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Can ancient pathogens emerging from glaciers and permafrost in Greenland reach Europe by aerosolization?

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Anna Bruhn (2023).
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Kan uråldriga patogener från Grönlands glaciärer och permafrost nå Europa genom vindtransport?
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Can ancient pathogens emerging from glaciers and permafrost reach Europe by aerosolization?

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Bachelor thesis, 15 credits, in **Physical Geography and Ecosystem Analysis**

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Abstract

Glaciers and permafrost capture bacteria and viruses when they form, which can be suspended for millennia. This includes long since extinct pathogens which are functionally novel. As polar regions get warmer these pathogens will emerge and spread through the local ecosystem, potentially altering it. Ancient pathogens do not only pose a risk to their local environments as they can be aerosolized and transported long distances by wind. In this study I aimed to answer the question whether such pathogen transport is possible from Greenland to Europe. Through reviewing and synthesising existing literature from multiple disciplines I found that aerosolized pathogen transport from Greenland to Europe is indeed possible. How likely this is to occur under future climate conditions is unknown, as there is no consensus on how atmospheric circulation over the Atlantic will change. As the possibility under current atmospheric conditions is established by this study, future interdisciplinary research to further explore this phenomenon is warranted.

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1. Introduction

When glaciers and permafrost are formed organisms can be frozen and stored long-term, like 2-million-year-old intact mastodon DNA recovered from Greenland permafrost (Kjær et al., 2022). Extinct bacteria and viruses have also been found in ice cores and permafrost, some of them still viable (Bidle et al., 2007; Gilichinsky et al., 2008; Shi et al., 1997; Yarzábal et al., 2021). This includes potential pathogens from extinct ecosystems, whose genomes are partly unknown to us (Bidle et al., 2007; Yarzábal et al., 2021). Furthermore, permafrost and glaciers may not only serve as storage for bacteria, as some "psychrophilic" species have adapted to be active and reproducing at temperatures as low as -17 °C (Bidle et al., 2007; Jansson & Taş, 2014; Yarzábal et al., 2021). As anthropogenic warming is raising mean temperatures globally, and polar regions are heating up faster than the rest of the world, these vulnerable frozen landscapes are expected to thaw (Constable et al., 2022). Bacteria and viruses which have been suspended for millennia will be released into the environment.

This can alter the local ecosystems by infection of animals and humans, as well as by lateral gene transfer (Rogers et al., 2004; Yarzábal et al., 2021). Lateral gene transfer is a process by which bacteria exchange genetic information, which may allow for ancient pathogens proliferating genes which are functionally new to current ecosystems. This is speculated to have caused jumps in microbial evolution during past glacial melts (Bidle et al., 2007).

There is potential for this to occur in Greenland as it is largely covered by the Greenland ice sheet and permafrost (Dahl-Jensen, 2009; Westergaard-Nielsen et al., 2018). The ice sheet grew to its maximum over the course of about 130 000 to 17 000 years ago (Vasskog et al., 2015), and currently has a volume of almost 3 million km^3 (Bamber et al., 2013). Permafrost is defined as ground which is frozen for at least two consecutive years (Harris et al., 1988). And though current permafrost and glaciers may remain seasonally frozen, melting occurs during summertime leading to bacteria and viruses being released into the environment.

Not only Arctic regions may be at risk of exposure to ancient pathogens, as they may be transported long distances via aerosolization.

1.1 Aerosolized pathogens

Bacteria and viruses may be transported individually or attached to aerosolized particulate matter (PM), such as dust and organic matter (Chen et al., 2020). This also occurs in marine environments, through bubble bursting events (Aller et al., 2005; Blanchard & Syzdek, 1982; Chen et al., 2020). The size of PM is a determining factor of what bacteria and viruses may be transported (Chen et al., 2020), as well as their likelihood of survival in atmosphere (Bovallius et al., 1980; Prospero et al., 2005). In the case of organic matter, viruses tend to adhere to smaller particles (<0,7 µm) than bacteria (>0,7 µm) (Reche et al., 2018). Therefore, viruses may remain suspended in the atmosphere longer and be transported farther (Reche et al., 2018). Viable bacteria have been found to be more abundant when attached to PMs between 3,3 – 4,7 µm (Chen et al., 2020). Hence, aerosolized viruses are most often found in the category of PMs smaller than 2.5 µm (PM2.5) and bacteria in the category of PMs smaller than 10 µm (PM10). These categories are broadly used in aerosol research as they are inhalable and pose health risks (US Environmental Protection Agency, 2022).

Aerosols are primarily transported within the troposphere, which is the lowest part of the atmosphere (Cooper et al., 2010). In polar regions the troposphere encompasses altitudes of 0 to 8 km (Cooper et al., 2010). Wind speeds generally increase with altitude, therefore long-range transport of aerosols occurs more frequently in the free troposphere, which typically begins at ~3 km (Cooper et al., 2010; Reche et al., 2018). Long-distance transport of bacteria and viruses via air has been recorded, including between continents (Bovallius et al., 1980; Federici et al., 2018; Prospero et al., 2005; Sharoni et al., 2015), and including psychrophilic bacteria (Federici et al., 2018). Some suggest that the recent COVID-19 pandemic was proliferated by such mechanisms (Hofmeister et al., 2021).

During transport in the atmosphere bacteria and viruses are exposed to stressors which affect their viability. These include UV radiation, temperature, and moisture availability (Aller et al., 2005; Prospero et al., 2005). The resistance to stressors varies depending on the type of bacteria or virus, type of particle they are attached to, and amount of time spent in atmosphere.

Eventually, they are deposited by adhering to exposed surfaces or by precipitation, known as dry and wet deposition respectively (Reche et al., 2018). Where this deposition occurs depends on where the wind is blowing.

1.2 Wind patterns

Greenland is located in the northernmost Atlantic, which is subject to both the midlatitude westerlies and the Arctic easterlies on the southern and northern side of the polar jet stream respectively (Cooper et al., 2010). The meandering of the jet stream is influenced by topography as well as interconnected pressure anomalies. Particularly the North Atlantic Oscillation (NAO) (Cooper et al., 2010), the Greenland Blocking Index (GBI) (Hanna et al., 2013), and the East Atlantic pattern (EA) (Wallace & Gutzler, 1981) influence the path that westerly winds follow while moving to Europe. These are the general circulation phenomena I will examine.

1.2.1 North Atlantic Oscillation

The NAO is referred to as the primary mode of variability of wintertime atmospheric circulation over the Atlantic (Comas-Bru & Hernández, 2018). It is defined by two nodes, a northern low pressure and a southern high pressure, typically over Iceland and the Azores (Wanner et al., 2001). The oscillation is often described as having two phases, a positive phase with a strong pressure gradient between the low- and high-pressure nodes, and a negative phase where the gradient is weakened (Wanner et al., 2001). The positive phase is characterised by high wind speeds in the westerlies and a lack of meandering in the polar jet stream (Wanner et al., 2001). The NAO exhibits multidecadal negative and positive trends, which are part of its natural variability (Moore et al., 2013). Fig. 1 below illustrates the structure of the NAO in a positive and a negative phase with geopotential height anomalies. Geopotential height is the altitude at which a certain pressure (in hPa) is found, fig. 1 shows deviations from average altitude of altitude of 500 hPa. The geopotential height is unusually low over the northern node during a positive phase where pressure is lower than the mean. During a negative phase the geopotential height over the northern node is anomalously high, as the pressure is higher than the mean.

