SESS REPORT 2018

The State of Environmental Science in Svalbard – an annual report

SIOS
SVALBARD INTEGRATED ARCTIC EARTH OBSERVING SYSTEM

SESS report 2018
The State of Environmental Science in Svalbard – an annual report

ISSN 2535-6321
ISBN 978-82-691528-0-7

Publisher: Svalbard Integrated Arctic Earth Observing System (SIOS)
Editors: Elizabeth Orr, Georg Hansen, Hanna Lappalainen,
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Editor popular science summaries: Janet Holmén
Layout: Melkeveien designkontor, Oslo

Citation:
Orr et al (eds) 2019: SESS report 2018, Longyearbyen,
Svalbard Integrated Arctic Earth Observing System

The report is published as electronic document, available from SIOS web site
www.sios-svalbard.org/SESSreport

Contents

Foreword

The Svalbard Integrated Arctic Earth Observing System (SIOS) is a Norwegian initiated international collaborative effort to develop and maintain a regional observational system for long-term observations in and around Svalbard. SIOS is interdisciplinary and focuses on processes and their interactions between the different spheres, i.e. biosphere, geosphere, atmosphere, cryosphere and hydrosphere. The core observational programme of SIOS provides systematic long-term observations of key variables to address Earth System Science questions related to global and environmental change. SIOS envisions a significant contribution to the systematic development of new methods and observational design in Svalbard. The programme is dynamic and can adopt new techniques and methods as they appear or society poses new questions. The annual SESS report is the fundamental catalyst to enhance interdisciplinary research and dynamic development of the observing system and our understanding of change in Svalbard. The SESS report has several goals:

i. to summarize the latest developments in the Svalbard environment and provide users with the core data underpinning our knowledge of the changes

ii. point out knowledge gaps for Earth System Science issues in the Svalbard region that are important for society

iii. provide recommendations regarding how to develop the observation system thus forming the basis for the work programmes of SIOS for the coming year

In the Strategy for research and higher education in Svalbard by Norwegian Ministries 2018, it is stated that the Government will work to ensure that research and higher education in Svalbard develop in a forward-looking, sustainable manner. One of the objectives mentioned in the strategy is that research communities active in Svalbard shall take the lead in moving towards shared research data and infrastructures. The aim is that SIOS by developing and building the multidomain research infrastructure further enhances Svalbard as an attractive location for world leading Arctic research. This means among other things sharing of data, infrastructure and findings. The gained knowledge can advance other observational networks and research infrastructures in the Arctic.

SIOS entered into its operational phase in January 2018, after ten years of preparation and implementation. One of the main products of the operational SIOS is this first SESS report. It takes us through all the spheres from the deep permafrost through the surface interfaces, into the ocean and into the upper atmosphere approaching space. It illustrates the breadth of Earth System Science questions as well as the breadth of Svalbard research. As the first report it contains more emphasis on knowledge gaps and recommendations on the future than providing comprehensive summaries of environmental developments. Now it is our, the SIOS consortiums', task to optimize the observing system according to results and recommendations from this report and indeed provide the data that society needs in order to make knowledge based judgements of climate and environmental change in Svalbard. During the coming year the consortium must also deliver on compiling all the diverse data that already exists such that we can address issues regarding how the changes observed influence each other to make more profound system statements rather than just discussing isolated observations of parameters.

We would like to thank the editorial board and anonymous reviewers for their invaluable contributions to this report. Thanks goes also to Janet Holmén who helped to translate the scientific language, which we scientist tend to be blind to, into a more understandable form. Thanks goes of course to all the authors for their time and efforts to improve the observational system of SIOS. We would also like to acknowledge the Norwegian Research Council and the Norwegian Space Centre for their financial support.

Longyearbyen, December 2018

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CHAPTER 1

Permafrost drilling near Barentsburg by the Russian team led by Dr. Nikita Demidov.

Permafrost thermal snapshot and active-layer thickness in Svalbard 2016-2017

Permafrost plays an important role in the Earth System underlying 25% of the terrestrial parts of Planet Earth. It is a thermal condition occurring in the ground in cold regions, and is defined as ground (soil, sediment, or rock) that remains at or below 0°C for two or more consecutive years.

We have for the first time gathered information from all existing permafrost observation infrastructure in Svalbard. We report on the two essential climate variables (ECVs) for permafrost, the permafrost thermal state and the active layer thickness based on the existing permafrost monitoring sites in Svalbard. Several new boreholes were established in different parts of western Svalbard during the last years, thanks to efforts from Italy, Russia, Germany, Poland and Norway. These boreholes have allowed us to compare the permafrost ECVs from sites in Ny-Ålesund, Kapp Linne, Barentsburg, Adventdalen and Hornsund through the hydrological year 2016-2017. We have studied ground temperatures and interpolated active-layer thickness in 11 boreholes, and two active-layer monitoring grids. Svalbard has the warmest permafrost this far north.

HIGHLIGHTS

Svalbard permafrost temperatures ranged during 2016-2017 from -1.1 to -5.2°C at 10-20 m depth. The thickness of the active layer ranged from 49 to 300 cm. Active-layer freeze-back durations varied from 18 to 140 days, reflecting the particularly warm, wet and long-lasting autumn 2016.

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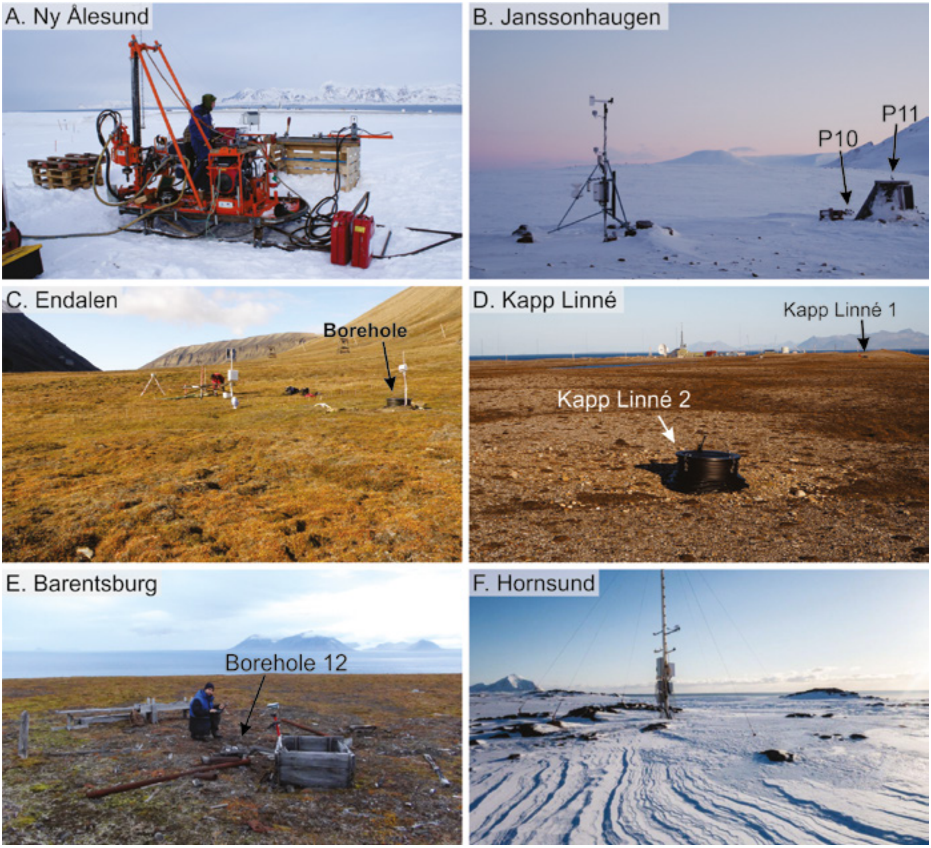

The permafrost borehole sites in Svalbard. Image A was taken during the drilling of the DBNyÅlesund borehole.

RECOMMENDATIONS

Previous and present observations focus on understanding permafrost conditions near to settlements and research stations in western and central Svalbard. However, ground thermal conditions there are likely not representative for the northern and eastern reaches of the archipelago, where the climate is considerably cooler and climate development might be different. Future observations efforts will therefore focus on characterising permafrost environments in northern and eastern parts of Svalbard. Including such areas will most likely allow observations of the full diversity of permafrost conditions throughout the entire Svalbard landscape.

In addition to the presented ECVs for permafrost, ground-ice content is a key parameter for assessing the response of permafrost landscape to changes in climate. Where permafrost contains an abundance of ice, warming and thawing will lead to marked geomorphic change. In flat areas, ground-ice degradation can result in thermokarst (the process by which characteristic landforms result from the thawing of ice-rich permafrost or the melting of massive ice). On slopes, excess water released during ground ice melting, particularly of the top permafrost, can initiate landslides.

CHAPTER 2

Microbial activity monitoring by the Integrated Arctic Earth Observing System (MamSIOS)

HIGHLIGHTS

Microorganisms play important roles in the generation and decomposition of climate-active gases, yet current climate models do not take account of microbial activity.

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1. Existing monitoring data

Fluxes of climate-active gases are currently being measured at specific field locations in Svalbard. These data are being used to represent the Arctic in the world-wide flux data sets that are incorporated into global climate change models. *To the best of our knowledge, none of the fluxes currently being measured derive from contemporary microbial metabolism.*

2. How can the data be used in a SIOS context?

SIOS offers a unique opportunity to use this information to develop a comprehensive picture of the manner and extent to which microorganisms in the Arctic influence climate processes and how they change over time.

3. What are the gaps in our knowledge?

The role of microorganisms in the production and destruction of climate active gases is not entirely clear. There is currently a pressing need to understand and monitor changes in the abundance, diversity and – particularly – the ecological function of microbial communities in the polar regions in order to produce more accurate greenhouse gas release models.

RECOMMENDATIONS

We propose following actions:
1. Conduct a comprehensive census of both biodiversity and functional diversity of microbial communities in Svalbard
2. Look at the distribution of this diversity in terms of habitat type
3. Determine the stability of the communities in which this biodiversity exists
4. Link this biodiversity and active gene composition to climate-active gas flux (as measured currently)
5. Use this raw data to construct preliminary models in order to open a broader debate with the climate change community about the relative significance and potential of microbially-mediated processes to bring about a paradigm shift, thus substantially advancing our understanding of climate processes.

Capacity building – Much of this work could potentially be conducted at current research stations in Svalbard. To enable this, further development of microbiology facilities and infrastructure (such as class II microbiological safety cabinets, autoclaves, clean rooms and molecular biology facilities) is an essential and pressing need.


Glacier surface albedo


Nutrient leaching

CHAPTER 3

HIGHLIGHTS

Snow covers all of Svalbard for up to 9 months a year and is very sensitive to warming. Snow is therefore ideal for studying the rate of climate change and predicting its impact on ecosystem functioning. Currently we lack a holistic picture of snow processes and ways of monitoring their effects.

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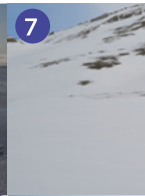

Snow research in Svalbard: current status and knowledge gaps

Snow cover affects all environments in Svalbard: glaciers, ocean (sea-ice) and land. Due to its high reflectivity, snow also impacts the atmosphere and the Earth's energy budget (less snow results in higher temperatures). Snow on the ground insulates the soil against cold air temperatures, and is considered one of the main factors influencing plants and microorganisms, as it determines water and nutrient availability and the length of the growing season. Snow is also very sensitive to climate and its changes; even a brief warm spell can turn a dry snowpack into an icy snowpack, or melt it away completely. A snow pack with icy layers has completely different properties than a homogeneous snow pack: it conducts more energy and can change the thermal profiles of glaciers or ground on which it rests. Reduced snow cover directly affects the health of a glacier, prolonging the melting season and increasing the annual melt rate.

Over the millennia, Arctic life forms have become well adapted to cold and harsh conditions. An altered climate with changed snow cover properties will make it harder for some species to survive. Reindeer will need to dig through ice layers to find food, and ptarmigans will be unable to burrow into the snow for protection against the cold. Ice that forms on the ground below the snow (basal ice), also affects plant growth and survival rates.

Snow and ice in Svalbard. Photos: JC Gallet.

RECOMMENDATIONS

During the last decades our understanding of snow processes has increased substantially. However, due to the specialisation within different research topics, a holistic picture of snow processes and their climate interactions is lacking. Improved knowledge and cross-disciplinary actions are needed to better understand:

1. The deposition processes of rain and snow, and transport of aerosols to the region
2. The chemical, biological and physical composition of precipitation events
3. The spatial-temporal variation of snow in the landscape, and how this can be captured in models
4. The altitudinal, latitudinal and glacier size dependence on snow deposition and snow redistribution by wind
5. The impact of snowpack characteristics on energy balance and how this can be captured by remote sensing
6. The interactions with solar radiation in terms of energy balance and chemical reactions
7. The influence of ice formation within the snow pack as well as on ground
8. The importance of a snow cover for ecosystems and the effects of basal ice formation
9. The rate, timing and release of fresh water during snow melt

Recovery of the Indian arctic multi-sensor mooring (IndARC) from Kongsfjorden. Photo: K Kumar

CHAPTER 4

Temperature time-series in Svalbard fjords. A contribution from the "Integrated Marine Observatory Partnership"

HIGHLIGHTS

West-facing fjords in Svalbard show water temperatures increasing by up to 2°C per decade. In the coldest months temperatures are increasing at around 1°C per decade, with the fjords rarely experiencing freezing temperatures. There have been no changes in the temperature of north-facing fjords.

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Many observations around Svalbard have tended to be biased towards summer and autumn and we don't always have a full picture of the annual cycles. However, some marine measurements have been sustained over many years; these are exceptionally valuable, as they enable us to quantify the environmental change.

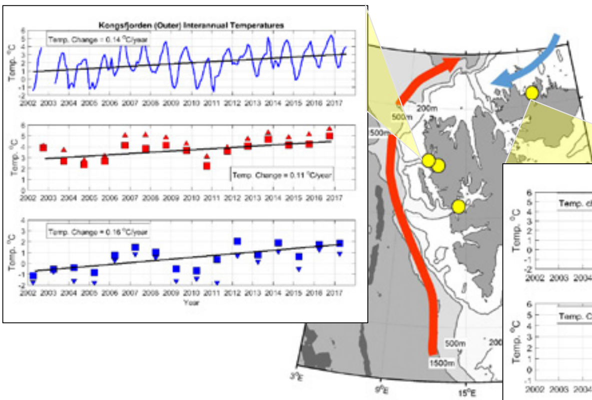
One rich source of data is the network of observatories in the coastal and offshore waters of Svalbard. Some of these observatories have been in operation for more than 15 years with instruments continuously recording data for a variety of parameters. As the data series builds up we reveal both the seasonality of the marine environment and the long term change.

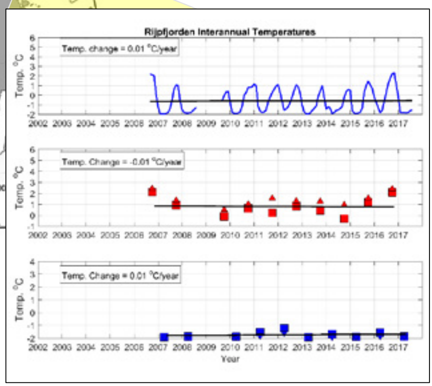
The Integrated Marine Observatory Partnership (iMOP) has studied water temperature records from three fjords. Kongsfjorden and Isfjorden are west-facing and influenced by the West Spitsbergen Current, which carries warm Atlantic Water to the Arctic Ocean. Rijpfjorden is north-facing and is influenced by the colder, fresher Arctic waters. The records come from contrasting locations which experience different oceanographic conditions during their seasonal cycles.

The west-facing, Atlantic fjords are both warming. Water temperatures are increasing in both the warmest months (September, October and November) and the coldest (March, April and May). The rate of change is up to 2°C per decade for the warmest months and around 1°C per decade for the coldest. The impact of warming means that the fjords experience fewer years where the water cools to the freezing point: this limits the formation of sea ice. The warming is related to both the temperature of the West Spitsbergen Current and the pattern of winds that help drive water towards the coast. In contrast, Rijpfjorden does not show any significant warming and sea ice regularly forms in the fjord.

RECOMMENDATIONS

- Develop the network of operators to encourage collaboration, communication and planning of future marine observatories - Analyse temperature records of all long-term inshore moorings and include, where possible, an analysis of water salinity
- Extend the analysis to include offshore moorings
- Identify similar long-term marine records (e.g. zooplankton or fish populations) and for other Earth System processes (e.g. records of meteorology or glaciers) and undertake coupled analyses





The locations of the four fjord temperature time series in this report are marked in yellow. The graphs show the contrasting changes in water temperature at two of those locations: Kongsfjorden (an 'Atlantic' fjord) and Rijpfjorden (an 'Arctic' fjord). Upper panel (blue line) monthly temperature values, middle panel (red markers) temperature of the warmest months (Sept/Oct/Nov), lower panel (blue markers) temperature of the coldest months (March/April/May). The data series are fitted with a simple linear regression.

CHAPTER 5

Calanus finmarchicus copepods

The Continuous Plankton Recorder Survey – Monitoring plankton in the Nordic Sea

HIGHLIGHTS

The Pacific diatom *Neodenticula seminae* (an indicator of trans-Arctic migration) was recorded off Svalbard in 2016, the easternmost observation of this diatom in the Nordic Seas.

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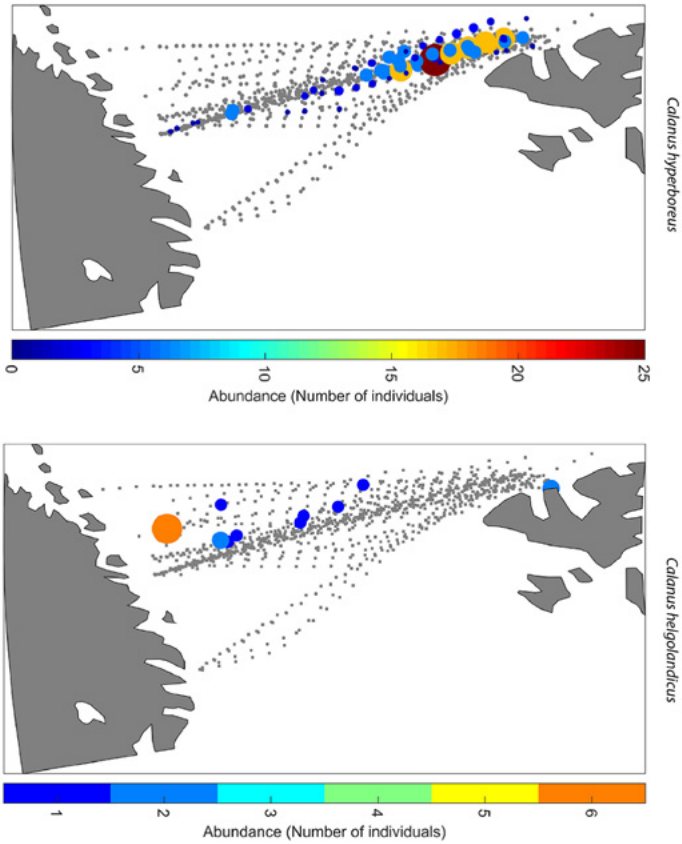
The Continuous Plankton Recorder (CPR) survey monitors plankton in the waters around Svalbard and south to northern Norway. Within this region of the Nordic Seas, the CPR survey adds to and complements other monitoring methods by providing a broader spatial and temporal perspective. Most other surveys are coastal or are sporadically sampled through time. The CPR survey also adds value by providing multi-decadal data at the Atlantic basin scale that can help disentangle and interpret changes observed in the Nordic Seas and help predict changes over the next coming decades. For example, regions that currently support Arctic ecosystems will instead support sub-Arctic systems within the next 10 to 20 years (if not sooner). The biological signals of change we see further south in Atlantic sub-polar systems now can be used to detect the early warning signs of change in the Arctic.

