může vést k tomu, že méně sněhové pokrývky odhaluje tmavou zem pod ní, což vede k pozitivní zpětné vazbě. Za jeden z nejdůležitějších LAI je považován černý uhlík (BC), ale v některých oblastech vyšších zeměpisných šířek bylo zjištěno, že vulkanický prach má větší dopad na albedo sněhového povrchu kvůli vysokým emisím prachu a přirozeně tmavé barvě. Pro arktické oblasti je Island jedním z nejdůležitějších zdrojů prachu vyšších zeměpisných šířek. Tato práce se zaměřuje na studium optických vlastností islandského sopečného prachu a na to, jak tento prach interaguje se slunečním zářením a ovlivňuje oblasti depozice. Optické vlastnosti vzorků islandského vulkanického prachu byly měřeny v laboratoři Finského geoprostorového výzkumného institutu (FGI) v Espoo ve Finsku pomocí nejnovějšího nastavení goniospektrometru FGI. Zjistili jsme, že v závislosti na velikosti částic může být albedo suchého vulkanického prachu ve viditelném spektru pouhých 0,03, což je podobné jako u BC. Tímto byla potvrzena teorie, že vulkanický prach vyšších zeměpisných šířek má stejný vliv na kryosféru jako saze a mělo by mu být věnováno vice pozornosti při posuzování změn klimatu. Prach vyšších zeměpisných šířek má své zdroje přímo v těchto oblastech a v místní atmosféře se ho nachází podstatně více než BC.

Klíčová slova: znečištění ovzduší, albedo, změna klimatu, kryosféra, optické vlastnosti částic

Abstract

It is increasingly recognized that light-absorbing impurities (LAI) deposited on snow and ice affect their albedo and facilitate melting processes. Reduced albedo of snow and enhanced melting can lead to less snow cover revealing dark ground underneath, leading to a positive feedback loop. One of the most important LAI is considered to be black carbon (BC), but for some areas volcanic dust has been found to have a larger impact on the snow surface albedo due to high dust emissions. For the Arctic areas, Iceland is one of the most important high-latitude dust sources. This work focuses on studying the optical properties of Icelandic volcanic dust to understand its interaction with the Sun's radiation and to estimate how this affects the natural areas of dust deposition. Optical properties of Icelandic volcanic dust samples were measured at the laboratory of the Finnish Geospatial Research Institute (FGI) in Espoo, Finland using the latest setup of the FGI's goniospectrometer. It was found that, depending on the particle size, the albedo of dry volcanic dust on the visible spectrum can be as low as 0.03, which is similar to that of BC. This confirms the previous suggestion that volcanic dust of high latitudes can be comparable to BC as strong LAI and highlighting the importance of Icelandic volcanic dust's role as an albedo reducing impurity on snow and ice in the Arctic areas. Volcanic- and high latitude dust should be included in studies on climate changes in Polar Regions not only for its absorbing optical properties, but also for significantly higher amounts in the Arctic atmosphere than BC.

Keywords: air pollution, albedo, climate change, cryosphere, optical properties of particles

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1. Introduction

The vulnerable areas of the Arctic are affected by climate change disproportionately. A phenomenon called Arctic amplification describes how the climate warms more in the Polar Regions than the rest of the globe (IPCC 2019). Arctic areas and ecosystems are more vulnerable to the effects of climate change because even a relatively small initial warming sets off events which amplify the warming further, such as the albedo-feedback mechanism. Additionally, even a small increase in temperature impacts the melting of glaciers and sea ice that many polar marine ecosystems are dependent on. Temperatures in high-latitude areas have been raising twice the global average (IPCC 2021), some even estimate warming up to four times faster than the rest of the globe (Rantanen et al. 2022), showing that the Arctic amplification is likely even more serious than previously estimated. The disproportionate warming of the Arctic causes melting of glaciers and sea ice loss both of which can have devastating effects around the world, for example in the form of rising sea levels. For example, mass loss of the Greenland Icesheet is predicted to raise the global sea level by more than 20 cm by the year 2100 and as such is of high importance to everyone on Earth (Rignot et al. 2011). Among the contributing factors to the Arctic amplification, changes of surface albedo are of high importance. These changes can be caused by impurities in snow or changes in temperature, both of which play a part in feedback mechanisms increasing absorption of solar radiation and the following retreat of snow- and ice-covered areas. This is why studying the effects of LAI on the cryosphere in the polar areas is important.

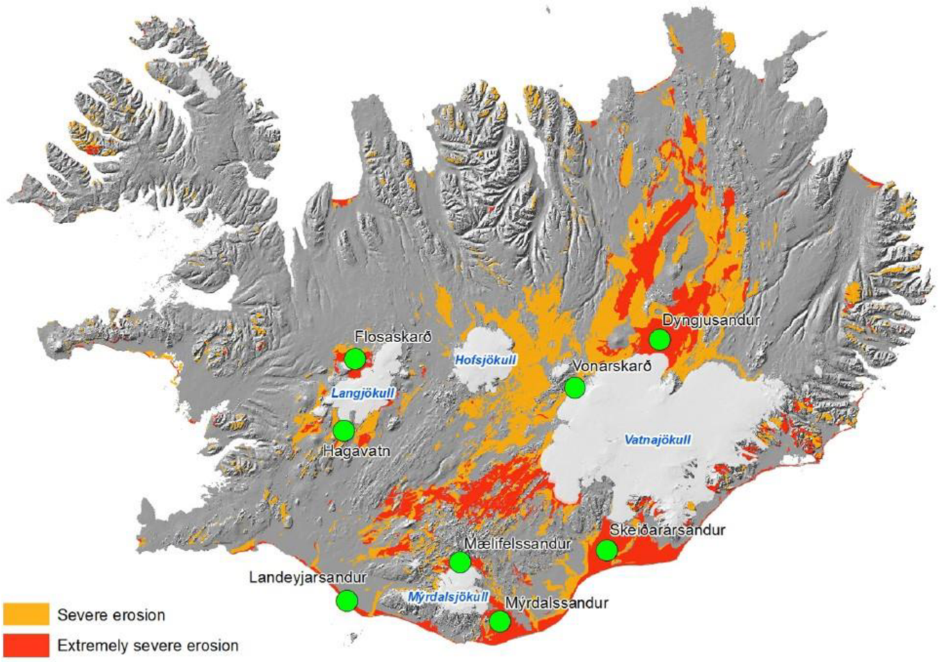

Figure 1. Areas of active erosion and dust hot-spots in Iceland. The orange areas represent areas with severe erosion and red areas represent areas of extremely severe erosion. Green dots depict dust hot-spot locations. (Arnalds et al. 2016)

It has been argued that light-absorbing impurities (LAI) on snow and ice affect the surface albedo, snow properties and snowmelt (Meinander et al. 2016). These light-absorbing impurities can come from anthropogenic sources, such as black carbon (BC) which is produced by incomplete combustion in diesel-engines, or natural sources such as the volcanic sand used in this study. The Icelandic volcanic material and sediments were formed during an interaction of volcanic and glacio-fluvial processes (Arnalds et al. 2016), in which streams of glacial meltwater carry and deposit fine-grained sediments to glacial floodplains where sediment is then easily picked up and redistributed by strong winds and storm events due to their unstable nature. The extent of deserts in Iceland is about 43 000 km^2, with volcaniclastic sandy desert covering around 20 000-22 000 km^2 (Arnalds et al. 2016). The extent of these areas is expected to grow in the future due to glacial retreat and reduction in snow cover extent and duration, revealing more erodible ground and consequently increasing the magnitude and frequency of dust events (Baddock et al. 2016, Arnalds et al. 2016, Crocchianti et al. 2021, Meinander et al. 2022). The 22 000 km^2 of volcaniclastic sandy desert consists of areas of different erodibility classified in Arnalds et al. (2016) as having either considerable erosion, severe erosion, or very severe erosion, out of which 15 000 km^2 consists of especially active areas in the latter two classifications (Fig. 1). This area of unstable desert means that Iceland has the largest active aeolian surfaces compared to other Arctic or European areas (Arnalds et al. 2016). The volcanic dust from Icelandic deserts is also easily distinguishable from dust of other sandy deserts in the world due to their unique composition consisting mainly of volcanic glass (Arnalds et al. 2016).

Volcanic dust of Iceland is found to be rich in iron (Fe) and as such can also be a nutrient source for micro-organisms in the sea as well as on snow or ice surface, where it can increase the amount of micro-organisms and algae which act as another light-absorbing impurity reducing the albedo (Arnalds et al. 2014, Lutz et al. 2016, Baldo et al. 2020). As the albedo is reduced, the impurities absorb more of the Sun's radiation causing warming at the snow surface and affecting the melting processes of snow and ice. Snow cover and ice caps retreat causing more erodible sediment being revealed and increasing the already large source areas for aeolian processes and increasing dust emissions.

