VILLUM
RESEARCH STATION, Station Nord

2020 AND 2021 ANNUAL REPORT

AARHUS UNIVERSITY

Grønlands Naturinstitut
Pinngortitaleriffik • Greenland Institute of Natural Resources

VILLUM RESEARCH STATION, STATION NORD

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Annual Report 2022

Data sheet

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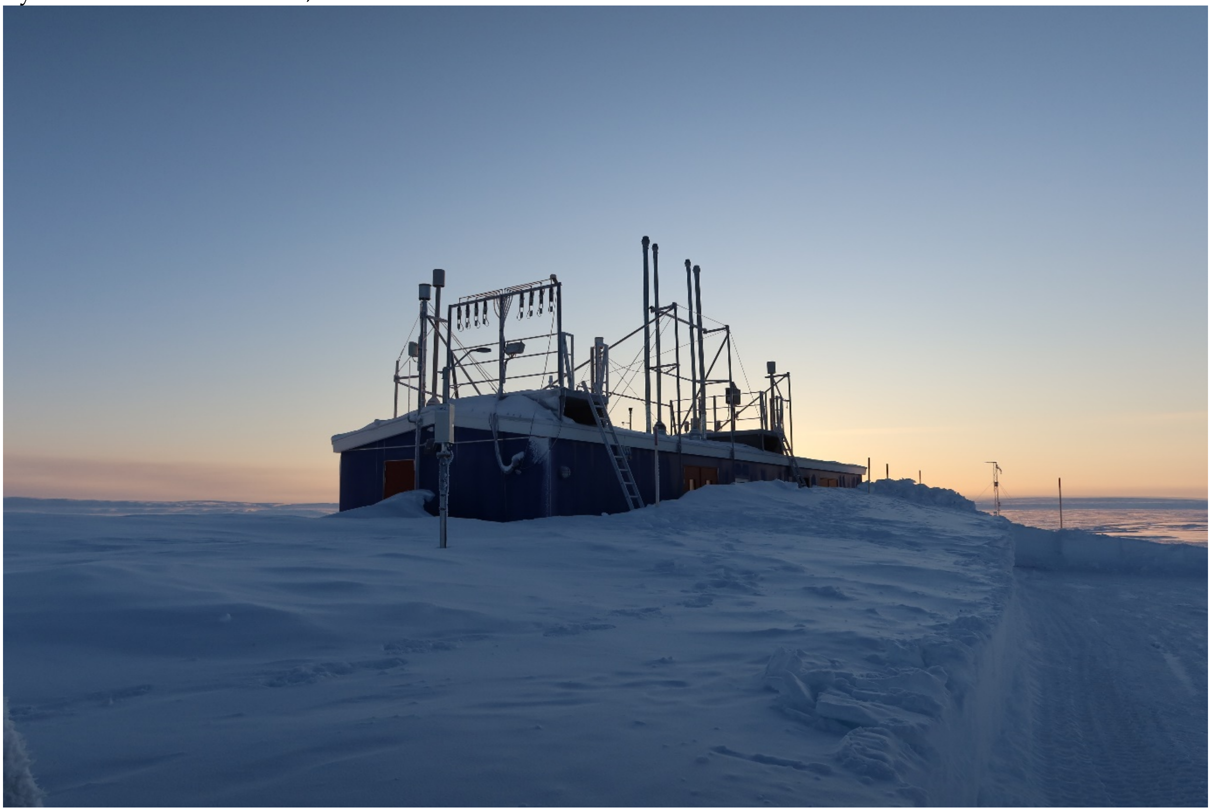
Content

Introduction

By Professor Henrik Skov, Scientific head of Villum Research Station



Dear Reader. Welcome to the sixth annual report of The Villum Research Station. Due to lockdown due to the covid19 epidemic, we have had limited activities in 2020 and 2021. Therefore, I decided to postpone the 2020 report and merge it with the 2021 report.
However, it is a pleasure for me to write the introduction to the Villum Research Station Annual Report again. Despite the challenges that we have got due to COVID19 lockdown, we have managed to keep the long-term continuous monitoring running and to service existing long-term activities of visiting research groups. The activities at the Station have resulted in 41 peer-reviewed articles in 2020 and 2021. Despite the lockdown, the number of publications per year is still increasing, and thus the impact of Villum Research Station on the scientific community and public is increasing fast.
The high Arctic is experiencing a still accelerating temperature increase that will cause large changes in the chemical and physical circulation of elements, as well as changing the biological food webs and systems. These changes might have strong feedbacks on climate. We now work at Villum Research Station under the hypothesis that human influence has led to irreversible changes, which will continue despite human climate abatement efforts. With other words that we have reached the point of no return. It is of uppermost importance to verify or reject this hypothesis and to establish the identity of the mechanisms and consequences of these changes and quantify them.
The Arctic is a sentinel for global change and, due to teleconnection, the temperature increase in the Arctic has global effects. Therefore, it is paramount to understand the Arctic changes in order to assess the needed adaptation of the world's society.
We work to intensify our research in this direction. In particular, we had planned intensive monitoring activities of atmospheric components in order to support the MOSAiC activities [1]. Due to the travel situation in 2019 at Villum, where we could not get landing permits flying from our usual starting point (Longyearbyen on Svalbard) and the challenges with Covid19 in 2020 we had to reduce our ambitions. We (2 researchers, 2 PhDs, 1 master student and 2 technicians) travelled to Villum in March 2020 with financial support from the Ministry of Climate, Energy and Utilities and from the Danish EPA by means from DANCEA to study short lived climate forcers and

the chemistry of mercury in the atmosphere. For this campaign, we departed as planned March 6th via Longyearbyen and arrived at Villum Research Station the day after. The temperature showed -39^{0} C, when we landed and during the next week, the temperature was constantly below -40^{0}C. At such low temperatures, outdoor activities are just getting very difficult and complicated. Things take much longer time to do. Handling instruments and equipment is challenging and secondly the low temperatures affect humans, causing fatigue and increase the risk for frostbites. Despite the difficulties, everything was up running within a week. During the week, we got more and more concerning messages from home due to the accelerating covid19 pandemic. Thus, it was decided that we all should be evacuated. Flights to and from Svalbard were closed and the only way out was flights along the east coast of Greenland. Fortunately, the Danish Defense helped us, as they had people they needed to evacuate themselves and we were offered to join their aircraft. The home travel was delayed a week as we were hit by a snow blizzard that closed the runway and made it very difficult to move around even within the area of Station Nord, where Villum Research Station is located. Thus, we ended the campaign without obtaining the result we had expected, but fortunately, the needed maintenance and replacement of monitors in our monitoring programs as well as of the long-term guest activities at the Station were accomplished and in the summer, we could return and carry out a part of the planned work. However, an important project was not accomplished. We had planned the first measurements of the vertical distribution of particle number concentration and black carbon concentrations on an UAV but the UAV stranded on Svalbard and eventually it was sent back to Denmark.

A series of external projects planned for 2020 were cancelled due to the Covid19 epidemic. All these projects were postponed to 2021 and thereafter cancelled. We have received many expressions of interests to carry out research at Villum and if Covid19 permits it, we will have more activities in 2022 and be on full activity level in 2023.

Despite the limitations, we have succeeded to have a long series of measurement results also relevant for the MOSAiC floating experiment MOSAiC Expedition (mosaic-expedition.org) and a series of joint papers are under preparation.

The scientific contribution to the resent report consists of eight articles showing the huge variation of topics studied at the station, ranging from research on polar bears over anthropogenic aerosol to phototrophic bacteria. Despite the difficulties opposed the station from outside events, it is a pleasure for me to see that Villum Research Station more and more fulfils its goal to host high scientific level multidisciplinary research.

1 Polar bear population studies in NE Greenland

Kristin Laidre, University of Washington and Greenland Institute of Natural Resources and Ian Stirling, Department of Biological Sciences, University of Alberta, and Wildlife Research Division, Environment and Climate Change Canada.

Polar bears (*Ursus maritimus*) in East Greenland are thought to constitute a single subpopulation with limited exchange with other sub-populations, including the adjacent archipelago of Svalbard. Consequently, the full responsibility for conservation and management of this subpopulation rests with the Government of Greenland. Furthermore, the IUCN Polar Bear Specialist Group lists the East Greenland population as "Data Deficient". That means the longer-term trend of the population, survival rates, and reproduction are unknown. Consequently there is insufficient scientific information available upon which to recommend sustainable harvest levels for the subsistence hunters or how the population might be affected by other human activities. However, assessing the size of the East Greenland polar bear subpopulation is a large and expensive undertaking. Conducting the research needed requires planning and studies to be conducted over a period of many years. To date, scientists from the Greenland Institute of Natural Resources (Grønlands Naturinstitut) have been capturing polar bears, attaching satellite radio collars to some, and collecting biological samples along the east coast since 2015. The information from these research studies will be used, together with Traditional Ecological Knowledge surveys (Laidre et al. 2018), to design a large-scale aerial survey, to provide the information needed for the Greenland government on sustainable levels of harvesting by subsistence hunters in East Greenland.

In April and May 2019, polar bear research conducted by the Greenland Institute of Natural Resources focused on NE Greenland, using the Villum Research Station as a base, with logistical support from Air Greenland and the Danish military at Station Nord. The field operation was supported by fuel depots placed along the coast. Searches by helicopter focused on Northeastern and Northern Greenland (between 77° and 83°N) (Figure 1). During the field studies, a total of 18 polar bears were captured and seven satellite radio collars were deployed on adult females.

During these searches conducted out of Danmarkshavn in April 2018, an interesting new aspect of polar bear ecology in the region was discovered. Some adult female polar bears are digging their maternity dens in snow drifts around icebergs grounded on the sea floor and/or frozen in the annual and multi-year fast ice (Figure 2, see also Laidre and Stirling 2020). This behavior had never before been reported in the scientific literature. In total, five polar bear maternity dens were confirmed, and a probable sixth one noted, approximately 1 to 10 km offshore dug into snowdrifts around the stranded icebergs. This type of potential maternity denning habitat is limited in distribution and is only possible in heavily glaciated regions of the Arctic where calving of marine-terminating glaciers calves icebergs large enough to drift away, become grounded offshore, and remain in place for months or years.

Northeast Greenland has long been known to be an important maternity denning region for the East Greenland polar bear population (Born et al. 1997; Laidre et al. 2015), yet the possible importance of grounded icebergs for maternity denning habitat had not been previously reported. In contrast throughout the rest of the Arctic, polar bear maternity dens have primarily been reported in snowdrifts on terrestrial sites. The continued decline of sea ice throughout the Arctic as a consequence of continued climate warming may eventually have a negative influence on the stability of grounded icebergs if break-up expands into new areas or occurs earlier. This will be an important subject to monitor in future years.