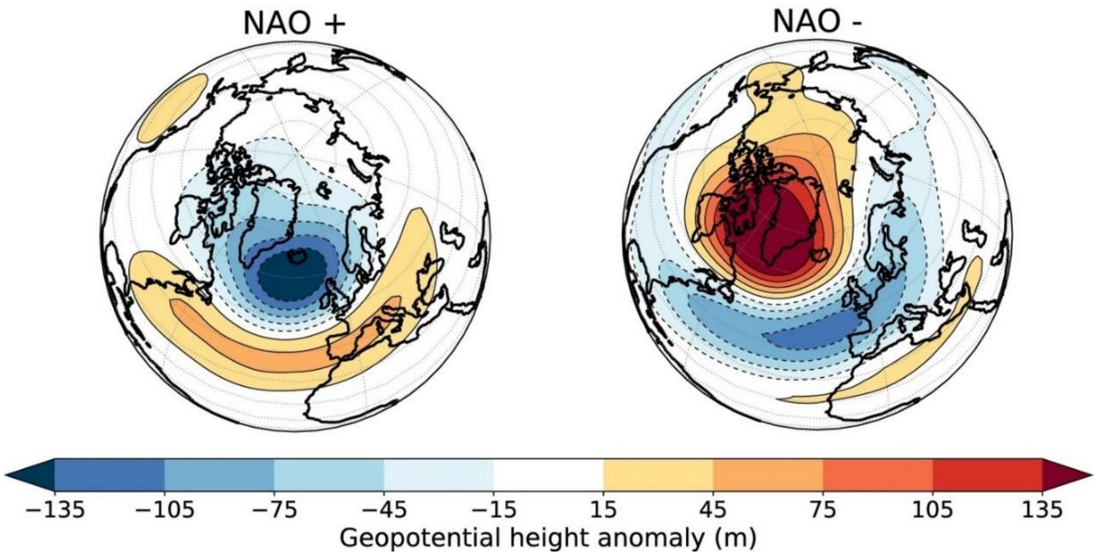

Figure 1. Geopotential height anomalies at 500 hPa of positive (left) and negative (right) NAO phases. Low pressure at the northern node characterises the positive phase, high pressure at the northern node indicates a negative phase. Adapted from Fabiano et al. 2020).

The NAO has a counterpart called the Summer North Atlantic Oscillation (SNAO) (Folland et al., 2009). The SNAO is defined by the same structure of a northern and southern node of low and high pressure respectively, though the southern node is located over north-west Europe (Folland et al., 2009). In terms of currently frozen microbes, the summertime wind patterns may be more relevant in the near future as permafrost and glaciers are likely to remain seasonally frozen, at least in the near future.

1.2.2 Greenland Blocking Index

The GBI is defined as the mean geopotential height of 500 hPa over Greenland (Hanna et al., 2013). A high GBI indicates a high-pressure system (anti-cyclone) which blocks westerly flow (Hanna et al., 2018). This blocking is correlated with a meandering polar jet stream and a negative NAO phase, which can be seen in fig. 1 above (Hanna et al., 2018). When GBI is high the jet stream tends to pass south of Greenland, meaning that the polar easterlies dominate while the westerlies pass farther south, though the position of the jet is variable (Hanna et al., 2018; Preece et al., 2022).

1.2.3 East Atlantic pattern

The EA is often referred to as the second mode of variability of wintertime circulation over the Atlantic, while being less well-defined in summer (Comas-Bru & Hernández, 2018). The definition of the EA varies in the literature, it may, in its simplest form, be described as a low-pressure monopole located west of Ireland at 55°N 20°W (Mikhailova & Yurovsky, 2016). Similar to the NAO, the positive phase of the EA (low pressure) enhances westerly winds (Mikhailova & Yurovsky, 2016). The negative phase indicates an anomalously high pressure, which diverts westerly wind flow (Mikhailova & Yurovsky, 2016), similar to a high GBI. Fig. 2 below shows the phenomenon of Atlantic ridging of the polar jet stream, as induced by the negative phase of the EA. The monopole is located at the centre of high geopotential height anomaly.

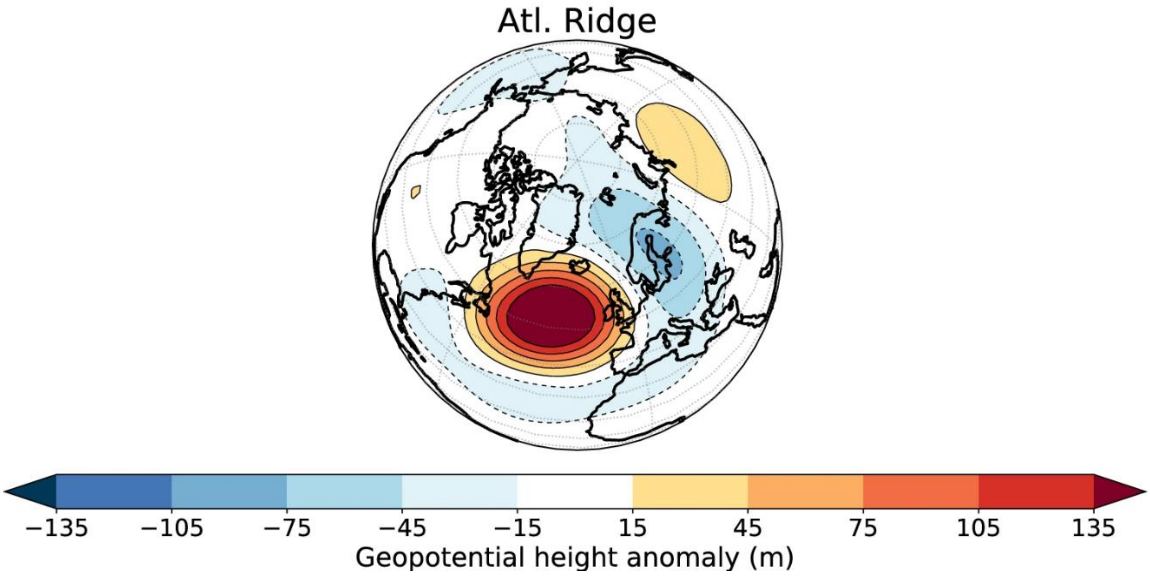

Figure 2. Atlantic ridging of the polar jet stream, causing it to shift northward of the mid-Atlantic, caused by a negative EA. The pressure monopole of the EA is located at the centre of the high geopotential anomaly over the Atlantic. During positive EA phases this would show a negative geopotential height anomaly. (Adapted from Fabiano et al. 2020)

The aim of this study is to investigate whether there is a possibility of ancient pathogens reaching Europe from Greenland by aerosolization. The second aim of this study is to examine this possibility in the context of climate change, as the emergence of ancient pathogens would be induced by future Arctic warming. I hypothesise that pathogen transport from Greenland to Europe is possible, including in a future climate when ancient pathogens may emerge from glaciers and permafrost. If this hypothesis is confirmed, then this study may serve as a basis for justifying further research of this phenomenon.