Desertification has long been a problem in Iceland, as sand and dust carried by wind and storm events falls on existing vegetation, suffocating it under the deposited dust as well as mechanically harming the vegetation (Crofts 2011, Arnalds et al. 2016). Consequent lack of vegetation cover is a contributing factor to the high dust emissions of Iceland. In a way of a positive feedback loop, the more erodible land is uncovered by icecaps or vegetation, the more dust is emitted and the growing amount of dust emissions then again contribute to the desertification and melting of snow and ice cover. Largest high-latitude dust emissions measured have been caused by storms and dust events. Dagsson-Waldhauserova et al. (2014b), investigated long-term weather dust observations (synoptic codes) showing that in a year there are 135 dust days or days with dust events in Iceland. Outside of dust events, Iceland is also generally windy with high wind velocities (Bullard 2013). Arnalds et al. (2016) stated that an estimated 30-40 million tons of dust emissions is produced in Iceland annually. Together the size of Icelandic deserts, the strong winds and the frequent dust storm events make Iceland one of the most important dust sources for the Arctic. Dust suspended in the atmosphere can be transported thousands of kilometers and Icelandic dust has been found in Svalbard, Greenland and Europe (Arnalds et al. 2016, Moroni et al. 2018, Dordevic et al. 2019). Arnalds et al. (2016) also mentions that dust particles have been observed to have been transported over the Atlantic and Arctic oceans for more than 1 000 km and fine dust particles could potentially travel up to 20 000 km in two weeks. Because of the long distance of transport, high emission rates, frequency of dust events and the nature of the dark light-absorbing particles, Icelandic dust can have large impacts on the Arctic environment and an indirect effect on climate change due to the effects on the surface albedo of glaciers, sea ice and snow-covered areas. Bullard et al. (2016) lists Iceland as one of the main active high-latitude dust source regions together with Greenland and Canada in the northern hemisphere and Antarctica, New Zealand and Patagonia in the southern hemisphere. Overall, about 1-5 % of the global dust emissions originate form high-latitude sources and of the dust deposited on snow- and ice-covered Arctic areas approximately 57% comes from high-latitude sources (Bullard et al. 2016, Groot Zwaaftink et al. 2016, Meinander et al. 2022). Dust emissions in these high-latitude areas are not limited to arid areas like in the mid- and low-latitudes, emissions occur because of lack of vegetation cover, high meltwater supply due to nearby ice areas and strong near ice-sheet winds driven by a pressure gradient, called katabatic winds (Prospero et al. 2012).

Black Carbon (BC) has been found to be the most powerful absorbing aerosol and as such is one of the most important anthropogenic pollutants (AMAP 2015). Research has found that some volcanic particles have similar thermal and optical properties to BC and therefore it is important to include volcanic dust in future climate research (Arnalds et al. 2016 ex. Yoshida et al. 2016, Boy et al. 2019). Importantly, impacts on the albedo of snow were found to be similar for Icelandic volcanic dust and black carbon (Peltoniemi et al. 2015, Wittmann et al. 2017, Dagsson-Waldhauserova & Meinander 2019). In some parts of the world high dust emissions lead to dust being the dominating LAI reducing snow albedo instead of BC (Svensson et al. 2018). Doherty et al. (2010) found that about 20-50% of the light absorption in the Arctic areas is by LAI other than BC. As previously mentioned, light-absorbing impurities can be particles from anthropogenic or natural sources, or micro-organisms like cyanobacteria and algae. Light-absorbing impurities deposited on snow affect the albedo of snow, measured as snow reflectance, by darkening the snow and enhancing the snowmelt (Svensson et al. 2018). Albedo describes the reflectivity of a surface, and it is a major part of the surface energy balance and the Earth’s energy budget. Snow and ice usually have a very high albedo and therefore even small amounts of dust deposited can reduce the snow albedo enough to cause significant changes in the radiative forcing, increasing warming and snowmelt (Wittmann et al. 2017). Impurities in snow also cause changes in snow grains size and snow density which themselves also affect the albedo and melting of snow (Meinander et al. 2014). Even small changes in the amount of absorbed and reflected radiation of snow and ice surfaces can have large impacts on the cryosphere of Earth (Wittmann et al. 2017). The cryosphere consists of Earth's surfaces covered by ice, snow or otherwise frozen areas including glaciers, ice caps, sea ice, permafrost, and snow cover. If this snow or ice cover is reduced by melting, it can reveal a surface underneath with a much lower albedo, lowering the surface albedo of Earth. Positive feedback loop can form by the increase of melting causing more albedo reduction and more absorbed radiation by darker surfaces which in turn enhances the melting (Wittmann et al. 2017).

Icelandic dust is dark volcanic dust which absorbs the shortwave and near-infrared radiation from the Sun more than mineral dust from other main deserts and unlike other mineral dusts likely causes positive radiative forcing (Baldo et al. 2020). "Clumping mechanism" has been also observed on snow due to Icelandic silty material, where fine particles on snow were found to form larger particles that accelerated snowmelt (Dagsson-Waldhauserova et al. 2015a). Not only can the dust emissions from Iceland impact air pollution in the Arctic and in Europe, but also affect the climate by depositing light-absorbing impurities on glaciers and sea ice. Most of the climate models do not take into account regional climate impacts of dust and snow albedo changes in the Arctic and end up underestimating the climate impacts of high-latitude dust (Kylling et al. 2018). Dark volcanic dust is one of the less studied LAI when it comes to climate modeling and predicting changes in the Arctic environment, therefore it is important to study its properties and impacts not only regionally but also globally.

2. Objectives of the thesis

The objective of this thesis is to measure and understand some of the optical properties of Icelandic volcanic sand and dust particles, with additional measurements of Chilean volcanic sand for comparison. Focus of this thesis is on Icelandic dusts, therefore the main samples chosen were Icelandic volcanic sand and glaciogenic silt. The albedo and bidirectional reflectance of these samples were measured using a goniospectrometer, and together with literature research the aim is to find how such particles interact with sunlight and possibly affect the surfaces they are deposited on.

Research questions are:

1. What is the role of Icelandic volcanic dust particles with regards to their possible effects on the Arctic environment, specifically snow and ice surfaces?

2. How are the volcanic dust particles comparable to BC as light-absorbing impurities?

The comparability has been suggested before and this study aims to further reinforce this claim by comparing the albedo measurements of the samples to the albedo of BC. The hypothesis is that these volcanic dusts are dark enough to be comparable to BC in their climatic impacts. Due to the high emission amounts from the volcaniclastic sandy deserts of Iceland it is possible that the impact of volcanic dust can be more significant than that of BC in certain areas. Thus, the properties of Icelandic volcanic dust are an important matter to study and research further in the future as they can play an important role in regional, and even global, climate change.

3. Literature review

Dust particles in the atmosphere affect air quality, climate, human health, transportation, and marine ecosystems. In the following chapter more of these widespread effects of specifically high-latitude (>60˚ N) and Icelandic dust are discussed based on literary review of articles and research on the topics. Dust originates from soils through natural processes, but human activities can influence dust emissions as well, for example deforestation and desertification caused by poor land management and improper land use can cause major dust events (Meinander et al. 2022). Notably dust storms have been reported to occur at large agricultural fields and surrounding areas, causing reduced visibility and problems in transport such as car accidents and road closures (Meinander et al. 2022). As Cvetkovic et al. (2022) also stated, mineral dust in the air during dust storm events can affect transportation by severely reducing visibility resulting in closed roads and halted traffic. During such events high amounts of air pollution have led to emergency hospitalizations and other health effects, outside of these dust events the air pollution caused by anthropogenic sources in Reykjavik is lower than in many other cities in Europe (Carlsen et al. 2015). Icelandic dust events cause PM10 pollution comparable to anthropogenic air pollution in large cities of other European countries (Dagsson-Waldhauserova et al. 2016). Even though anthropogenic air pollution emissions are quite low in the Arctic, they can become ”trapped” in the atmosphere during winter. Arctic haze describes a phenomenon that happens over the Arctics where there are dark layers of, for example soot present in the troposphere during winter and early spring, eventually it is removed by falling snow or dry deposition (Doherty et al. 2010). Anthropogenic pollution from residential heating, transport, industry, and biomass burning accumulate in the stable Arctic atmosphere over winter forming this dark Arctic haze layer (Dagsson-Waldhauserova & Meinander 2019).

Iceland has large areas of erodible sediment from which sand and dust is easily continuously resuspended by aeolian processes because of favorable conditions for wind erosion such as lack of vegetation cover. Approximately 10% of Iceland’s area is glaciers and with Iceland being an active volcanic island, volcanic activity within these glaciers is common (Baldo et al. 2020). Cvetkovic et al. (2022) state that Icelandic topsoil sediment is the most important and largest mineral dust source in

Europe, partly because of the intense aeolian and glacial activity and the high wind conditions in the area inducing intense emissions and carrying them for thousands of kilometers. The erodible sediment of Iceland consists of volcanic deserts and glacial sediment areas, where glacial rivers deposit huge amounts of sediment (Cvetkovic et al. 2022). The sediment at these glacio-fluvial outlets consist largely of basaltic glass fragments, formed when magma from active volcanic systems under the glacier is cooled down so rapidly in contact with water that crystallization of minerals does not occur (Cvetkovic et al. 2022, Baldo et al. 2020). Dust hotspots are often located at these glaciofluvial floodplains because of the deposition of fine sediments by glacial meltwaters and rivers (Baldo et al. 2020, Arnalds et al. 2016). The increase in melting of snow and glaciers followed by increase in emissions can create a positive feedback loop, one of many connected with LAI and the Arctic (Boy et al. 2019). Prospero et al. (2012) concludes that these dust-related processes can be expected to be happening in other high-latitude glacial areas as well and that the dust activity will become more widespread and intense in the future as climate change continues.