To develop the observation system further, the CPR survey currently works closely with Norwegian scientists to coordinate its sampling on board "ships of opportunity". These are often cargo vessels that regularly ply the same route. They are outfitted with instruments that automatically and routinely collect a range of data on oceanographic parameters.

It is hoped that in the near future, the CPR survey will form part of a more integrated observation system within these waters and enhance its monitoring with an additional suite of biogeochemical and molecular sensors. It is also foreseeable that additional CPR routes could be towed using other ships of opportunity in this region, such as tourist vessels.

RECOMMENDATIONS

The Norwegian FerryBox system is one such ship of opportunity. The CPR survey, by coordinating its sampling programme with the FerryBox system, can obtain valuable complementary information such as pCO2 in the waters where the sampling was done.



The spatial distribution and abundance of the calanoid species *Calanus hyperboreus* and *Calanus helgolandicus*. Colours represent abundances per sample.

CHAPTER 6

One year after being deployed, the oceanographic buoy and all its instruments returned to the surface with valuable information about deep sea variability
Photo: SOA

Spitsbergen Oceanic and Atmospheric interactions – SOA

HIGHLIGHTS

The deep sea is a little-known environment. How it is responding to recent climate change remains to be discovered. The variability of the bottom currents and thermohaline properties in the deep sea west of Svalbard display an interesting coherence with meteorological processes.

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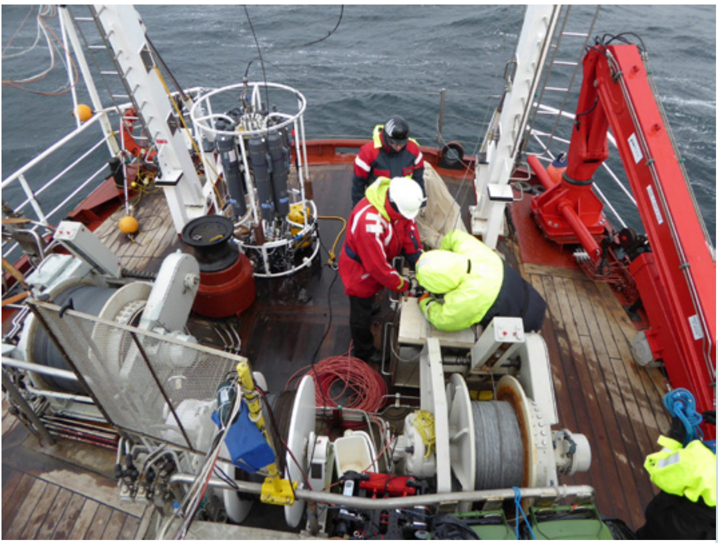
In the Fram Strait, a remarkable increase in the temperature and salinity of inflowing Atlantic Water has been observed since the 1990s. This is in part a natural trend, but recent temperature anomalies, ~1°C relative to the 1970s are related to anthropogenic causes. Air temperature increased by about 3°C in the 20th century and meteorological stations at Svalbard confirm this positive trend.

At the West Spitsbergen margin, Atlantic and Arctic waters converge, mix and exchange, while air–sea interactions and shelf–slope dynamics trigger vertical mixing and formation of cold and salty water. This water is sufficiently dense to sink to greater depths and contribute to the global thermohaline circulation. The circulation process permits exchange of heat (i.e., energy) between low and high latitudes. Since the formation of dense water and its spreading at greater depths are strongly influenced by the properties of Atlantic Water, which have been changing in the last decades, we cannot exclude the possibility that the global thermohaline circulation may change in the near future.

We analysed oceanographic data (obtained from shelf and deep-sea oceanographic moorings and hydrographic cruises) and meteorological data from the west Svalbard margin, comparing temperature and salinity variability in the deep ocean flow and the wind regime. Time-series revealed occasional intrusions of warm and salty waters at 1000 m depth, mainly during the period October – April, quasi-simultaneously at several locations more than 150 apart, along the continental slope west of Svalbard. The fact that the most energetic events, both in the deep flow and in the wind speed, occurred with similar periodicities (10-20 days) suggests atmospheric storms as the likely forcing mechanism underlying the observed deep sea variability. Others energetic events with periodicity of 12 and 24 hours, instead, could be related to internal tidal oscillations. The fact that the most energetic events, both in the deep flow and in the wind speed, had similar periodicities (10-20 days) suggests atmospheric storms as the likely forcing mechanism underlying the observed deep-sea variability. Other energetic events with periodicity of 12 and 24 hours could instead be related to tidal oscillations.



Operations on board the research vessel *Oceania* (IOPAN)
Photo: SOA

RECOMMENDATIONS

The Arctic is changing rapidly. Interaction between atmospheric and oceanic processes is not still completely understood. Effective implementation of in-situ measurements and multidisciplinary numerical modelling is needed to clarify the effects of anthropogenic forcing on the "natural variability" of the Arctic Ocean.

CHAPTER 7

Kongsfjorden seen from the Zeppelin Observatory (Photo: O Hermansen)

The Lower Atmosphere above Svalbard (LAS): Observed long-term trends, small-scale processes and the surface exchange

The lower atmosphere is where clouds and atmospheric particles interact with sunlight and infrared radiation, ultimately driving the heating and cooling of the surface. The surface interacts with the lower atmosphere through transfer of energy, gases and particles between the land, snow, ice or ocean and the atmosphere. With all of these interactions going on, this part of the atmosphere must be well monitored to understand changes in climate and the processes behind them. In addition to measuring long time series of the basic state of the atmosphere (temperature near the surface, frequency of cloud cover, total amount of water vapour, etc.), it is also important to coordinate measurements of different variables to understand complex processes and feedbacks. Clouds cannot be well understood without knowledge about the tiny particles in the atmosphere on which cloud droplets form, where those particles come from and how they are

HIGHLIGHTS

Svalbard has warmed faster than most of the planet over the last decades. Understanding the role of natural versus human-related and global versus regional processes requires detailed observations of many aspects of the lower atmosphere. This work is under way in Ny-Ålesund, but much remains undone.

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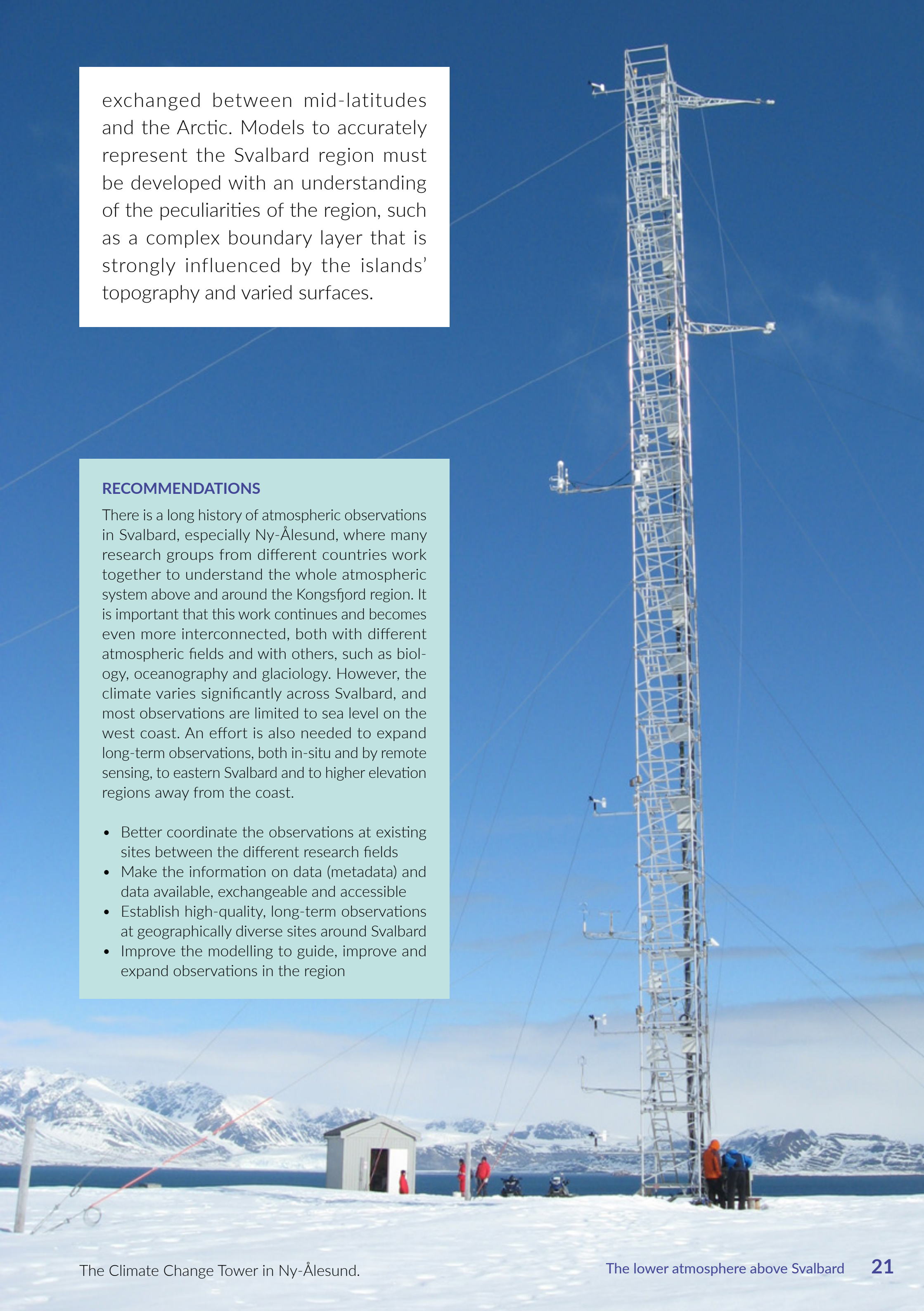
exchanged between mid-latitudes and the Arctic. Models to accurately represent the Svalbard region must be developed with an understanding of the peculiarities of the region, such as a complex boundary layer that is strongly influenced by the islands' topography and varied surfaces.

RECOMMENDATIONS

There is a long history of atmospheric observations in Svalbard, especially Ny-Ålesund, where many research groups from different countries work together to understand the whole atmospheric system above and around the Kongsfjord region. It is important that this work continues and becomes even more interconnected, both with different atmospheric fields and with others, such as biology, oceanography and glaciology. However, the climate varies significantly across Svalbard, and most observations are limited to sea level on the west coast. An effort is also needed to expand long-term observations, both in-situ and by remote sensing, to eastern Svalbard and to higher elevation regions away from the coast.

- Better coordinate the observations at existing sites between the different research fields
- Make the information on data (metadata) and data available, exchangeable and accessible
- Establish high-quality, long-term observations at geographically diverse sites around Svalbard
- Improve the modelling to guide, improve and expand observations in the region



The Climate Change Tower in Ny-Ålesund.

CHAPTER 8

Observations of the solar UV irradiance and ozone column at Svalbard

HIGHLIGHTS

Measurements of solar ultraviolet (UV) radiation and the ozone column over Svalbard have been ongoing for many decades. Better understanding of their behaviour requires the integration of our efforts and the creation of a local instrumental network for use in future investigations.

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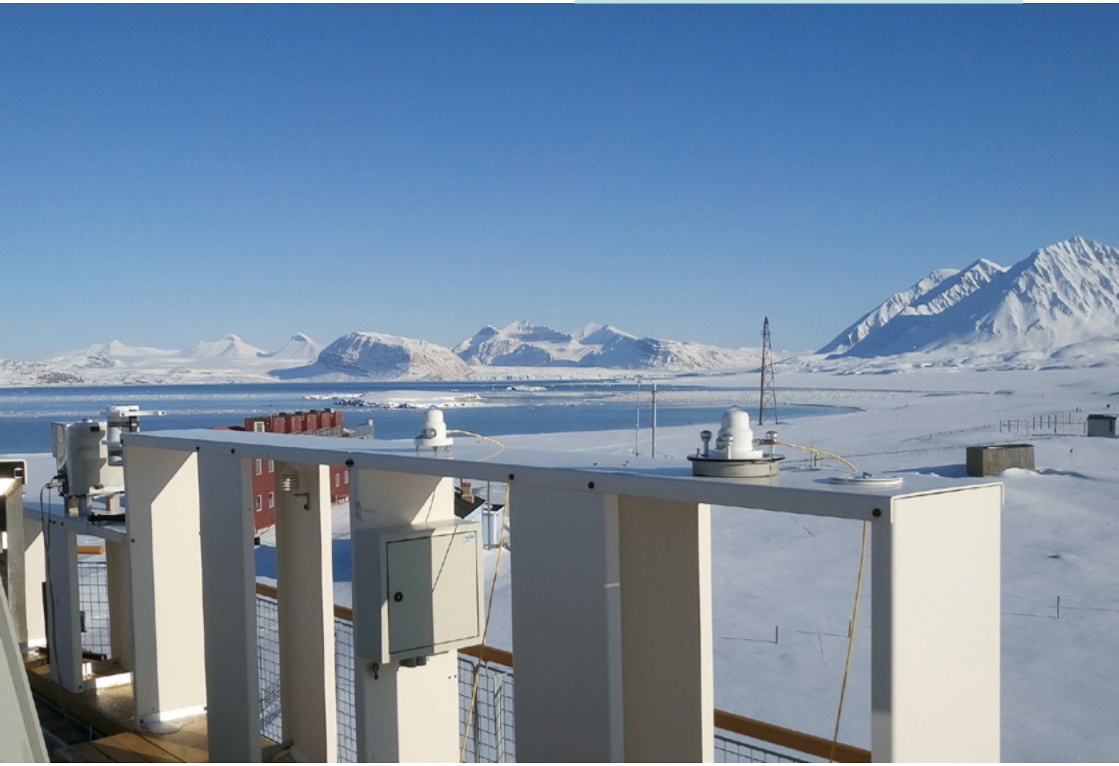
Solar radiation is the earth's main energy source and governs a variety of chemical and biological processes in the atmosphere and biosphere. The amount of solar radiation that enters the atmosphere varies mainly due to two important astronomical parameters. First, Earth's orbit is elliptical rather than perfectly round; second, the planet's spin axis is tilted in relation to the plane of its orbit. These parameters cause seasonal changes at different latitudes and polar nights and days. As it passes through the atmosphere, solar radiation is scattered and absorbed by molecules and aerosols. Scattering and absorption are complex processes that strongly depend on a range atmospheric parameters and conditions, and they induce additional variations in the amount of solar radiation that reaches the earth's surface. Thus, examination of the variability in the irradiance at the surface can contribute significantly to our knowledge about atmosphere and climate.

Solar ultraviolet (UV) radiation reaching Earth's surface is an important factor for various chemical and biological processes. Propagating through the atmosphere, a significant part of UV irradiance is strongly absorbed by atmospheric ozone, which in turn raises the temperature of the middle atmosphere and affects dynamical processes. This makes the study of solar UV radiation and the total amount of ozone an important task.

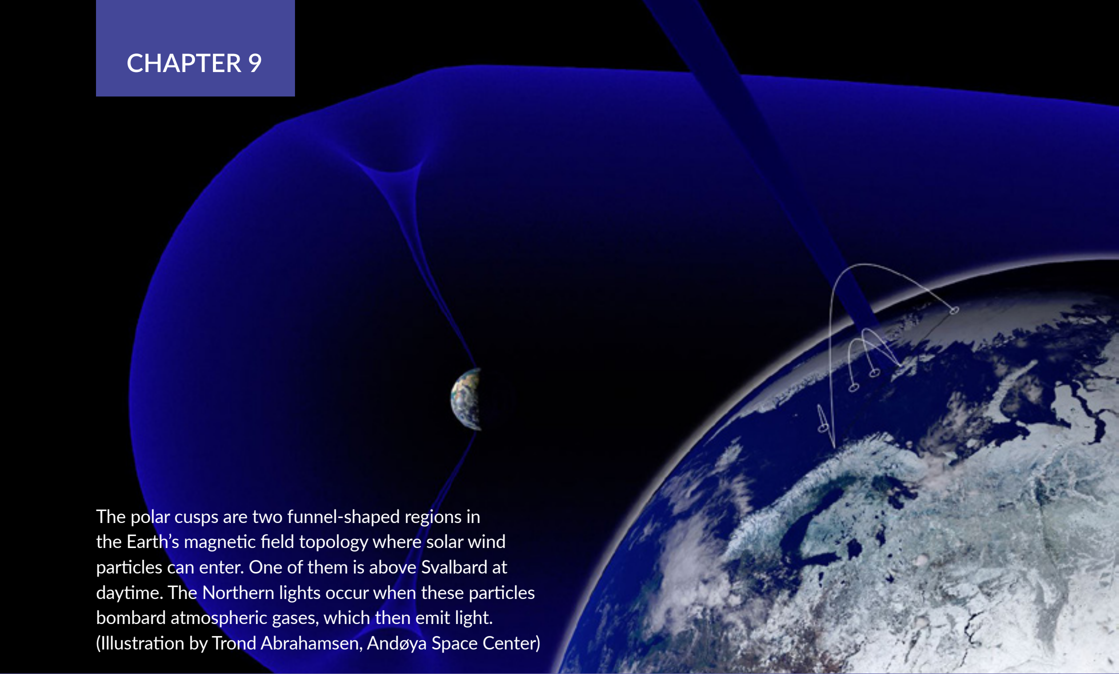
At Svalbard, measurement UV radiation and ozone levels started in 1950 and continue to this day. This long observational series has provided better understanding of the climatic processes in polar regions, and the conclusions reached through these years have been published in scientific journals. However, our picture of the polar environment is still far from complete.

RECOMMENDATION

To advance our understanding of the processes governing how UV radiation and ozone amount interact we need to combine our research efforts. Integrating the instrumental infrastructure, and creating a local Svalbard network with common methods for data analysis, will contribute to enhancing our knowledge about polar environment and climate.



CHAPTER 9



The polar cusps are two funnel-shaped regions in the Earth's magnetic field topology where solar wind particles can enter. One of them is above Svalbard at daytime. The Northern lights occur when these particles bombard atmospheric gases, which then emit light. (Illustration by Trond Abrahamsen, Andøya Space Center)

Grand Challenge Initiative – Cusp: rockets to explore solar wind-driven dynamics of the top side polar atmosphere

HIGHLIGHTS

GCI-cusp comprises twelve rockets to study the solar wind forcing of the top side polar atmosphere. Four rockets will be launched over Svalbard in December 2018, two from Andøya and two from Ny-Ålesund. Svalbard is the only place in the world to explore daytime auroras by rockets.

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"The Grand Challenge Initiative – Cusp" (GCI-Cusp), a strategic coordination between the Japanese Aerospace Exploration Agency, NASA, SIOS and UiO, is the largest sounding rocket project ever. Twelve sounding rockets will be launched during the winters of 2018/19 and 2019/20. Each mission has been selected by their respective funding agency as a stand-alone project with the potential to do compelling science. Andøya Space Center can support two simultaneous launches from both Andøya and Ny-Ålesund. Thus, by coordinating missions, we may have up to four rockets in the sky nearly at the same time.