2. Method

This literature review attempts to synthesize information from several different disciplines. Due to this broad scope, I prioritised finding literature reviews, where information is already summarised and contextualised. Furthermore, literature reviews cite multiple useful sources and important authors. The selection of what articles to read, and eventually which I cited in these results, was biased by prioritising literature reviews as well as publications from authors which were commonly cited.

I primarily used Google Scholar and LUBsearch to search for relevant literature. Web of Science and Crossref were used to find “cited by” lists of relevant articles. Keywords were first entered into LUBsearch, if I could not find useful sources, I then searched Google Scholar. Ranasinghe et al. (2021) and Constable et al. (2022) were found through the IPCC.

Firstly, I searched for sources on bacterial and viral storage in permafrost and glaciers broadly, then Greenland specifically.

Secondly, I looked for studies of aerosolized microbes, viruses, pathogens; how they are aerosolized and how they are transported. Owen Cooper was a recurring author during this part of the literature search. Through his publication history on Google Scholar, I found the UN report on intercontinental transport of ozone and particulate matter (Cooper et al., 2010).

Thirdly, I looked for information on north Atlantic wind patterns, specifically the North Atlantic Oscillation in relation to Greenland. This led me to discover the Greenland blocking phenomenon, and the East Atlantic Index. The sources mentioning Greenland blocking often cited several studies by Edward Hanna, which led me to look through his history of publication, which informed much of the relationship between Greenland and wind patterns. Richard Hall was often cited by Edward Hanna's publications, which led me to Hall et al. (2015). As was Tim Woollings, which led me to Woollings et al. (2010).

Furthermore, as I read about different ways of tracking air masses, I found the term "retroplume" (a reconstruction of the trajectory of an air parcel). By searching for retroplumes from Greenland to Europe I found Evangeliou et al. (2019), a study of open fires on Greenland transporting PMs to Northern Europe. This led me to investigate the possibility of bacteria and viruses being aerosolized by fire, which in turn led me to the history of publication from Leda Kobziar, which includes Kobziar et al. (2018, 2022) and Moore et al. (2021). A publication from 2020 by Kobziar and Thompson (not used) led me to Cottle et al. (2014). The size of PMs released from the peat fires is also relevant to my study, which led me to Kiely et al. (2019) and subsequently Kuwata et al. (2018).

Table 1. Description of literature search for information used in the results section. Table includes database and keywords used, as well as number of hits. The references used in this study are listed under "Source", "Reference list", and "'Cited by'".

Database	*Keywords*	*Number of hits*	*Source*	*Reference list*	*"Cited by"*
LUBsearch	Permafrost pathogens	182	Wu et al. 2022 (not used)	Jansson & Taş, 2014	
Google Scholar	Greenland ice sheet microbes	77	Irvine-Fynn et al., 2021		
Google Scholar	Permafrost pathogens review	14 000	Yarzábal et al., 2021		
Google Scholar	Bacteria in arctic glacial meltwater	14 400	Perini et al., 2019		
LUBsearch	Intercontinental transport bacteria	21	Prospero et al., 2005		Alsante et al., 2021 (In Web of Science)
LUBsearch	Airborne microbes	2 071	Chen et al., 2020	Aller et al., 2005; Brown & Hovmøller, 2002; Federici et al., 2018	
Google Scholar	HYSPLIT model backward trajectory Europe	14 400	Kulesza, 2023		

Google Scholar	Free troposphere microbes	18 700	Smith et al., 2012		Smith et al., 2013 (In Web of Science)
LUBsearch	Microbes in Arctic air	82	Harding et al., 2011		
LUBsearch	Aerosolized viruses	2 920	Sharoni et al., 2015		
Google Scholar	Aerosolized bacteria Atlantic	18 200	Lang-Yona et al., 2022		
LUBsearch	Deposition of airborne bacteria and viruses	34	Reche et al., 2018		
Google Scholar	Cyclones over Greenland	25 900	Liang et al., 2021		
LUBsearch	Greenland blocking summer	258	Preece et al., 2022		
LUBsearch	North Atlantic Oscillation East Atlantic Index	2 000	Mellado-Cano et al., 2019		
Google Scholar	North Atlantic Oscillation climate change	374 000	Gillett et al., 2003		Eade et al., 2022 (In Crossref)
Google Scholar	Retroplume Europe Greenland	63	Evangeliou et al., 2019		
Google Scholar	East Atlantic index climate change	2 290 000	Comas-Bru & Hernández, 2018		
Google Scholar	Particulate matter from peat fires	6 300	Kiely et al., 2019	Kuwata et al., 2018	

It must be noted that the search algorithm of Google Scholar adjusted to my search history and began prioritising publications relevant to and similar to what I had previously read. This impedes repeatability of my method as I used Google Scholar extensively to establish my background knowledge before beginning my literature search.

3. Results

3.1 Glacial and permafrost pathogens

Yarzabal et al. (2021) reviewed studies on pathogens being stored in, and released from, glaciers and permafrost. Several pathogenic, as well as novel viruses have been found in Greenland's ice and permafrost (Perini et al. 2019; Bellas et al. 2015 in Yarzábal et al., 2021). Viable bacteria and viruses have been found in ice cores ranging from 500 to 157 000 years old (Knowlton et al. 2013 in Yarzábal et al., 2021). Though it is noted by Knowlton et al. (2013) that viability decreases with age. Viruses in ice from Greenland ranging 500 to 10 000 years old were found capable of infecting bacteria (Castello et al. 2005 in Yarzábal et al., 2021). As glaciers are melting and permafrost is thawing the potential pathogens they store are being released into the environment. Irvine-Fynn et al. (2021) studied abundance of microbes in the melting surface of the ice sheet on western Greenland. They estimated a concentration of microbes in the tens of thousands per millilitre in glacial meltwater, which they state may include large viruses. Total biomass concentration in the melting crust of the Greenland ice sheet was 1.5×10^{15} cells per km^2 in the uppermost part of the ice sheet. These findings show an abundance of microbes, and possibly viruses, present in glaciers and permafrost in Greenland. Melting of the Greenland ice sheet will continue as the Arctic gets warmer, and the melting surface will reach older layers of ice, containing older bacteria and viruses.

Via meltwater these potential pathogens will spread through the ecosystem, potentially altering it by disseminating heretofore extinct genetic material. As mentioned in the introduction, bacteria and viruses may be aerosolized from terrestrial or marine sources. As meltwater will likely transport emerging bacteria and viruses to the Atlantic Ocean, marine sources may be more relevant to this study.

3.2 Aerosolization and transport of pathogens

I have found several examples of both bacteria and viruses being aerosolized from marine environments and transported over long distances. Alsanté et al. (2021) reviewed literature in the field of ocean aerobiology. Transport of various marine bacteria and viruses can span millions of kilometres, as a theoretical upper limit. Smaller particles are transported further. The authors found that between 1 – 25% of aerosolized marine bacteria and viruses remain viable when they are deposited. A study by Sharoni et al. (2015) proved that marine viruses dispersed by air could infect phytoplankton. Furthermore, they investigated potential trajectories of these aerosolized viruses in the Atlantic, finding they travel hundreds of kilometres. Given consistent wind directions during transport, these viruses are not necessarily broadly dispersed. To summarise, bacteria and viruses can be aerosolized from the sea and remain infectious, and if wind conditions are favourable, they can stay highly concentrated over hundreds of kilometres.