Baddock et al. (2016) found a seasonal variability in the dust emissions between northern and southern dust sources in Iceland, in the north snow cover persists longer and restricts emissions in the winter and in the south during summer the wind velocity is lower and so dust events are less likely during these times at these hotspot areas. Overall, the dust emissions have been found to be highest during spring and summer when snow and ice covers are melting, revealing erodible sediment and depositing sediment with meltwater floods (Prospero et al. 2012). But large meltwater flood events can happen all throughout the year in the form of jökulhlaups, glacial flood events triggered by volcanic-glacial activity, transporting, and depositing high amounts of fine sediments to glacial outwash plains, often connected to subsequent high emission events (Prospero et al. 2012, Baddock et al. 2016). Soil texture is an important characteristic affecting susceptibility to wind erosion and thus dust emission, silt and clay particles up to 50-60 µm particle size are the most susceptible, but sometimes larger particles are suspended as well, usually only during extreme winds and for shorter distances (Cvetkovic et al. 2022). Icelandic dust differs from low-latitude dust in composition and mineralogy because of the basaltic composition of parent sediment, glacial processes and a lower degree of chemical weathering (Baldo et al. 2020). Most papers reviewed reported their Icelandic samples being uniform and consisting mainly of basaltic amorphous glass particles, in concordance with this for example Baldo et al. (2020) stated that their samples consisted primarily of amorphous basaltic materials. The shape of the particles can affect how easily it can be suspended in air, Icelandic particles often contain gas bubbles or are in an elongated shard-like shape that can allow for suspension even right after rain (Dagsson-Waldhauserova et al. 2014b, Dagsson-Waldhauserova et al. 2015a).

Icelandic volcanic particles are very dark, almost near black with a low spectral reflectance of <0.03, and so it is suggested that they can have similar effects on the albedo of snow as BC (Cvetkovic et al. 2022, Meinander et al. 2014, Meinander et al. 2016, Peltoniemi et al. 2015, Dagsson-Waldhauserova & Meinander 2019). As found by Arnalds et al. (2014), Baldo et al. (2020), Cvetkovic et al. (2022) and others, Icelandic dust often contains high amounts of iron (Fe) around 10-13%, compared to continental dust such as north African dust at 1-8%. Baldo et al. (2020) also found that the Fe in Icelandic dust is often more soluble compared to other dusts. Because of the high Fe content of Icelandic dust and the potential high solubility, it can act as a nutrient source for Fe-limited marine ecosystems when deposited at sea and so impact the primary productivity, affect the biogeochemical processes and enhance carbon uptake (Cvetkovic et al. 2022, Baddock et al. 2016, Baldo et al. 2020). In such a way it can affect the carbon budget and climate, contributing to the instantaneous radiative forcing in the Arctic (Kylling et al. 2018, Baldo et al. 2020). Radiative forcing, or climate forcing, describes the changes of energy flux in the atmosphere caused by different factors of climate change in W/m^2. These can be of natural or anthropogenic sources such as the surface albedo of Earth and aerosols and greenhouse gases in the atmosphere. Mineral dust in the atmosphere is generally considered to be mainly a particle that scatters light but when deposited on a snow or ice surface it is considered a mainly absorbing particle, although volcanic dust is strongly absorbing due to its low spectral reflectance of 0.03 (Dagsson-Waldhauserova & Meinander 2019). Icelandic dust can affect the climate directly by dust-radiation interaction and indirectly by dust-cloud interaction, the snow and ice albedo effect and impacts on biogeochemical cycles (Baldo et al. 2020). The atmosphere can be cooled or warmed by changes in the radiation balance, the balance can be affected by mineral dust suspended in the atmosphere absorbing and scattering solar radiation or terrestrial radiation (Baldo et al. 2020). Direct radiative forcing by dust aerosols include scattering and absorbing solar and thermal radiation (blocking sunlight), and indirect radiative forcing include the function of dust particles to act as condensation nuclei for water droplets or ice nucleating particles (clouds and cryosphere) (Lambert et al. 2013, Kylling et al. 2018, Baldo et al. 2020). When suspended in the atmosphere the dust mixes with other aerosols from anthropogenic or natural sources (Crocchianti et al. 2021), dust can also be integrated in the snowfall affecting the otherwise albedo increasing effect of the new fresh snow cover (Dagsson-Waldhauserova et al. 2015a). Kylling et al. (2018) found that high-latitude dust contributes about 52% of the Arctic bottom of the atmosphere instantaneous radiative forcing (IRF) per annum and about 39% of the Arctic top of the atmosphere IRF, implicating important regional climate impacts. Climate models do not often include such regional climate impacts, nor do they account for changes in the snow albedo and so they end up underestimating climate impacts of dust and the high-latitude dust sources (Kylling et al. 2018).

Clouds over the Arctic affect the local climate and Arctic amplification, as the clouds can be mixed phase with water and ice. Ice in the clouds causes more longwave radiation downwards and with this positive feedback can contribute to the amplification of warming (Meinander et al. 2022). And with the phase of clouds having such a feedback effect, it is possible that impurities that act as ice nucleating particles can strengthen it (Meinander et al. 2022). The Arctic is warming faster because of the polar amplification or in this case Arctic amplification phenomenon, for which mineral dust has been suggested to be a contributing factor, especially light absorbing particles that reduce the albedo and increase the melting of snow and ice thus affecting the ice-albedo feedback or surface albedo feedback mechanism (Crocchianti et al. 2021, Dagsson-Waldhauserova & Meinander 2019). The systems of these high-latitude polar areas are more sensitive and vulnerable to temperature changes causing glacier retreat, permafrost thaw and overall decrease in snow cover extent and duration. The ice-albedo feedback is an important positive feedback process impacting the climate, where the decrease in ice and snow cover decreases the surface albedo and increases the amount of radiation absorbed, warming the surface of the Earth which in turn again accelerates the melting. Thin or thinning snow layer can have similarly decreased albedo as dirty snow, because the underlying dark ground or vegetation starts affecting the surface albedo as it is increasingly visible with only a thin snow layer (Doherty et al. 2010, Doherty et al. 2013). Highly reflective snow covering darker surfaces like ground or older dirty snow or ice is one of the main feedback processes connected with the cryosphere and LAI (Dumont et al. 2014).

Albedo or reflectance is one of the main characteristics affecting the surface radiation balance of snow and ice surfaces (Meinander et al. 2022), it is wavelength dependent and very high for clean fresh snow. The albedo of snow depends on the grain size, wetness, and impurities (Meinander et al. 2014), and as snow gets older the albedo decreases because of these changes in snow grain size and impurities present (Dagsson-Waldhauserova & Meinander 2019). The absorption of radiation of snow and ice at visible and near-ultraviolet wavelengths is very little so even small amounts of light-absorbing impurities on snow can majorly affect the surface energy budget and increase snowmelt by reducing albedo and absorbing more radiation (Doherty et al. 2010). BC is regarded as the main impurity influencing the surface albedo of snow in the Arctic, but other already mentioned LAI contribute to the albedo reduction as well, sometimes possibly even more. BC is recognized to be the strongest absorptive impurity per unit mass and an undoubtedly important albedo reducing impurity but for some areas the amount of dust deposited on snow and ice is so high that dust becomes of higher importance (Doherty et al. 2010). Doherty et al. (2010) also found that approximately 20 to 50% of the absorption of light on snow and ice is by particles other than BC. It has been found in multiple studies that particles, especially dark particles like BC and volcanic dust have positive radiative forcing effects when deposited on the surface of snow and ice, reducing albedo, and increasing melting rate (Baldo et al. 2020, Wittmann et al. 2017). Impurities, particularly absorbing particles deposited on snow, affecting the physical and optical properties and solar radiation fluxes are a part of another feedback process called radiative feedback (Meinander et al. 2022, Peltoniemi et al. 2015, Dracosics et al. 2016). Other light-absorbing impurities reducing snow albedo include mineral dust and micro-organisms like cyanobacteria and algae, cyanobacteria have a unique ability to move upwards in the snow towards light and remain in the top layers of snowpack (Dumont et al. 2014). Glacier ice algae can bloom as a result of deposition of mineral dust that can serve as a nutrient source (Meinander et al. 2022). An albedo reduction of only 0.02 is significant for the climate but is undetectable by eye (Doherty et al. 2010), Dumont et al. (2014) though state that albedo reduction of 0.01 would be enough to accelerate melt. During dust events in Iceland the albedo has been observed to have reduced by as much as 0.18 (Dagsson-Waldhauserova & Meinander 2019). Icelandic dust is significant for local ice caps and glaciers because of its effects on the cryospheric processes.

LAI can also reduce the density of snow, and BC could affect the water holding capacity as well (Meinander et al. 2014, Dagsson-Waldhauserova & Meinander 2019). Meinander et al. (2014) found that larger BC content in the snow correlated with lower density by creating an air pocket surrounding the particle, they also found that impurities can affect the water retention capacity (lowering it and releasing meltwater faster). Insoluble LAI have been found to have remained at the snow surface instead of being removed by the meltwater as the snow melts, increasing the concentrations of insoluble LAI on the snow surface and further reducing the snow albedo (Doherty et al. 2013, Meinander et al. 2014, Meinander et al. 2016). This concentration of impurities at the snow surface during melt creates another feedback loop that increases the surface melt (Dumont et al. 2014). Dumont et al. (2014) also explains an intrinsic snow albedo feedback where warmer snow causes growth of snow grain size and so further reduces albedo. As stated above, the particles on snow surface have also been observed to clump together to form larger particles and further decrease and melt snow (Dagsson-Waldhauserova et al. 2015a, Dagsson-Waldhauserova & Meinander 2019, Peltoniemi et al. 2015).