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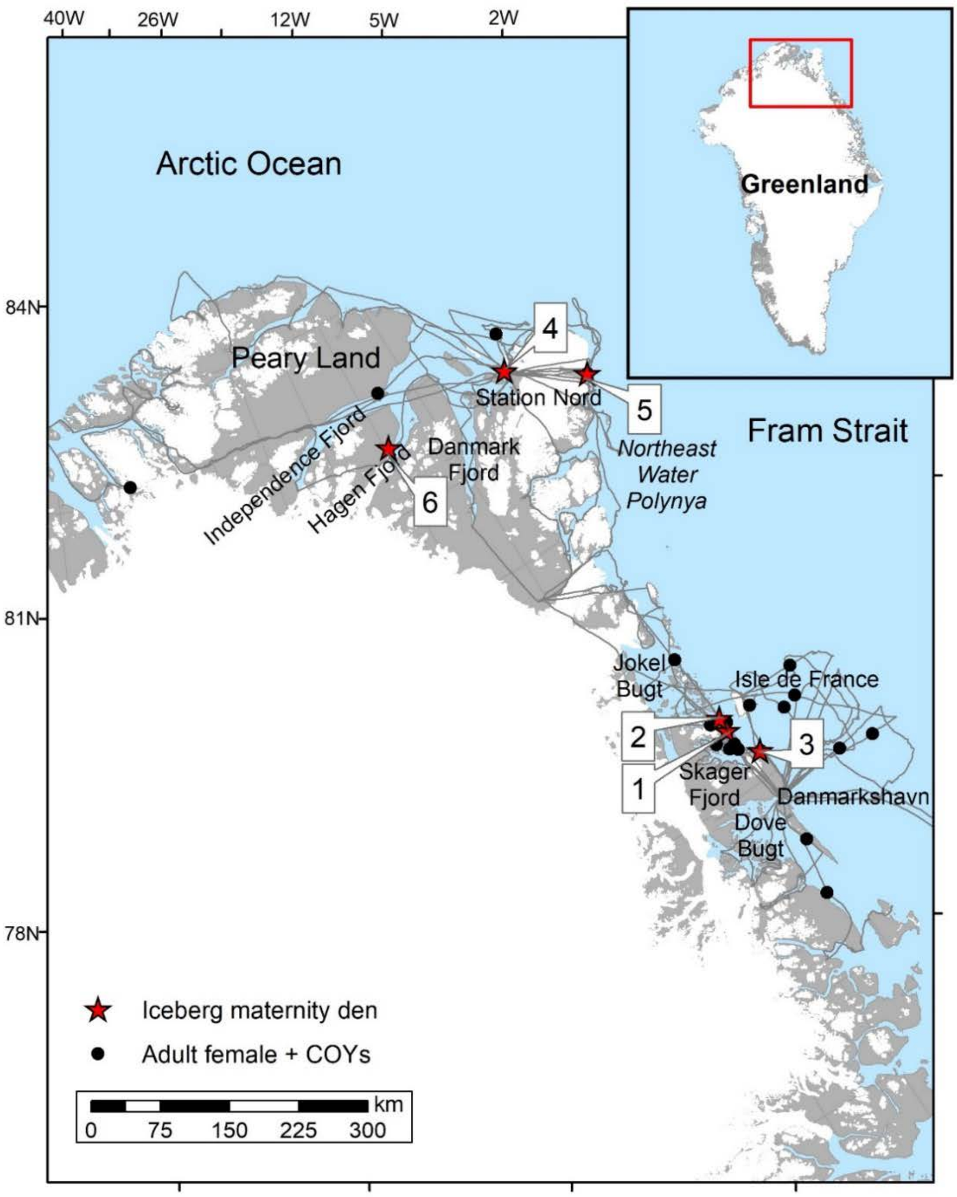

Figure 1.1. Map of polar bear maternity dens found in or around grounded icebergs in offshore North and Northeast Greenland based on searches in April and May 2018 and 2019 (work was conducted in 2019 from the Villum Research Station). Observations or physical captures of family groups (adult females with n=1 or 2 cubs of the year [COYs]) are also shown (black dots) with helicopter search tracks (gray lines) flown.

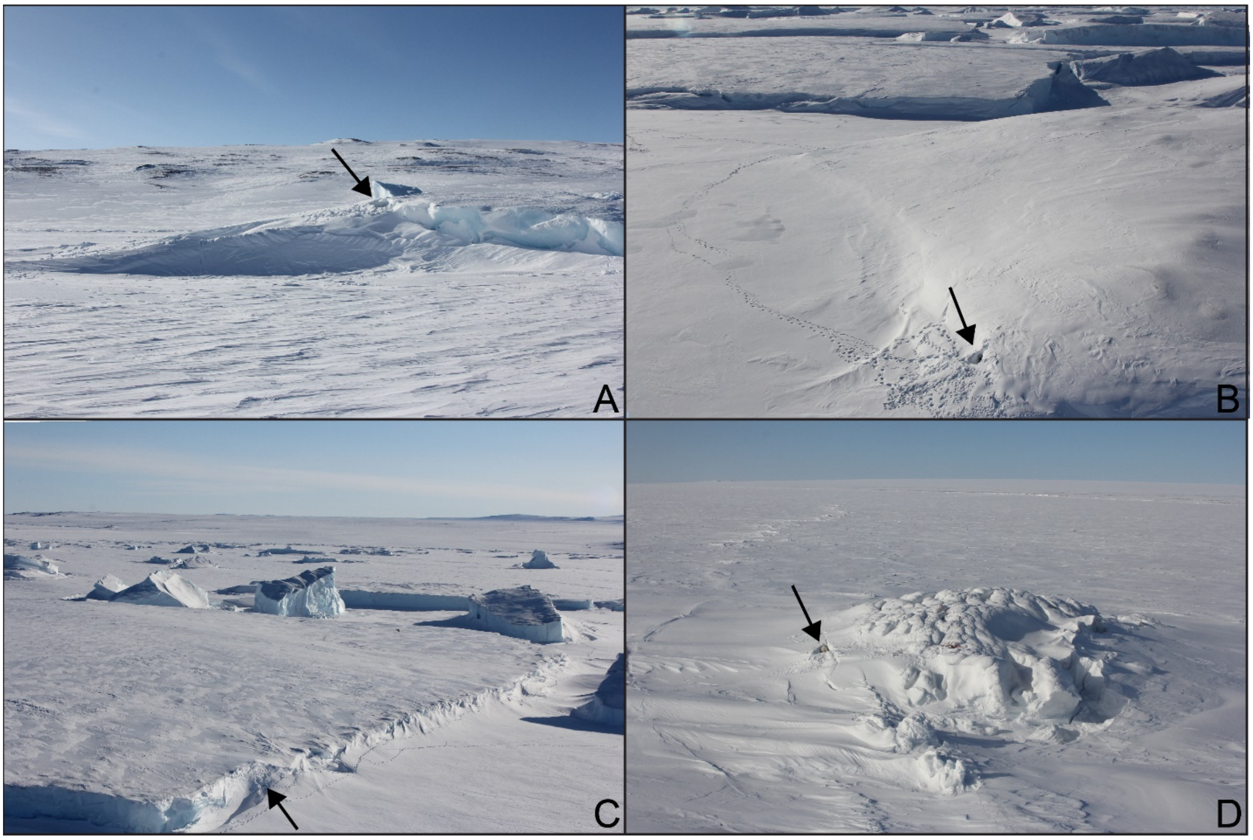

Figure 1.2. Images of maternity dens build in icebergs grounded in the fast ice. Arrows show the lo-cation of the den opening on or at the base of the iceberg. In Figure 2D the adult female is visible at the den opening.

2 Effect of ikaite precipitation on phosphate removal in sea ice

By Yu-Bin Hu (Institute of Marine Science and Technology, Shandong University, China) and Feiyue Wang (Centre for Earth Observation Science, University of Manitoba, Canada).

Ikaite ($CaCO_3 \cdot 6H_2O$), a metastable form of calcium carbonate mineral, was predicted to occur in sea ice some 60 years ago (Assur 1958), yet was not directly confirmed until 2008 (Dieckmann et al. 2008). Since then, ikaite has been ubiquitously identified in both Antarctic and Arctic sea ice, and its role in CO_2 exchange between the atmosphere and ocean has caught much interest (Rysgaard et al. 2013). A laboratory study also revealed that phosphate could be strongly co-precipitated with ikaite; depending on experimental conditions, about 42–97% of the phosphate could be removed from solutions because of ikaite precipitation (Hu et al. 2015). If these laboratory-based results hold true under natural sea-ice conditions, phosphate could be preserved in ikaite during wintertime, and released again when ikaite dissolves in spring at the same time as the ice melts, which could boost biological activity in the underlying seawater.

To test the hypothesis of phosphate removal by ikaite precipitation in natural sea ice, we went to the Villum Research Station (VRS) in April 2015 during its inaugural year. When we set foot on the frozen Wandel Sea, we were amazed by how thick the snowpack was: at least 1 m of snow everywhere. This is quite unusual with Arctic sea ice where the overlying snow depth rarely exceeds 50 cm. As snow acts as a good insulation layer, even though the air temperature was as low as –20 ^{o}C, the underlying sea ice was quite warm, always above –5 ^{o}C. The salinity of the bulk ice was also very low, averaging around 1–2. Those conditions meant that the ikaite concentration in the sea ice was fairly low, as ikaite formation is favored at low temperatures and high salinities. Nevertheless, after the hard work of shoveling off the thick snow, we were able to collect enough surface ice, which is expected to have the highest concentration of ikaite.

Indeed, we found ikaite in the surface ice samples, but as suspected the concentration was not very high (~13.8 $\mu mol \cdot kg^{-1}$). Contrary to our hypothesis, we did not see a change in the phosphate concentration before and after ikaite dissolution, which meant the formation of ikaite did not remove phosphate from the brine (Hu and Wang 2020).

So why is the result of the field work different from that of the laboratory study?

First of all, the ikaite concentrations used in the laboratory study were more than two order of magnitude larger than those detected in sea ice from the Wandel Sea. Is this the reason why no phosphate removal was observed in natural sea ice? As revealed by the laboratory study, phosphate removal due to ikaite precipitation mainly occurs at the ikaite nucleation stage; further growth of ikaite crystals does not have a significant impact on phosphate removal, suggesting that phosphate removal is not related to the amount of ikaite precipitated. The laboratory study further indicates that a larger amount of phosphate is co-precipitated with ikaite at a higher solution saturation level with respect to ikaite. Therefore, the fact that no or negligible phosphate was removed by ikaite precipitation in the natural sea ice seems to suggest that ikaite might have precipitated at a rather low solution saturation level.

It is a bit frustrating that the result from the field study does not support our hypothesis, but that is often how science works. We never know what the truth is until we explore it deeply. So, for that, we owe our thanks to the VRS!

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Figure 2.1. Ice coring in a snowing day (photo: Yu-Bin Hu).

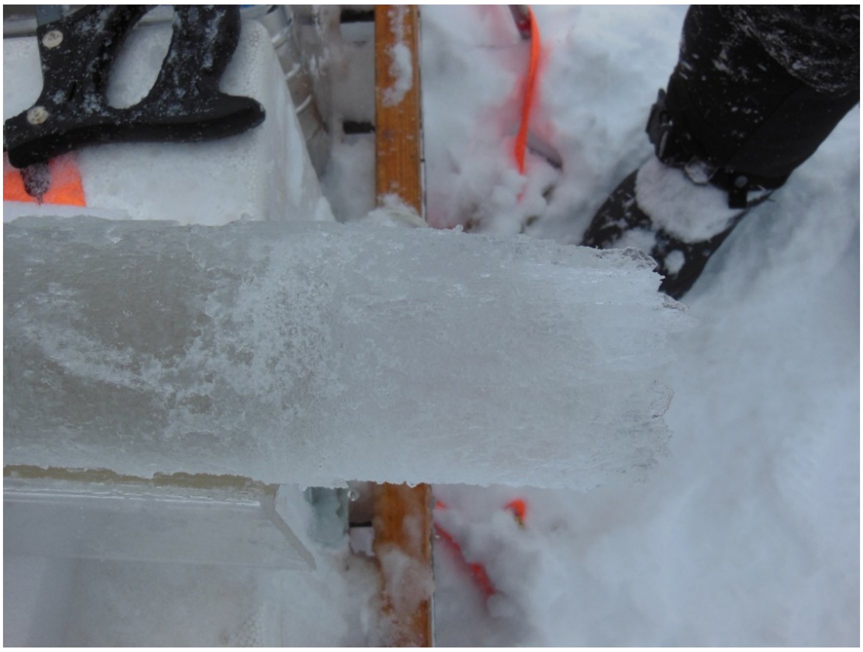

Figure 2.2. Ice core (photo: Yu-Bin Hu).