Wind dispersal of bacteria in polar regions may have already occurred. Harding et al. (2011) sequenced genomes of bacteria from snow and air in the Canadian Arctic. They found high similarity in genomes, and some identical species, compared to the rest of the Arctic and Antarctica. They conclude that bacteria have been dispersed by wind, which has created similarities in the global cryosphere's microbial ecosystems. Furthermore, they found marine bacteria in the snowpacks. They speculate this is due to aerosolization from the sea, and that the aerosols act as condensation nuclei on which snowflakes form. Long-range transport of bacteria in polar regions may be a recurring phenomenon, responsible for similar microbial ecosystems in both the Arctic and Antarctic.

In the context of this study marine aerosolization in the Atlantic is relevant, as described in section 3.1. A study by Lang-Yona et al. (2022) suggests that microbes from the Atlantic may not be a large source of airborne bacteria. They investigated the structure of microbial communities in the surface waters of the Atlantic and Pacific, as well as the communities in the lower atmosphere above the oceans. In the Atlantic atmosphere, microbes originated primarily from land, carried by dust. They found fewer marine bacteria in the air over the Atlantic than the Pacific. These findings imply that there is limited interaction between the microbial communities in the Atlantic and the overlying atmosphere.

As for terrestrial sources, dust seems to be the most effective conduit for long-range transport. For example, Smith et al. (2013), found two long-range transport occurrences where viable airborne bacteria from Asia reached North America with dust plumes. Prospero et al. (2005) found viable bacteria transported by wind from Sahara to the Caribbean, in connection with dust storms. The bacteria remained viable after approximately 7 days of transport from northern Africa, though bacteria of other origins were not found to be viable. The authors suggest that this relates to adverse conditions in the atmosphere, such as UV radiation, temperature, and moisture availability. They speculate that the physical attributes of both the dust particles and the Saharan bacteria aided in maintaining viability in spite of atmospheric stressors.

There are examples of plant pathogens being spread intercontinentally via air. Smith et al. (2012) discovered viable bacteria transported in the free troposphere from around China or Japan, including plant pathogens. Brown and Hovmøller (2002) reviewed historical outbreaks of plant disease and found examples of long-range transport of pathogenic fungi. For example, sugarcane rust was spread from west Africa to the Caribbean by wind. The authors include three other potential examples of plant pathogens spreading disease intercontinentally, and they suggest that viruses may be spread in a similar way.

A surprising finding made during the writing of this study is in the field of "pyroaerobiology". Specifically publications from Kobziar et al. (2018, 2022) and Moore et al. (2021) have proven that bacteria may be aerosolized through fire and remain viable, including pathogens. In fact, they found that concentration and viability of bacteria was higher in smoke than ambient air. The fires aerosolized PM10 and PM2.5, these particle sizes were correlated to bacterial abundance (Kobziar et al., 2022; R. A. Moore et al., 2021). The abundance of viable bacteria is made possible by the higher temperature and relative humidity within smoke than the ambient air. The traits of the bacteria and the PMs to which they are attached are also thought to affect viability. Furthermore, they bring up the possibility of bacteria adjacent to the fire being aerosolized by the lifting of hot air, which Kobziar et al. (2022) calls "pyroconvection". Moore et al. (2021) bring up potential global spread of bacteria via smoke, as smoke transport has been observed on continental scales. Fires should not be possible in Greenland's frozen landscape, though it has occurred and is further explored in section 3.4 of this study.

There are several instances of smoke plumes being transported intercontinentally. Like Cottle et al. (2014), who found that PM2.5 concentrations increased in Canada as a result of smoke from fires in Siberia being transported in the free troposphere. Law et al. (2010) summarizes observational evidence of long-range aerosol transport in a report for the UN. Their findings include instances of transport across the Atlantic, from northern Africa to North America as well as from North America to Europe. One example of smoke from wildfires in the Ural Mountain region was transported eastward, over Canada and Europe and back to the Ural Mountains in approximately two weeks. Additionally, smoke from Alaskan fires were discovered over the north Atlantic and western Europe. This occurs due to plumes of smoke from forest fires efficiently lifting aerosols into the free troposphere, where potential for long-distance transport increases with wind speed.

Lifting of PMs into the free troposphere may also occur through cyclonic activity. Liang et al. (2021) investigated wintertime cyclone formation in Baffin Bay, west of Greenland. They found that some cyclones moving over Greenland pass to Europe before terminating (see fig. 13 in Liang et al. 2021). Though this occurs rarely, the ability of cyclones to cause convection and therefore potentially aerosolize PMs to high altitudes make this phenomenon relevant. Even when cyclones do not move to Europe, they may serve to aerosolize bacteria and viruses from Greenland and the surrounding Atlantic.

Based on the studies presented above (sections 3.1 and 3.2), it is reasonable to suggest that bacteria and viruses will be released from ice and permafrost in Greenland due to anthropogenic warming. Furthermore, there is potential for them to be aerosolized to the free troposphere through fires and cyclones, though fires are not common in Greenland. Aerosolization from marine sources seems likely to be more common as frozen bacteria and viruses are transported to the Atlantic through meltwater.

3.3 Wind patterns

The general circulation of wind over the Atlantic determines where aerosols are transported and deposited. Here I will include results describing the effect of the NAO, GBI, and EA on aerosol transport from Greenland to Europe.

3.3.1 North Atlantic Oscillation

Cooper et al. (2010) found that long range-transport of PMs over the Atlantic increases during a positive NAO phase due to higher wind speeds. Though this report does not specifically examine air transport from Greenland but rather North America, the same principals apply to Greenland transport being facilitated by a positive NAO. This was noted by Kulesza (2023), who modelled 72 hour back trajectories of air masses reaching Poland. Using the HYSPLIT model three out of seven source clusters identified encompassed some part of Greenland. These are sources for trajectories C, D, and E in fig. 3 below.

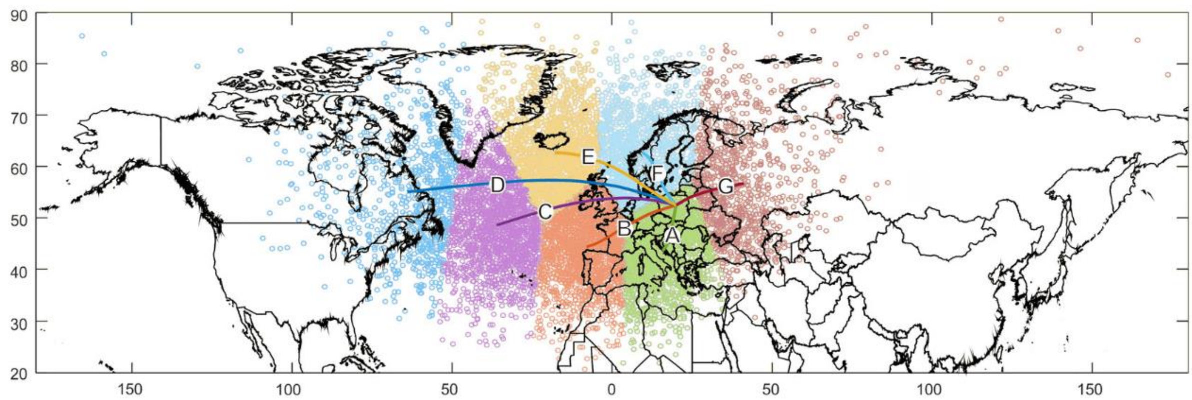

Figure 3. 72h back trajectories of air masses reaching Poland at 3000 m altitude shown with coloured lines labeled A-G. The clustered source regions of these air masses are shown in dots of corresponding colour (Figure 2 in Kulesza, 2023).