Polar cusps are two funnel-shaped regions in the Earth's magnetic field, where solar wind particles can enter the polar atmosphere, where their collisions produce the Northern lights. Cusp aurora is the technical term for the Northern lights in daytime. In Svalbard, this phenomenon is visible to the naked eye during December and January. Since Svalbard is the only place in the world where cusp aurora can be studied by rockets, cameras and radars, it is a world class laboratory for studying solar wind interactions with the atmosphere. Major research infrastructure such as the EISCAT Svalbard Radar, the Kjell Henriksen Observatory and SVALRAK has been built to capitalise on Svalbard's unique location. These ground instruments will be key in defining the launch condition for each rocket.

GCI-Cusp questions:

The polar atmosphere is strongly forced by the solar wind. The major Grand Challenge questions to be addressed in 2018/19 include how the spatio-temporal behaviour of how the solar wind couples to the Earth's magnetic field (TRICE-2), how solar wind particles are accelerated by waves along the magnetic field lines (CAPER-2), and how these energy inputs into the Earth's atmosphere lead to upwelling and escape of oxygen (VISIONS-2). The Norwegian rocket, ICI-5, to fly in December 2019, will be equipped with 12 ice hockey puck size daughters to obtain a 3D imaging of turbulence within the northern lights. This turbulence sometimes gives rise to severe disturbances/black-out of radio signals. This new instrument will be test flown on the student rocket G-CHASER in January 2019.

Svalbard is the only place in the world where we can explore the daytime northern lights (cusp aurora) with sounding rockets. (Illustration by Trond Abrahamsen, Andøya Space Center)

RECOMMENDATION:

GCI-Cusp will implement the SIOS Data Management System (SDMS). Standardised data formats expressed in SI units will be essential in stimulating efficient collaboration within a broader community including Earth System Science modellers.

Permafrost thermal snapshot and active-layer thickness in Svalbard 2016–2017

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Keywords: permafrost, active layer, meteorology, ground temperature, Svalbard

Introduction and objectives

This report is the product of international collaboration of several permafrost researchers working in Svalbard. The report aims to provide an overview of ground thermal conditions and active-layer thickness as they are recorded at five sites during the 2016/2017 hydrological year from 1 September 2016 to 31 August 2017 in Svalbard. We report on this period, as this is when observation variables are available from all sites. This provides the basis for comparison of spatial variations in permafrost thermal conditions and active layer thickness in Svalbard. For earlier summaries of permafrost conditions on Svalbard see Humlum *et al.* (2003) and Christiansen *et al.* (2010).

The specific objectives of this report are to: (1) introduce the study area and permafrost in Svalbard; (2) describe instrumentation and operation at each of the five sites; (3) characterize the ground thermal regime and present the active-layer thickness from the last 2016-2017 hydrological year; (4) provide an overall analysis of the ground-thermal observations with a focus on the implications of changing permafrost on other parts of the cryosphere relevant for the SIOS network; (5) ensure access to the reported data through the Global Terrestrial Network on Permafrost (GTN-P) adhering to the SIOS Data policy and (6) point to potential avenues and geographic locations for future permafrost observation needs in Svalbard.

This report builds on the IPY 2007-2008 snapshot of the permafrost thermal state and active layer thickness in Svalbard (Christiansen *et al.*, 2010), but now provides ground temperatures from more areas in Svalbard thanks to the international collaboration. The report may serve as a baseline for future regional observation programs and collaborative activities within the SIOS network.

Permafrost background

Permafrost plays an important role in the Earth System as it underlies 25% of the terrestrial parts of Planet Earth. It is a ground thermal condition occurring in cold regions, and is defined as ground (soil, sediment, or rock) that remains at or below 0°C for two or more consecutive years. Svalbard has the warmest permafrost this far north (Romanovsky et al., 2010). The thickness of permafrost on Svalbard is believed to range from a few meters in coastal areas to several hundred meters in mountain peaks (Liestøl, 1977; Humlum, 2005). Permafrost regions are further characterized by the presence of an active layer – the layer above the permafrost which thaws during summer and refreezes during winter. The active layer is of significance as it is the main zone through which water moves in permafrost landscapes, and in which chemical and biological processes are most active (French, 2013).

Due to the nature of permafrost being a negative thermal state of the ground that is often close to the freezing point, it can be affected by climatic changes. However, the relationship between air temperature and ground temperatures is mediated by conditions at or near the ground surface (Smith & Riseborough, 2002). Snow cover impacts ground temperatures, through its insulating effect, by reducing heat loss from the ground during the winter season. In addition, variations in the thermal properties of the active layer, between frozen and unfrozen states, reduce the heat flow into the ground. The thermal conductivity (the readiness with which a material conducts heat) is approximately four-times higher for ice than for liquid water. This means that the ground cools more readily when frozen. Finally, the amount of time it takes for the active-layer to freeze-back during the late autumn and early winter has a significant impact on the underlying permafrost. During active-layer freeze-back, temperatures in the active layer are isothermal above the phase-equilibrium temperature, and the permafrost is less directly influenced by the atmosphere (Osterkamp & Romanovsky, 1997). Following the freeze-back of the active layer, the temperatures at the permafrost surface is permitted to decline (c.f. Burn & Zhang, 2009). The duration of active-layer freeze-back is an important variable as it is a derivative of several factors including: active-layer moisture content, snow cover timing and thickness, and autumn air temperatures. Longer freeze-back durations reduce the amount of time available for ground cooling, resulting in increased ground temperatures in the permafrost.

Essential climate variables on permafrost in Svalbard

The monitoring of essential climate variables, ECVs, for permafrost is delegated to the Global Terrestrial Network on Permafrost (GTN-P) by the World Meteorological Organization (WMO). GTN-P established permafrost temperature and active-layer thickness (ALT) as ECVs related to two specific monitoring programs: 1) TSP (Thermal State of Permafrost) and 2) CALM (Circumpolar Active Layer Monitoring) (Romanovsky *et al.*, 2010; Shiklomanov *et al.*, 2012). GTN-P was developed in 1999 by the International Permafrost Association (IPA) with active support by the Canadian Geological Survey (Burgess *et al.*, 2000) under the Global Climate Observing System (GCOS) and the Global Terrestrial Observing Network (GTOS). The purpose of GTN-P is to establish an open access early warning system for the consequences of climate change in permafrost regions. The first overview of GTN-P observations and their key results include data from Svalbard (Biskaborn *et al.*, 2015).

Ground temperature monitoring sites consist of three elements: a borehole, an encased thermistor string and an automated data logger. As sites were established independently, there are differences in the instrumentation used and the depths at which ground temperature sensors (thermistors) are positioned. The density of temperature sensors generally decreases with depth as the temperature signal at the ground surface is rapidly attenuated moving with depth into the ground. The automatic data loggers in all boreholes are programed to record the borehole temperature at regular intervals (varying from 1 to 6 hours). The instrumentation used at each site is included in Table 1. Boreholes vary in length from a few meters to upwards of 100 meters. For this report, ground temperatures from within 20 m of the ground surface are included to characterize the upper part of the permafrost profile, the part that is most directly affected by climatic variations. We are aware that for some boreholes the casing might affect the ground temperatures recorded closer to the ground surface. To study the active layer dynamics we have also used data from all parts of the boreholes.

The thickness of the active layer is either recorded directly through probing or estimated by interpolating the depth of the 0°C isotherm using borehole thermal measurements (Burn, 1998). Probing is suitable only in fine-grained soils, without gravel and boulders. In addition to point measurements, made at each borehole, two Circumpolar Active Layer Monitoring (CALM) sites are established in Svalbard, one in Adventdalen (UNISCALM) and one near Barentsburg (Fig. 1; Christiansen & Humlum, 2008; Shiklomanov *et al.*, 2012). These CALM sites consist of a grid, measuring 100 m x 100 m or 50 x 50 m with 10 or 5 m grid size, and probe measurements are made at the 121 regularly spaced grid points. Measurements are repeated throughout the thawing season to monitor the thaw progression in the UNISCALM site.

In Svalbard, systematic measurements of active-layer thickness and ground-temperature profiles are presently limited to sites in the western and central parts in Spitsbergen (Fig. 1). Data from Ny-Ålesund, Adventdalen, Barentsburg, Kapp Linné, and Hornsund are examined. These areas are all located near major settlements and research stations in Svalbard, and have been established independently by scientists based in Norway, Svalbard, Germany, Italy, Russia, and Poland. The results of this report will therefore be of significance to those working in these areas, and form the foundation for a collaborative international long-term permafrost monitoring network in Svalbard as part of SIOS.

Table 1: Site information and metadata for permafrost boreholes used in this report.

Location	Borehole name/ ID	Operator	Longitude	Latitude
Adventdalen	Old Auroral Station 2	The University Centre in Svalbard	15°50'05"E	78°12'05"N
	Endalen	The University Centre in Svalbard	15°46'54"E	78°11'26"N
	Breinosa	The University Centre in Svalbard	16°04'01"E	78°08'35"N
	Janssonhaugen/ P10	Norwegian Meteorological Institute	16°28'01"E	78°10'46"N
	Janssonhaugen/ P11	Norwegian Meteorological Institute	16°28'01"E	78°10'46"N
Ny Ålesund	Bayelva	SPARC, Alfred Wegner Institute (AWI)	11°50'03"E	78°55'15"N
	DBNyÅlesund	Insubria University	11°52'00"E	78°55'14"N
Kapp Linné	Kapp Linné 1	University Centre in Svalbard	13°38'05"E	78°03'21"N
	Kapp Linné 2	University Centre in Svalbard	13°38'13"E	78°03'15"N
Barentsburg	Borehole 12	Arctic and Antarctic Research Institute (St. Petersburg)	14°14'27"E	78°05'42"N
Hornsund	Meteo	Polish Polar Station, Hornsund	15°31'59"E	76°59'58"N

*New borehole established in summer 2017, but not reported on here as not yet a full year data series.

Elevation (m a.s.l.)	Borehole depth (m)	Landform	Instrument manufacturer	Sensor depths (m)
9	9.85	Loess on terrace	Geoprecision	0, 0.25, 0.5, 0.75, 1, 2, 3, 5, 7, 9.85
53	19	Solifluction sheet	Campbell	0, 0.25, 0.5, 0.75, 1, 1.5, 2, 2.5, 3, 4, 5, 6, 7, 8, 9, 10, 12, 15, 19
677	10	Blockfield	Geoprecision	0, 0.25., 0.5, 1, 2, 3, 4, 5, 7, 10
254	102	Hilltop (bedrock)	Campbell	0.2, 0.4, 0.8, 1.2, 1.6, 2, 2.5, 3, 3.5, 4, 5, 7, 9, 10, 11, 13, 15, 20, 25, 30, 40, 50, 60, 70, 80, 85, 90, 95, 97.5, 100
254	15	Hilltop (bedrock)	Campbell	0.2, 0.4, 0.8, 1.2, 1.6, 2, 2.5, 3, 3.5, 4, 5, 7, 10, 13, 15
25	9.3	Ground moraine	Geoprecision	0, 0.5, 1, 1.5, 2.5, 3.5, 5.5, 7.5, 9
55	48.5	Ground moraine	Campbell	0.3, 1, 1.5, 2, 2.5, 3, 3.5, 4, 5.5, 8, 10, 13, 16, 20, 23.5, 30.3, 35.3, 40.3, 45, 48.5
20	29	Strandflat bedrock outcrop	Campbell	0, 0.25, 0.5, 0.75, 1, 1.5, 2, 2.5, 3, 4, 5, 6, 7, 8, 9, 10, 12, 15, 20, 25, 29
20	38	Strandflat with beach deposits over bedrock	Campbell	0, 0.25, 0.5, 0.75, 1, 1.5, 2, 2.5, 3, 4, 5, 6, 7, 8, 9, 10, 12, 15, 20, 25, 30, 35, 38
95	20	Marine terrace (gravels)	Geoprecision	0, 0.75, 1.5, 2.25, 3, 3.75, 4.5, 5.25, 6, 6.75, 7.5, 8.25, 9, 9.75, 10, 11.25, 12, 12.75, 13.5, 14.25, 15
10	1, 12*	Raised beach deposits (gravels)	Vaisala QMT107	0.05, 0.1, 0.2, 0.5 0.2, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, 8.0, 10.0, 12.0*

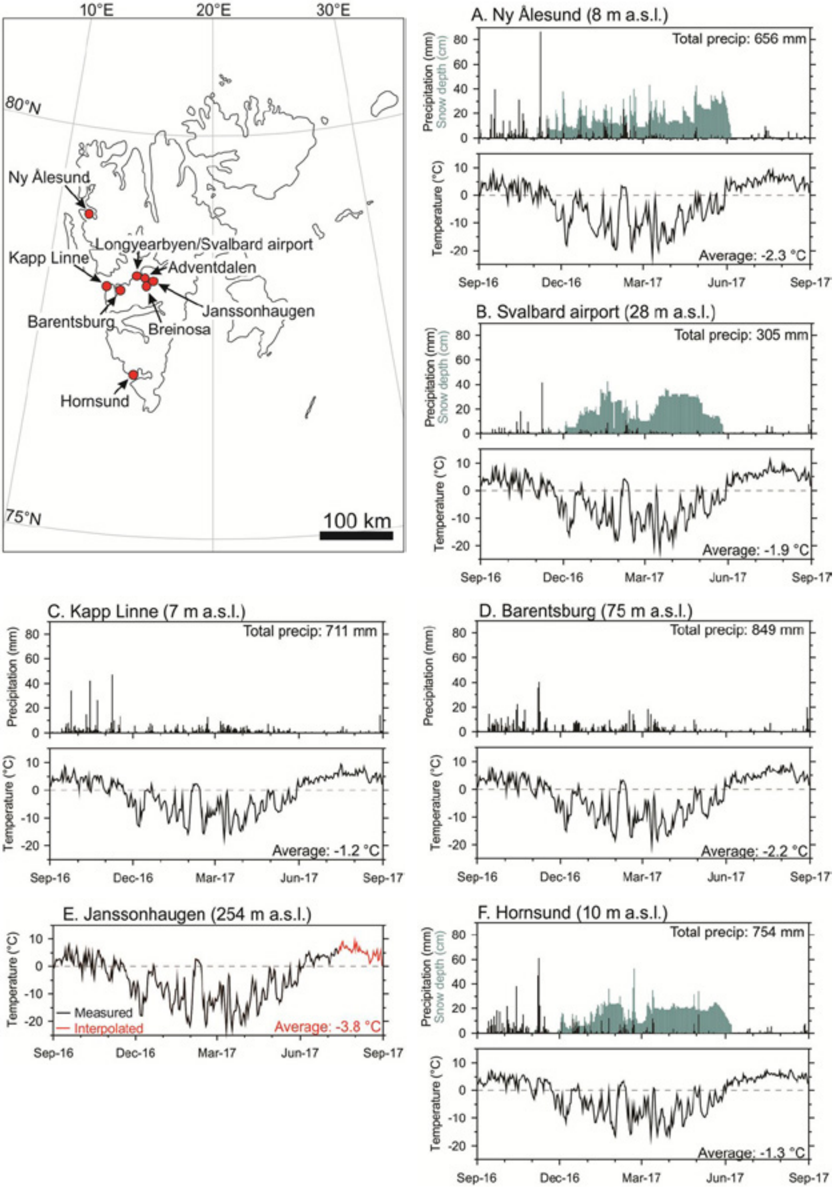

Figure 1: Location of the reported permafrost observations in Svalbard, and meteorological parameters recorded close by. Included in the A-F meteorological plots are the average air temperatures for the hydrological year 2016-2017. The interpolated data series in E is based on regional meteorological stations and included to complete the time series.

Meteorology 2016-2017 and long-term permafrost observations in Svalbard

The climate of western and central Spitsbergen is strongly influenced by the warm Norwegian current, flowing along the western coast (Førland *et al.*, 2011). In addition, Svalbard is located within the North Atlantic cyclone track (Hanssen-Bauer *et al.*, 1990). Cyclones lead to relatively high air temperatures, especially during the winter period. The net effect of these geographic phenomena is that western and central Spitsbergen is markedly warmer than other locations at comparable latitudes. While other sites throughout the high Arctic recorded mean annual air temperatures (MAAT) ranging from -9°C to -15°C in 2009 (Eckerstorfer & Christiansen, 2011), MAAT during 1981-2010 in western and central Svalbard ranged from -3.8°C at the most maritime site at Isfjord Radio (close to the permafrost site at Kapp Linné) to -5.2°C at the northernmost site in Ny-Ålesund (Førland *et al*. 2011; Gjelten *et al*. 2016). Ny-Ålesund and Svalbard Airport were coldest in winter, spring and autumn, whereas in summer Hornsund in the south is coldest, probably due to more lingering sea ice than at the other stations (Gjelten *et al*. 2016).

The hydrological year 2016-2017 had a particularly warm, wet and long-lasting autumn in Svalbard (Fig. 1). Several all-time high air temperature and precipitation extremes were registered on Svalbard, and in the Arctic in general (AMAP 2017). Mean air temperature (MAT) at e.g. Svalbard Airport during autumn (SON) 2016 was 2.2°C, which is 6.2°C above the 1981-2010 average, and 2.3°C higher than the previous maximum in 2000 (Nordli et al. 2014). Ground freezing generally begins towards the end of September in Svalbard. However, air temperatures in September and October, 2016, remained above freezing, and the freezing season was delayed into mid-November. Thus, air temperatures during the study period were significantly higher than normal, affecting the permafrost thermal regime, as the time available for the ground cooling was shorter than in other years. Within the study sites, the average air temperature during the 2016-2017 hydrological year ranged from -1.2°C at Kapp Linné (Isfjord Radio), to -3.8°C at Janssonhaugen (Fig. 1). In general, air temperatures decreased with distance from the coast, in a northerly direction and with altitude. These trends illustrate the increasing degree of continentality moving east (cf. Gjelten *et al*. 2016) and cooling with elevation. Precipitation amounts were additionally greatest at the coastal sites, 656 mm in Ny-Ålesund, 711 mm in Kapp Linné (Isfjord Radio), 849 mm in Barentsburg, and 754 mm in Hornsund, and lowest at the more continental site in Longyearbyen (Svalbard Airport) with 305 mm.

Compared to the Arctic regions in Russia and North America, the ground thermal records in Svalbard are of short duration (Romanovsky *et al.*, 2010). Fragmentary ground temperature data were first obtained at Kap Thordsen, in central Svalbard from 1882 to 1883 during the first IPY (Ekholm, 1890; Wood and Streletskiy, 2008). Since then, however, systematic permafrost temperature measurements extend back to 1998 (Isaksen et al. 2001; Christiansen *et al.*, 2010; Boike et al. 2018). Ground temperatures have been reported to increase over the duration of this period of time at both the Adventdalen (Janssonhaugen), Kapp Linne and Ny Ålesund sites, whereas such long records do not exist from the other two sites (AMAP, 2017; Romanovsky et al., 2017; Boike *et al.*, 2018). These changes conform to observations from throughout the circum-Arctic (IPCC, 2013; AMAP, 2017). It should therefore be recognized that ground temperatures from the 2016/2017 hydrological year are likely to be among the highest during the period of the instrumental record, when also air temperatures peaked.