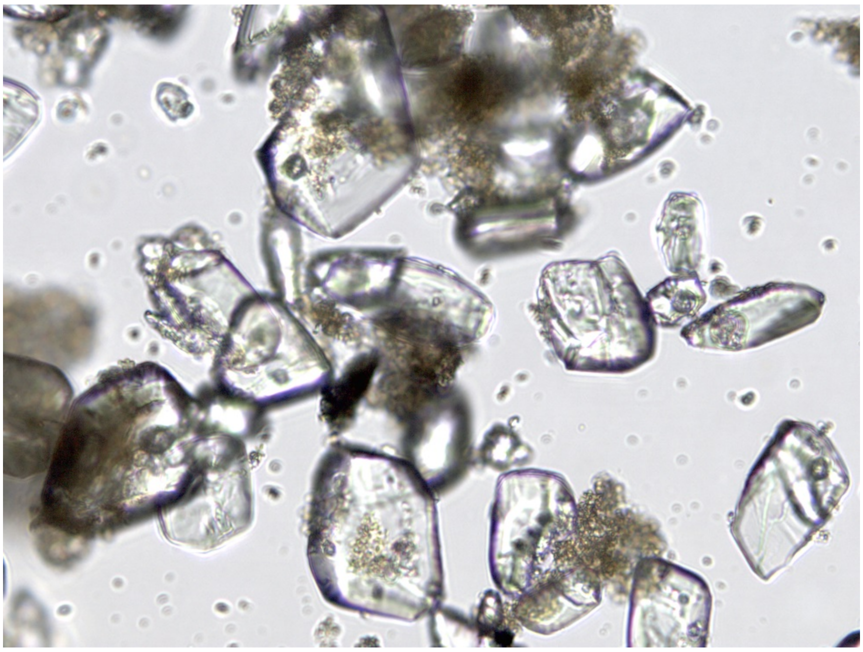
Figure 2.3. Ikaite crystals under the microscope (photo: Yu-Bin Hu)


Figure 2.4. BBQ party at the VRS (photo: Feiyue Wang)

3 Clouds and the depth of the aerosol layer

By Sven-Erik Gryning[1], Ekaterina Batchvarova[1,2], Rogier Floors[1], Christoph Münkel[3], Henrik Skov[4] & Lise-Lotte Sørensen[4]

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The Arctic amplification of climate warming is attributed to several factors where clouds are known to be a major contributor. However, the features and persistence of clouds are not well captured in numerical models, which contributes to the large spread among climate models. It is also evident that information on the depth of the aerosol layer near the ground and the cases where a depth cannot be estimated might be helpful for understanding the chemical observations and origin of the greenhouse gases at the Villum Research Station in northern Greenland.

Furthermore, the Arctic cloud seasonality is complex with different processes and atmospheric conditions operating in different temporal scales. This has spurred interest in measurements based on remote sensing instruments of the aerosol profiles near the ground and cloud measurements in the Arctic but such measurements are very difficult due to the harsh conditions for the instruments.

We operated a remote sensing instrument, a so-called ceilometer, since 2011 at Villum Research Station. A ceilometer is an active fully automatic continuous operational remote sensing instrument. The instrument transmits very short (110 ns) pulses of light, vertically or near vertically, corresponding to an effective pulse length of about 16 m. The light beam is backscattered as it impacts on aerosols and clouds. It was mounted on the roof of a monitoring hut (Flygers Hut, see Figure 1). Contrary to the aerosols in the clear air, backscatter from clouds is very strong and easily detected. Figure 2 shows a backscatter signal where cloud layers are seen at both around 3 km as well as 5 km. A contemporary photo of the sky nicely illustrates the actual conditions with a broken cloud cover is seen in Figure 3. Because the ceilometer is transmitting a very narrow pulse, it detects either cloud or no cloud conditions as the clouds are advected over the ceilometer beam. These cloud/no cloud observations are used to derive the fraction of the cloud cover.

Annual and seasonal cloud cover variation is derived. The cloud cover is larger during the autumn and winter as compared to summer and spring. The cloud cover exhibits a substantial variation from year to year without a clear trend. This is opposite to the expected and modelled changes due to global warming over the Arctic Ocean. The cloud cover during the autumn of 2016 is lowest compared to the other years and it has not yet been possible to come up with an explanation of this phenomena. It seems, at least, not to be connected to changes in the El Nino or the North Atlantic Oscillation.

As shown in Figure 4, the hourly cloud cover turned out to follow a U-shaped rather than a Gaussian-like distribution. When working with cloud climatology it should be emphasized, that a universally accepted definition of a cloud is still lacking. Cloud statistics are often studied using observations of cloud amount and type made by human observers, or by the ability of a sensor to detect some minimum concentration of a given particle size, or a signature in the cloud. Therefore, the understanding of what a cloud is, depends entirely on the objectives of the study and the instrument for observations that are used to estimate the clouds. Any cloud is therefore specific to the instruments and methodology that are used to observe it. A comparison of cloud cover observed by different types of remote sensing instruments and output from meteorological models with the cloud amount that is estimated by human observers following the WMO (World Meteorological Organization) standard could be very helpful.

We also looked at the aerosol backscatter under conditions of a clear sky or below the clouds where the backscatter is much less and the analysis is therefore more demanding. Despite the enormous changes in the meteorology due to the long dark winter and summer with the sun up all time, typically an aerosol layer of a depth of 250 m was observed during both summer and winter but in such a way that the variation in depth was larger during the winter. It should be noted however, that for about 25% of the backscatter profiles there was no well defined depth of the aerosol layer either because the backscatter profiles were irregular or, as quite often was the case, the aerosol concentration (attenuated backscatter) was increasing with height. This nicely illustrated the complexity of the meteorology in the Arctic being a mix of processes operating on different spatial and temporal scales.

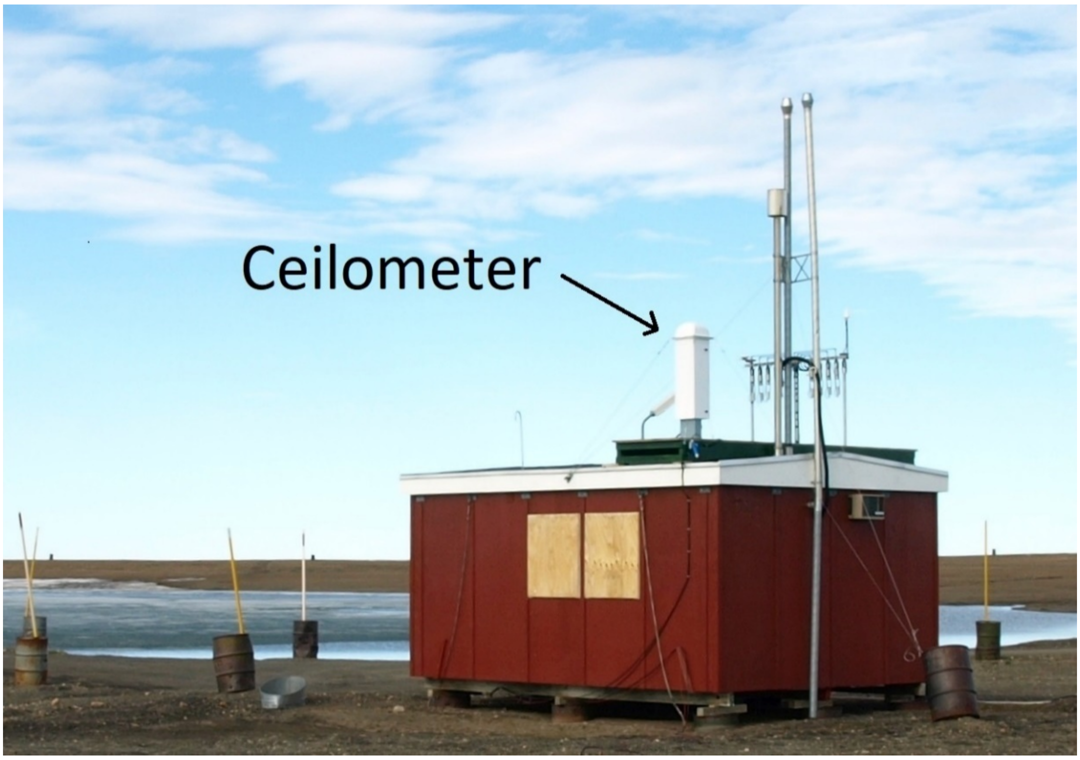

Figure 3.1. Flygers Hut with the ceilometer mounted on the roof.

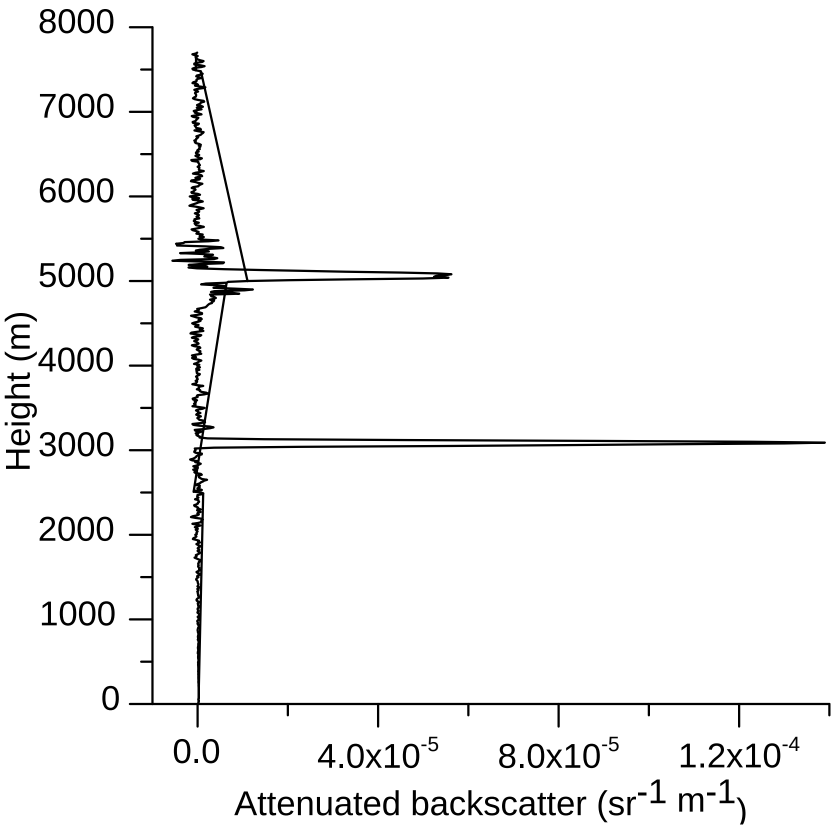

Figure 3.1. Profile of attenuated backscatter measured at the same time as the photo of the broken clouds (Figure 3). Clouds are seen at 3 and 5 km height.

Figure 3.2. Photo of the sky with broken clouds taken concurrent with the attenuated backscatter profile.