Cvetkovic et al. (2022) suggest that Icelandic sediment is the most important European mineral dust source because of the strong winds connected with the cyclone circulation of the north Atlantic, causing high rates of emissions and potentially carrying them for thousands of kilometers. Meinander et al. (2022) states that globally, northern high-latitude dust sources have strong seasonal variability and depend often on extreme weather, unlike southern high-latitude sources which have favorable conditions for dust emission throughout the whole year. Baldo et al. (2020) states that majority of Icelandic dust is deposited on land and around 18-35% on the oceans.

Greenland's albedo has been observed to have declined due to snow grains becoming larger because of the warming climate, but Dumont et al. (2014) show that the decrease in albedo and darkening of the icesheet is also caused by increased amounts of LAI in snow and in the atmosphere. The continuing darkening of Greenland Icesheet can contribute to its melting (Dumont et al. 2014). Baddock et al. (2016) mentions that cyclonic events create a pathway from west and southwest of Iceland towards Greenland and the Denmark strait between Iceland and Greenland raising dust from sources all over Iceland. Another path towards north and northeast is also mentioned as it is common due to strong southernly winds typical especially for the northern dust source areas in Iceland. Meinander et al. (2022) described a global high-latitude dust belt in areas >60˚N in Eurasia and >58˚N in Canada.

It has also been confirmed that a thick enough layer of dust could insulate snow and ice instead of accelerating melt. Dracosics et al. (2016) studied the melting and insulating effects of volcanic ash and dust on snow and ice. A thin layer up to 1 mm on the surface of snow or ice increases the melting but a thicker layer creates an insulating effect when it is of certain thickness of around 9-15 mm varying based on the ash or dust grain size (Dracosics et al. 2016).

Climate change shortens the duration of seasonal snow cover, affecting the retreat of glaciers, increasing droughts, heatwave frequency and intensity causing topsoil more favorable for dust emissions and storms (Meinander et al. 2022). Doherty et al. (2010) states that because the BC content in the Arctic atmosphere has decreased since 1989 and the sea ice loss has continued to increase, they are doubtful that BC would be the cause of the Arctic sea ice loss. This seems to be contradictory to many of the other sources. With the ice loss the Earth's albedo is overall reduced leading to positive feedback further warming the atmosphere (Dagsson-Waldhauserova & Meinander 2019). If the increase of dust emissions and their transport through the shortening of seasonal snow cover and retreat of glaciers in the future continues, it will amplify the decrease in the Greenland icesheet albedo and its surface energy and mass balance, accelerating surface melt and the connected sea level rise can happen at a faster rate than previously thought (Dumont et al. 2014).

4. Methodology

The methodology of this study consists of description of sample sites and laboratory measurements of the optical properties of volcanic sand and glaciogenic silt samples.

4.1 Samples and sample sites

The samples used were volcanic sand samples from Iceland and Chile, and glaciogenic silt from Iceland, provided by FGI and Pavla Dagsson-Waldhauserova.

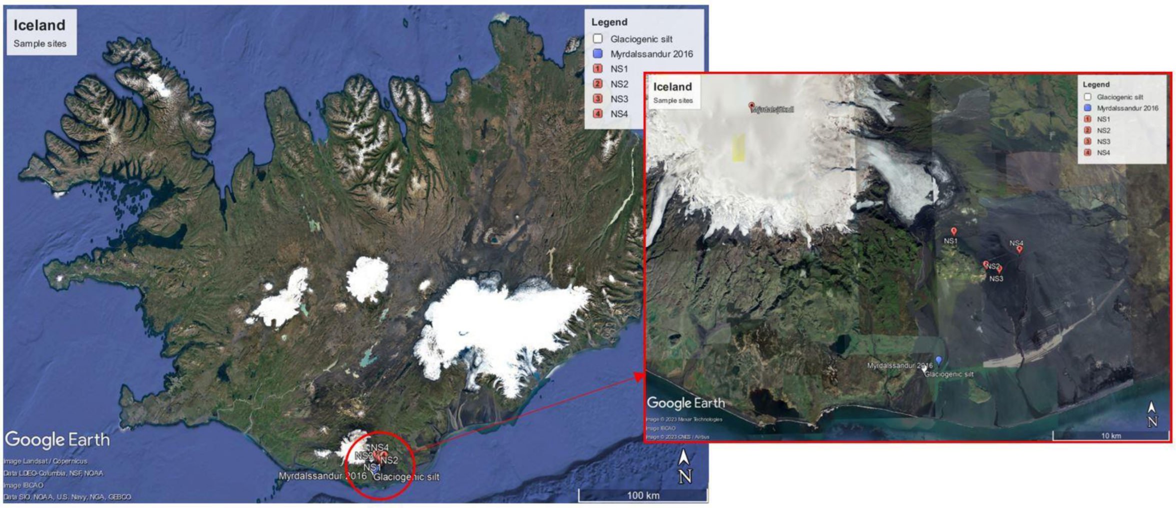

Figure 2. Map of Iceland with collection sites of all Icelandic samples in the southern part of Iceland, near Mýrdalsjökull glacier, and a closer view. Generated in Google Earth Pro on 22.03.2023.

The volcanic sand was collected from the Mýrdalssandur outwash plain, which is a large dust source in southern coast of Iceland in March 2016. The exact coordinates of the collection point are 63.44255518836723° N, 18.818398953674148° W. The material originates from the Mýrdalsjökull glacier and was transported by glaciofluvial processes and deposited to the outwash plain. Mýrdalssandur outwash plain is between two glacial rivers Kúðafljót on the eastern side and Múlakvísl on its western side. Kúðafljót is one of the biggest glacier rivers in Iceland. Because of the wind conditions the material has possibly been re-suspended and mixed over time, and so some of the finer silt-sized material may have been removed from the site by aeolian processes.

Mýrdalssandur 2022 samples	Latitude	Longitude
NS1	63.541803˚N	18.786155˚W
NS2	63.514962˚N	18.732505˚W
NS3	63.511365˚N	18.709778˚W
NS4	63.526218˚N	18.673987˚W

Table. 1. Coordinate locations of volcanic samples collected in 2022 from Mýrdalssandur.

The newest volcanic samples, named and subsequently referred to as NS1-NS4 were collected in Mýrdalssandur on 24th August 2022. The locations of these samples are given in Tab. 1. as coordinates and visualized in the map in Fig. 2.

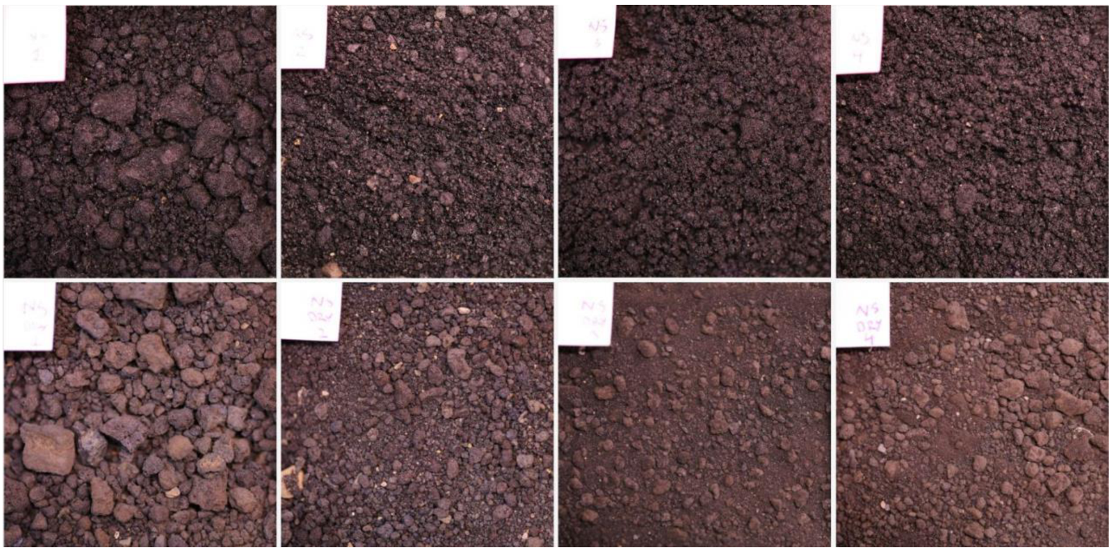

Figure 3. The 2022 collected Mýrdalssandur samples pictured with a SLR-camera. On the top row the samples were pictured moist and on the bottom they were pictured dry. From left to right the samples are: NS1, NS2, NS3, NS4.

As the laboratory measurements were conducted soon after the samples were collected, the samples were fresh enough to still contain some moisture making them appear darker visually by eye (Fig. 3) but also in the measurements, these samples were also left to dry and measured again as dry samples.

The glaciogenic silt sample was collected from Múlakvísl, a glacial river 10 km from the Mýrdalsjökull glacier at 63.43622305424746˚N, 18.84433465910551˚W. The glacier is affected by the Katla volcanic system underneath, materials created are then transported by the Múlakvísl, one of the main glacial rivers draining the glacier. The silt sample is much brighter in color than the volcanic sand samples, it consists mainly of silt and clay-sized particles, an easily suspended and re-suspended material with a potential to be transported distances of hundreds of kilometers. Locations of all the samples collected in Iceland can be seen in Fig. 2.