Svalbard permafrost observations

Ground thermal conditions studied from boreholes in Svalbard all come from the five field sites: Ny-Ålesund, Adventdalen, Barentsburg, Kapp Linné, and Hornsund (Fig. 1). Borehole locations and metadata is provided in Table 1. Sites and instrumentation are discussed in detail below.

Ny-Ålesund

Meteorological data from Ny-Ålesund records a MAAT of -2.3°C and 656 mm of precipitation for the 2016-2017 hydrological year. There are two boreholes at this location: DBNyÅlesund (48.5 m deep) and Bayelva (9.3 m deep). The DBNyÅlesund borehole is located at 55 m a.s.l. on *Kolhaugen*, between the coast and the Austre Broggerbreen forefield. The borehole stratigraphy consists of ca. 14 m of diamicton, possibly a glacial till, with bedrock from ca. 14 m depth. The gravimetric ice content of the permafrost ranges from ca. 10% to 40%, and no excess ice was observed. Several inactive sorted circles occur in the area as well as some soli-gelifluction lobes and terracettes. The Bayelva borehole is located between two mountains (Zeppelinfjellet and Scheteligfjellet), ca. 3 km from Ny-Ålesund. This borehole is located on top of the Leirhaugen hill, which consists mainly of rock, but is partly covered by till, together with fine-grained glaciofluvial sediments and clays. The vegetation cover is approximately 50–60%, with the remainder being bare soil with a small proportion of stones (cobbles and gravel; Lloyd *et al.*, 2001). The site is described by Boike *et al.* (2018).

There is a grid for recording active layer thickness in Ny-Ålesund next to the DB/Meteo borehole. Due to the blocky substrate, it is only possible to report the active layer depth as an average of 10 grid points, where thermistors are installed in combination with the borehole data. This is because probing in not possible.

Adventdalen

The Adventdalen study area is located in central Svalbard near the town of Longyearbyen. Average air temperature during the study period, as measured at the Svalbard Airport, was -1.9°C and approximately 305 mm of precipitation was reported. Five boreholes (Table 1) encompass the range in landform and local topographical locations which cause different ground thermal conditions, have been selected for this study: Endalen, Old Auroral Station 2, Breinosa, and Janssonhaugen. These sites have previously been described by Christiansen *et al.* (2010). Active-layer measurements are made in the UNISCALM site (Christiansen & Humlum, 2008) with 121 points in a 100 x 100 m site, monitored with 10 m grid size.

The 19 m deep Endalen borehole is located at 53 m a.s.l. and is drilled within a solifluction sheet. The stratigraphy at Endalen has 6 m of solifluction material overlying sedimentary bedrock. The 10 m deep Old Auroral Station 2 site is located at 9 m a.s.l and installed in an aggrading loess terrace. The borehole stratigraphy consists of sands and the gravimetric moisture content varies between ca. 30% and 150%. The 10 m deep Breinosa borehole is located at 677 m a.s.l in a blockfield consisting of *in situ* weathered bedrock. The Janssonhaugen boreholes –102 m and 15 m deep are located at 254 m a.s.l. and are drilled into fine-grained porous sandstones and siltstones. The vegetation cover on Janssonhaugen is sparse and surficial deposits are made up of *in situ* weathered bedrock (Isaksen *et al*. 2001).

Barentsburg

The Barentsburg study area is located at the mouth of Grønfjorden, in the vicinity of the Barentsburg mining settlement (Fig. 1). The average air temperature was -2.2°C and 849 mm of precipitation was reported during the study period. Long-term permafrost observations began at the permafrost site of the Russian Scientific Center in Svalbard in summer 2016 (Demidov *et al.*, 2016). Permafrost temperature observation sites are established in a sequence of Holocene marine terraces. Automated thermistor cables were installed in three boreholes, each 7 m to 15 m deep, to monitor the temperature close to the depth of zero annual amplitude and seasonal distribution of the zero-degree isotherm. Data from the 2016/2017 hydrological year is only available from borehole 12, which is 15 m deep. Permafrost temperatures from two additional boreholes (borehole 2, 7.5 m deep and borehole 8, 15 m deep) will be available in the coming years.

Borehole 12 was drilled during coal exploration in the early 1930s. The borehole was cased and instrumented for ground-thermal monitoring in August 2016. It is situated on a gently inclined surface, sloping 2° to the NW, at the top of a set of marine terraces near the Barentsburg aerodrome. The soil is 80 % plant-covered and 20 % covered by rocks. Geologically, the borehole site has fractured sandstone and mudstone overlain by 2 m of gravelly loam with rocks. The terrace surface around the borehole has a poorly defined pattern structure. A 15 m thermistor cable is installed in this borehole.

A CALM site was established in September 2016 including 121 point with a 10 m grid size. In September 2017, the CALM site was reduced to a 5 m grid size to observe in a more homogeneous setting. Stratigraphically the CALM site has interlayering sand, loam and clay with rare boulders. The surface has a distinct pattern structure with sorted circles.

Kapp Linné

The Kapp Linné region in western Spitsbergen (Fig. 1) has a maritime and relatively warm local climate. Mean air temperature and precipitation sum at the nearby meteorological station at Isfjord Radio during the study period was -1.2°C and 711 mm respectively. Two boreholes are located at this site: Kapp Linné 1 (KL-B-1) and Kapp Linné 2 (KL-B-2). Kapp Linné 1 is 29 m deep and drilled into an outcrop of silicified carbonate and clastic sedimentary bedrock. Kapp Linné 2 is 38 m deep and drilled through ~6.2 m of gravels overlying the same type of bedrock. Both boreholes are located on a strandflat, with extensive coarse-grained raised marine beach ridge at ca. 30 m a.s.l. (Christiansen *et al.*, 2010). The sites were established to test the variability between sedimentary and bedrock boreholes, as they are only 200 m apart on the strandflat.

Hornsund

The Polish Polar Station Hornsund is located on the northern shore of the Hornsundfjord on Wedel Jarlsberg Land in SW Spitsbergen (Fig. 1). The mean annual air temperature at the metrological station was -1.3°C and 754 mm of precipitation was reported during the study period. Since July 1978 shallow year round ground temperature observations were established. Variations of ground thermal conditions for the entire study period were measured within the top one meter of the ground surface only near the meteorological station. In spring 2017, three additional boreholes (10 m to 20 m deep) were established. The first deeper full-year permafrost time-series will be available from summer 2018. The ground temperature data included in this report consist of the near-surface ground temperatures together with the ground temperature measured at 12 m depth, which is only recorded in July and August 2017, near the meteorological station. The temperature at 12 m depth, has measured in a new deep borehole at the meteorological station, and has been included as a preliminary estimate of ground temperature near the depth of zero annual amplitude.

Ground thermal regime & active-layer thickness 2016-2017

Permafrost thermal state

Mean ground temperature measured at the depth of zero annual amplitude (ZAA) (Table 2), or the depth at which there is no annual fluctuation in the ground temperature, provide the point to monitor the response of permafrost to climate change. Ground thermal profiles recorded throughout the period are summarized in Fig. 2 and Fig. 3. The highest mean ground temperature was observed as -1.1°C in Hornsund, but only measured during 2 months (so not yet a full year). The highest full-year permafrost temperature measurement at -2.3°C was recorded at Barentsburg, which was then higher than the -2.6°C and -2.8°C recorded further out at the west coast at Kapp Linne. Adventdalen had the lowest permafrost temperatures at -5.2°C, but with a rather large variation with up to -2.7°C for the Endalen site. The permafrost in the Ny-Ålesund area is almost as warm as the other west coast sites with respectively -2.8°C and -3.1°C. The -3.1°C value measured in the deep borehole show somewhat colder conditions in this northern most part.

The mean ground surface temperatures and mean temperature at the permafrost surface were highest closest to sea level (Fig. 3; Table 2). Comparing all sites, the air temperature range was 2.6°C, whereas there was 4.5°C of variation in mean temperature at the ground surface. In addition, a large degree of local variation in temperatures at the ground surface and permafrost surface are identified, particularly in Adventdalen, where more boreholes exist. The range and local variation in mean ground surface temperature is attributed to the effect of snow, which is unevenly distributed throughout the landscape due to variations in topography and wind-exposure. Sites such as Endalen, which experience thick and long-lasting snow cover, have a higher mean ground surface temperature of 0.4°C. Sites where relatively little snow accumulates however, are comparatively cooler even with a distance of only 500 m apart, such as the Old Auroral Station 2 which measures temperatures of -1.3°C.

Generally both the permafrost surface temperatures and the permafrost temperature at ZAA were lower than the air temperatures. This and the shape of the ground thermal profiles (Fig. 2) show warming permafrost conditions.

Table 2: 2016-2017 hydrological year thermal characteristics, snow conditions, and active-layer thickness at the permafrost borehole sites. Reported active-layer thickness determined by interpolation.

Location	Borehole name/ ID	MAT (°C)	MGST (°C)	
Adventdalen	Old Auroral Station 2	-1.9	-1.3	
	Endalen	-1.9	n/a	
	Breinosa	-3.8	-4.1	
	Janssonhaugen/ P10	-3.8	n/a	
	Janssonhaugen/ P11	-3.8	-3.7(0.2 m)	
Ny Ålesund	Bayelva	-2.3	-3.6	
	DBNyÅlesund	-2.3	-2.8 (0.3 m)	
Kapp Linné	Kapp Linné 1	-1.2	-1.6	
	Kapp Linné	-1.2	-1.6	
Barentsburg	Borehole 12	-2.2	-0.8	
Hornsund	Meteo	-1.3	-1.0	

MAT = mean air temperature (at nearest meteorological station)

MGST = mean ground surface temperature

MPST = mean temperature at the permafrost surface

MGT = mean ground temperature (at depth of zero annual amplitude if different from total borehole depth or at lower most sensor)

ALT = active-layer thickness (as estimated from interpolating the depth of the 0 °C isotherm)

**Only recorded during July and August 2017*

MPST (°C)	MGT (°C)	Duration of AL freeze-back (days)	Maximum snow depth (cm)	ALT (cm)
-3.2	-5.2 (9.9 m)	22	ca. 20	94
-0.5	-2.7 (19 m)	140	ca. 50	190
-4.0	-5.1 (10 m)	18	<50	49
n/a	-5.0 (20 m)	n/a	<20	n/a
-3.7	n/a	41	<20	185
-2.7	-2.8 (9 m)	49	< 30	200
-2.7	-3.1 (20 m)	35	<30	192
-1.8	-2.6 (20 m)	44	<10	300
-1.5	-2.8 (20 m)	49	<10	190
-1.3	-2.3 (15 m)	59	ca. 20	175
n/a	-1.1* (12 m)	n/a	46	n/a

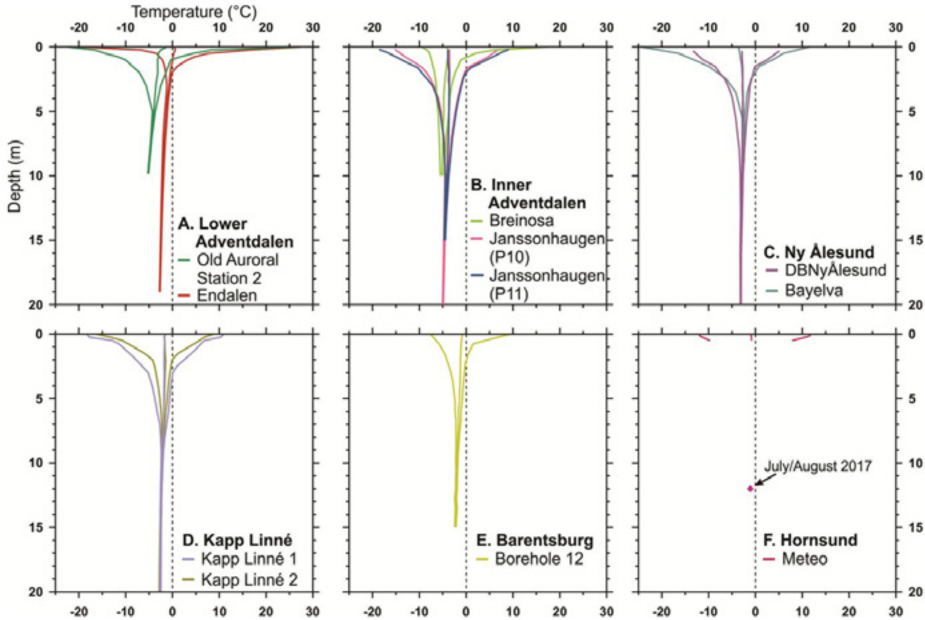

Figure 2: Ground thermal snapshot (minimum, mean, and maximum temperatures) as measured in the upper 10 to 20 m of the permafrost observation boreholes in Svalbard during the 2016/2017 hydrological year.

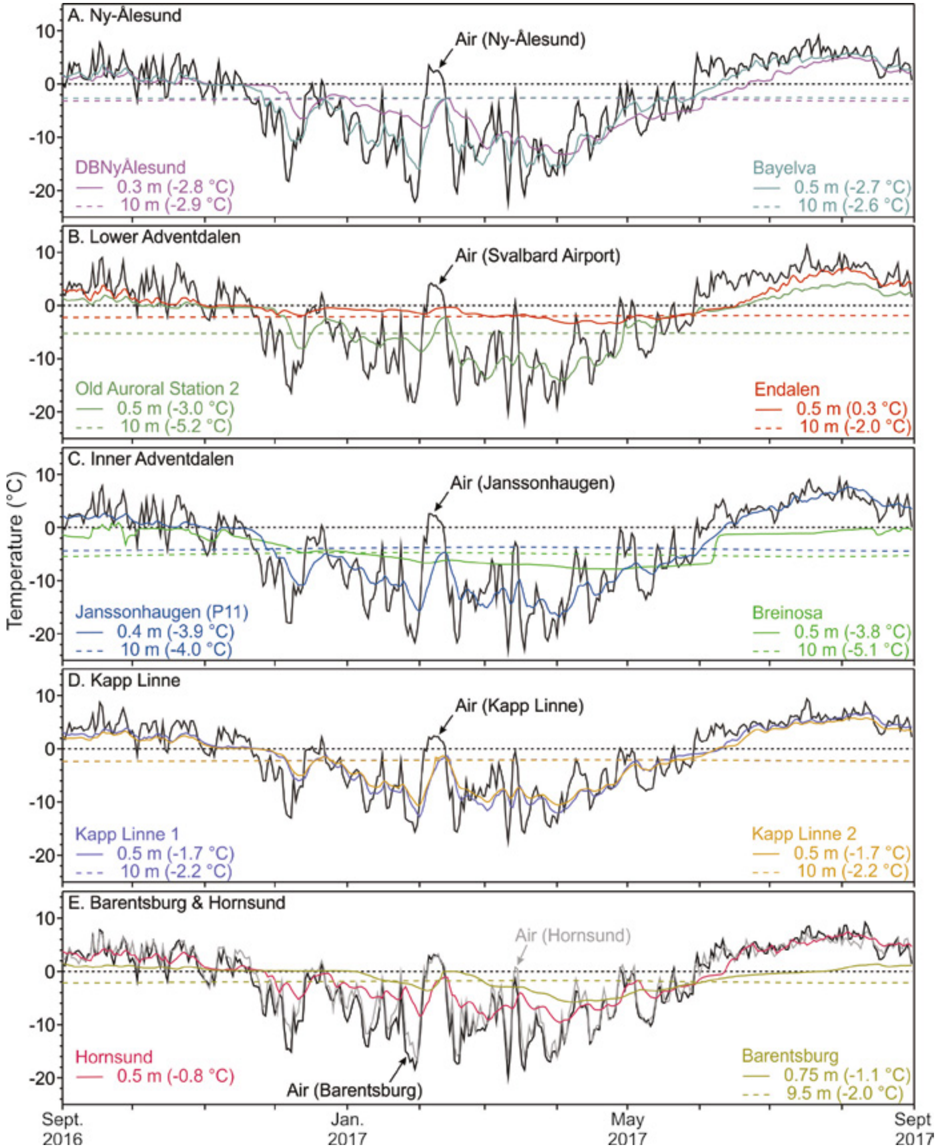

Figure 3: Continuous air and ground temperatures during the 2016-2017 year for the five permafrost observations sites in Svalbard. The presented selected sensors are located approximately in the middle of the active layer at 0.5 m depth (or as close to as possible) and at 10 m depth (where possible). The mean ground temperature, calculated at each depth, is presented in brackets.

Active-layer thickness

The active-layer thickness, as measured in autumn 2017, is presented in Fig. 4 and Table 2. Except for the CALM sites in Barentsburg and Adventdalen, active-layer thickness was estimated by interpolation of the zero-degree isotherm. Active-layer thickness in the study area ranges between ca. 49 cm (Breinosa) and ca. 300 cm (Kapp Linné 1), with most sites falling in the range of 100 cm to 200 cm. Spatial trends in active-layer thickness are difficult to discern due to the range in factors which influence ground thawing. However, boreholes in bedrock (Janssonhaugen & Kapp Linné 1) generally have a thicker active-layer than those in soil or sediment, due to lower ice content and a higher thermal conductivity. The thinnest active layers are in the more continental parts of the archipelago in a high-lying coarse-grained blockfield and in sediments with higher ice content.

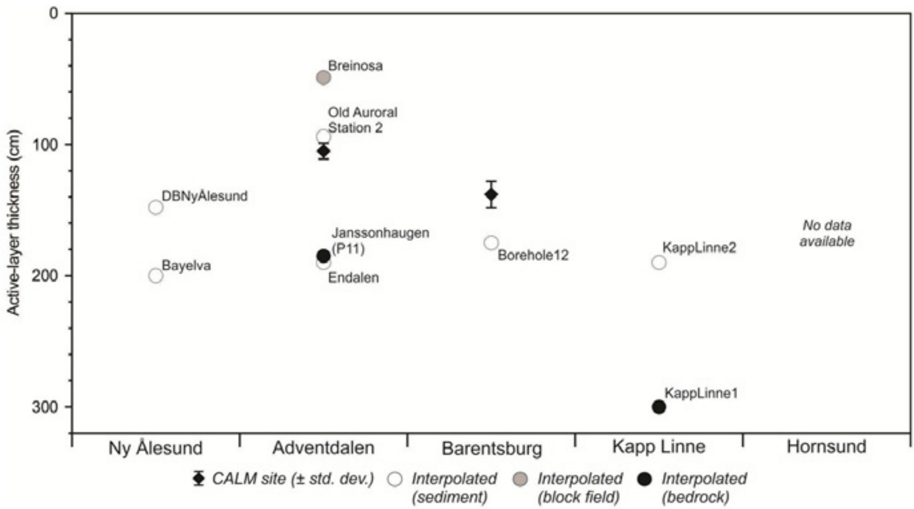

Figure 4: Active-layer thicknesses recorded at the end of August, 2017 from CALM grids and interpolated from the reported boreholes. The active-layer at the Bayelva site in Ny Ålesund was estimated using the Stephan equation. Note shading denotes substrate type.

Active-layer freeze-back duration

The duration of the active-layer freeze-back, measured as the period extending from when sustained freezing temperatures are established at the ground surface to when the temperature at the permafrost surface begins to decline, record when a complete phase change has occurred. Freeze-back durations are listed in Table 2, and range from 18 days to 140 days. At sites in block fields (Breinosa) and relatively dry locations (Old Auroral Station 2), freeze-back occurs quickly (18-22 days). At sites with a thicker active-layer and higher soil moisture content (e.g. Endalen) the period of active-layer freeze-back occupies a significant fraction of the freezing season (140 days). The duration of freeze back is important in regulating when permafrost cooling can begin. Therefore, sites with long active layer freeze-back commonly have higher permafrost temperatures, as a smaller proportion of the freezing season is available for permafrost cooling (Table 2).