Kulesza (2023) states that these trajectories passed over northern Europe before reaching Poland from the north, north-east or east. Kulesza also connects transport from these sources to a positive NAO phase, as it creates higher wind speeds than the negative phase, allowing for longer-range transport. Similarly, these sources are less frequent in summer due to wind speeds being generally lower than in winter.

Hall et al. (2015) examined polar jet stream variability over the Atlantic. In summer it is generally located farther north due to a decreasing temperature gradient between the pole and the equator. However, during a negative SNAO phase it is shifted farther south. The jet has trended to a more northern position up to the 21st century. As with the NAO, the positive phase of the SNAO would increase the likelihood of westerly winds passing over Greenland. Though, even with a poleward shifted jet stream in summer, which increases likelihood of air from Greenland reaching Europe, wind speeds are generally lower, which lowers that likelihood.

Higher wind speeds increase the possibility of long-range aerosol transport and decreases the time spent in atmosphere over long distances. The shorter time spent in atmosphere increases the probability of pathogen viability after transport. Dispersal of aerosols is generally more long-range in winter than summer, as well as during positive NAO phases. However, bacteria and viruses in Greenland are likely to only emerge during summer melt. Hence, long-range transport of pathogens from Greenland to Europe are most likely in summertime, during positive NAO phases.

3.3.2 Greenland Blocking Index

Wind speed is not the only quality of positive NAO phases which may facilitate aerosol transport from Greenland, the pattern of wind flow is also relevant. As mentioned in the introduction, the negative phase of the NAO is characterised by meandering of the polar jet stream (as well as lower wind speeds) which does not allow much of the westerly winds to pass over Greenland. However, the positive phase, shifts the jet stream, and thereby the westerly winds, northward. This is correlated to the GBI.

Hanna et al. (2018) presents a time-series of the GBI from 1851 – 2015. They found significant year-round negative correlations between the GBI and the NAO; when NAO is positive, GBI is low and vice versa. Fig. 4 below shows figure 4(d) from Hanna et al. (2018). It displays mean anomalies of summertime wind patterns during the five years with the highest number of anomalously high GBI days (GBI > 1). Vectors indicate wind direction.

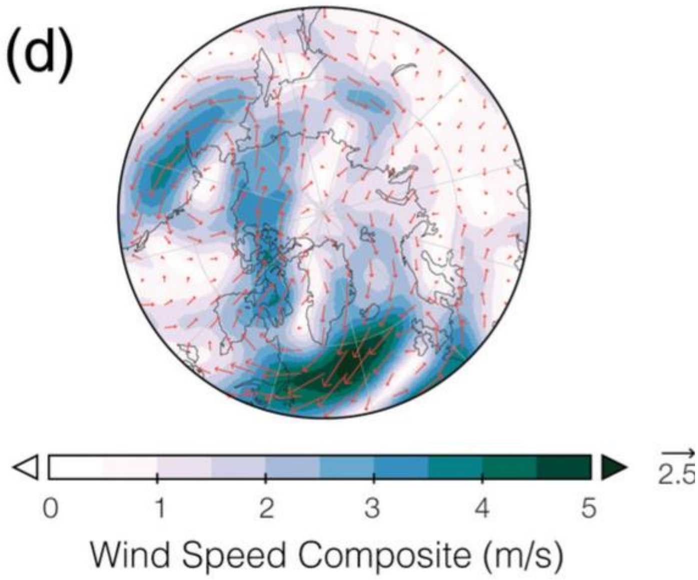

Figure 4. Mean anomalies of summertime (June-July-August) wind speed during five years with highest number of days with GBI>1 during 1851-2015. Directions are shown with red vectors (Figure 4(d) in Hanna et al., 2018).

The figure shows anticyclonic flow over Greenland and north-western Canada, there is no flow from Greenland to Europe. The same pattern can be observed in wintertime, shown in figure 4(c) in Hanna et al. (2018). Though it should be noted again that this figure is a composite of years with the highest GBI and may not be representative of all instances of blocking. Hanna et al. (2018) also found that during low GBI events the polar jet stream shifts to higher latitudes (see figure 5 in Hanna et al. 2018). Which is consistent with a positive NAO and could allow westerly winds to pass over Greenland and subsequently reach Europe.

As mentioned in the introduction of this paper, the GBI is an indicator of high-pressure anomalies over Greenland. Hanna et al. (2013) found that a high GBI causes melting of the Greenland Ice Sheet. This is due to a high-pressure system (anti-cyclone) causing warm air from the south to sink over Greenland. The extreme melting of the ice sheet in the summer of 2012 was caused by extremely high blocking (Hanna et al., 2014). While high GBI decreases the likelihood of air from Greenland transporting bacteria and viruses to Europe, it is also a mechanism which causes bacteria and viruses to emerge by melting.

As melting of the Greenland ice sheet is correlated with high Greenland blocking, but Greenland-Europe air flow is more likely with low blocking, aerosolization would need to occur between blocking episodes. Preece et al. (2022) investigated different types of Greenland blocking, in four day episodes during summertime (June-July-August) 1979 – 2019. The second definition identified a total of 963 blocked days, not only including 4-day blocking episodes. This would indicate that 2 717 of 3 680 summer days were not blocked during 1979 – 2019. Though it is worth noting that frequency of blocking increased during 2000 – 2019. Greenland blocking could create a back-and-forth between melting causing emergence of bacteria and viruses and westerly winds over Greenland not being blocked.

A high GBI blocks westerly flow and is correlated with a negative NAO phase. Therefore, a situation with low GBI and a positive NAO phase is more conducive to Greenland-Europe airflow as the westerlies are more likely to pass over Greenland than south of it. Furthermore, the positive NAO creates higher wind speeds, which aids the long-range transport of viable bacteria and viruses. While a high GBI makes airflow to Europe less likely, it also enhances melting in Greenland which may be key to pathogens emerging in current climate conditions.

3.3.3 East Atlantic pattern

The EA also influences the pattern of westerly winds over the Atlantic. Mellado-Cano et al. (2019) analysed the wintertime relationship between the EA, NAO, and the polar jet stream based on observational data. They found that a negative EA is associated with less or no Greenland blocking. The combination of a positive NAO index and a negative EA index shows the greatest possibility of wind flow from Greenland to Europe, when the polar jet stream is shifted north (see fig. 3 in Mellado-Cano et al., 2019).

Similarly, Woollings et al. (2010) investigated the literature on wintertime positioning of the polar jet stream, in connection to the NAO and EA. Like Mellado-Cano et al. (2019), they found that the jet shifts northward when the EA is negative (high pressure). The high pressure (anti-cyclone) causes blocking and clockwise air flow in the middle of the Atlantic, which can cause westerly winds to flow over Greenland toward the British Isles, and possibly farther east. This pattern can be found during a negative EA in combination with a neutral or positive NAO.