Most dust emission hotspots in Iceland are near glaciers, like glacial floodplains, old lakes, jökulhlaup deposit areas and sandy beaches (Meinander et al. 2022). Iceland has such a high density of dust sources in the southern coast that it is suggested that this could be considered one complete large dust source but because of differences in the characteristics like size distribution and optical properties of the particle material they should still be studied as separate sources (Meinander et al. 2022). Characteristics common for Icelandic dust particles are dark color, porousness, and angular shape, they are formed by erosion of basaltic lava (Butwin et al. 2020).

The volcanic samples from Chile were collected by Maria Gritsevich at Llaima volcano, Chile in July 2019. Chile sample 1 was collected from an open area near the volcano on the eastern side slope, the exact coordinates for sample 1 are 38.6974836˚ S, 71.626842˚ W, at an altitude of 999 m. The Chile sample 2 was collected near Laguna Quilillo O Verde at an altitude of 990 m, with the exact coordinates of 38.69742175˚S, 71.6219245˚W. Llaima is one of the most active volcanoes in Chile, the last eruptions happened from 2008 to 2009. It is located in the Conguillio national park and the sediment around Llaima volcano is mainly basaltic andesite, common for the Andes.

4.2 Laboratory measurements

The measurements were conducted at the laboratory of The Finnish Geospatial Research Institute (FGI) of the National Land Survey of Finland (NLS) in Otaniemi, Espoo, Finland. The optical properties, namely the bidirectional reflectance factor (BRF) and the albedo of the volcanic sand and silt samples were measured using goniospectrometry. The BRF is a function that describes the directional dependence of reflected radiance from a surface or a sample measured from each direction. The bidirectional reflectance factor (BRF) is defined as the ratio of reflected light intensity of a sample surface to an ideal Lambertian surface under identical setup geometry and same illumination conditions (Schaepman-Strub et al. 2006, Peltoniemi et al. 2015).

An ideal Lambertian surface, or an ideal diffuse surface, is a surface that appears uniformly bright from all directions of view and reflects the entire incident light. The spectralon reference used in the measurements is highly Lambertian in this way.

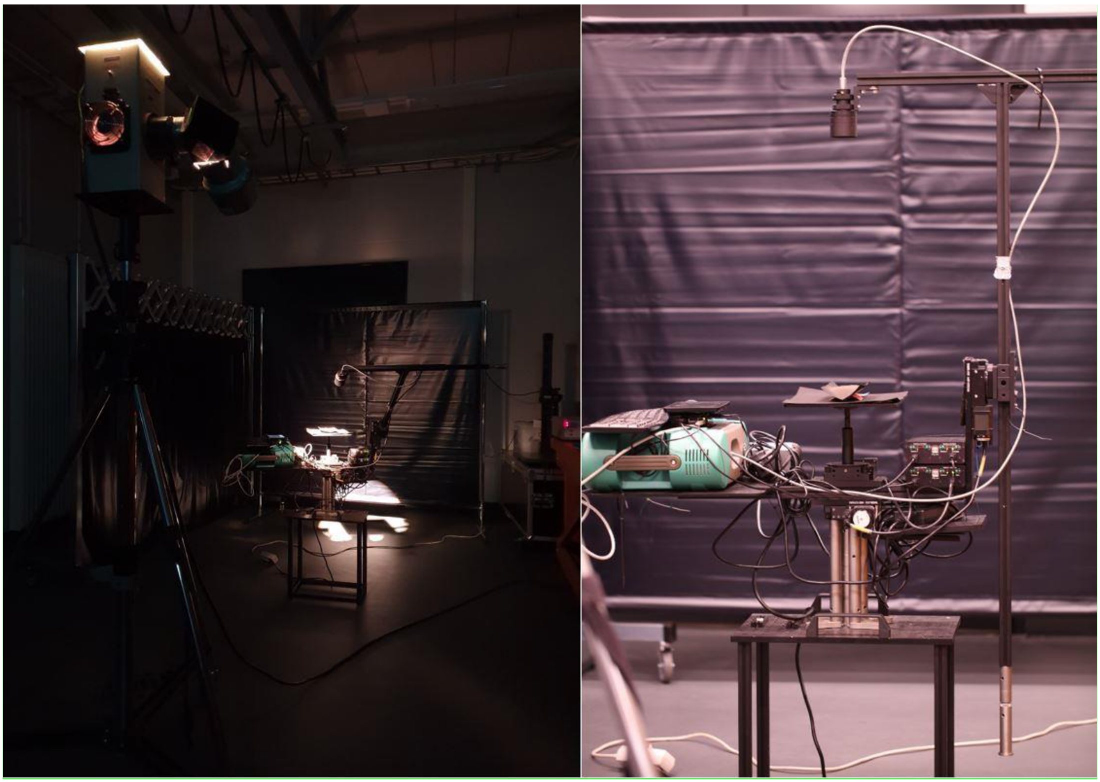

Figure 4. The goniospectrometer at the Finnish Geospatial Research Institute (FGI) laboratory. The picture on the left shows the instrument in the middle of measurement cycle with the light source in the foreground. The picture on the right side provides a closer look at the instrument. Green box is the ASD FieldSpec 4 spectroradiometer, on top of it rests the Raspberry Pi computer tablet and a keyboard for the operation of the instrument. At the center of the image, the sample tray with a volcanic sample and directly above it are the measuring optics, connected to the ASD FieldSpec by a light fiber cable.

The instrument used was the FGI space goniometer, a system that was built in the Otaniemi laboratory using various motors, optics, arms, and other parts. Peltoniemi et al. (2022) describes the previous FGI goniometer setup well in detail and the operation of the system works largely the same in this study. At the base there is the ASD FieldSpec 4 spectroradiometer (Analytical Spectral Devices), connected to sensing optics with a light fiber cable, and to a Raspberry Pi computer which is also connected to multiple motors that allow the movement of the arm with attached optics, rotation of the sample and rotation of the whole system (Fig. 4). The ASD FieldSpec 4 spectroradiometer measures across the full range of solar irradiance spectrum of 350-2500 nm. The Raspberry Pi tablet has a Linux operating system and the software to control the machine is written in Python. The measurement sequence set for these measurements took approximately 16 minutes. Separate from the instrument there was also the light source, for the measurements here the light source used was a ThermoOriel QTH lamp with 1000 watts, but 750 watts of power was used for the measurements in this study to avoid overheating (Fig. 4). The light source, optics and the sample were aligned for the measurement, the room was darkened from any other lights or daylight during the measurements. The raw data from the measurements was then processed and visualized in Python and Spyder. As a white reference a Spectralon disc was used, Spectralon is a material with the highest diffuse reflectance known.

The measurements were done in the following sequence. Turn power on for the spectrometer, light the source and other electronics, and then wait for 30 minutes to allow for the system to warm up and stabilize. Sign into the operating computer tablet to begin the measurements. First it is necessary to measure the dark current and the white reference, dark current is measured by closing a manual shutter before the light fiber input to the optics and after this the white reference is measured by placing the Spectralon white reference disc on the sample tray. Any visible dust or debris was cleaned from the white reference by compressed air when necessary. The Spectralon reference was handled with rubber gloves and stored in a plastic bag to avoid any stains or dirt. After measuring the baseline references the sample can be placed on the sample tray and the measurement sequence started. Measurement of one sample took approximately 16 minutes after which a different sample could be measured directly if the measurement conditions have not changed. The references were remeasured at the beginning of each day of measurements. The motors of the system facilitate the change of the zenith angle by tilting the arm holding the optics and another motor turns the system to a selected azimuth angle.