During the 2016/2017 hydrological year, ground freezing initiated in November. As a result active-layer freeze-back extended into December or January at most sites, and into April at the Endalen location. The net effect of this was relatively high temperatures in the near surface of the ground-temperature profile (Fig. 2). This effect is also observed when comparing temperatures at the permafrost surface and ground temperatures (Table 2). In all cases, temperatures at the permafrost surface are significantly higher than at depth.

Conclusion

The reported ground temperatures and active layer thicknesses illustrate the range in the observed permafrost conditions in Svalbard in 2016-2017. In general, westerly sites, close to the coast are warm, while sites at higher elevations or in the more continental central parts of Svalbard are cooler. Exceptions are sites which experience a thicker winter snow pack. The following points summarize the observed distribution of ground temperatures and active-layer depths in Svalbard:

- Mean annual air temperature and total precipitation during the study period ranged between -1.2°C and -3.8°C, and 305 mm and 849 mm, respectively at the five studied permafrost sites in western and central Svalbard. In general, maritime sites situated closer to the coast were wetter and warmer than those in more central areas or at higher altitudes. In this particularly warm hydrological year 2016-2017 ground freezing only started in November, with active layer freeze-back lasting from December to April for the studied sites. This causes relatively high permafrost temperatures in the top permafrost.
- Permafrost temperatures were highest at coastal sites or where a thicker snow cover during winter occured. Mean annual ground surface temperatures during the

2016-2017 hydrological year (1 September 2016 to 31 August 2017) observed in boreholes in the five permafrost study sites in Svalbard, ranged from -1.0°C to -4.1°C. Mean annual temperatures at the permafrost surface ranged between -0.5°C and -4.0°C, and permafrost temperatures at or close to the depth of zero-annual amplitude varied from (-1.1°C) -2.3°C to -5.2°C. Differences are attributed to variations in snow cover, landforms, the degree of continentality and ground ice contents. All the results clearly show that we have rather warm permafrost in extensive parts of particularly the lowland Svalbard landscape, which is especially sensitive to climatic warming and where the population is living. Along the west coast there is a clear gradient from the warmest permafrost in the south at Hornsund -1.1°C, over -2.3°C at Barentsburg, and to the coldest in the north at Ny-Ålesund with -3.1°C.

- The thickness of the active layer, as measured in autumn 2017, varied from 49 to 300 cm, but generally fell within the range of 100 cm to 200 cm. The thinnest active-layers are reported from blockfields at higher elevations and in sediments. Thicker active-layers are encountered in bedrock settings.

Future permafrost observations in Svalbard

Previous observations have focused on understanding permafrost conditions near to settlements and research stations in western and central Svalbard. However, ground thermal conditions are not likely to be representative of the northern and eastern reaches of the archipelago, where the climate is considerably cooler. Future observations efforts will therefore focus on characterizing permafrost environments in northern and eastern parts of Svalbard. Including such areas will most likely allow observations of the full diversity of permafrost conditions throughout the entire Svalbard landscape. New permafrost observations to be established in these areas will be co-located with automatic weather stations (AWSs) within the Norwegian project *SIOS – Infrastructure development of the Norwegian node* (*SIOS-InfraNor*) and potentially also by other SIOS partners in national or international collaborations. This will expand our existing understanding of permafrost conditions throughout Svalbard, and provide the baseline infrastructure required for observing responses of the Svalbard permafrost to climate changes.

In addition to the discussed ECVs for permafrost, ground-ice content is a key parameter for assessing the response of permafrost landscape to changes in climate. Where permafrost contains an abundance of ice, warming and thawing will lead to marked geomorphic change. In flat areas, ground-ice degradation can result in thermokarst and subsidence; excess water on slopes released during ground ice melting, particularly in the top permafrost, can initiate landslides. Degradation of permafrost through the increase in active-layer thickness is of significance for local ecosystems and hydrology. Nutrients, gasses and minerals frozen within the upper meters of the permafrost zone can be released into local eco- and hydrological systems during permafrost thaw. Continued research in these areas will further aid in coupling changes within permafrost to the remainder of the cryosphere, as is a goal for a better Earth System understanding.

Data accessibility

All reported data have been submitted into the GTN-P database (https://gtnp.arcticportal.org/). This includes both metadata and direct access to the data.

Acknowledgements

We are grateful to SIOS for supporting us to meet and discuss how to develop this reporting and for supporting working time to develop this report (Research Council of Norway, project number 251658, Svalbard Integrated Arctic Earth Observing System - Knowledge Centre (SIOS-KC)). Both the meteorological and permafrost data that this report is based upon has been funded by our national research councils and the participating institutions, which the authors are based in.

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Microbial activity monitoring by the Integrated Arctic Earth Observing System (MamSIOS)

2

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Keywords: bacteria, microorganisms, biogenic, ice nucleation, albedo, methanogenesis

Scientific background

Microorganisms, though already integral elements, are likely to play an increasingly important role in the Earth's climate system (Falkowski et al., 2008) and are known to affect polar biogeochemical cycles (Larose et al., 2013a). In particular, they play important roles in the generation and decomposition of climate active gases. However, current climate models do not take into account the response of microbial activity and their influence in biochemical cycles (Incorporating microbial processes into climate models, ASM report). To improve the predictive ability of climate models, it is important to understand the mechanisms by which microorganisms regulate terrestrial greenhouse gas flux and to determine whether changes in microbial processes will lead to net positive or negative feedbacks on greenhouse gas emissions (Singh et al., 2010). This contribution has been particularly overlooked for the polar regions (Figure 1), where the environment has traditionally been considered too harsh for significant microbial activity to occur. It has long been considered that any life, if present at all, was either dormant or functioning sub-optimally, as living organisms have to be well adapted or highly resistant to extreme cold and desiccation, low nutrient availability and seasonally variable UV radiation levels in order to survive (Harding et al., 2011; Cameron et al., 2012; Goordial et al., 2013; Larose et al., 2013a). However, it is now clear that microbial presence is ubiquitous across the polar regions, and recent research into the polar aerobiome points toward a potentially dynamic polar microbial community and with it, the possibility of significant microbial activity within the snowpack (Redeker et al., 2017), even in the most remote locations (Pearce et al., 2009). Research into the aerobiome has also demonstrated that microorganisms in aerial fallout may remain both viable and active (Sattler et al., 2001; Harding et al., 2011). Furthermore, the presence of microbes in remote, low nutrient, low water, very cold environments such as polar glacial surfaces is now well established for a number of key sites (Hodson et al., 2008; Larose et al., 2010).

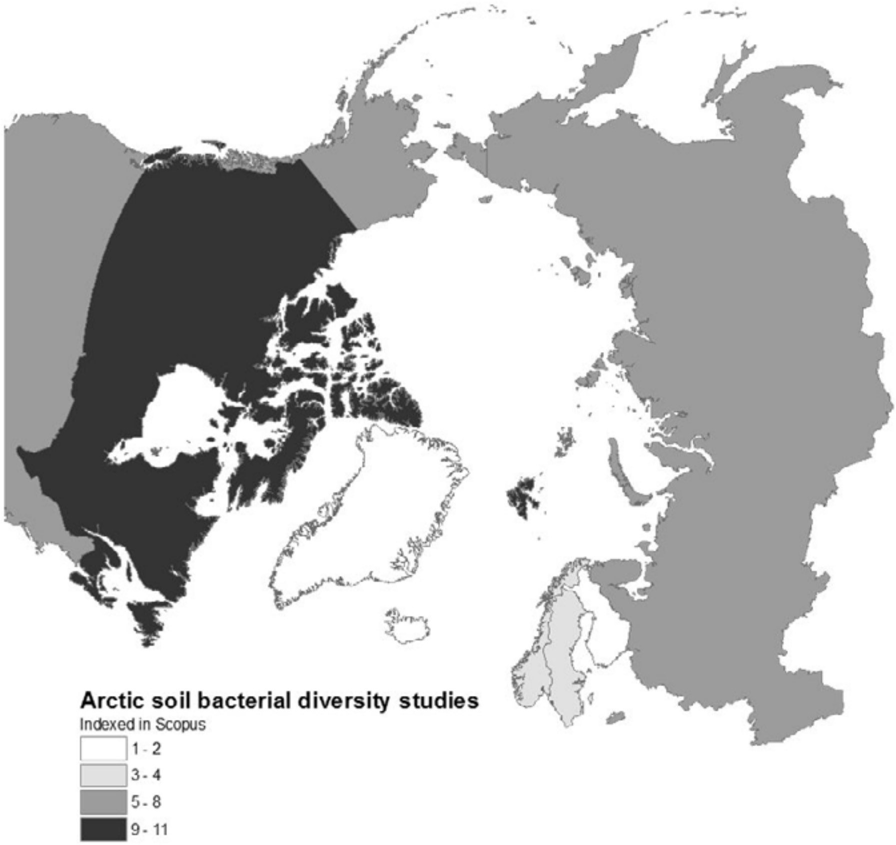

Figure 1: Soil bacterial diversity studies across the Arctic region as evidenced by publications in the literature cited in SCOPUS (2017). Adapted from Malard and Pearce (2018).

Polar terrestrial environments, including snow and ice, are dominated by microorganisms. Arctic soils are known to harbour significant microbial abundance and diversity, with huge potential to alter the global climate system. For example, Arctic soils alone are known to store over 1500 Pg of carbon (Koven et al., 2011) and, as the Arctic region continues to undergo drastic changes linked to human activities, the likelihood of release of greenhouse gases such as CO_2, CH_4 and N2O will continue to increase. Environments so far thought to be microbiologically inactive, such as ice caps and the polar firn, have increasingly been demonstrated to influence greenhouse gas cycling. These then present a huge potential for positive feedback effects on climate, highlighting the pressing need to understand and monitor changes in the abundance, diversity and particularly ecological function of microbial communities in the polar regions in order to produce more accurate greenhouse gas release models.

The polar cryosphere represents approximately 14% of the Earth's surface (Morita, 1975; Larose et al., 2010; Boetius et al., 2015; Lutz et al., 2016). In this region, microorganisms can thrive and are present in abundance. This includes the tundra (Lee et al., 2013), taiga (Neufeld and Mohn, 2005), snow (Larose et al., 2013a), glaciers (Anesio et al., 2009), permafrost (Mackelprang et al., 2011) as well as marine (Ghiglione et al., 2012), freshwater (Crump et al., 2012) and aerial (Cuthbertson et al., 2017) ecosystems.

Microbial metabolic activity can potentially influence climate and biogeochemical processes through:

1. Physical albedo (through ice nucleation activity and cloud formation)
2. Biological albedo (through significant pigmentation associated with snow algal blooms)
3. Methane cycling – production (methanogenesis)
4. Methane cycling - degradation (methane oxidation)
5. Carbon fixation (autotrophy and bacteriorhodopsins)
6. Carbon sequestration dynamics (in deep sea sediments)
7. Nitrogen cycling (in particular N_2O production)
8. Sulphur cycling (dimethyl sulphide production in soil)
9. Permafrost thaw (and the microbial response)
10. Recent discoveries (such as methyl halide degradation)

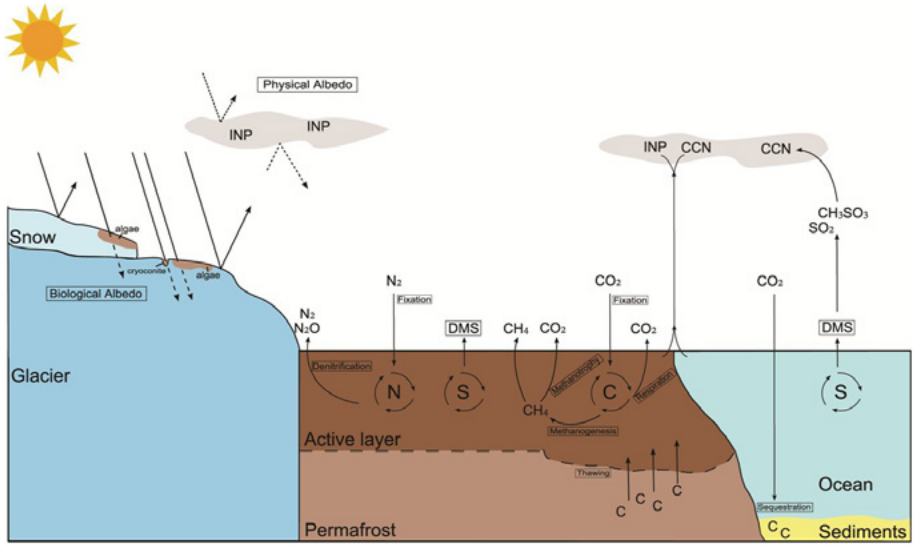

Figure 2: Diagram of microbial metabolic activities influencing climate and biogeochemical processes. Cloud condensation nuclei (CCN) and ice nucleating particles (INP) can come from all environments, including glacial ice, sea ice and snow. Sulphate aerosols such as Sulphur dioxide (SO_2) and methanosulphate (CH_3SO_3) react with cloud condensation nuclei (CCN).

Physical albedo (Ice nucleation)

Bacteria and other primary biological aerosol particles are now known to enhance cloud formation through acting as cloud condensation nuclei (CCN) or through the expression of ice nucleation proteins in their cell membranes, hence acting as ice nucleating particles (INP). Clouds play an important role in the global climate system (IPCC, 2013). Depending on their optical properties either their reflection of shortwave solar radiation dominates - hence exerting a cooling effect - or reflection of terrestrial longwave radiation dominates – resulting in a warming effect. The net radiative effect of a cloud is a function of its altitude, size, thickness, and the number of liquid droplets and ice crystals (Shupe and Intrieri, 2004). Furthermore, the brightness (albedo) of the underlying ground is decisive. This is particularly important in the Arctic, where snow and sea ice feature a very high albedo and clouds hence act as a 'blanket' increasing the temperature at the surface (Stramler et al., 2011). This effect is most critical in the transition from winter to spring time, when the Arctic becomes more cloudy and the net cloud radiative effect results in warming, moving the sea ice and snow closer to the melting temperature (Stramler et al., 2011).

With the recognition of the importance of cloud radiative effects on the Arctic cryosphere, it becomes apparent that improving the representation of cloud properties in climate models is essential. To date, however, a number of studies have shown that radiation biases through the misrepresentation of clouds in climate models are alarmingly high in the Arctic (Tjernstrom et al., 2008; English et al., 2014; English et al., 2015), in the range 10 – 25 W m_{-2}. For reference, an imbalance of +10 W m_{-2} is roughly equivalent to the annual loss of 1000kg of ice per m_2. One of the uncertainties associated with cloud properties in the Arctic is the presence of CCN and INP that determine the liquid and ice water content of the clouds and hence their optical properties.

The sources of aerosols for cloud formation in the Arctic are limited. Excluding situations in which long-range transport is present, for which it is known that the additional particles form clouds and modify their properties (Stohl et al., 2007; Maahn et al., 2017), microbial particles originating from the sea surface micro layer are thought to play an important role. The sea surface micro layer (SML) (Leck and Bigg, 2005) can contain aggregates of whole microorganisms, such as bacteria, viruses or phytoplankton, or their fragments, together with micro-gels or transparent exopolymer particles (Leck and Bigg, 2005; Hawkins et al., 2010; Russell et al., 2010; Orellana et al., 2011; Quinn et al., 2015; Schwier et al., 2015; Wilson et al., 2015). Several studies have stressed the importance of SML biological material as marine CCN and INP (Leck and Bigg, 2005; Bigg and Leck, 2008; Alpert et al., 2011a; Alpert et al., 2011b; Knopf et al., 2011; Karl et al., 2013; Heintzenberg et al., 2015; Wilson et al., 2015). However, other studies showed that marine micro-gels and bacteria have a low hygroscopicity (Després et al., 2012; Dawson et al., 2016). In fact, microbial exudates in seawater were found to decrease the CCN activity of sea spray particles (Wex et al., 2010).

Perhaps more important is the role of microorganisms to the Arctic INP population because of the presence of ice nucleating proteins on their cell surfaces. These ice nucleation proteins serve to encourage the crystallization of ice outside the cell and thereby protect the cell itself from ice damage. The expression of such proteins leads to the condensation of liquid water and freezing and hence enhances cloud production (Amato et al., 2005; Amato et al., 2006; Burrows et al., 2009; Bowers et al., 2011; Joly et al., 2013; Amato et al., 2015; Moffett et al., 2015; Moffett, 2015; Mortazavi et al., 2015; Šantl-Temkiv et al., 2015; Wilson et al., 2015; Hara et al., 2016; Lu et al., 2016; Smets et al., 2016). To date the quantity and origin of airborne INP over the remote oceans in general remains elusive (Bigg, 1973; Fall and Schnell, 1985; Rosinski et al., 1986; Junge and Swanson, 2008; Burrows et al., 2013; Wilson et al., 2015), even though research in the 1970s already showed that laboratory cultured phytoplankton can produce large amounts of INP (Schnell, 1975). The scarcity of data is particularly true for the Arctic where only very recently the role of marine organisms has been elucidated and particles < 0.2 µm, likely ultra-microbacteria, viruses or extracellular material from phytoplankton or bacteria exudates, were identified as candidates for INP (Irish et al., 2017). For a long time, no marine organism had been unambiguously identified as effective INP (Fall and Schnell, 1985; Junge and Swanson, 2008). Recently, Knopf et al. (2011) and Alpert et al. (2011a) were able to show that the marine diatom *Thalassiosira pseudonana* initiates ice formation under circumstances relevant to the marine mixed-phase and ice cloud regimes. Conversely, others attributed marine INP to the species' exudates, heat-sensitive organic material < 0.2 µm (Wilson et al., 2015). While there are indications that marine INP are associated with decaying phytoplankton blooms (Wang et al., 2015; McCluskey et al., 2017), the origin of INP remains completely unclear over ice covered regions like the central Arctic Ocean.

From the above, it is evident that the sources and activity of Arctic INPs are not well understood. However, to estimate the radiative properties of Arctic clouds in the future, to enhance e.g. sea ice predictions, understanding the mix of liquid and ice water content in clouds is important. It is known that liquid-only clouds have a three times stronger longwave radiative effect (warming) than ice-only clouds in the Arctic (Shupe and Intrieri, 2004). As the Arctic becomes rapidly warmer, the cloud water phase might shift toward more liquid clouds, resulting in positive feedback. However, if Arctic microorganisms were efficient INP and become more abundant in a warmer Arctic, e.g. through more exposed open ocean, they could induce a negative feedback. Some biological particles are known to be very efficient ice nuclei, and they can nucleate ice at temperatures as high as – 4°C (Després et al., 2012).

To understand what the source of INP in the Arctic are today, and how they will change and influence Arctic clouds in the future, dedicated studies need to be initiated. We suggest installing e.g. filter samplers at observatories and remote locations around Svalbard that represent marine and terrestrial aerosol sources. With these filters, ice nucleation studies can be conducted in parallel with microscopy and microbiological investigations that attempt to close the link between the presence of biological particles and INP concentrations.