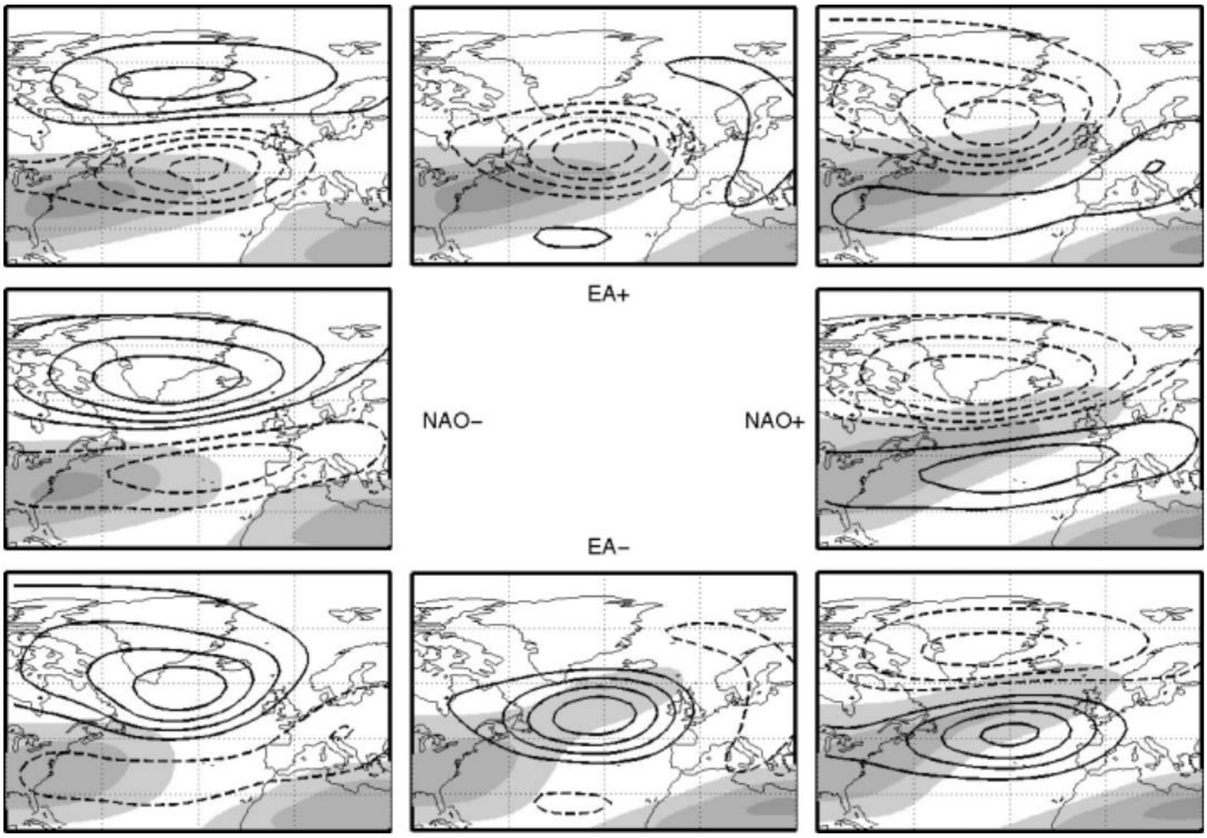

Figure 5. Phases of the NAO and the EA. NAO: negative in the left column, neutral in the middle column, positive in the right column. EA: positive in the top row, neutral in the middle row, negative in the bottom row. Solid lines indicate high pressure, dotted lines indicate low pressure (Figure 10 in Woollings et al., 2010).

Fig. 5 shows the negative EA is a high pressure, which has anti-cyclonic flow (clockwise) passing over southern Greenland and moving east over Iceland and the British Isles when the NAO is neutral. This can also be seen in fig. 2 in section 1.2.3. When the EA is negative, and the NAO is positive there is a low pressure in the north Atlantic and over Greenland. This cyclonic flow (counter-clockwise) causes convection, which can lift PMs and transport them east.

The findings of both Mellado-Cano et al. (2019) and Woollings et al. (2010) indicate that a negative EA (in combination with a positive or neutral NAO) creates the highest likelihood of air from Greenland reaching Europe.

3.4 Deposition of pathogens

Deposition processes affect virus and bacteria in different ways. Reche et al. (2018) studied deposition rates in the Sierra Nevada mountains in Spain, they collected samples at altitudes in the free troposphere, above the lower troposphere. This was done to examine deposition of bacteria and viruses which have presumably been transported long-range. They found that airborne bacteria are significantly affected by wet deposition, and that their presence in air was correlated with dust particles. Viruses however are deposited by wet and dry processes in roughly equal amounts, and mostly originated from marine environments. The total deposition of viruses in the free troposphere was in the order of billions of viruses per m^2 per day, and the deposition of bacteria was in the order of tens of millions of bacteria per m^2 per day. Wet deposition is likely to only play a significant role in the free troposphere, according to Cooper et al. (2010). They state that precipitation is scarce in the lower troposphere, by logical extension this indicates that dry processes dominate deposition in the lower troposphere. Conceptually, PMs in the lower troposphere may be washed out by precipitation originating from air masses at higher altitudes, though it is more likely that wet deposition affects PMs in the free troposphere.

Dry deposition is hard to predict, while wet deposition can be extrapolated from studying patterns of precipitation and their correlation with circulation phenomena. Comas-Bru and Hernandez (2018) found that the EA is positively correlated year round to precipitation in the British Isles, a positive EA leads to more precipitation. While the negative EA phase increases likelihood of air from Greenland reaching the UK and Ireland, this also implies less precipitation. Though dry deposition may still occur, as the high-pressure anomaly of a negative EA causes anti-cyclonic flow and advection. Mellado-Cano et al. (2019) found similar precipitation patterns, which suggests that dry deposition may be more relevant for bacteria and viruses reaching Europe form Greenland, at least in relation to the EA.

A rare example of tracking particles from Greenland is presented by Evangeliou et al. (2019), who studied transport of particles released from peat fires in south-western Greenland that occurred 2017. The fires occurred between 31st of July and 21st of August. Cumulative deposition of black carbon, organic carbon, and brown carbon by August 31st (shown in fig. 6) was found in northern Europe, mostly in Iceland, the British Isles, and Norway. Some of these particles may be of sizes relevant to aerosolized viruses and bacteria, which are primarily <0,7 µm for viruses and 3.3 – 4.7 µm for bacteria. In studies of Indonesian peat fires, Kiely et al. (2019) found that these fires caused significant emissions of PM2.5, and Kuwata et al. (2018) found that peat fires emit PM10. These fires emit PMs of optimal size for viruses and bacteria to attach to.