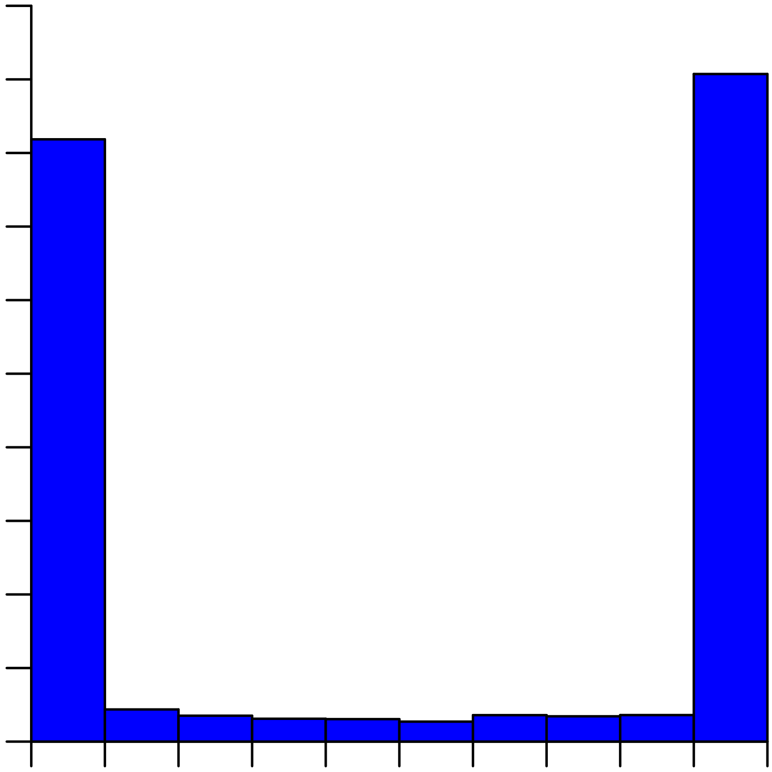

Figure 3.4. Distribution of the cloud cover at the Villum Research Station. It can been see that the predominant conditions correspond to fully overcast or clear sky.

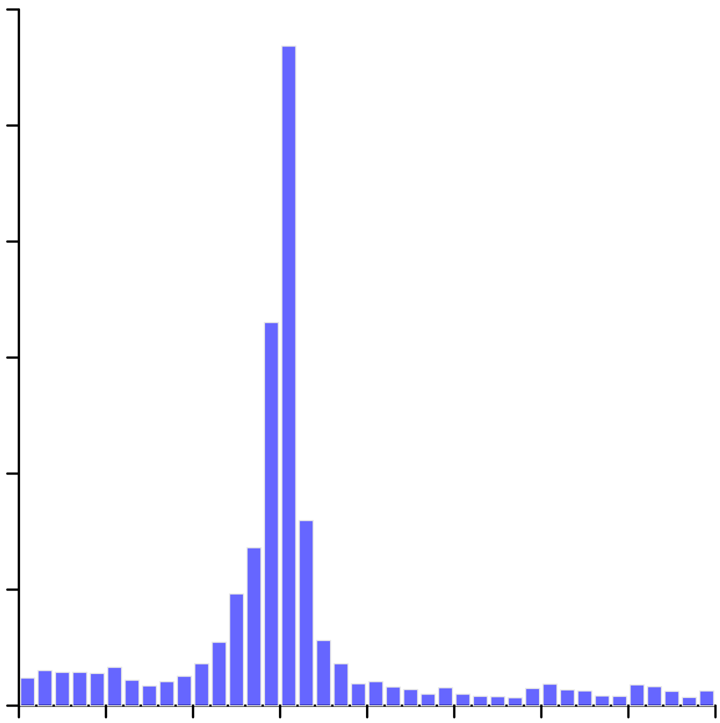

Figure 3.5. Histogram of the depth of the aerosol layer representing a full year of observations. It can be seen that the most common depth of the aerosol layer is around 250 m.

4 Changes in anthropogenic aerosols and their implications for the Arctic environment

By Jakob Boyd Pernov, Daniel Charles Thomas, Jacob Klenø Nøjgaard, and Andreas Massling, Department of Environmental Science, Aarhus University

Introduction

The Arctic has undergone significant changes in the past few decades, characterized by rising temperatures, reduced sea ice, and changing atmospheric composition of gases and aerosols. In fact, the temperature in the Arctic is rising faster than anywhere else on Earth, in a phenomenon known as Arctic amplification. Aerosols are one of the most important constituents in the Arctic atmosphere and affect the radiative balance in two ways: directly, through the scattering and absorption of incoming light, and indirectly, through the modification of cloud properties. When aerosols scatter sunlight in the atmosphere, less of the light reaches the Earth's surface, resulting in cooling. Conversely, when aerosols absorb sunlight, they tend to re-emit the energy and cause atmospheric warming. The radiative forcing effects of aerosols depend on their particle size, composition and abundance, as well as the underlying surface properties and meteorological conditions, thus their contribution to climate forcing is associated with a large uncertainty—especially in the Arctic.

There are strong seasonal variations in Arctic aerosol concentration, size, and chemical composition. In winter and spring, we see increased levels of anthropogenic pollution arriving via long-range transport from the mid-latitudes. This is commonly referred to as Arctic Haze, and consists of sulfate and black carbon among other compounds (Heidam et al., 2004). It can be seen with the naked eye, shown in Fig. 1 as the haze layer above the horizon. In the summer and autumn, biogenic emissions consisting of sulfate, organics, and acids originate from more local or regional sources and become the predominant source of aerosols (Willis et al., 2018).

To further our understanding of the role of aerosols in Arctic climate change, we investigated long-term trends of environmental parameters such as sea ice extent and air temperature, as well as concentrations of sulfate and elemental carbon (EC).

Methods & Materials

All measurements were collected at Villum Research Station (Villum), located at Station Nord in Northeastern Greenland. Using a custom-built filter pack sampler (FPS, Figure 2), weekly filter pack samples were collected from 2007 onwards. Sulfate (SO42-) was measured by Ion Chromatography (IC) from 2007. EC was collected onto quartz fiber filters using a High-Volume Sampler (HVS) and measured via the Thermal/Optical Method, from 2009 onwards. Air temperature measurements from 2007 until 2014 were collected by the Danish Meteorological Institute (DMI) at Station Nord, and from 2014 they were recorded at the Air Observatory at Villum. Daily sea ice extent (2007–2019) and monthly sea ice concentration (March & September 1989 and 2019) were obtained from the National Snow and Ice Data Center (NSIDC, https://nsidc.org/data). Sea ice edges for March and September 1989 were obtained from DMI (http://ocean.dmi.dk). Trends were analyzed using the Mann-Kendall test and the associated Theil Sen's slope on yearly medians. Relative trends were calculated by dividing the absolute slope by the median for the entire period.

Results

Significant decreases in sea ice extent have occurred year-round from 1989 to 2019, as seen in Fig. 3, for the yearly maximum (March) and minimum (September). The black line indicates sea ice edge in 1989 for reference. From Fig. 3, it is evident that sea ice shrinkage is greatest during September. Since 2007, sea ice extent in the Arctic has been significantly decreasing at a rate of -0.5 % yr-1 (absolute rate of -0.056 106 km2 yr-1, Fig. 4). Interestingly, there are several locations where sea ice concentration has increased. One such location is located directly south of Villum, making this site an ideal location to study the complexity of climate change in the Arctic.

Aerosols are predicted to play an important role in the changing Arctic climate and associated sea ice loss. For example, sulfate aerosols are highly scattering and therefore lead to cooling, whereas EC is highly absorbing, leading to atmospheric warming. Aerosols can also play a role in feedback mechanisms. An example is that when EC is deposited onto snow or ice, the surface albedo is reduced, resulting in greater absorption of light by the surface. This will cause snow and ice loss, and the exposed land or open water underneath will be much darker, further decreasing its albedo and warming the surface.

Air temperatures were found to have increased at a rate of 1 % yr-1 (absolute rate of 0.27 °C yr-1, Fig. 4) at Villum since 2007. While concentrations of sulfate and EC have both been significantly decreasing at a rate of -7.8 % yr-1 since 2007, the absolute decrease in sulfate is an order of magnitude higher than EC (Fig. 4), -17 vs -1.4 ng m-3 yr-1, respectively. Modeling studies indicate that this decrease in highly scattering aerosols from anthropogenic sources is a major contributor to the observed temperature increase in recent years, outweighing reductions in EC over the same period (Breider et al., 2017). Thus, future reductions in sulfate will likely lead to rising air temperatures and sea ice loss.

Outlook

These changes also have implications for more local emissions of natural/biogenic aerosols in the Arctic. The opening of the Arctic waters has increased sea spray emissions and microbial activity—a significant source of biogenic aerosol precursors. Freshly formed aerosols can, after aging processes, be involved in cloud formation and impact cloud properties, which thus influences the Arctic climate. Additionally, although local anthropogenic emissions in the Arctic (i.e., ship traffic, transportation, and resource extraction) are presently minor, they are becoming more important, especially in the context of future sea ice loss (Law et al., 2017). These processes need further investigation and require an extended measurement program focusing on biogenic aerosol precursors and aerosol microphysical properties, in addition to the traditional chemical characterization that previously has focused predominantly on anthropogenic pollutants. How these changing local anthropogenic emissions and natural biogenic emissions will affect the Arctic climate remains an open question.

Figure 4.1. Photograph displaying the Arctic Haze phenomenon as seen by the layer of haze above the horizon. The photograph was taken outside of Flyger's Hut in March 2020. Photo: Jakob Boyd Pernov.

Figure 4.2. Sampling inlet for the filter pack sampler on the roof of the Air Observatory. Photo: Jakob Boyd Pernov.

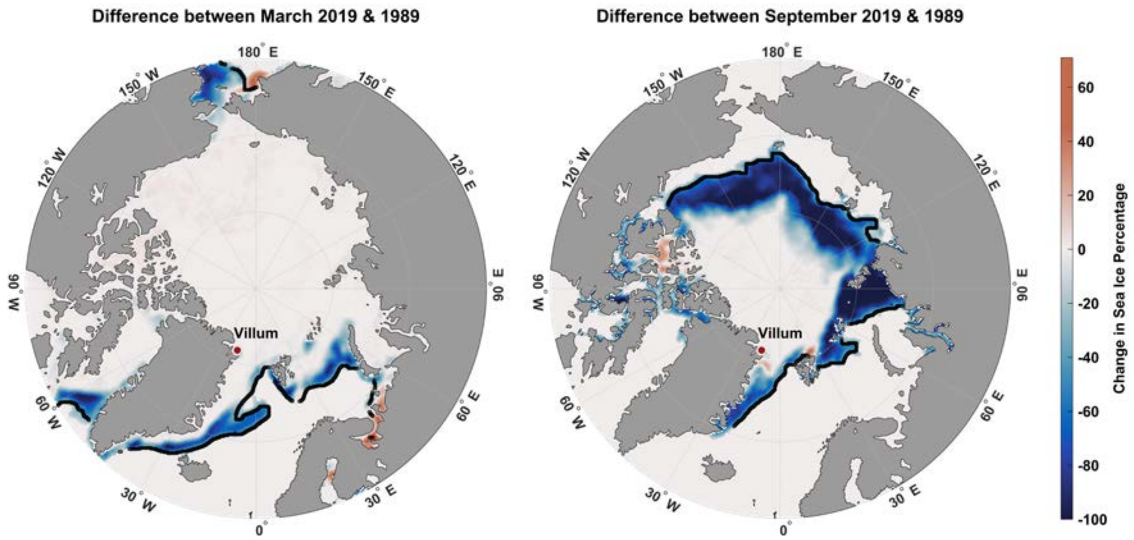

Figure 4.3. Differences between sea ice surface area concentration for (left) March and (right) September 2019 and 1989. The sea ice edge for the respective month during 1989 is shown in black. Maximum (minimum) sea ice area extent and concentration occur in March (September).