Biological albedo: snow algae

Microbes can darken the surfaces of snow and ice, thus reducing its reflectance or albedo, and increasing the rate of ablation during the summer (Kohshima et al., 1994). The process is best understood in the context of the direct effects, which relate to the production of pigments in response to either high levels of irradiance or nutrient limitation (Cook et al., 2017b). Pigment change to an existing surface population, the exposure of a previously buried community and the proliferation of cells as a result of biological growth all result in darker snow surfaces, and thus enhance the melt for a given solar irradiance value. Heavily pigmented snows have been described in some of the earliest scientific literature from the polar regions (Horner, 2017). Ongoing research in Svalbard and elsewhere has sought a deeper understanding of the biosynthesis of pigments, in conjunction with work on cell physiology (Müller et al., 1998; Remias et al., 2005) and, more recently, molecular techniques (Lutz et al., 2015). Until recently, biotechnology, rather than an interest in bioalbedo *per se*, has been the principal driver of such research (Leya et al., 2009).

The indirect effects of microorganisms upon albedo, linked to the feedbacks associated with snow grain metamorphosis and increased water content adjacent to the cells, have been largely overlooked. This means our understanding of so-called "bioalbedo" is incomplete. The most promising way forward, resulting in a predictive understanding of how microorganisms influence the rate of snow ablation through both direct and indirect processes, involves the application of radiative transfer theory, rather than empirical techniques. However, establishing empirical relationships between cell biomass and snow albedo are still valid for monitoring purposes (Stibal et al., 2017). The fully physically-based approach offered by radiative transfer theory has resulted in a first generation of models that predict the spectral albedo of snow under different physical and biological conditions, the latter incorporating snow algal cell counts and pigment concentrations (Cook et al., 2017a). More recent work has refined the underlying physical basis of the modelling and has also developed a workflow for the successful measurement of snow algae and other parameters during fieldwork and sample processing (Cook et al., 2017b).

The links between cell biomass, albedo, and melting have led to great interest in the climate change feedbacks associated with snowpacks becoming wetter for longer periods during the summer, and therefore potentially darker on account of there being more opportunity for pigmented bloom development (Ganey et al., 2017). The direct link between pigment production and surface melt rate has been heavily exploited via the community response to funding calls. However, the spatial variability in snow biomass across large parts of the Arctic is poorly resolved and, hence, our understanding of the true impact of bioalbedo. Current work suggests that the direct influence of pigmented snow algae upon albedo is clear in some relatively large sub-Arctic 'snowfields' (Painter et al., 2001; Takeuchi et al., 2006; Ganey et al., 2017). These sites are fascinating, but there is a risk that the data they generate will be used to over-generalise the global influence of biological albedo forcing. Establishing the regional distribution of snow biomass is, therefore, a clear research priority, and Svalbard can offer much in this context with respect to the development, ground truthing and application of relevant techniques for addressing this problem. Furthermore, there also needs to be a better emphasis upon the vertical distribution of biomass, because solar radiation penetrates snow packs to enable sub-surface photosynthesis and biomass change (Hodson et al., 2017). The contribution made by the absorption of such light to snow grain metamorphosis and melt is almost completely unexplored.

Biological albedo: ice algae

The exposure of bare glacier ice following the retreat of seasonal snow is the largest event in the seasonal albedo evolution of glacier surfaces. This is because the ablation area of glaciers accumulates dust and other debris over long periods, resulting in a heterogeneous veneer of debris aggregates called "cryoconite" (Cook et al., 2016). Microorganisms play a cardinal role in the persistence and impact of cryoconite because they induce aggregation through bioflocculation (Langford et al., 2010; Takeuchi et al., 2010), often using debris particles as a surface for attachment and growth. The attachment processes are often facilitated by the production of extra-cellular exudates and aggregate growth can last for several ablation seasons (Takeuchi et al., 2001; Hodson et al., 2010). Measurements of the reflectance of dry cryoconite from a range of locations (including Svalbard) typically show values of < 20% across the entire visible to near-infra-red spectrum in cases where the granules contain an appreciable amount of organic matter (Takeuchi, 2002). When wetted by meltwater, the albedo of cryoconite granules can be as low as 5%, an order of magnitude lower than bare glacier ice with no such impurities, and almost 20 times lower than fresh snow (Bøggild et al., 2010). However, the thermodynamics of enhanced melting beneath cryoconite are such that the aggregates melt into the ice to become shaded, thus reducing their impact until they are melted out by non-solar-derived energy (turbulent heat fluxes). Therefore quantifying the impact of cryoconite upon ablation is not a simple calculation, as it depends upon the ratio of turbulent to radiative heat (Tedstone et al., 2017). Furthermore, the stronger the melt, the greater the probability that cryoconite and other dark impurities will be washed off the glacier (Takeuchi et al., 2003). However, one thing is clear, microorganisms are essential to the persistence and therefore the duration of biological albedo forcing on the ice surface. Svalbard research has been critical to the development of this realization and has been the location of many pioneering process studies (Cook et al., 2010) and monitoring applications (Hodson et al., 2007; Irvine-Fynn et al., 2011) relevant to bioalbedo. For example, airborne UAV mapping was pioneered in Svalbard (Hodson et al., 2007) some ten years before it was undertaken in Greenland (Ryan et al., 2018), where interest in ice surface albedo has received considerable recent coverage. Here, cryoconite is a strong contributor to the lowest albedo surfaces found in the so-called "Dark Zone" (Wientjes and Oerlemans, 2010; Tedstone et al., 2017). Future research in Svalbard can add a much-needed addition to that on Greenland, especially if the emphasis is given to its ice caps, which offer an idealized, whole system perspective on the life cycle of dust and other albedo-reducing impurities at a very manageable spatial scale.

In recent years, there has been increasing attention to the influence of heavily pigmented micro-algae growing on the ice surface and often between the melt pools formed by the denser, mineral-rich cryoconite (Yallop et al., 2012; Stibal et al., 2017; Williamson et al., 2018). Unlike cryoconite, algae such as *Mesotaenium berggrenii* do not melt into the ice and can develop strong purpurogallin pigmentation due to almost constant, direct illumination

(Remias et al., 2012). These algae, along with cryoconite, contribute strongly to albedo reduction in the important "Dark Zone" of the Greenland Ice Sheet, but research is required to understand their importance elsewhere. They are certainly present in Svalbard, but often not in high densities. Furthermore, the overlapping spectral reflectance characteristics of purpurogallins, dust, black carbon and other biological pigments such as chlorophyll, mean that unravelling their separate albedo influence will take some time and is beyond simple empirical techniques.

Future research in Svalbard and other areas subject to intense mass loss by surface melting will, therefore, have to address this problem. In so doing, particular attention needs to be given to the extremely complex nature of the upper metre or so of melting glacier ice: the so-called "weathering crust". Work in Svalbard and other regions has demonstrated that significant, additional complexity is associated with the transient water storage and ice crystal metamorphosis in the weathering crust (Cook et al., 2012; Irvine-Fynn et al., 2012; Rassner et al., 2016; Stevens et al., 2018). This storage provides prolonged opportunities for biological processes, but its rapidly changing reflectance properties will make accurate predictions of bare ice albedo and surface biomass distribution a major challenge for some years.

Methanogenesis (Methane cycling – production)

The active layer of permafrost is estimated to store 500 Pg of carbon while the permafrost in its entirety may store over 1000 Pg, giving an overall terrestrial Arctic carbon pool of over 1500 Pg (Koven et al., 2011; Mackelprang et al., 2011). In summer, the active layer affects soils thawing, leading to a sharp increase in microbial activity and thus, to increased nutrient cycling activity (Mackelprang et al., 2011). Although CO_2 will be released to the atmosphere upon permafrost thaw through increased microbial respiration, the release of methane in substantial amounts is more worrying to climate scientists, as it is a greenhouse gas over twenty times more potent than CO_2 (Wagner et al., 2005; Madigan et al., 2010; Coolen et al., 2011; Mackelprang et al., 2011). Methane is produced through anaerobic microbial respiration, exclusively by methanogenic Euryarchaeota (Mackelprang et al., 2011).

Research on methane biogeochemistry in Svalbard is dominated by the attention given to sea floor emissions (Sahling et al., 2014; Mau et al., 2017). This reflects the fact that very significant emissions of both biogenic and thermogenic methane occur along the continental shelf. Emissions also appear to have occurred in Svalbard fjords in response to deglaciation, resulting in multiple fjord floor features known as pockmarks (Crémière et al., 2016; Portnov et al., 2016). Recent research shows that the contemporary release of methane makes very little impact upon the methane content of the atmosphere on account of effective removal processes that include an active methanotrophic community in the sea (Gentz et al., 2014; Myhre et al., 2016) and sediments (Hong et al., 2016). However, it is not known whether methanotrophy and other removal processes accounted for as much of the emissions during ice sheet retreat and the formation of the pockmarks.

Research on the terrestrial methane cycle associated with Arctic soils, wetlands and lakes is well documented on account of the globally important organic carbon resource in permafrost and its sensitivity to climate change and permafrost thaw (Schuur et al., 2015). In Svalbard, research has therefore focused upon methanogenesis and methane oxidation in these habitats, albeit with less intensity than other Arctic regions such as Alaska and Siberia. One reason for this is the fact that yedoma-type sedimentary habitats, known for their very high organic carbon and methanogenesis potential, are not well represented in Svalbard, and especially near the international research station at Ny Ålesund. However, there have been meaningful emission studies in valley wetlands (Pirk et al., 2016; Pirk et al., 2017), glacier forefields (Adachi et al., 2006) and bird colonies (Zhu et al., 2012), as well as detailed studies of methanotrophy in Svalbard soils (Graef et al., 2011; Müller et al., 2018). These include molecular studies of both the methanogenic and methanotrophic communities (Wartiainen et al., 2003; Høj et al., 2005; Graef et al., 2011; Tveit et al., 2013; Tveit et al., 2014) and their response to climate change (Høj et al., 2006; Tveit et al., 2015). However, research on the source of atmospheric methane in the atmospheric boundary layer from Ny Ålesund has assigned little importance to local emissions, indicating instead that biomass burning, Siberian wetlands, and anthropogenic gas flares are the dominant sources (Fisher et al., 2011). The inference, therefore, is that rates of local methanogenesis are either low, or methane oxidation, including methanotrophy, is sufficient to minimize its influence on the local atmospheric boundary layer.

However, one significant issue that has been overlooked is that there are significant methane reserves beneath the permafrost with the capacity to by-pass methane oxidation in the active layer or water column. These include sub-permafrost ground water springs, which contain high dissolved gas concentrations up to the solubility limit for methane in water (ca. 41 mg L^{-1} at 0 °C) (Hodson et al, in review). The source of the sub-permafrost methane is a mixture of both thermogenic and biogenic methane. Strong relationships between the stable isotopic composition of the water and gas in the fluids escaping via springs point to an active methanogenic community of microorganisms beneath the permafrost that has yet to be characterized (Hodson et al, in review).

Methane oxidation (Methane cycling – degradation)

Methanotrophs are a highly specialized group of Gram-negative bacteria widespread in various environments that use CH_4 as the sole energy and carbon source (Hanson and Hanson, 1996). This functional group of bacteria therefore play an important role in modulating CH_4 fluxes, as they are the only known biotic terrestrial sink of CH_4 (Dedysh et al., 1998; Bárcena et al., 2011; Knief, 2015; Chiri et al., 2017). The common view has been that aerobic methanotrophs can only utilize C1 compounds, and are unable to grow on organic compounds with carbon-carbon bonds.

However, recent data have shown that *Methylocella* species can use compounds such as acetate as an energy source, this then suppressing their CH_4 oxidation (Dedysh et al., 2005; Theisen et al., 2005; Degelmann et al., 2010). Therefore, facultative methanotrophs that can use multicarbon compounds may also be found in various environments in addition to the obligate methanotrophs (Dedysh et al., 2005).

Carbon fixation (autotrophy and more recently bacteriorhodopsins)

The biological carbon cycle is driven by the interactions between photosynthesis, respiration, and decomposition (Horwath, 2015). The balance between these processes determines whether ecosystems are sources or sinks of carbon. In soils, cyanobacteria are largely responsible for CO_2 uptake, in addition to plants. Although they can be free living in tundra soil, mainly Oscillatoriales and Nostocales orders (Steven et al., 2013) are often identified in biofilms or soil crusts, where they are likely protected against environmental conditions (Zakhia et al., 2008). In soil crusts, Synechoccales, Nostocales, and Oscillatoriales have been consistently identified as the dominating orders of cyanobacteria (Yoshitake et al., 2010; Steven et al., 2013; Pushkareva et al., 2015). Studies of glacial forefields have also shown that cyanobacteria are early colonizers of soils, and generally, Synechoccales and Nostocales are the dominant orders (Kaštovská et al., 2005; Yoshitake et al., 2010).

Generally, Arctic cyanobacteria are psychrotrophic with specific adaptations to survive cold temperature, desiccation and UV radiation (Dodds et al., 1995). Increased polyunsaturated fatty acids in the membrane provide increased fluidity, complex DNA repair mechanisms allow UV damaged DNA to be repaired (Zakhia et al., 2008), while the production of akinetes facilitates survival when environmental conditions are not favourable (Olsson-Francis et al., 2009). Fixed carbon is then available for other microorganisms through the food web or through decomposition of organic matter.

Decomposition of organic matter can be a large source of CO_2 release to the atmosphere. Fungi are the main decomposers of organic matter in terrestrial ecosystems (Ludley and Robinson, 2008). Arctic studies have demonstrated that fungal communities are dominated by Ascomycota and Basidiomycota (Wallenstein et al., 2007; McGuire et al., 2013) and that communities are influenced by soil horizon, soil properties, depth, and vegetation (Wallenstein et al., 2007; McGuire et al., 2013). Other large sources of CO_2 release to the atmosphere include microbial aerobic respiration by heterotrophic organisms. The balance between photosynthesis, decomposition, and respiration will determine the amounts of CO_2 and CH_4 released to the atmosphere and consequently, their impact on Earth's climate.

Autotrophic CO_2 fixation is arguably one of the most important biosynthetic processes globally, if not the most important, being responsible for the net fixation of 7 x 10^{16} g carbon annually (Berg, 2011). This process is especially critical in oligotrophic environments, such as those found in Arctic terrestrial ecosystems, and can constitute the main carbon source for microbial communities inhabiting them. The photosynthetic path of carbon (reductive pentose phosphate - Calvin-Benson Cycle) was first discovered in the 1940s and fully characterized in the 1950s and since then, five more pathways have been elucidated. In order of discovery, these pathways are: the CB cycle, the reductive citric acid cycle (Evans et al., 1966), the reductive Acetyl-CoA pathway (Fuchs and Stupperich, 1980), the hydroxy-proprionate bi-cycle (3-hydroxyproprionate cycle) (Holo, 1989; Herter et al., 2002), the 3-hydroxyproprionate/4-hydroxybutyrate cycle (Berg et al., 2007) and finally the dicarboxylate/4-hydroxybutyrate cycle (Huber et al., 2008). The enzymes, oxygen requirements and organisms involved in each pathway are summarized in Table I. The variety and the distribution of these pathways in the environment is a reflection of both the ecological niches available and the diversity of organisms that have evolved to carry out this process (Thauer, 2007; Berg, 2011).

Table I: Summary of carbon fixation pathways (summarized from Thauer (2007) and Berg (2011))

Pathway	Environmental conditions	Organisms
Calvin-Benson Cycle	*Aerobic, anaerobic*	*Plants, algae, Cyanobacteria, Proteobacteria (anaerobes and aerobes, alpha, beta, gamma)*
Reductive citric acid cycle	*Anaerobic, microaerobic*	*Green sulfur bacteria, Proteobacteria (delta, epsilon), Nitrospirae, Thermoproteus (anerobic Crenarchaeota), Aquifex/ hydrogenobacter*
Reductive Acetyl-CoA pathway	*Strictly anaerobic*	*Methanogenic archaea, acetogenic bacteria, anaerobic ammonia-oxidizing planctomycetes*
3-hydroxyproprionate cycle	*Neutrophilic, alkaliohilic*	*Green nonsulfur bacteria Chloroflexus*
3-hydroxyproprionate/4-hydroxybutyrate cycle	*Aerobic, microaerobic*	*Microaerophilic Crenarchaeota (Metallosphaera, Sulfolobus, Acidianus, Nitrosopumulis, Crenarchaeum)*
dicarboxylate/4-hydroxybutyrate cycle	*Anaerobic*	*Crenarachaeota, Thermoproteales, Desulforococcales*

Aquatic environments - Carbon fixation has been identified and characterized in several aquatic- terrestrial ecosystems such as cryoconite (Stibal and Tranter, 2007), perennial cold springs (Perreault et al., 2008) and Arctic lakes (Markager et al., 1999). Microbial communities in cryoconite holes both respire and photosynthesize at rates comparable to microbial ecosystems in much warmer nutrient-rich environments (Hodson et al., 2007; Anesio et al., 2009; Anesio et al., 2010; Hodson et al., 2010; Telling et al., 2011). In cryoconite holes, laboratory experiments suggested that cyanobacterial photosynthesis (75–93%) was the main process responsible for inorganic carbon fixation, while heterotrophic uptake (6–15%) only accounted for a minor part. The major sources of primary production in Arctic lakes are phytoplankton, aquatic plants, benthic macroalgae, photosynthetic microbes, and chemosynthetic bacteria, but their photosynthetic yields have been shown to be three- to six-fold lower than for polar marine environments, which is likely due to nutrient limitation (Markager et al., 1999). Primary production by chemoautotrophs was shown to be an important process in perennial cold springs, and they represented up to 40% of the total microbial community (Perreault et al., 2008).

Snow - Snow algae are a group of freshwater algae representing several genera that are capable of thriving on semi-permanent to permanent snow and ice fields in polar and alpine regions (Kol and Flint, 1968). In a recent survey of 21 glaciers across the Arctic, Lutz et al. (2016), showed that snow algae were cosmopolitan, and that their biodiversity was low. In wet, carbon and nutrient rich green snow, *Microglena* spp. dominate, while dry, nutrient poor red snow is colonized by *Chloromonas* spp. In dry, cold snow packs, algae are rarely observed, however, autotrophic bacteria can be abundant (Harding et al., 2011; Larose et al., 2013a).

Soils - Carbon fixation is a critical process in Arctic soils, especially in recently deglaciated forefields. Prior to plant colonization, microorganisms use both autochthonously produced and allochtohonously delivered nutrients for growth (Bradley et al., 2014). Based on a combined field, laboratory and modelling approach, Bradley et al. (2016) showed that initial microbial communities were dominated by bacteria outwashed from the glacial environment, while older soils were characterized by autotrophic and heterotrophic bacteria. In older, established tundra soils, carbon fixation is also an important process. The presence of a permafrost layer, in addition to high soil moisture and low organic carbon concentrations, limits air diffusion in Arctic soils (Bockheim and Tarnocai, 1998), likely favoring carbon fixation. Based on recent work by Šantrůčková et al. (2018), dark CO_2 fixation appears to be a ubiquitous process in Arctic tundra soils, which becomes increasingly important with soil depth. This process, involving carboxylase enzymes, was shown to account for up to 16% of net respiration in permafrost soils and could be attributed to a broad range of heterotrophic microorganisms (Šantrůčková et al., 2018). However, dark inorganic carbon fixation was not linked to biomass production (Alonso-Sáez et al., 2010), suggesting that it may only enable microorganisms to maintain metabolic activity and not growth (Šantrůčková et al., 2018).