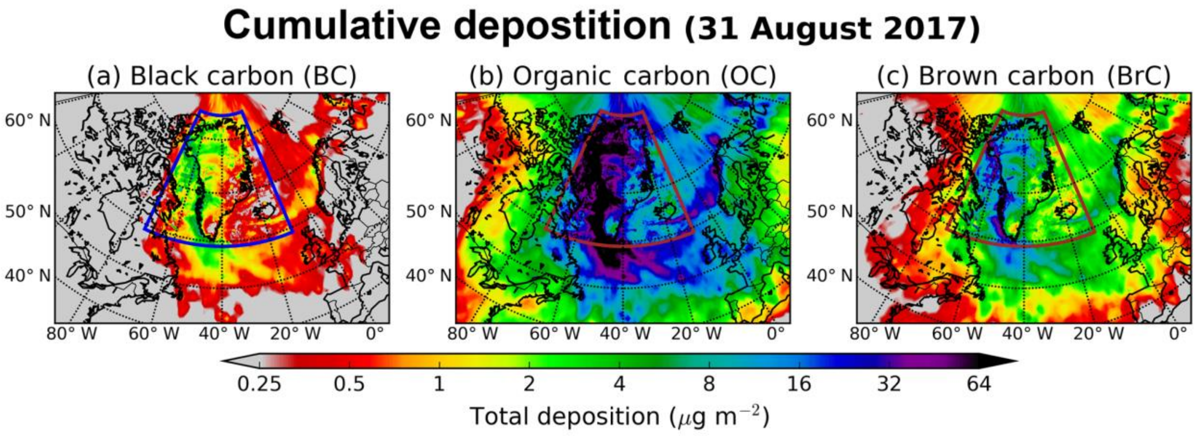

Figure 6. Maps of modelled cumulative deposition of black/organic/brown carbon (µg/m^2) from Greenland fires by 31st of August 2017 (Figure 2 in Evangeliou et al., 2019).

The authors found that most of the smoke was transported back over Greenland due to anti-cyclonic flow, which indicates a high pressure and high GBI. A high GBI would likely occur in correlation with a negative SNAO, which was the case during these fires according to historical indexes (National Oceanic and Atmospheric Administration, 2023b), furthermore the EA was positive (National Oceanic and Atmospheric Administration, 2023a). The negative phase of the SNAO causes meandering of the polar jet stream, the shape of which can be distinguished by high deposition areas in fig. 6 above, passing eastward across the Atlantic and curving north along the west coast of Norway. Most of the deposition occurred over Greenland and the Atlantic, however during a positive SNAO phase the westerlies could potentially transport PMs farther.

3.5 Future conditions

The NAO index has, according to Gillett et al. (2003), experienced a positive trend in frequency and intensity from the 1960's through the 1990's. By reviewing a multitude of models investigating the reason for this trend, they concluded that natural decadal variability likely does not account for the changing NAO. Several mechanisms contribute to the NAO pattern, but they found that increased emission of greenhouse gases is decidedly part of it. Models also underestimate the changes in the NAO in comparison to observational data. However, the long-term positive trend of the 1960's to the 1990's did not continue, and the NAO switched to a more negative trend. Eade et al. (2022) found that the extended positive trend of the NAO was likely not caused by greenhouse gas emissions, but rather natural decadal variability, the likelihood of which has been underestimated by climate models. They cite Gilette et al. (2003) as disproven speculation.

Furthermore, Hanna et al. (2015) found that the current trend of a more negative NAO is due to the SNAO becoming increasingly negative, while the winter months are more variable. This seasonal change was not accounted for in the Global Climate Models and CMIP5 models which Hanna et al. (2015) investigated. A significant increase in the frequency and intensity of high GBI (dramatic increase in summer and more variable in winter) is instead considered to be a leading cause, though the authors do not discount the possibility of natural variation explaining this trend. The increase in GBI is speculated to be influenced by snowmelt occurring earlier in the year as well as decreases in sea ice, among other factors. Which could indicate that anthropogenic warming may in fact cause the NAO to become more negative, though this conclusion is not certain.

Future increase in GBI may increase the likelihood of peat fires similar to those studied by Evangeliou et al. (2019), see section 3.4. The authors noted that south-western Greenland had been experiencing anti-cyclonic flow, which occurs during high GBI, for eight consecutive days before the fires started. They speculate that this anti-cyclone caused warm and dry enough conditions for the peat to self-ignite. Peat fires will likely become a more common phenomenon in the future, given that the peat became combustible due to permafrost degradation and a high GBI created conditions for ignition, both of which are on a positive trend (Constable et al., 2022; Hall et al., 2015).

However divisive the future of the NAO may be, which Hall et al. (2015) also discuss, there is broader consensus that wind speeds over the Atlantic and Europe will decrease, likely due to a decreasing temperature gradient between the equator and the Arctic (Ranasinghe et al., 2021).

4. Discussion

A key finding is the study by Evangeliou et al. (2019). It shows that aerosols from Greenland can be deposited in Europe. I have not found other studies that track transport from Greenland, as it is no great source of pollution or dust. This study is relevant beyond showing PMs from fire acting as a proxy for aerosolized bacteria and viruses, when viewed in combination with pyroaerobiology, which indicates a possibility of viable bacteria being aerosolized by fire

(Kobziar et al., 2018, 2022; R. A. Moore et al., 2021). Furthermore, other peat fires have emitted both PM10 and PM2.5 (Kiely et al., 2019; Kuwata et al., 2018), categories which include all particle sizes that are optimal for both bacteria and viruses to be aerosolized. It is possible for bacteria and viruses, including potential ancient pathogens, to be aerosolized from Greenland's permafrost and reach Europe.

Peat fires are likely to become more common in Greenland due to arctic warming (Constable et al., 2022; Evangeliou et al., 2019). The fires of 2017 may have been caused by prolonged Greenland blocking, causing warm and dry conditions. This may also contribute to higher risk of fires in the future as the GBI is currently becoming more positive in summer (Hall et al., 2015). As presented in section 3.3.2 the GBI is correlated with a negative NAO, meandering jet stream, and slower wind speeds. The meandering of the jet stream can be seen in fig. 6, where deposition is most highly concentrated to the east of Greenland. These factors decrease the likelihood of air from Greenland reaching Europe, yet significant deposition occurred in Iceland, the British Isles, and Norway. The fact that deposition of PMs occurred in Europe during the most unlikely atmospheric circumstances raises the question of where deposition would occur if conditions were optimal, with no Greenland blocking, positive or neutral NAO, and a negative EA.

It should be noted that Kobziar et al. (2018, 2022) and Moore et al. (2021) did not investigate long-range transport and deposition of viable bacteria aerosolized by fire. Given that they describe the smoke plume over a fire as a warm and humid hospitable environment for bacteria, it is reasonable to assume that concentration of viable bacteria will decrease as the smoke plume is dispersed over intercontinental distances. Furthermore, the potential for pyroaerosolization of viruses is not explored in these articles and would need to be supplemented by further literature searching or further studies. Though, it may be possible that viruses are pyroaerosolized intracellularly, and likely that they can be convected adjacent to fires. Further research is required to evaluate the likelihood of permafrost bacteria and viruses surviving pyroaerosolization and subsequent long-range transport.

Beyond the potential for long-range transport by pyroaerosolization, the existing examples of intercontinental transport of viable bacteria and viruses are relevant to confirming my hypothesis. Bacteria may remain viable after intercontinental transport across the Pacific and the Atlantic, which are longer distances, and imply longer residence time in atmosphere, than between Greenland and Europe. However, the bacterial transport via dust seems most common, or at least most commonly detected. As mentioned, Greenland is no great source of dust. I was unable to find an example of viable bacteria or viruses transported via air in the Arctic. Although, Harding et al. (2011) suggest that wind dispersal of bacteria in polar environments might be a recurring phenomenon, responsible for high similarity of microbial ecosystems in the global cryosphere. On the other hand, Prospero et al. (2005) noted that the viable bacteria they discovered in the air in the Caribbean originated from Sahara, while those from other sources were not viable. They suggest it is due to the Saharan bacteria having traits more suited to surviving prolonged time in atmosphere. Whether bacteria and viruses from Greenland's frozen landscapes could survive the stressors of long-range atmospheric transport is unknown and requires further study.