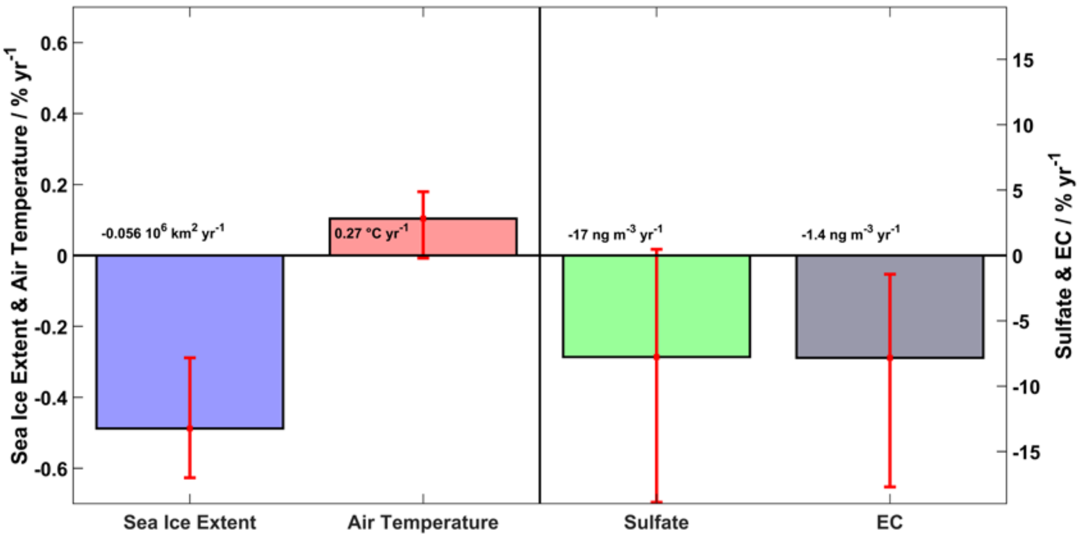

Figure 4.4. Relative trends in sea ice extent, air temperature, sulfate, and EC. Relative slopes are represented by the colored bars and 95 % confidence intervals of the slopes are given by the red error bars. The absolute trend in each parameter is also listed. Note the different y-axes used. Trends in sea ice extent, temperature, and EC are statistically significant on the 90th % confidence level (CL), while sulfate is only statistically significant on the 85th % CL.

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5 Greenland: a cool wonderland for phototrophic bacteria

By Yonghui Zeng. Department of Plant and Environmental Sciences. University of Copenhagen

The glaciers and soils in Greenland have been known teeming with microbes, both above- and under-ground, that have direct impact on global changes, e.g., accelerating surface glacial melt or releasing greenhouse gases from permafrost. How these microbes have evolutionarily adapted to the cold, nutrient-poor terrestrial environments in Greenland (Figure 1) has long fascinated me. Over the past years, my research focus has been placed on phototrophic bacteria that can harvest sunlight as an energy source. These tiny colourful microbes are present everywhere on the Earth's surface for more than three billion years, representing fantastic models for studying the co-evolution of microbes and the Earth's surface environments. Greenland can be a cool wonderland for phototrophic bacteria given that the light-harvesting capability can be particularly useful for surviving the harsh environments in Greenland. The questions I ask are whether the unique environmental conditions in Greenland have fostered unique phototrophic bacterial species and how their genomes have been evolving with respect to their photosynthesis function. I hope my recent research results can attract more interest into this topic.

Thanks to the support from two Villum Experiment grants (2017-2021), I was able to visit the Villum Research Station (VRS) in the summer of 2018 to carry out the fieldwork and use the excellent facilities at VRS for my microbiology research. Together with Jørgen Skafte, we digged a 2-m deep snow pit at the "Lille Firn" glacier (81.566° N, 16.363° W) in the Knuths Fjeld area, 5.6 km away from VRS (Figure 2). From the pit, we sampled about 100 kg of the surface ice that formed during the previous season. The melt water was used for bacterial isolation in the VRS lab (Figure 3) and for later community DNA extraction and direct DNA sequencing back in Denmark.

In addition to hundreds of phototrophic bacterial isolates obtained, an enormous amount of sequencing data was generated from this work. From these datasets, one particularly exciting finding was that some glacial bacteria appear to be capable of performing two types of phototrophy simultaneously, opening a new research avenue into how bacteria maximize their energy gain from solar radiation (ref. 1). There are only two general biological systems that have evolved in bacteria for net energy conservation via light harvesting: one is based on the pigment of (bacterio-)chlorophyll and the other is based on proton-pumping rhodopsin proteins. There is emerging genomic evidence that these two rather different systems can co-exist in a single bacterium to take advantage of their contrasting characteristics in the number of genes involved, biosynthesis cost, ease of expression control, and efficiency of energy production and thus to enhance the capability of exploiting solar energy. I isolated four bacterial strains from the "Lille Firn" glacier ice, the genomes of which were sequenced and closed. Their genomes provide the first clear-cut evidence that such "dual phototrophy", a new term I proposed, potentially exists in glacial bacteria. Further public genome mining and another published work done at my collaborator's group in Czech Republic (ref. 2) suggest that this understudied dual phototrophic mechanism is possibly more common than our data alone suggested. I hope these findings can provide a strong case supporting that glacier can be an invaluable system for study bacterial genome evolution.

The other reason why I hold a strong belief that Greenland is a wonderland for phototrophic bacteria is the finding of a member of the highly sought group of phototrophic bacteria called Gemmatimonadetes, which is a bacterial phylum with very few phototrophic representatives so far. Gemmatimonadetes is an important but yet understudied group in natural microbial communities. The isolation of the only phototrophic member of this phylum, Gemmatimonas phototrophica, was reported in 2014 (ref. 3), which expanded the list of known bacterial phyla capable of performing (bacterio-)chlorophyll-based photosynthesis. Since then, no new phototrophic member of this phylum has been isolated. By applying a novel isolation strategy that combines mass spectroscopy-based high-throughput profiling and rapid screening for phototrophic bacterial colonies, I successfully isolated the second phototrophic member of this phylum - Gemmatimonas groenlandica (ref. 4) - from a stream in northeast Greenland, close to the Zackenberg Research Station. It is my honor to name this species after Groenland (Greenland in Danish). Its discovery confirms the widespread presence of phototrophic Gemmatimonadetes bacteria in natural environments and raises an intriguing question on the evolutionary history of phototrophy in this phylum. I strongly believe there are many more unknown, evolutionarily exciting phototrophic microorganisms in Greenland awaiting discovery.

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Figure 5.1. The landscape of coastal northeast Greenland photographed from the transport aircraft flying from Longyearbyen, Svalbard to the Villum Research Station. Photo by Yonghui Zeng on 30 June, 2018.

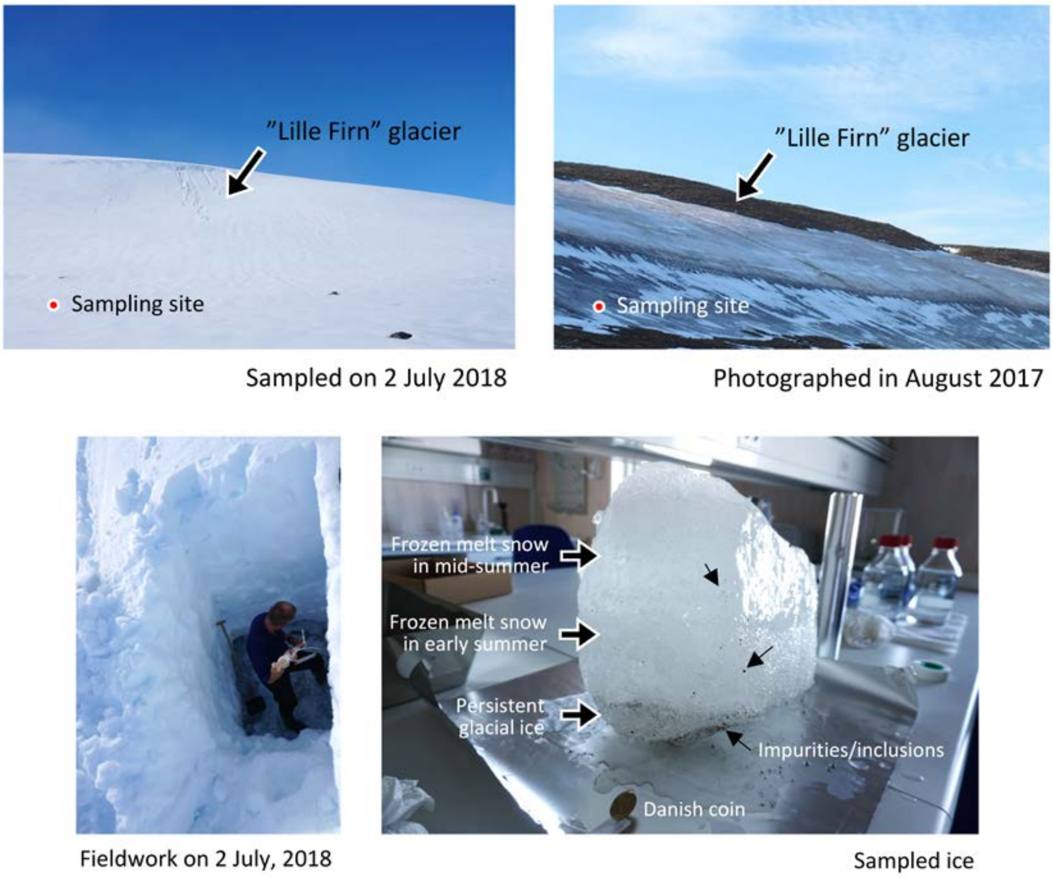

Figure 5.2. Sampling of the surface ice at the "Lille Firn" glacier for microbiology studies. See more details in the ref. 1.

Figure 5.3. Author's selfie working at the VRS lab in the summer of 2018.

6 Crossing the Greenland icecap on a tailwind

By Morten Frederiksen. Department of Ecoscience, Aarhus University

In the summer of 2018, we tagged 18 ivory gulls with GPS transmitters near Station Nord (see 2018 Annual Report). The main aim of this study was to improve our understanding of the foraging ecology of this high-Arctic specialist seabird, including mapping the most important foraging areas during the breeding season. However, when our radio download device was set up at the station in July 2019, we were lucky enough to obtain year-round tracking data from two individuals.

In rough terms, the annual cycle of the ivory gull is quite well known. Ivory gulls are tightly linked to ice edge habitats all year, and the main wintering area for the population breeding in Northeast Greenland is in the Davis Strait between Southwest Greenland and Canada (although some birds migrate to the Bering Sea). However, this is the first time that individuals have been followed throughout the annual cycle using high-precision techniques.

The two birds initially followed very similar routes: after leaving the colony in August, they first spent some weeks north of Svalbard and then moved south along the east coast of Greenland, around Cape Farewell and into the Davis Strait. Here they remained for several months, moving a bit north and south along the ice edge. One bird left the ice edge in mid-March, crossed to the Greenland coast and followed the same route south of Greenland back to the breeding area. The other bird did something very different. It remained in the wintering area until mid-May, and then followed the ice edge north into the Baffin Bay. On 30 May late in the evening, it left its final staging site at 71.5° N (north of Uummannaq) and crossed the Greenland icecap, arriving in a small polynya off the east coast after covering 1345 km in 29 hours.

In itself, such a crossing was impressive, but several other aspects were noteworthy. The bird made six shorter and longer stops on the way, with a total duration of six hours. The total flight time was thus 23 hours, and the mean ground speed more than 58 km/h. To achieve this, the bird made use of a tailwind of on average 11.5 km/h. Most of the way, the bird appeared to fly close to the surface of the icecap, but over the ice-free parts of West and East Greenland it increased its altitude substantially to more than 2000 m above the ground, or more than 4000 m above sea level in East Greenland.