There is consequently an urgent need to understand the balance between fixation and decomposition of organic compounds through the microbial community, and in particular, its seasonal variability and long-term change.

Carbon sequestration (in deep sea sediment)

As the ice and snow retreat, soil formation leads to the creation of a standing carbon pool. Whilst this is dynamic, the average biomass of carbon remains locked in the solid phase. Fixation of atmospheric CO_2 by marine phytoplankton is an important mechanism by which CO_2 is drawn out of the atmosphere and sequestered in marine sediment (particularly deep-sea sediment). The efficacy of the process largely rests on the ability of the microbial community in the surface waters to break it down again and release it back into the atmosphere.

The deep ocean represents the largest active carbon sink on Earth (~38,000 Pg), with sediments also forming a globally significant reservoir (~6000 Pg) (Houghton, 2007). Ocean fertilisation with increased primary production and carbon fluxes into the deep ocean has been suggested as a potential way of removing or offsetting increased levels of atmospheric carbon dioxide. However, evidence suggests that in regions of high surface water productivity, most of the total primary production is consumed within the water column, where it either supports elevated biomass (Steinberg et al., 2008) or results in higher rates of microbial activity (Zubkov et al., 2007). Accordingly, carbon export from the surface layer and, in particular, the ability of the ocean and its sediments to sequester carbon for many years remains poorly understood.

In shallow seas, evidence for a clear link between bacterioplankton diversity and surface water productivity has been widely reported and both benthic and mesocosm studies have demonstrated that temporal changes in sediment bacterial abundance and distribution can be linked to surface-derived labile organic matter. Conversely, in the deep-sea, bacteria do not show significant differences in biomass and abundance with changes in depth, regardless of the continual decrease of food supply with increasing distance from the sea surface and from land. However, some studies have suggested a rapid increase in deep sea sediment bacterial activity in response to particulate organic matter input from the euphotic zone (Lochte, 1992; Witte et al., 2003; Moodley et al., 2005). Resource availability (derived from primary production) as well as microbial biomass may also be a key determinant of benthic biodiversity in marine systems. It has, therefore, been suggested that deep-sea processes are likely to differ from those occurring in shallow waters and the processes that define species composition in deep-sea sediments are largely unknown (Moodley et al., 2005).

High similarity between surface sediment bacterial communities from different productivity regimes reflects the stability of the deep-sea environment. Changes that occur in the water column and sediment contact water before reaching the sediment, however, suggest that additional carbon might be remineralized in the water column before it reaches the sea bed. This is mediated by combinations of changes in microbial community structure; microbial activity in the water column (Zubkov et al., 2007) and some two-fold higher respiration rates in the sediment. It is therefore possible that additional CO_2 fixation in marine surface waters will not lead to increased carbon sequestration in deep-sea sediment.

The difference between sediment and water column bacterial communities beneath areas of contrasting productivity indicates that most of the POM produced at the ocean surface is remineralized before reaching the sea bed. This suggests that enhancing atmospheric CO_2 sequestration through ocean fertilisation may not result in increased sediment accumulation.

Nitrogen cycling (in particular N_2O production)

Nitrogen is a key growth limiting nutrient in soil and can take many forms through various complex processes, driven by microorganisms. Nitrogen is often the limiting nutrient for plant growth, and thus, limits primary production (Chapin et al., 1991). Dinitrogen (N_2) is the most abundant form of nitrogen, yet, plants are unable to use it and only a small proportion of prokaryotes are able to fix N_2. Cyanobacteria, in addition to their role in CO_2 uptake, are the main N_2 fixers and thus, the main source of nitrogen in Arctic environments (Chapin et al., 1991). Specialized N_2 fixing species form heterocysts, which are specialized cells with thicker cell walls to protect nitrogenase from O_2 inactivation (Kumar et al., 2010). *Nostoc* sp. are found in abundance in Arctic soils (Dodds et al., 1995; Steven et al., 2013; Pushkareva et al., 2015), transforming N_2 into organic N, which can then be used by plants and other microorganisms. As most microorganisms cannot fix N_2, they use available organic nitrogen to produce ammonia/ammonium (NH3/NH_4^+) through ammonification. NH_3/NH_4^+ can then be oxidized through nitrification to form nitrite (NO_2^-) or nitrate (NO_3^-).

Some Betaproteobacteria, notably in the genera *Nitrosomonas* and *Nitrosospira*, are well known ammonia-oxidizing bacteria (AOB) (Fierer et al., 2007; Palmer et al., 2012) while Thaumarchaeota are ammonia-oxidizing archaea (AOA) (Alves et al., 2013). Studies have shown that, although AOB are often identified, AOA usually have a greater abundance (Leininger et al., 2006; Alves et al., 2013). Anaerobic oxidation of NH_3/NH_4^+ through anammox is carried out by Planctomycetes and leads to the production of N_2 (Humbert et al., 2010; Robertson and Groffman, 2015). Planctomycetes inhabit marine and freshwater environments but have also been identified in low abundances in terrestrial environments (Humbert et al., 2010), including in Arctic soils (Wagner et al., 2009; Hultman et al., 2015).

As only a limited number of studies have identified Planctomycetes in Arctic soils, whether they thrive there and are functionally active has not yet been investigated. Thus, rates of anaerobic ammonia oxidation in terrestrial Arctic environments are unknown. Some organisms can, in turn, take in NO_3^- and through denitrification, transform it to NO_2^- or even gaseous forms such as nitric oxide (NO), nitrous oxide (N_2O) or back to stable N_2. Nitrous oxide, a greenhouse gas, is 298 times more potent than CO_2 (IPCC, 2007; Palmer et al., 2012) and is also released upon permafrost thaw. When released in the atmosphere, N_2O reacts with ozone (O_3) in the stratosphere, damaging the ozone layer while forming nitrite (NO_2^-) which returns to the surface as nitric acid (HNO_2) in rain (Madigan et al., 1997; Fierer et al., 2007; Marushchak et al., 2011; Palmer et al., 2012). N_2O is produced through aerobic nitrification and anaerobic denitrification (Fierer et al., 2007; Elberling et al., 2010; Marushchak et al., 2011; Palmer et al., 2012). *Paracoccus denitrificans*, *Thiobacillus denitrificans* and some *Pseudomonas* sp. (Baumgärtner et al., 1996) are known denitrifiers but their presence in Arctic soils is still to be investigated, although many studies have shown denitrification occurs and N_2O is released to the atmosphere (Fierer et al., 2007; Elberling et al., 2010; Palmer et al., 2012). N_2O production seems to be strongly influenced by O_2 availability as well as moisture content in soils (Fierer et al., 2007; Elberling et al., 2010; Marushchak et al., 2011). The Arctic region was not considered a large N_2O producer until studies showed the potential release rate of N_2O into the atmosphere. In fact, studies have shown a large increase in N_2O production and subsequent release in the atmosphere following freeze-thaw cycles and rewetting of soils (Elberling et al., 2010). These rates of N_2O release are equivalent to the release of N_2O by tropical forests, which are among the top N_2O producers (Elberling et al., 2010; Palmer et al., 2012). Studies suggest that hotspots of N_2O production and release exist and further research should be conducted to provide estimations of N_2O release in the context of climate change and permafrost thawing (Elberling et al., 2010; Marushchak et al., 2011). The Arctic region should now be considered a potentially large source of N_2O emission and further studies are required to estimate the amounts released associated with climate change and Arctic warming.

There are currently four ongoing projects on N_2O emissions in Svalbard (RiS). All projects involve air sampling to measure N_2O levels in the atmosphere. However, no research is investigating sources and sinks of N_2O and the processes by which it is produced and released to the atmosphere. Investigating the nitrogen cycle in Svalbard soils through measurements of ammonium (NH_4^+), nitrite (NO_2^-) and nitrate (NO_3^-) combined with the investigation of microbial communities through 16S rRNA sequencing and shotgun metagenomics would provide information on the processes involved in N_2O production and emissions. It would also allow the identification of emission hotspots in Svalbard, as with cryoturbated peat soils identified in the Russian Arctic (Palmer et al., 2012).

Sulphur cycling (more recently the description of dimethyl sulphide production in soil)

Bacteria produce dimethyl-sulphide (DMS), traditionally considered to be an oceanic process. It is becoming increasingly apparent, however, that they can also generate DMS in terrestrial environments such as the soil (Levasseur, 2013; Carrión et al., 2015). This implies that existing estimates of DMS production from marine sources could be an underestimate for the polar regions as a whole. Sulphur is released through weathering and can then be mineralized, oxidized, reduced or incorporated into organic compounds (Kertesz and Frossard, 2015). *Thiobacillus* and *Acidithiobacillus* are the main genera of bacteria using S or S-compounds as their primary source of energy. Many heterotrophic bacteria are able to oxidize S-compounds, including members of *Bacillus, Micrococcus, and Pseudomonas* (Kertesz and Frossard, 2015). The sulphur cycle has been particularly studied in the atmosphere in association with marine environments (Levasseur et al., 1994; Levasseur, 2013). The largest concentration of DMS is found in surface seawater, and is the product of the degradation of dimethylsulfoniopropionate (DMSP) by phytoplankton (Dacey and Wakeham, 1986; Lomans et al., 1997; Bopp et al., 2003; Cameron-Smith et al., 2011). When DMS is released to the atmosphere, it can be oxidized into sulphur dioxide (SO_2), sulphate (SO_4^{2-}) and methanosulphate (CH_3SO_3) (Madigan et al., 1997; Ayers and Gillett, 2000; Bopp et al., 2003). Sulphate aerosols react with cloud condensation nuclei (CCN) and thus, participate in cloud formation over the oceans (Ayers and Gillett, 2000; Cameron-Smith et al., 2011). Conversely, when DMS is released in anoxic environments, it can be fixed to yield dimethyl sulphoxide (DMSO) or it can be used for methanogenesis, yielding CH_4 and hydrogen sulphide (H_2S) which in turn, if not oxidized, play an essential role in climate alteration (Lomans et al., 1997; Madigan et al., 1997; Lomans et al., 1999).

There are two ongoing projects investigating DMS concentration in the atmosphere around Svalbard (RiS) but none investigating production rates and emissions of DMS from terrestrial sources. Measurements of the different states of sulphur in soils such as reduced S (sulphotanes), oxidized S (sulphate esthers) and intermediate redox states (sulfones, sulfoxides), would provide a better understanding of the sulphur cycle in soils. These should be complemented by 16S rRNA and metagenomic studies to investigate the microbial communities actively involved in sulphur cycling. Measuring DMS concentration in the air over different regions of the Svalbard tundra would inform on the potential of soils for DMS production and emission.

DMS emissions have been extensively studied in the marine environment but the production of DMS by terrestrial systems has yet to be investigated. It is estimated that 80% of DMS emissions come from oceanic sources while the remaining 20% combine anthropogenic sources, potential terrestrial emissions and plant emissions (Schäfer et al., 2009).

Permafrost thaw (and the microbial response)

Polar environments represent some of the most extreme environments on Earth, and until recently the assumption of a biological inactivity was considered as well within reason. For example, Arctic average winter daytime temperatures range from -34° to 0° C, and available water, nutrients and sunlight are limited throughout the year (Przybylak et al., 2003). However, as the climate warms and the active layer of the permafrost starts to increase in depth, so this trapped carbon is increasingly being released leading to a positive feedback loop.

The Arctic includes some of the most rapidly warming regions on the planet. Arctic soils are thus currently the focus of intense research initiatives due to their recognized vulnerability to climate change, in particular with respect to the unknown consequences of warming on the enormous carbon reserves that are sequestered in permafrost. Permafrost is defined as material frozen for two consecutive years. Climate fluctuations in the Arctic are expected to have a major impact on soil microbial community composition and activity, and it is assumed that this will consequently affect nutrient turnover in Arctic soil environments. Measurements and monitoring of permafrost on Svalbard started seriously in 2000, although the surface few centimetre of soil where the large majority of microbial activity is, is not typically monitored in detail in permafrost studies (Convey et al., 2018), and since then the temperature has gradually increased. The year 2016 was measured as exceptionally hot, and in recent years, the rate of temperature increase has been very strong throughout the Svalbard region.

Permafrost in Svalbard is up to 450 m thick in the mountains surrounding Adventdalen (Liestøl, 1977) and thins towards the shore in the valley bottom (Humlum et al., 2003). Mean annual ground temperatures in Adventdalen vary from -3.5 to -6.9 °C (Christiansen et al., 2010; Cable et al., 2018). In Adventdalen, the active layer reaches down to about 1 m depth (Christiansen et al., 2010). Samples from the active surface layer are expected to have a higher microbial biomass and complexity compared to the deeper layers, including permafrost. In studies from permafrost cores collected in Adventdalen in 2012, a lower microbial diversity was found in permafrost compared to the active layer (Müller et al., 2018) and this is in agreement with studies reported from the Canadian Arctic (Mackelprang et al., 2011). In the samples from Adventdalen a distinct shift in community composition along the depth profile was seen, with a high biomass and diversity in the upper 60 cm representing the active layer. A distinct shift in community composition with a dominance of the phylum Bacterioidetes was reported indicating a transition zone. A further shift in composition occurred in the permafrost layer, where a microbial community strongly dominated by one single Actinobacteria family (Intrasporangiaceae) was seen. The contrasting abundances of these two taxa caused a community difference of about 60%, within just 3 cm from the transition zone and into the permafrost layer (Müller et al., 2018). Samples from the three distinct layers were used for incubation experiments at 4 (±1) °C to measure the potential for microbial activity response upon thawing using gas flux analysis (CO2, CH4, and N2O) to identify potential connections between the microbial community structure and greenhouse gas fluxes. Independent of soil layer and community structure, respiration rates were higher under aerobic than anaerobic conditions, with up to four times more CO2 produced. These results are in agreement with a permafrost study from Greenland (Elberling et al., 2013) and a comparative study investigating aerobic and anaerobic permafrost incubations from different locations in Alaska and Siberia (Lee et al., 2012).

Current studies focus on understanding the role of microbial communities in cycling of carbon and regulation of greenhouse gas fluxes. Although microbes are recognized as key players in these processes, their contribution is poorly incorporated into existing climate models. This deficiency is largely due to the difficulty in the study of largely uncultivated and unknown permafrost microbes. We need to improve our understanding of the underlying mechanisms that control microbial diversity in low temperature environments and the possible impact on these of climate variability in the Arctic. In order to properly understand how carbon processing is controlled by microorganisms in the Arctic and how these processes are impacted by climate change a combination of state-of-the-art sequencing and omics technologies to reveal the identities and functions of the key players in Arctic ecosystems is needed.

In transiently cold environments, methanogen communities have been shown to rapidly respond to moderate short-term increases in temperature, but not necessarily to the seasonal release of previously frozen organic carbon from thawing permafrost soils. As temperatures increase such inputs of carbon will likely have a greater influence on methane production and methanogen community structure. Understanding the action and limitations of anaerobic microorganisms within cold environments may also provide important information, which can be used in defining biogeographical differences in microbially-mediated processes, which ultimately control the methane flux to the atmosphere (Blake et al., 2015).

Recent discoveries (e.g. methyl halide degradation)

As frozen environments have increasingly become recognized as true habitats, their exploration has revealed high levels of microbial diversity and complexity using a combination of both culture-dependent and culture-independent techniques. In 2006 a novel methane-oxidizing bacterium, *Methylobacter tundripaludum* sp. nov., was isolated from Arctic wetland soil on Svalbard. Tveit et al. (2013) then reported a population of CH_4-oxidising bacteria closely related to *M. tundripaludum* to be the dominating active group of methanotrophs. Based on this in-depth characterisation of the microbes and their genes, they concluded that Arctic peat soils will in time become CO_2 sources owing to increased active layer depth and prolonged growing season. However, the extent of future CH_4 emissions will critically depend on the response of the methanotrophic bacteria. Microbial diversity has been studied in various habitats such as soil (Zhou et al., 1997; Chu et al., 2010; Edwards et al., 2011; van Dorst et al., 2014), ice (Junge et al., 2002; Brinkmeyer et al., 2003; Yu et al., 2006; Bottos et al., 2008; Collins et al., 2010), permafrost soil (Hansen et al., 2007; Steven et al., 2007; Wilhelm et al., 2011), sediments (Lysnes et al., 2004; Li et al., 2006a; Li et al., 2006b; Perreault et al., 2007; Forschner et al., 2009; Li et al., 2009; Bienhold et al., 2012; Zhang et al., 2014), snow (Larose et al., 2013b) and cryoconite (Edwards et al., 2011; Chrismas et al., 2016). Several organisms have also been cultivated, including a strain that is active at -15°C (Mykytczuk et al., 2013), thus challenging our perception of the limits of life. The desire to better understand the functioning of microorganisms in the cryosphere has led to discoveries of adaptations to conditions at both the molecular and cellular level, such as the synthesis of antifreeze proteins and cold-active enzymes (Feller and Gerday, 2003; Singh et al., 2014) that help them sustain metabolic activities of the cell at non-permissible temperatures.

High industrial/biotechnological interest has also been displayed in enzymes obtained from organisms living in extreme ecosystems because the harsh environments in which they live can provide analogous challenges to life to those found in certain industrial processes (Santiago et al., 2016). Psychrophilic enzymes have been shown to be advantageous over mesophilic/thermophilic enzymes, because of their high catalytic efficiency at low and moderate temperatures, leading to shorter process times and lower energy costs. These features have garnered interest from a variety of industries, such as molecular biology, medical research, industrial food or feed technologies, detergents and cosmetics (Kuddus, 2015). Some cold-adapted bacteria are already being used in waste water treatment (Margesin and Feller, 2010). These microorganisms and their genes could be invaluable also in the development of low temperature technologies for temperate climates, for example, low temperature anaerobic digestion, which could help pave the way to the low carbon economies we will need in the future. As sequencing technologies become more accessible, the potential for new discoveries is growing. Future research directions include the search for new antibiotic molecule discovery but also using polar microorganisms for bioremediation of contaminated sites (Kuddus, 2015).

Elsewhere, methyl halides are known to be produced and degraded by photochemical processes in the snow. It has recently emerged, however, that methyl halides can also be degraded through the action of microorganisms in the polar snowpack (Redeker et al., 2017).

Whilst it is clear that photochemical activity in the atmosphere is primarily responsible for climate processes, it is now becoming clear that microorganisms may have a significant role to play and our understanding of the extent of this role may be limited only by research activity in this area to date.

Future directions

Priorities and opportunities (for development under SIOS):

1. Conduct a comprehensive census of both microbial biodiversity and functional diversity on Svalbard

Much of the work concerning microbial communities on Svalbard to date is focused at key sites or around specific functional questions. In order to fully understand the role and activity of microbial communities, it is necessary to conduct a full and broad-ranging biogeographical microbial biodiversity survey, taking into account the full range of microbial life, from viruses to prokaryotes (eubacteria including cyanobacteria, Archaea) and eukaryotes (fungi and protozoa to pico-eukaryotes).

Recommendation: A comprehensive microbial biodiversity study across Svalbard

2. Look at the distribution of this diversity in terms of habitat type

Svalbard contains a wide range of habitats for microbial growth, from the rock itself (endolith and sublithic communities), diverse soil types (Malard and Pearce, 2018), freshwaters (including meltwater, streams, rivers and lakes but also the ice and snow itself), brackish and transitional waters to the marine ecosystem itself, and into the air. It also contains a wide range of 'hotspots' for specific diversity, such as hydrothermal systems, within and in association with animals and plants and acid mine drainage systems (to name but a few). A full habitat survey with respect to microbial communities would allow Svalbard to form a case study for the wider integration of microbial influences on climate active gas cycling across the globe.