Marine aerosolization may be more relevant in the case of Greenland. Potential pathogens stored in both glaciers and permafrost may reach the Atlantic Ocean via. Aerosolization from the Atlantic is, according to Lang-Yona et al. (2022), less common than from the Pacific. Furthermore, the presence of sea ice prevents aerosolization, though sea ice cover is reducing due to anthropogenic warming (Constable et al., 2022). However, Reche et al. (2018) and Sharoni et al. (2015) both found viable airborne viruses which originated from marine environments. In the case of pathogens, viability does not necessarily mean that they are capable of infection, and there is more information on the viability of frozen and aerosolized pathogens than their infectivity (Yarzábal et al., 2021). Although, Sharoni et al. (2015) also found marine viruses to be capable of infecting bacteria after atmospheric transport. This suggests that pathogens from glacial and permafrost meltwater which reach the Atlantic could be aerosolized and transported to Europe while remaining infectious.

The general circulation patterns which would make Greenland-Europe transport most likely are as follows: positive (or neutral) NAO/SNAO, low GBI, and negative EA. During positive NAO/SNAO phases the jet stream, and thereby the westerlies, is shifted northward (Hall et al., 2015). Furthermore, the jet stream is also generally shifted north during summer (Hall et al., 2015) when melting on Greenland may cause pathogens to emerge. The positive phase of the NAO/SNAO also causes higher wind speeds over the Atlantic, which increases likelihood of long-range PM-transport (Cooper et al., 2010; Hall et al., 2015). This also increases the chance of pathogens remaining viable at the time of their deposition, as they spend less time being exposed to the stressors of the atmosphere. High GBI largely diverts the westerlies and shifts the polar jet stream south of Greenland (though jet stream positioning is variable) (Hanna et al., 2018). This blocks westerly flow and reduced the likelihood of Greenland-Europe transport. Though in terms of frozen pathogens being aerosolized the GBI may play a crucial role, as the high pressure causes melting of the Greenland ice sheet (Hanna et al., 2013, 2014). It is therefore the westerly winds passing over Greenland in between blocking episodes that have the highest potential of transporting pathogens to Europe. As for the EA, the negative phase can create wind patterns of flow from Greenland to Europe (Mellado-Cano et al., 2019; Woollings et al., 2010). This is due to the high pressure in the centre of the North Atlantic creating anti-cyclonic flow which causes clockwise airflow from Greenland to Iceland and the British Isles (see fig. 2 and 5). Additionally, the anti-cyclone causes sinking of air which can potentially contribute to dry deposition of aerosolized pathogens over Iceland and the British Isles. When the EA is in its positive phase it enhances westerly flow (Mikhailova & Yurovsky, 2016), therefore a positive EA may not counteract Greenland-Europe airflow, though the negative phase contributes to it. The EA is not as consistent a circulation pattern in summer as in winter (Woollings et al., 2010), which limits its relevance to transportation of currently frozen pathogens in Greenland, as the melting season is currently limited to the summer. Though this melting season may become longer in the future, the dynamics of atmospheric circulation over the Atlantic will likely also change with anthropogenic warming.

How the NAO will behave in the future is unclear. There is no broad consensus, except for its inherent unpredictability caused by its decadal variability (Eade et al., 2022; Hall et al., 2015). However, the GBI has recently been on a positive trend during summer and Hanna et al. (2015) speculate that this is due to climate change and is therefore likely to continue in the future. As mentioned above, higher GBI is correlated with a negative NAO, which decreases the chance of wind flow from Greenland to Europe. Preece et al. (2022) also found that Greenland blocking is increasing during summer. Though their findings also show that the majority of summer days 1979 – 2019 were unblocked. As high GBI causes melting of the ice sheet, there is potential for pathogens to emerge. So long as the blocking is not constant over the whole melt season they can be transported eastward. This intensified melting increases the likelihood of pathogen emergence of pathogens, when the blocking ceases transport to Europe is possible. It must be noted that part of the increase in GBI is due to geopotential heights increasing globally, and not only the intensification of the Greenland blocking phenomenon (Preece et al., 2022). One can with more certainty predict the increased risk of future peatland fires, as they are made possible by degradation of permafrost which is already occurring due to anthropogenic warming (Constable et al., 2022).

I believe this study makes a compelling case for the possibility of both bacterial and viral Greenland-to-Europe transport via air, though the limitations of this study are numerous. Most of the literature included in this study focuses on bacteria, while seemingly not as much attention has been paid to viruses in permafrost and glaciers or attached to aerosols. The risk of pathogens spreading from Greenland can be further clarified by additional studies of aerosolized viruses, particularly in Arctic environments. The potential for lateral gene transfer and its implications for Greenland's ecosystems also require further study as it may be key to future disease spread from Greenland's frozen landscapes. The concentration of pathogens emerging from glaciers and permafrost might not be significant enough to cause disease outbreaks, particularly after aerosolized transport to Europe. Sharoni et al. (2015) found that airborne viruses may remain highly concentrated after hundreds of kilometres of transport, though generally high wind speeds disperse aerosols over larger areas, lowering their concentration. However, if the unknown genes of these emerging pathogens can be proliferated in the local ecosystem the concentration of pathogens may become significant downwind. The process of wind dispersal can also be examined in more detail than presented in this study, taking into account anomalies like sudden stratospheric warming events as well as other circulation patterns like the Atlantic multidecadal oscillation (AMO) and the Scandinavian pattern (SCA). Furthermore, variation of the NAO, GBI, and EA is due to the influence of global teleconnections which are not so comprehensively understood that predictions of future changes can be made with any great amount of certainty. For example, Hanna et al. (2018) found that the GBI may be influenced by sea surface temperature anomalies in the Pacific. Uncertainty of teleconnections will likely be reduced as this field of research continues to develop, though I would stress the need for further interdisciplinary studies, especially considering aerosol transportation and deposition.

5. Conclusion

The first aim of this study was to identify the possibility of ancient pathogens stored in glaciers and permafrost in Greenland reaching Europe through aerosolization; a phenomenon which is, to my knowledge, unexplored. I hypothesised that such pathogen transport is possible. To summarise, I have presented evidence of the following statements.

- Potentially pathogenic bacteria and viruses have been found viable after millennia spent stored in glacial ice and permafrost.
- As the Arctic gets warmer these pathogens will emerge.
- It is possible for these pathogens to be aerosolized through wildland fires and remain viable.
- It is possible for these pathogens to be aerosolized from the sea and remain viable and infectious.
- Airborne pathogens can remain viable after intercontinental atmospheric transport.

- Deposition of PMs originating from Greenland have been found in Europe, which shows the possibility of pathogens attached to such PMs being deposited in Europe.

The evidence presented in this study confirms my hypothesis; pathogens can be transported from Greenland to Europe under current climate conditions. Though I also sought to investigate the future of atmospheric circulation over the Atlantic, there exists no consensus on how these wind patterns will change. Further research ought to expand on this study, particularly to reduce uncertainty about future circulation regimes. I encourage closer examination of glaciers and permafrost as possible source of pathogens, and the likelihood and implications of wind spreading them globally.

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