This anecdotal observation raises several very interesting questions. Firstly, why did the second bird choose to cross the icecap rather than take the detour south of Greenland? Most seabirds rarely cross major terrestrial barriers during migration, preferring to remain over the sea. Perhaps the bird was aware that it had strayed so far north that the southern route would have been very much longer, and that the season had progressed so far that it was time to get back to the breeding site. The very direct track during the crossing – only 3% longer than the shortest possible track – indicates good navigation skills. Secondly, why did the bird fly so high over the ice-free parts of Greenland? This may have been to achieve more favourable wind conditions, and indeed the tailwind was stronger at flight altitude than at ground level in West Greenland – but not in East Greenland. It may also have been to avoid predation by falcons, or to be able to see far ahead and plan a route to the nearest open water. Thirdly, why did the bird stop along the way? There's no food on the icecap, but the bird may have eaten snow to rehydrate. Or perhaps it just needed a rest – unlike some other migratory birds, gulls are not known for very long non-stop flights. Clearly, there is still a lot to learn about bird migration – the more detailed data we obtain, the more specific question we can ask!

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DOI: 10.1111/ibi.12903

Figure 6.1. The solar-powered GPS device has just been mounted on the back of this ivory gull – just about to be released to collect data! Photo: Henrik Haaning Nielsen.

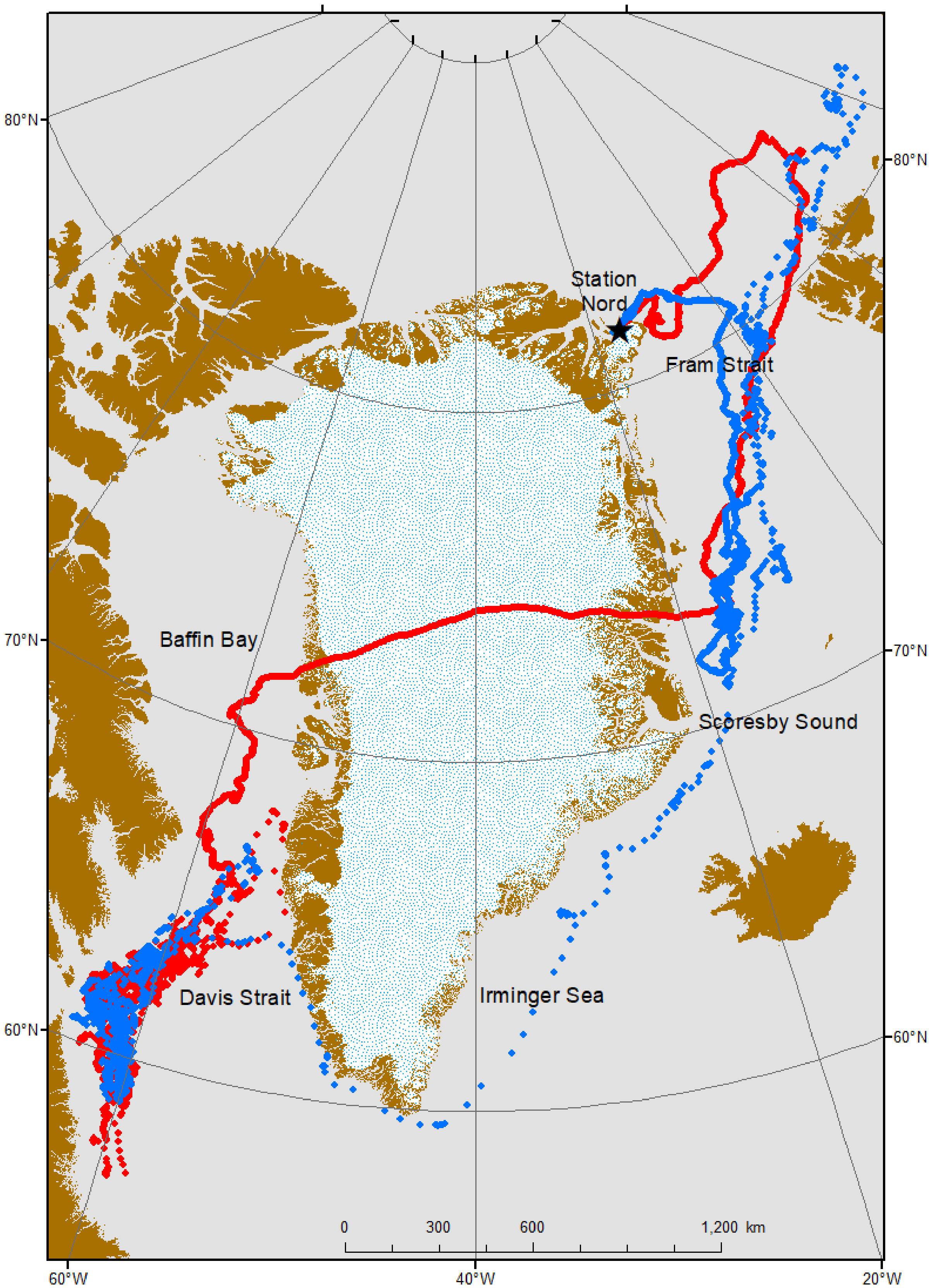

Figure 6.2. Tracks of the two ivory gulls from 1 January 2019 until arrival in the breeding colony near Station Nord. The autumn migration is not shown, but followed roughly the same route as the blue bird did in spring. Positions are at approximately 60-minute intervals during January-April, and 5-minute intervals during May-June.

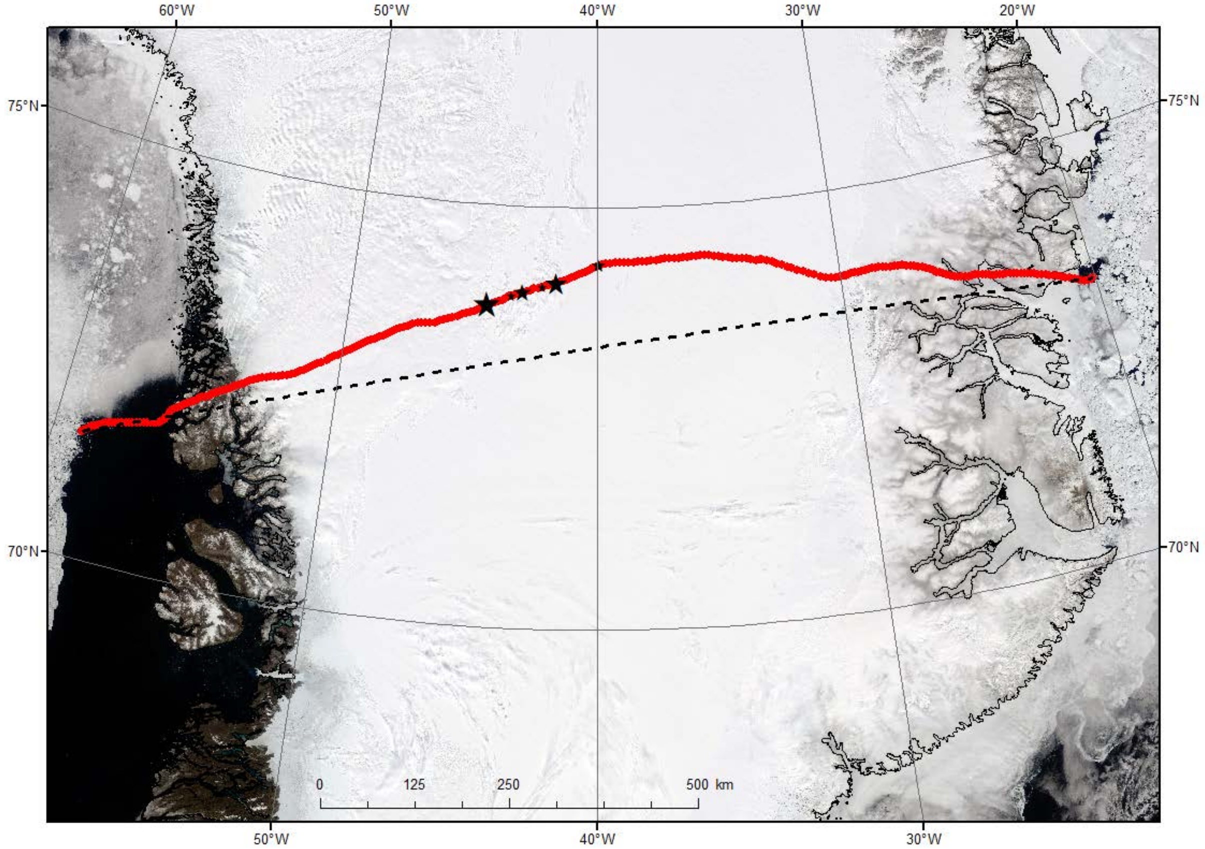

Figure 6.3. The track of the ivory gull which crossed the Greenland ice cap 31 May 2019, shown in red. The dashed line shows the shortest possible track between the staging sites in Baffin Bay and the Greenland Sea. The black asterisks mark the locations of the stops made by the bird during the crossing, with larger symbols indicating longer stops. The background is a composite satellite image from the same day.

7 Permafrost thermal dynamics and cryostratigraphy at Villum Research Station

By Hanne H. Christiansen[1], Sarah M. Strand[1,2] and Graham L. Gilbert[1,3]

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[2]Department of Geosciences, University of Oslo, Oslo, Norway.

[3]Natural Hazards Market Area, Norwegian Geotechnical Institute, Oslo, Norway

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Introduction

Permafrost is widespread in the periglacial terrestrial Arctic. The thermal state of permafrost and active layer thickness (ALT) are key indicators for monitoring permafrost as an essential climate variable, designated by the Global Climate Observing System. Evaluating permafrost change is important given present and predicted Arctic warming, and the central role of permafrost in Arctic terrestrial environments. The permafrost thermal regime is dependent on climate, substrate, specifically lithology and ground ice content, and surface conditions including snow cover, hydrology, and vegetation.

Field measurements are necessary to characterize the ground thermal regime, and detailed field studies are required to develop a process-based understanding of the ground thermal regime development and its dynamics. In the high Arctic, permafrost direct field measurements are sparse; in all of northern Greenland, only three sites are instrumented to monitor permafrost conditions: Zackenberg (74° N), Thule Airbase (76° N), and Station Nord (81° N) (Fig. 1). Given the absence of measurement sites, little is known about ground thermal regime and its variability in northern Greenland, which includes the northernmost land on Earth.

Two 20 m deep boreholes were drilled in August 2014 in collaboration with the University Centre in Svalbard, UNIS, establishing Villum Research Station (VRS) permafrost monitoring. The permafrost borehole temperature measurements are a permanent component of VRS's climate monitoring program. Through INTERACT funding a field visit was secured in 2017, and thanks to good collaboration with the VRS staff, further data downloading was performed during December 2021. This allows for analyses of a 7-year (2014-2021) dataseries of the ground thermal regime and the sedimentary stratigraphy of the two 20 m deep boreholes (SN1 and SN2) at VRS, providing the northernmost analysis of ground thermal regime in Greenland, and the second northernmost worldwide.

Results

The mean annual permafrost temperature at 20 m depth in the borehole SN1 increased from -8.1°C to -7.7°C over the 7-year period, while in the borehole SN2 it increased from -7.3°C to -7.0°C over the same period (Fig. 2 and 3). The two permafrost monitoring boreholes are located ca. 100 m west of the VRS atmospheric observatory. They are both drilled into raised beach ridges and are 70 m apart. SN1 is located on the flat top of a beach ridge at 36 m asl, while SN2 is located downslope in a shallow depression at 27 m asl. This topographical difference controls the difference in ground thermal state, as more snow accumulates over the SN2 site. Generally, more than one meter of snow accumulates at the VRS station site, which clearly increases the permafrost ground temperature given the northerly location.