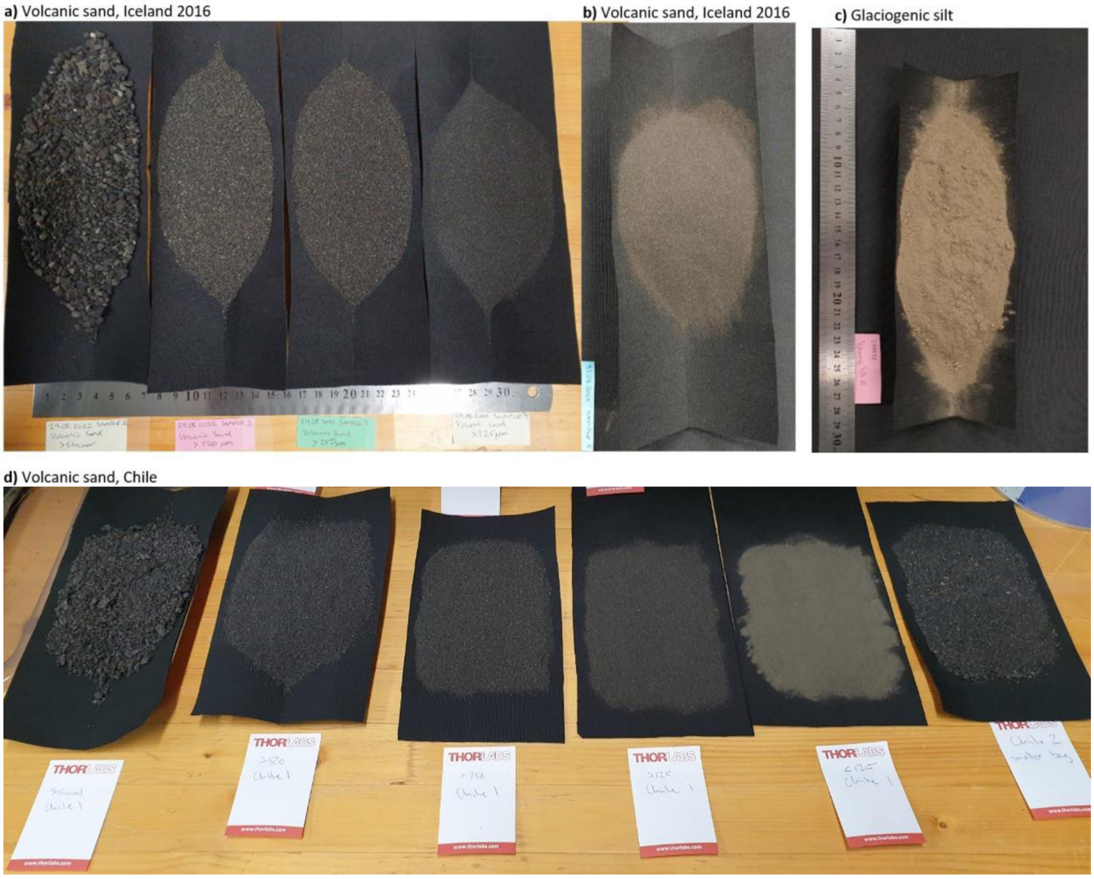

Figure 5. Samples in measurement trays. In a) Volcanic sand from Iceland 2016 can be seen as un-sieved, above 500 µm, above 250 µm and above 125 µm. In b) the same sample as in a but sieved to under 125 µm. Picture c) shows glaciogenic silt sample. In d) from left to right Chile sample 1 un-sieved, above 500 µm, above 250 µm, above 125 µm, below 125 µm and lastly the Chile sample 2.

The samples were all sieved through a set of laboratory sieves from the brand Retch, the mesh sizes were 500 µm, 250 µm and 125 µm, except the NS1-NS4 and Chile sample 2 due to small amount of the material. The samples were also first put through an ordinary kitchen strainer to separate larger particles before the sample was put in the laboratory sieve. Each sample thus had subcategories of un-sieved or what was left in the strainer, larger than 500 µm, smaller than 500 µm but larger than 250 µm, smaller than 250 µm but larger than 125 µm and the smallest subcategory of only particles smaller than 125 µm. Although the 125 µm was the smallest mesh size in the available sieves, it can be assumed that fine silt and clay sized particles are present in the samples as shown in other studies with Icelandic dust (Arnalds et al. 2016). Each sieved sample was then put on a receptacle made from a very dark curtain blinds fabric in order to have the least interference with the measurements. The material of the sample receptacle must not be too light in color or reflective. From this dark fabric sample receptacles were prepared and approximately 1 dl of sample was placed in them, making sure that the surface of the sample was as flat as possible but not physically flattened with a tool but sprinkled in order to get the most accurate readings. For the NS1-NS4 and some of the Chile samples and subcategories the receptacles used were just a flat piece of the fabric because there was not enough sample material to fill a similar receptacle used for the other samples, as seen in Fig. 5.

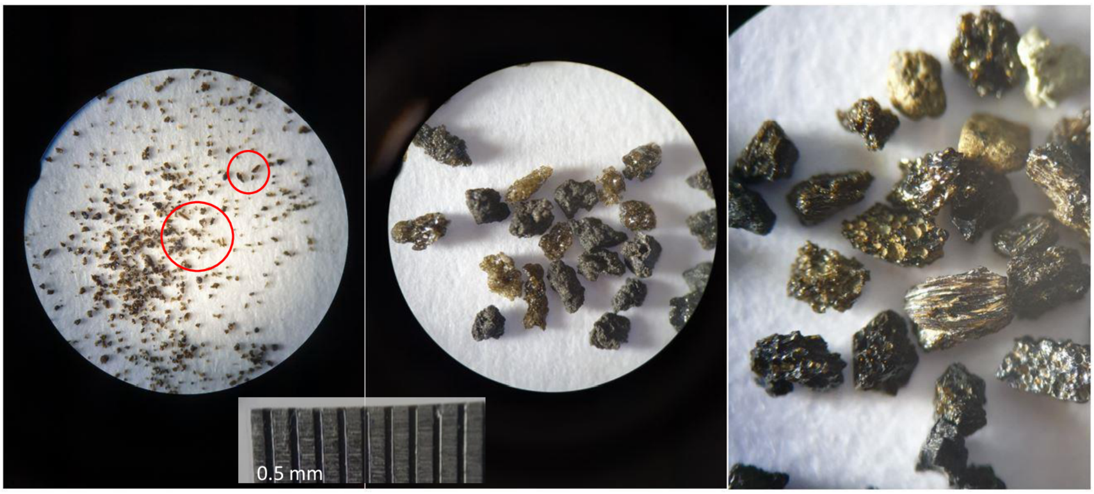

Figure 6. Close-up pictures taken through a stereomicroscope. On the left, some finer particles of NS2 in 3x magnification with shard like particles circled in red. In the middle, Chile sample 1 particles from above 500 µm subcategory under 3x magnification. For approximate scale a ruler under 3x magnification is pictured in between these images, the ruler has marks every 0.5 mm or 500 µm. On the right, a zoomed in picture of Mýrdalssandur 2016 sample under 3x magnification, not in scale. The typical physical characteristics, such as amorphous particles, porousness and shard like particles can be well seen in these images.

Samples were photographed with a high-quality SLR-camera and a mobile phone through a stereomicroscope for close-up images of the material and particles to study their physical characteristics. Images shown in Fig. 3 and Fig. 6 are analyzed further in discussion.

5. Results

The laboratory measurement results are visualized in Fig. 7 and Fig. 8 below, these figures show graphs depicting the bidirectional reflectance factor (BRF) of the sample based on the zenith angle of the measurement optics in near infrared wavelengths and the albedo of the sample for different wavelengths. Zenith angle is the angle from zenith (vertical).

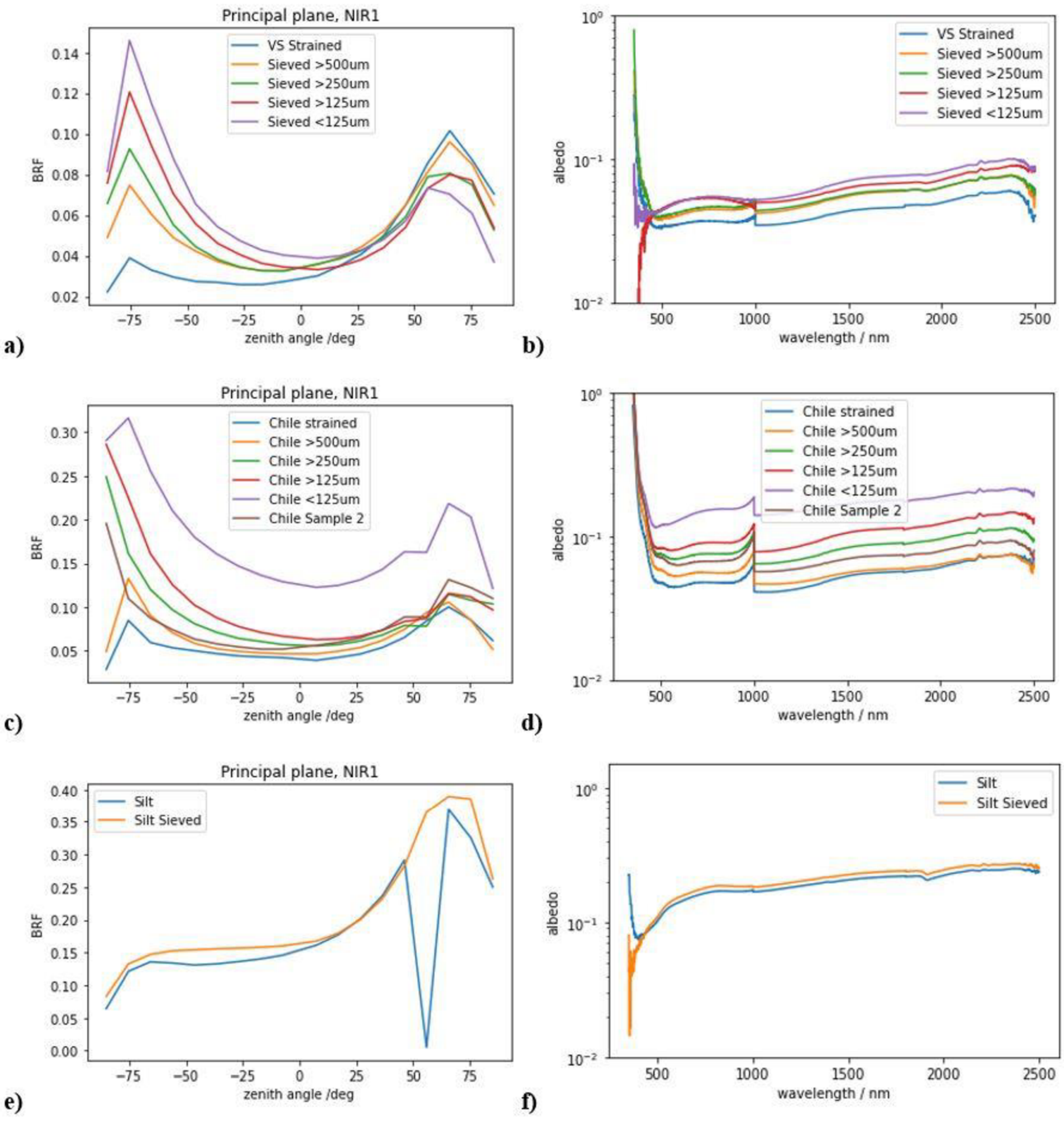

Figure 7. Visualization of optical measurements. Bidirectional reflectance factor (BRF) and albedo measurements of volcanic sand sample from Mýrdalssandur 2016 seen in a) and b), volcanic sand samples from Chile in c) and d), and the glaciogenic silt sample in e) and f). Zenith angle on the left side graphs is the angle of measurement optics from zenith (vertical). Some discrepancies caused by the measurement technology can be seen as abrupt jumps, for example in albedo graphs at wavelength of 1000 nm. These jumps and the border regions are unstable data to be disregarded.