The active layer thickness varied from 0.8 to 1 m at the SN1 site, and from 0.5m to 1.2m at the SN2 site over the 7-year observation time (Fig. 3). There was no trend in these changes, again most likely due to the large snow dynamics control on ALT.

When drilling the boreholes cores were collected were possible down through the two boreholes. Generally, the cores only had sediment pore-filling ice, called pore ice present, where ice is limited to the spaces between sediment grains. This ice type is formed by the freezing of pore water. The absence of visible ice was corroborated by the consistently low moisture content: 90% of the samples had a gravimetric moisture content less than 20%. Three stratigraphic units were identified from the collected cores and borehole material.

Conclusion

The interplay between snow dynamics, specifically snow timing and depth, and seasonal air temperatures is the most important element controlling ground thermal regime at this location. Air temperatures during autumn and mid-winter, the fastest warming seasons, clearly influence the ground thermal regime despite a snowpack that exceeds 1 m. This is possible due to the gradual increase in snow depth throughout the snow season and the density of the snowpack arising from the dominance of wind-redistributed snow. We anticipate continued permafrost warming on the Prinsesse Ingeborg Halvø, in line with the area's air temperature increase. Land surface change will be limited due to the absence of excess ice. Increased precipitation is predicted for northeast Greenland and the Arctic overall; the effect of this on snow depth and permafrost conditions on the Prinsesse Ingeborg Halvø will depend on sea ice extent and conditions for wind-redistributed snow, along with the seasonal precipitation distribution and the length of the snow cover period.

Read more

If you like to read more about the details of this study, please check out Journal of Geophysical Research, in which the following manus has been accepted for publication: Strand, S.M., Christiansen, H.H. & Gilbert, G.L. Permafrost thermal dynamics and cryostratigraphy at Villum Research Station, Station Nord, eastern North Greenland (81° N), Journal of Geophysical Research, Earth Surface.

Acknowledgements

The authors are grateful for the opportunity to collaborate with VRS on permafrost monitoring as part of their climate monitoring program. When VRS was established in 2014, the permafrost researchers at UNIS were asked to establish the permafrost monitoring sites as the closest neighboring institution with a permafrost drill rig that could be transported by air to Station Nord. Wesley Farnsworth, UNIS, Graham Gilbert UNIS, and Ullrich Neumann Kolibri Geo Services drilled the boreholes and collected the samples in August 2014.

Jørgen Skafte and Kirsten Christoffersen kindly assisted with downloading the borehole temperature data in summer 2019 and winter 2021. We would like to thank the Station Nord military personnel and the staff and researchers associated with VRS for helping with logistics and contributing to an excellent fieldwork and research environment. Prof. Henrik Skov has been particularly supportive of this project and ensured successful fieldwork in August 2017. This research received funding from INTERACT under the European Union H2020 Grant Agreement No.871120; this funding covered the summer 2017 fieldwork costs through INTERACT's transnational access program. The JGR paper will form part of the PhD thesis of S. Strand.

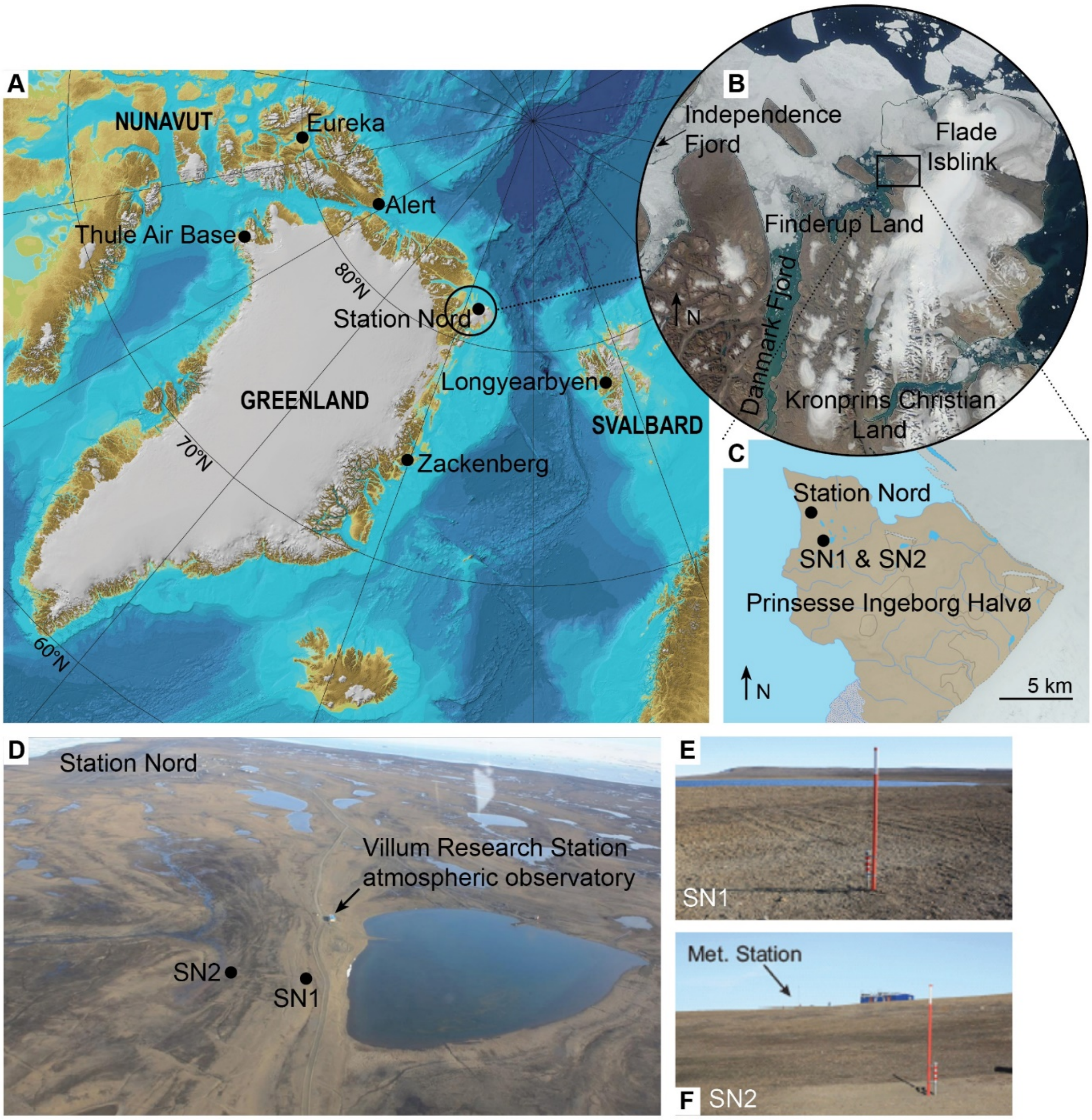

Figure 7.1. Overview map (base map by Jakobsson et al., 2012) with a black circle designating Kronprins Christian Land and parts of the Independence-Danmark Fjord system in eastern North Greenland. Other permafrost borehole locations this far north is also marked. B) Terra/MODIS corrected reflectance (true color) satellite image from 30 July 2019 showing Kronprins Christian Land and neighboring regions with typical late-summer sea ice conditions (image acquired through NASA Worldview, https://worldview.earthdata.nasa.gov/). The black box marks the Prinsesse Ingeborg Halvø. C) Geological Survey of Denmark and Greenland (GEUS) topographic map of the Prinsesse Ingeborg Halvø (map available at http://www.greenmin.gl/). D) Oblique aerial photo of the study area on northern tip of the Prinsesse Ingeborg Halvø in August 2014, looking north. E) Borehole one, SN1. F) Borehole two, SN2.

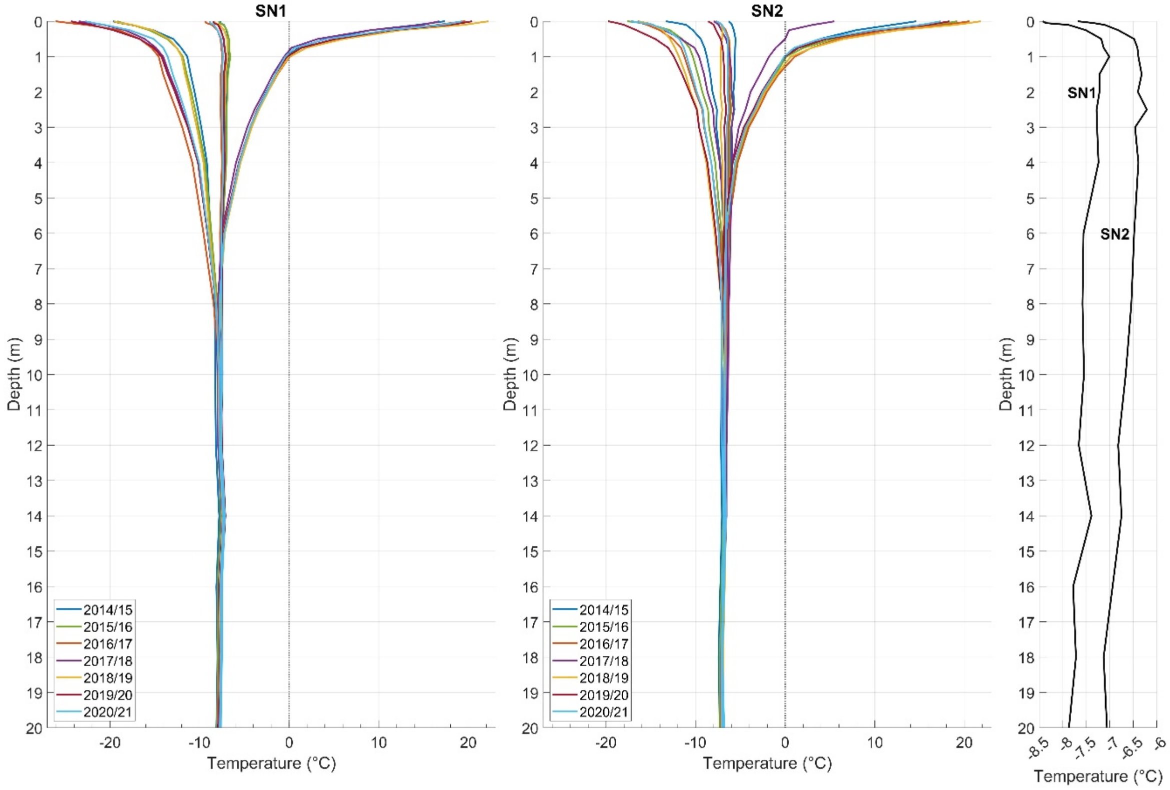

Figure 7.2. Ground temperature conditions in borehole SN1 and SN2, showing winter minimum, mean, and summer maximum ground temperature profiles for each hydrological year. The rightmost panel shows the overall mean ground temperature profiles for SN1 and SN2, which are the average of the seven hydrological year mean profiles for each site.