In the Fig. 7 results of the optical measurements of the 2016 volcanic sample from Mýrdalssandur outwash plain, Iceland in graphs a) and b), volcanic sand samples from Chile in graphs c) and d), and glaciogenic silt sample measurements in graphs e) and f).

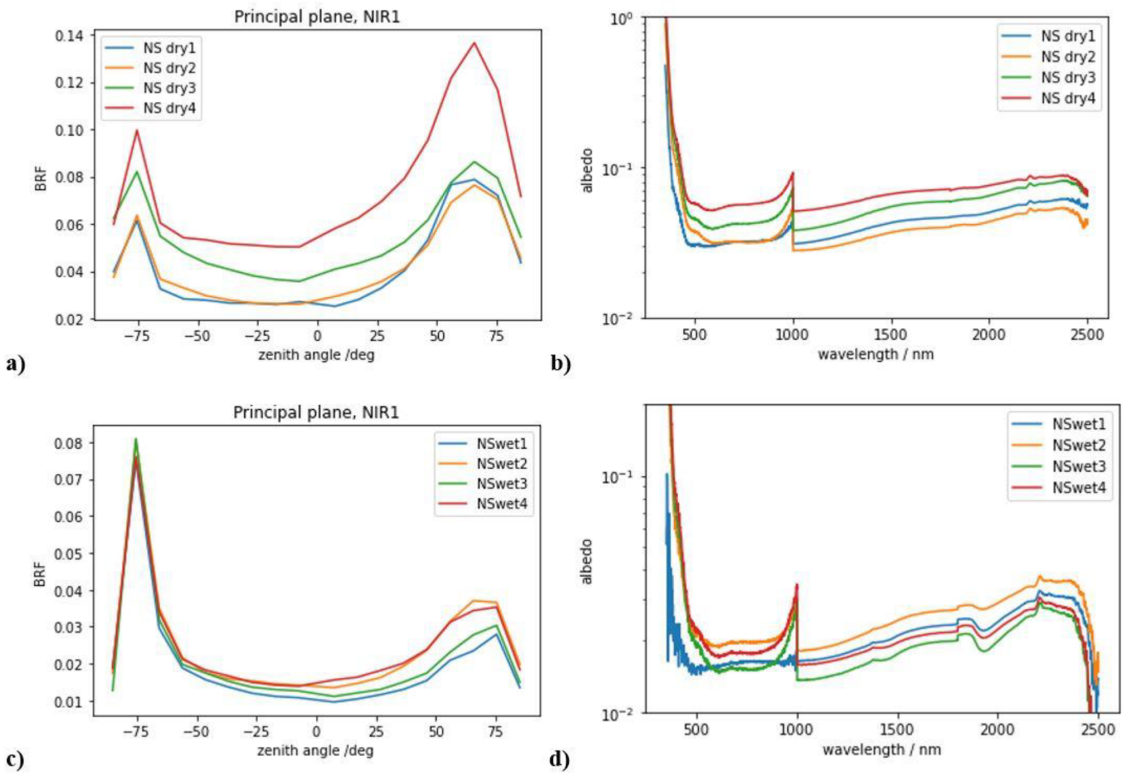

Figure 8. Visualization of optical measurements of NS1-NS4. Bidirectional reflectance factor (BRF) and albedo measurements of volcanic sand samples from Mýrdalssandur 2022. Samples NS1 to NS4 are visualized in the same graphs. The samples NS1-NS4 measured dry in a) and b), and wet/moist in c) and d). Zenith angle on the left side graphs is the angle of measurement optics from zenith (vertical). Some discrepancies caused by the measurement technology can be seen as abrupt jumps, for example in albedo graphs at wavelength of 1000 nm. These jumps and the border regions are unstable data to be disregarded.

The graphs on the left side of both Fig. 7 and Fig. 8 show the BRF of near infrared at different zenith angles, where the measurement optics were directly above the sample at 0 degrees. Near-infrared is generally considered to be 750-1400nm. The graphs on the right side in Fig. 7 and Fig. 8 show the spectral albedo of the samples, or the diffuse reflection to many different directions rather than just reflection towards one specific angle of different wavelengths of light. Most solar energy reaching the surface of earth is between 300-3000 nm, out of which the visible light spectrum is 400-700 nm explaining why surfaces with low albedo appear dark and surfaces with high albedo appear bright. In this work, focus is mainly given for measurement results in the visible spectrum. Albedo of the volcanic sand sample from Mýrdalssandur 2016 is approximately 0.03-0.05 in the visible light spectrum (Fig. 7). The results show that the smaller the particle size in the sample, the brighter the sample is. The volcanic sand sample from Iceland from 2016 shows this in both BRF and albedo measurements, but not as clearly as the comparison sample from Chile. From strained volcanic sample to under 125 µm the albedo increase is approximately 45% and the Chile sample 1 had an increase of approximately 162%. The Chile sample 1 is also noticeably brighter than Icelandic volcanic sample as seen from Fig. 7. The albedo of the Chile sample 1 is 0.04-0.09 for most of the particle size categories and even higher for the smallest under 125 µm sample at 0.1-0.2, which is quite bright for a volcanic sample. The under 125 µm sample of Chile sample 1 has almost as high albedo as glaciogenic silt in the visible spectrum, as seen in the graphs d) and f) in Fig. 7. Chile sample 2 was measured untouched without sieving because of the small amount available. The Chile sample 2 measurements are closest to the Chile sample 1 category of particles above 250 µm. The glaciogenic silt was measured first untouched but because it had formed some clumps it was sieved and measured again; the measurements do not differ much but as the sieved is more uniform it is likely more accurate for the silt sample.

Fig. 8 shows the results of optical measurements of the volcanic samples from Iceland 2022 referred to as NS1-NS4. As the sample material was fresh it still contained some moisture, which is why the samples were measured wet and dry. The NS1 through NS4 were small samples and so they were not sieved but measured as is. From the graphs in Fig. 8 it is apparent that the wet samples are very dark, and all appear to have similar optical properties (graphs c and d) but a significant difference is seen when these wet measurements are compared to the dry measurements (graphs a and b). The NS1-NS4 samples were all quite dark even when dry, with an albedo from 0.03 to 0.06 in the visible spectrum. When the NS1-NS4 samples were dry the clear difference in brightness was observable by eye but when moist this was not as clear. This can be seen in the measurements as well, where the moist samples all were much closer in the BRF and albedo measurements and very different from each other when measured dry. The moist samples were very dark with an albedo measurements between 0.01 and 0.02 on the visible spectrum.

6. Discussion

The average albedo of Earth is about 0.3, with albedo of different soils, minerals and urban areas being typically in the range of 0.05-0.4, oceans and other water areas can be even less than 0.1 (Rees 2001, Wallace & Hobbs 2006, IPCC 2021). Snow and ice have an albedo around 0.7-0.9, with fresh snow's albedo potentially being almost 1. Loss of snow cover, ice sheets and glaciers have significant impacts on the energy budget of Earth (IPCC 2021). Especially loss of sea ice means that an area that used to have an albedo around 0.7-0.9 drops drastically to less than 0.1. For the melting processes of snow and ice, an albedo reduction of only 0.01 is significant enough, but the albedo changes on icecaps after dust events in Iceland is in most cases much higher than this (Wittmann et al. 2017, Gunnarsson et al. 2021). Small changes in snow albedo impact melting, but are not necessarily visible by naked eye, which could be the reason why the topic of darkening snow and ice areas by impurities and the following climate impacts seem to be less known and discussed by the general public compared to other climate forcers such as greenhouse gases. The albedo changes and impacts of LAI on the melt of snow and ice areas can be expected in all high-latitude glacial areas and the scope of dust emissions can be expected to become more intense and expansive in the future as the climate change continues (Prospero et al. 2012, Meinander et al. 2022, Kavan & Strzelecki 2023).

Even though the dust emissions in Iceland are found to be the highest during spring in the southern part and during summer in the northern part, the jökulhlaup glacial flood events triggered by volcanic-glacial activity occurring in any season can cause high dust emission events throughout the year (Dagsson-Waldhauserova et al. 2014b, Nakashima & Dagsson-Waldhauserova 2019). Approximately 4.5 million tons of dust is deposited on the Icelandic glaciers annually (Arnalds et al. 2014), undeniably affecting the snow and ice areas of Iceland with the deposition of dark volcanic dust.