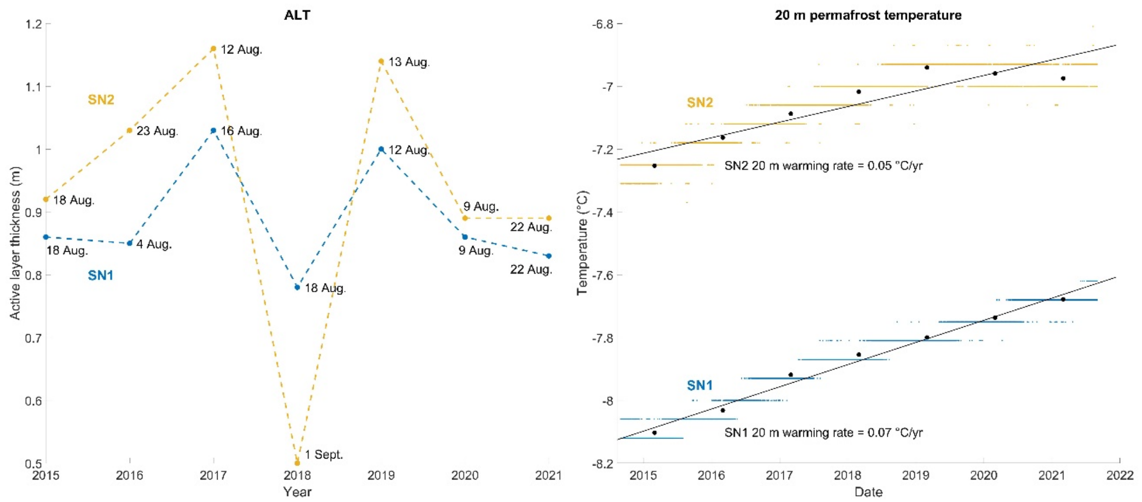

Figure 7.3. Left: Linearly extrapolated active layer thickness (ALT) at SN1 and SN2; datapoint dates indicate the date of maximum extrapolated thaw depth and thus ALT. Right: Six-hourly 20 m temperature at SN1 and SN2 during the seven-year study period with linear trend lines (in black). The stepped appearance of the data is caused by the thermistors' 0.065°C resolution. Black dots indicate hydrological year mean temperature at 20 m and are plotted in the middle of the hydrological year which they represent (e.g. 2 March 2015 for the hydrological year 1 September 2014 – 31 August 2015).

8 Trends and seasonality in tropospheric ozone at a High Arctic research facility

By Henrik Skov, Jens Hjorth, Jakob Boyd Pernov and Claus Nordstrøm. Department of Environmental Science, Aarhus University

In the public, ozone is best known from the stratosphere, where it protects life on Earth against destructive ultraviolet radiations from the sun. In the lower part of the atmosphere – the troposphere – ozone is also important. It is formed by photochemical reactions in the atmosphere involving NO_x together with methane and other volatile organic compounds or carbon monoxide. In the troposphere, ozone absorbs incoming sunlight and outgoing radiation from the Earth and thus it is an important greenhouse gas. Finally, ozone is the source for OH radicals that is the main tropospheric oxidant.

$O_3 + h\nu \rightarrow O_2 + O(^1D)$

$O(^1D) + H_2O \rightarrow 2OH$

We have studied ozone at Villum research Station in the framework of the "Arctic Monitoring and Assessment Program" since 1996 with a break between June 2002 and June 2007 (see Figure 1) to get deeper insight into the general chemistry in the Arctic atmosphere.

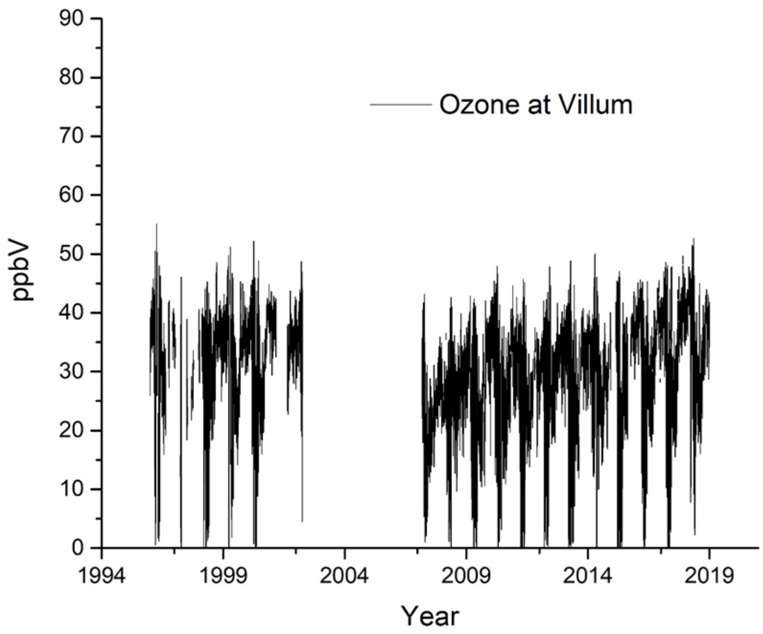

Figure 8.1. Time series of ozone mixing ratio at Villum Research Station.

A distinct seasonal pattern is evident. A maximum ozone concentration is observed during winter, in spring a highly perturbed period where ozone is depleted during ozone deletion episodes (ODEs), thereafter a local maximum is seen in June and another minimum in July and August.

This seasonality is demonstrated more clearly in Figure 2, where the monthly medians of all the years are shown together with the quartiles.

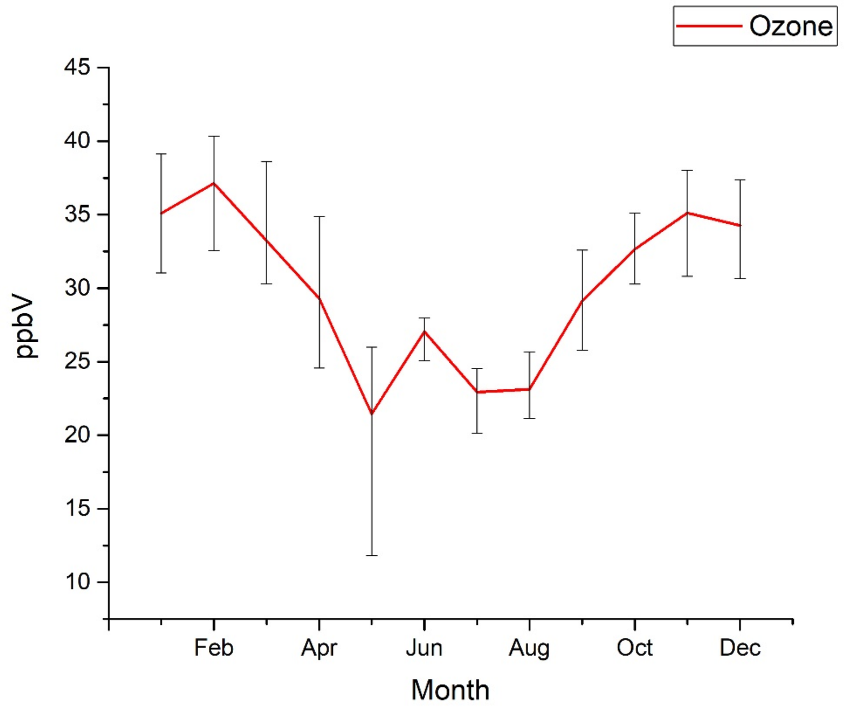

Figure 8.2. Average monthly concentrations at Villum for the years 2007-2019.

The spring minimum is due to the depletion of ozone that is observed at Arctic coastal stations (AMAP 2021) and is connected to the depletion of mercury (Skov et al. 2020). It is now proven that the occurrence of ODE is due to catalytic degradation of ozone by reaction with Br (Wang et al., 2019):

$O_3 + Br \rightarrow BrO + O_2$

$2BrO \rightarrow Br_2 + O_2$

$Br_2 + h\upsilon \rightarrow 2Br$

The source for bromine is more open for discussion. The most common believe is that Br2 is released to the atmosphere by heterogeneous reactions from refreezing leads or produced from windblown snow containing marine salt (Yang et al., 2020; Wang et al., 2019).

Heterogeneous reactions

$Br^- + O_3 \rightarrow BrO^- + O_2$

$BrO^- + Br^-_{aq} + 2H^+_{aq} \rightarrow Br_2\uparrow + H_2O$

or

$HOBr \rightleftharpoons HOBr_{aq}$

$HOBr + Br^-_{aq} + H^+_{aq} \rightarrow Br_2\uparrow + H_2O$

HOBr is produced in the atmosphere from e.g.

$BrO + OOH \rightarrow BrOH + O_2$

Currently we are working on the analysis of long time series of measurements of atmospheric BrO to get a deeper understanding of the chemistry of Br species and of ozone. Trends are analyzed by the non-parametric Mann-Kendall regression analysis method.

Ozone itself does not show a significant trend looking at all data from 1997 until today, but from 2007 and until today there is a significant increase, especially in the winter months (see Figure 3).

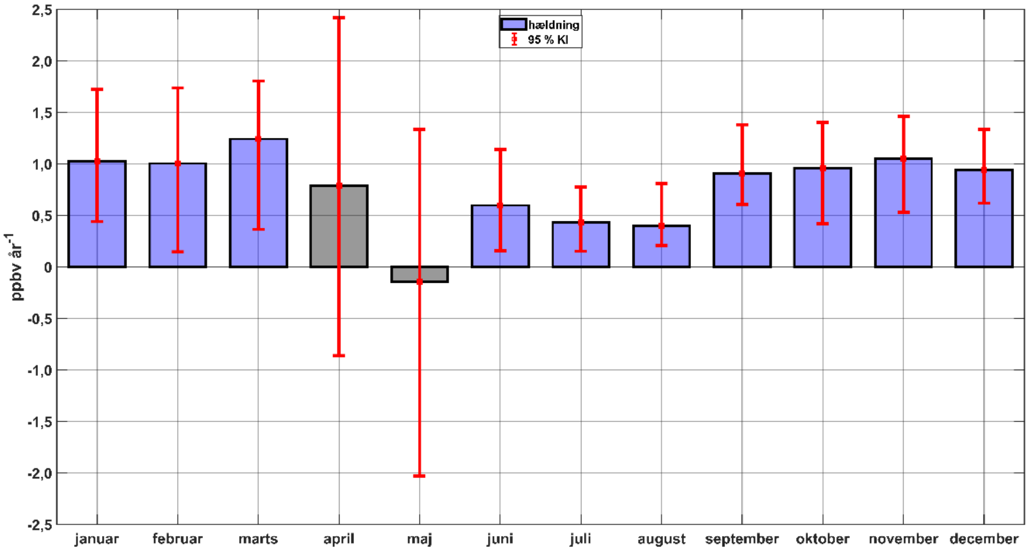

Figure 8.3. Seasonal Sen slopes of ozone monthly median concentrations calculated by de-seasoned Mann-Kendall test for 2007 to 2019, including 95% confidence interval. Months with significant trends are in blue and non-significant trends are in grey.

The increase in the ozone mixing ratio is significant for all months but April and May, where the ODE's occur. In the spring, the special halogen chemistry might be the reason for this lack of increase. The increase in ozone has previously been explained by decreasing emission of NOx because this reduces the removal of ozone by reaction with NO. In the summer (June, July and August), the lower increase might be explained by the retreating sea ice and greening of the Arctic that lads to faster deposition of ozone.

The results from Villum will be integrated in a scientific paper together with results from other Arctic Stations {Law et al., 2021) and we are planning another one, where we compare measured and modelled data for Villum.

Acknowledgement

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Publications 2015 -2021

Below you find an overview of the numbers oof publications based on activities at Villum Research Station 2015-2021.

Year	Research papers	Book chapters	Reports	PhD dissertations
2015	3			
2016	11	1		
2017	9			1
2018	14			
2019	23		4	1
2020	18	2	1	
2021	23			1
Total	101	3	5	3

Publications 2020

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Arctic Sea Ice Ecology.

Seasonal Dynamics in Algal and Bacterial Productivity

Chapter 1 The Book, and Ecology of Sea Ice

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Chapter 3 Winter, Cold and Mature Sea Ice

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