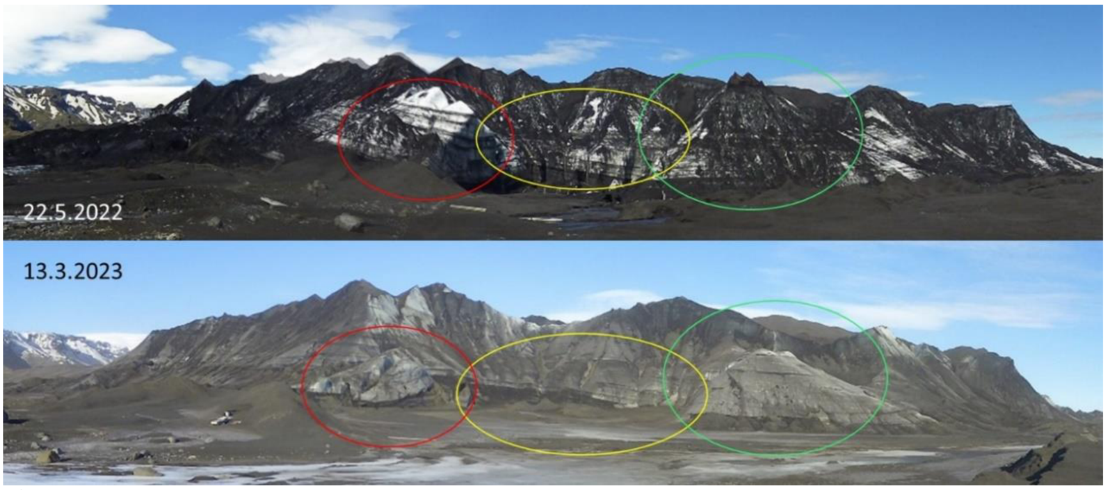

Figure 9. Melting of glacial areas. The outlet glacial areas in the images have melted despite the thick layers of ash/dust on top of them, suggested to prevent melting and isolate the ice. Image by: Pavla Dagsson-Waldhauserova.

Volcanic dust and ash were found to have an insulating effect on snow, but most studies focus on amounts of ash deposited during volcanic eruptions (Driedger 1981, Dracosics et al. 2016). This insulating effect does not last indefinitely (as seen in Fig. 9) and so ultimately after a certain amount of time the ash could start affecting in the opposite way and increase melt as was observed on the glacier outlet of the Mýrdalsjökull glacier in South Iceland in 2022-2023 (project Climate watch by Enlaps). Often the ash layer can be very thick after a volcanic eruption, but the layer is usually thin and expected to increase melting after dust events (Dracosics et al. 2016, Gunnarsson et al. 2021). The insulating effect seems to be more occasional and importance should be given to the melting effects of impurities on snow and ice surface. During volcanic eruptions the sulfur released to the atmosphere is generally considered to have a negative radiative forcing effect, but as it is deposited on snow and ice this is counteracted by the albedo decrease of the snow and ice (Wittmann et al. 2017). In addition, volcanic dust is effective in removing the SO2 from the atmosphere (Urupina et al. 2019). The environmental impacts of volcanic eruptions are generally short term as ash is removed from the surfaces by strong winds in less than one year (Butwin et al. 2020). Contrarily, dust storms provide the non-limited supply of LAI on glaciers year-round (Dagsson-Waldhauserova et al. 2014b, Dagsson-Waldhauserova & Meinander 2019, Gunnarsson et al. 2021).

This study shows that volcanic dusts from Iceland are very dark (albedo of 0.03-0.06) and they get darker when wet. This is comparable to the around 0.03 spectral reflectance for dry Icelandic volcanic dust measured in a laboratory with a spectrophotometer in Dagsson-Waldhauserova 2014a. Their highly absorbing properties can be compared to BC (Dagsson-Waldhauserova et al. 2018). This is important because volcanic dust is a less researched and studied LAI than BC, but seemingly it can be very similar in its effects on the cryosphere and climate. For example, Svensson et al. (2016) found that soot (used as a proxy for BC) deposited on snow decreased the albedo of snow from 0.83 for reference snow to 0.52 after soot deposition, and during the following two days the snow-surface albedo continued to drop to 0.35 whereas the reference snow-surface albedo increased to 0.86. Dal Farra et al. (2018) measured the spectral reflectance of a BC particle to be around 5% (albedo about 0.05) with their modified Hyperspectral Imaging Microscope Spectrometer (HIMS) which is comparable to the albedo measurements of bulk Icelandic volcanic dust in this study.

The measurements of Icelandic volcanic sand in this study are comparable to the measurements done with an ASD spectrophotometer in Peltoniemi et al. (2015), BRF of volcanic sand samples in near infrared is found to be at lowest 0.02 and at the highest 0.14 depending on the zenith angle, measurements of Peltoniemi et al. (2015) followed similar directional reflectance and was at lowest 0.02 and highest 0.07. Specifically in the case of the dry NS1 to NS3 the BRF measurement results are very similar to those in Peltoniemi et al. (2015). The mentioned study also measured the same glaciogenic silt sample as was used in this study, coming to almost identical results in albedo measurement in the visible spectrum.

Smaller volcanic particles in a sample appear brighter than the larger particles as evidenced in this study or in Arnalds et al. (2019). This study confirms this from observations with naked eye, but when it comes to Icelandic volcanic dust the samples with smaller particles are still very dark with an albedo around 0.04-0.05 in the visible spectrum using the instrument. The brightening of the volcanic samples was seen in both Icelandic and Chilean samples, but it is significantly more visible in the Chile sample 1 under 125 um. This can be seen well in Fig. 5 even by eye the smallest subcategory of under 125 µm samples are comparably brighter to the rest. Chile under 125 µm sample is similar to the glaciogenic silt in color which is closer to brown in color compared to the near black volcanic sand samples (Fig. 5). This can also be seen in Fig. 7 albedo measurements of glaciogenic silt (graph f) and under 125 µm Chile sample 1 (graph b) being quite similar. The lightness of the Chile samples specifically could be explained by other causes, for example due to other types of lighter dust being mixed in or different parent sediment.

The NS1-NS4 were darker when wet as can be seen in Fig. 3 and in the measurements in Fig. 8. Fig. 3 shows also the differences in particle sizes of these samples. The albedo measurements confirmed a decrease in albedo in the visible spectrum from 0.03-0.06 when dry to 0.01-0.02 when wet. Therefore, it could be assumed that even if dust would not be so dark when dry, after deposition on snow or ice and the subsequent melting they will only darken. More experiments and observations are, however, needed. This is an important matter for future research for laboratory measurements of dust to better represent the natural conditions.

The samples were studied with a stereomicroscope to see the shape and characteristics of the particles; they were found to be mostly volcanic glass, see Fig. 6. Therefore, it was deduced that when forming, the magma had cooled down so rapidly that minerals did not have time to form as is common for Icelandic sediments (Baldo et al. 2020). From these images the physical characteristics can be well observed, the Icelandic volcanic samples were quite amorphous and contained sharp shards and gas bubbles typical for volcanic particles, seen in Fig. 6. These typical physical characteristics allow suspension and transport of even quite large particles (Dagsson-Waldhauserova et al. 2015b).

Despite the fact that the smallest sieve size used for processing of the samples in this study was 125 µm, the presence of even smaller particles is assumed without knowing the exact particle size distribution (Arnalds et al. 2016). As mentioned before, particles most susceptible to wind erosion are silt and clay particles up to 50-60 µm but larger particles are suspended as well although for much shorter distances during strong winds (Cvetkovic et al. 2022). Additionally, the distinctive morphological characteristics of volcanic particles mentioned earlier increase the potential for suspension and transport of large volcanic particles compared to other mineral particles of the same size.

To conclude, the high emissions, transport potential and other characteristics of Icelandic volcanic dust make it an integral part of the albedo reduction of glacial and snow areas in the Arctic. For some areas it can be of a higher importance than BC due to high deposition. This is not to say that BC is not influential but to highlight the significance of dust alongside it. The distribution and deposition of dark dusts, such as volcanic dust, are important matters to study in the future in order to improve the climate models and their accuracy in predicting climate change. Especially as the frequency and magnitude of dust emissions, and following deposition, are expected to rise in the future (Boy et al. 2019, Meinander et al. 2022).

7. Conclusions and future research

The information compiled in this thesis gives an overview of the properties of Icelandic volcanic dust and how it affects snow and ice areas and the changing climate not only in the Arctic, but also globally. Icelandic volcanic dust has an integral role in reducing the albedo of snow- and ice-surfaces and the regional climate change in the Arctic. The literature review provides a deeper understanding of the processes that dust takes part in and gives a broader context and compares high-latitude dust to mid- and low-latitude dusts. Focus is given to Icelandic volcanic dust and how it sets apart from other dust sources. The laboratory measurements found that volcanic sand is comparable to BC as a light-absorbing impurity due to its optical properties, namely the very low albedo measurements comparable to a near-black body.

The deposition of Arctic dust on snow and ice is 70% higher than deposition of BC globally, and specifically in the Arctic regions the deposition of Arctic dust on snow and ice is 580% higher than BC (Meinander et al. 2022), which highlights the importance of high-latitude dust sources. The laboratory measurements of the optical properties of volcanic dust could help in developing climate models to better account for the impacts of dust emissions on the albedo and regional climate to hopefully prevent the underestimation of dusts effect on the global scale.

Dust emissions occur throughout the year and in high amounts, particularly significantly higher amounts than any other LAI. In the future the frequency and emission load are predicted to be higher, showing the need for more detailed research.

The topic of this work will be further presented by the author at the 28th International Union of Geodesy and Geophysics (IUGG) General Assembly in July 2023, with further plans to write a scientific paper on the topic, as well as conduct future research.

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