Recommendation: A comprehensive habitat classification study across Svalbard

3. Determine the stability of the communities in which this biodiversity exists

Microbial communities are not static and are subject to strong and cyclical selection pressures in a relatively extreme environment. Coupled with this, microorganisms are raining down onto the surface from the atmosphere in precipitation and via air movements. For this reason, measuring activity at one point in time may not be representative of the community as a whole. We need to understand how these communities change over time (and in response to which environmental signals) to put their activity into context.

Recommendation: A time series study at a series of key 'indicator' sites to establish stability

4. Link this biodiversity & active gene composition to climate active gas flux (as measured currently)

There are current studies ongoing that are measuring the flux of climate active gases. These fluxes need to be matched to microbial activity at the location through functional gene enumeration, functional gene expression studies and stable isotope probing to start to unpick how much of the observed gas flux is influenced by microbial activity.

Recommendation: Link current and future flux measurements to concurrent microbial activity

5. Use this raw data to construct preliminary models in order to open the debate with the climate change community more widely about the relative significance and potential of microbially-mediated processes to generate a paradigm shift in our understanding of climate processes.

In order to determine the effect on the climate system, the impact of microbial activity toward climate active gases needs to be incorporated into global climate models. The best approach to enable this to happen would be to develop a case study that would demonstrate unequivocally that the impact is significant at the regional scale. Svalbard is ideally suited for this initial study given its research infrastructure, current monitoring capability, and field logistics.

Recommendation: Develop a small-scale model including microbial activity for Svalbard

Capacity building - Much of this work could potentially be conducted at current research stations on Svalbard. To enable this to happen the further development of microbiology facilities and infrastructure (such as class II microbiological safety cabinets, autoclaves, clean rooms, and molecular biology facilities) is an essential and pressing need.

Acknowledgements

This work was supported by the Research Council of Norway, project number 251658, Svalbard Integrated Arctic Earth Observing System - Knowledge Centre (SIOS-KC). In addition, this work was, in part, supported by a grant from the European Commission's Marie Sklowdowska Curie Actions program under project number 675546.

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Snow research in Svalbard: current status and knowledge gaps

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Keywords: snow, climate, cryosphere, glaciology, ecology, sea-ice

1 Overview

1.1 The importance of snow in Svalbard

Next to the ocean, snow is the second largest interface between the atmosphere and Earth's surface during winter. Snow deposited on land or ice surfaces is thermodynamically unstable and in constant evolution through snow metamorphism, which is controlled by temperature gradients in the snowpack. Seasonal snowpacks are therefore very sensitive to changing climate conditions. In Svalbard, the seasonal snowpack (including glaciers) covers ~60 to 100 % of the land between winter and summer. Changes in Arctic snowpack properties have been observed in the last decade in response to high-latitude warming (Bokhorst et al., 2016), and will likely continue in the future, with important anticipated effects on different aspects of the Svalbard environment, as reviewed below. Snow research could therefore become an important vehicle for monitoring and analysing the rate and effects of climate change in Svalbard. However, while efforts are on going to develop more and better remotely-sensed snow products for this region (Malnes et al., 2015; Aalstad et al., 2018), there are presently few regular *in situ* measurements in Svalbard for even basic snowpack properties (snow depth, density, temperature, hardness, the presence of ice layers, etc.). For example, Norway's Environmental monitoring of Svalbard and Jan Mayen (MOSJ) only reports snow cover duration data in three areas (Longyearbyen, Ny Ålesund and Sveagruva). More of these measurements, and others, are needed both to validate space borne observations, and to better understand and anticipate interactions between the changing snow cover and other Earth system components, i.e. the atmosphere, glaciers, soils, freshwater networks, the ocean and sea-ice. In what follows we discuss some of these aspects, with emphasis on recent research from Svalbard.

1.2 Snow-atmosphere interactions: Climatic and biogeochemical consequences

Owing to its high reflectivity (visible albedo of up to 0.9), snow cover plays a crucial role in Earth's energy budget (Lemke et al., 2007). Snow also has a very high specific surface area, allowing it to absorb and scavenge a wide variety of gases and aerosols from the atmosphere (Grannas et al., 2007; Nawrot et al., 2016), including some that affect its radiative properties. For example, many recent studies have focused on the black carbon (BC) content of Arctic snow packs (Aamaas et al., 2011; Forsstrom et al., 2009, Khan et al., 2017; Sviashchennikov et al., 2014), which reduces the albedo of snow because the BC strongly absorbs solar radiation (Pedersen et al., 2015; Warren, 1984; Sviashchennikov et al., 2015). Physical, chemical, and biological processes involving organic matter in the snowpack also have significant impacts on atmospheric and biogeochemical cycles of carbon, nitrogen and other elements (Morin et al., 2008; McNeill et al., 2012). For example, the photochemistry of organic compounds stored in the snowpack leads to volatile organic compound (VOC) production (i.e. CO_2, $CHCl_3$, $(CH_3)_2S$, CS_2, $CHBrCl_2$), and conversely acts as a sink for other compounds such as CO, COS, some halogenated compounds and hydrocarbons. As the Arctic climate warms, seasonal snow coverage is expected to decrease in some areas, exposing new sources of windblown dust and other aerosols, with impacts on the radiative balance of the atmosphere and cryosphere (Kylling et al., 2018). And as snow melts, the impurities stored within, including organic matter, nutrients, impurities and pollutants, can be released to the atmosphere or transferred by melt waters to soil or aquatic ecosystems (Kuhn, 2001, Björkman et al., 2014). Snow also provides nutrients for bacterial and fungal growth and acts as a habitat for a diverse community of micro-organisms (Maccario et al., 2014) that, if active, metabolize chemical compounds and contribute to changes in the composition of the snow and the overlying atmosphere (Domine & Shepson, 2002, Amoroso et al., 2010). These microorganisms can in return, modify the albedo of the snow/ice and affect glacier melt rates (Ryan et al., 2018). Understanding and quantifying these processes necessitates interdisciplinarity and the consideration of a large number of variables, some of which are still difficult to measure in the field and require very specialized instruments and field protocols. Some current process-oriented research in Svalbard contributes to address this knowledge gap (e.g. Björkman et al, 2014: Hodson et al, 2010; Larose et al, 2010), but there remains a great degree of unfulfilled potential which should be addressed in future research priorities.

1.3 Snow is key for glacial mass balance and climate modelling

Svalbard is an ideal physical laboratory for understanding how changes in snow cover can influence glacial processes, and its consequences for ecosystems. Snow is the dominant mode of accumulation on Svalbard glaciers and therefore controls mass balance change (van Pelt et al., 2016a; Sobota, 2017) due to its high reflectivity that regulates melting efficiency, and its porous properties that store significant volumes of melt (Østby et al., 2017, Christianson et al., 2015; Ivanov, Sviashchennikov, 2015). For example, snow can delay the melt season of glaciers by several days following just 1 to 2 cm of fresh snow fall in the summer (Box et al., 2012; Østby et al., 2013). Smaller, lower elevation Svalbard glaciers are cooling and undergoing a transition from poly-thermal to cold-based temperature conditions (e.g. Hodgkins et al., 1999), which has marked effects on glacier dynamics. Modelling studies have now demonstrated the importance of snow cover for both initiating and maintaining rapid ice flow at the bed of glaciers (Schäfer et al, 2014). Storage of melt water within snow also moderates the transfer of water to the snow/ice interface and further to the subglacial environment via moulins and crevasses, thus further influencing subglacial hydraulics and glacier dynamics (Irvine-Fynn et al., 2011). Therefore, changes in snow cover influences ice dynamics, mass balance and the cascade of melt water, and the sediment and solute (including nutrients) discharged by glacier-fed rivers during the summer (Hodson et al., 2005). However, due to the spatial variability of snow accumulation (Taurisano et al., 2007; Moller et al., 2011), and significant redistribution effects by wind (Sauter et al., 2013; Laska et al., 2017); determining the total amount of mass accumulated on glaciers is difficult, time-consuming and still requires ground validation (van Pelt et al., 2016b).

1.4 Importance of snow over sea ice

Sea ice that forms, grows, and melts on the ocean surface is primarily found in the Polar Regions and is generally overlain by snow. Climate change influences the extent and duration of sea ice cover (Arzel et al., 2006), which in turn affects ocean-atmosphere interactions and impacts marine ecosystems and biogeochemical processes (Montes-Hugo et al., 2009). Sea ice and snow packs are active interfaces, in which a range of physico-chemical and microbially mediated reactions involved in global biogeochemical cycles occur (Amoroso et al., 2010; Domine & Shepson, 2002; Larose et al., 2013a,b; Spolaor et al., 2014; Vancoppenolle et al., 2013). The most prominent example is the formation of reactive halogen species (e.g. Br atoms and BrO) over snow-covered sea ice (Simpson et al., 2007) that can destroy ozone in the boundary layer on a large-scale (Jacobi et al., 2010). Models predicting the consequences of sea ice retreat rarely describe snow cover further than a single layer with invariable properties, despite its dynamical changes and its critical role in modulating sea-ice melt and dynamics. For example, the high albedo of snow almost prevents the ice from absorbing energy and therefore reduces its melting. However, snow is also a very good insulator (Sturm et al., 1997), protecting the ice surface from cooling in winter, which consequently reduces its growth (Sturm et al., 2002). Due to the opacity of the sea-ice-snow system to incoming light, snow also controls the amount of light reaching the ocean surface, thus, controlling the phytoplankton production underneath sea ice (Fernández-Méndez et al., 2018).

1.5 Importance of snow for terrestrial ecosystems

The influence of seasonal snow cover on soil temperature, soil freeze-thaw processes, and permafrost (Etzelmüller et al., 2011, Gisnås et al., 2014) has considerable impacts on the carbon exchange processes and on the hydrological cycle in cold regions. Soil moisture is regulated by the supply of snowmelt water and rainfall as well as by the depth of the top layer of permafrost (thaw depth), which determines the level of groundwater during the growing season. Changes in snow depth and duration can have variable effects on plant growth and health (Opala-Owczarek et al., 2018). A warmer climate may lead to more frequent rain on snow (ROS) events and winter warm spells (Vikhamar-Schuler et al., 2016) with severe impacts for the vertebrate resident communities in Svalbard (sibling vole, Svalbard reindeer, rock ptarmigan and Arctic fox), where population growth rates, survival and reproduction success can be reduced (Hansen et al., 2011, 2013a; Stien et al., 2012). Ice on the ground also impacts the herbivorous populations in relation to foraging availability (Phoenix & Bjerke, 2016). More interdisciplinary research is required to link snow physical properties (such as e.g. snow cover, depth, thermal and optical properties, liquid water and ice content, permeability) to the biology of plants and animals. Changing snow pack properties can therefore, affect the linkage between plants and herbivores, not only by modulating available forage quantity during the ice-covered period, but also through changes to the abundance of forage plants during summer, which impacts animal energy use and their spatial and temporal habitat (Loe et al., 2016; Stien et al., 2010).

1.6 Importance of snow for high latitude communities and societies in Svalbard

In Svalbard, snow cover affects the entire environment but also has direct and indirect economic, social and cultural impacts, notably including snow avalanche risk (Eckerstorfer & Christiansen, 2012, Eckerstorfer et al., 2014) and fresh water supply in remote settlements like Longyearbyen and Barentsburg. Changes in the frequency and type of winter precipitation will change the avalanche hazard for structures, residents, and visitors in Svalbard (Bokhorst et al., 2016). As a result of more frequent large winter storms, snow clearing costs in Arctic settlements could increase. Regional increases in winter snow accumulation could also lead to a deepening of the permafrost active layer, destabilizing infrastructures on permafrost (Etzelmüller et al., 2011; Instanes, 2016). Conversely, earlier and/or increased snowmelt could cause flooding, and damage to municipal water pipes and drainage systems (Instanes et al., 2016; Shevnina et al., 2017), and the frequency of soil desiccation can affect living conditions. Snow environments also attract hundreds of thousands of (eco) tourists to Svalbard. The snowy spring period (March-May) is getting more attractive with the number of monthly guest nights in April growing from 4000 in 1995 to 16000 in 2015 (Eeg-Henriksen & Sjømæling, 2016). Whether these tourists are looking to observe biodiversity or enjoy outdoor winter activities (e.g. skiing, dog-sledding, snow-mobiling), snow cover changes will affect their recreational activities with important economic impacts for local stakeholders.

1.7 Snow precipitation, wind redistribution and sublimation

Meteorological observations have been conducted around Longyearbyen since 1912, presumably making this the longest record from the High Arctic (Nordli et al., 2014). The recorded precipitation is very low on average—about 190 mm annually—throughout the entire record, which suggests that this area is an Arctic desert. The an annual precipitation in Ny-Ålesund is slightly higher (385 mm) with most precipitation falling in August-October (mainly as rain) and March (mainly as snow), while May-June correspond to the lowest rates (Førland et al. 2011). For the entire Svalbard archipelago, annual precipitation is estimated to range from 190 to 525 mm (Førland, Benestad et al. 2011). The harsh weather conditions (e.g., blowing and drifting snow, undercatch in precipitation gauges during snowfall, and high wind speeds) complicate precipitation measurements in the Arctic (Førland et al. 2011). Despite new techniques, such as snow depth sensors (Hanne H. Christiansen, 2013), correct precipitation values are still difficult to obtain. The precipitation series from Norwegian Arctic stations share a common feature; they all show a positive trend in the annual precipitation through the period as a whole, even though they begin at different points in time (from MOSJ precipitation dataset). Furthermore, snow drift and sublimation could play an important role in snow accumulation and the formation of the annual snow strata (Pomeroy et al. 1998). In particular, wind erosion and sublimation can remove the snow accumulted in the coastal areas, thereby exposing the ground or the ground ice layer if present. Additionally, snow distribution by wind drift could produce accumulation areas and increase the risk of avalanches in certain areas (Eckerstorfer & Christiansen, 2011; Hancock et al., 2018).

2 Current snow-related research in Svalbard

Many different research groups from several countries and scientific disciplines have been or are currently investigating snow or snow-related phenomena in Svalbard. At least some of these groups have produced multi-year datasets of snowpack properties based on *in-situ* observations (Table 1). While some of these data are published (e.g. Boike et al., 2018; Ivanov et al., 2014; Kępski et al., 2017) or available on-line in data repositories, most are not. It would be beneficial to increase their accessibility through SIOS in order to reach a larger community of users.

Table 1: Lists, know to SESS authors, long-term snow related datasets. As open-data policies among research operators on Svalbard are still under development, most of the datasets are not yet accessible on-line.

Region	Responsible institution(s)	Land cover type	Data coverage *(Time coverage may differ for various snow properties)*	Data type(s)	Data access
Austfonna	UiO/NPI	Glacier	10 years	Snow depth, SWE	Data access on request.
Barentsburg	Murmansk Management of Hydrometeorological Service (Barentsburg research station), AARI	Land	Since 1947	Snow depth (routine measurements) since 1947. Snow-area surveys (surrounding glaciers in Grønfjorden area), since 2002.	Data access on request. Recent snow depth record can be decoded from Barentsburg WMO 20107 SYNOP messages
Pyramiden	AARI	Land, land-fast ice	1948-1957	Snow depth, snow-area surveys	Data access on request.
Central Spitsbergen	UU	Glacier	> 20 years	Snow depth, SWE, ionic composition of annual snow cover	Data access on request.
Hornsund	IG PAS	Glacier	Since 2005	Snow depth	Data accessible via Polish Polar Station Hornsund monitoring database https://monitoring-hornsund.igf.edu.pl
Hornsund	IG PAS	Land	Since 1983	Snow depth, SWE	Data accessible via Polish Polar Station Hornsund monitoring database https://monitoring-hornsund.igf.edu.pl

Hornsund	IG PAS	Land	Since 2014	Snow cover extent (time-lapse camera)	Processed time-lapse imagery for period 2014-2016 accessible via PANGAEA: https://doi.org/10.1594/PANGAEA.874387 Unprocessed imagery accessible via Polish Polar Station Hornsund monitoring database https://monitoring-hornsund.igf.edu.pl
Hornsund	US	Glacier	Since 2008	Snow depth (GPR profiles)	Data accessible via Center for Polar Studies database http://ppdb.us.edu.pl/geonetwork
Longyearbyen	UNIS	Glacier	10 years	Snow depth, SWE	Data access on request.
Longyearbyen	NVE	Land		Snow information related to avalanches (eg. imagery, field reports, snow profiles)	Data accessible via regObs data portal https://www.regobs.no/
Ny-Ålesund	NPI	Land, glacier	10 years	Snow depth, SWE Basal ice on land	Data access on request.
Ny-Ålesund	Met.no	Land	1978-2003	Snow depth	Data accessible via eKlima http://eklima.met.no/
Ny-Ålesund	AWI & others	Land	1998-2017	Snow depth and dielectric properties	Data accessible via PANGAEA https://doi.pangaea.de/10.1594/PANGAEA.880120
Ny-Ålesund	CNR-IDPA	Glacier	Since 2011	Chemical composition of annual snow cover	Data access on request.

Ny-Ålesund	CNR-ISAC	Snow- atmosphere	Since 2009	Vertical temp profile, Climate Change Tower (CCT)	Data access on request.
Ny-Ålesund	CNR-IIA	Land, glacier	2014-2017	Spectral albedo (CCT)	Data access on request.
Ny-Ålesund	CNR-IIA	Land, glacier	Since 1998	Spectral albedo on snow and ice on Brøggerhalvøya	Data access on request.
Ny-Ålesund	AWI-IPEV/CNRS	Land	Since 2016	Snow depth	Data access on request.
Ny-Ålesund	UiO	Land	2012-2014	Snow cover extent (time-lapse camera)	Processed time-lapse imagery for period 2014-2016 can be accessed via PANGAEA: https://doi.pangaea.de/10.1594/PANGAEA.846617
Svea	Met.no	Land	1974-1979; 2009-2018	Snow depth	Data accessible via eKlima http://eklima.met.no/

Acronyms: AARI: Arctic and Antarctic Research Institute (Russia); IG PAS: Institute of Geophysics, Polish Academy of Sciences; US: University of Silesia; NPI: Norwegian Polar Institute; UU: University of Uppsala; UNIS: University Centre in Svalbard; Met.no: Norwegian Meteorological Institute; NVE: Norwegian Water Resources and Energy Directorate; AWI: Alfred Wegener Institute for Polar and Marine Research; CNR: National Research Council of Italy; which includes IDPA: Institute for the Dynamics of Environmental Processes, ISAC: Institute for Atmospheric Science and Climate, and IIA: Institute for Atmospheric Pollution; IPEV: Institut Polaire Paul-Émile Victor, CNRS: National Research Center; UiO: University of Oslo.

2.2 Snow observation platform and data exchange

Currently several platforms exist for both researchers and the public to share and download snow related data (e.g. RIS, REGOBS, MOSJ or eKlima). However, these platforms are usually oriented towards single disciplines or report already processed data. For example, REGOBS mainly focuses on precipitation related hazards, while MOSJ reports mass balance data calculated from snow accumulation and snow melt data, the actual snow density and depth data are absent. Most snow related data from Svalbard are still stored at a personal, network or institutional level and then only available on request (Table 1). Several research organizations and institutes are planning to establish data bases for this kind of data. A common SOIS driven platform for including data stored elsewhere with the possibility to upload and credit new data sets, would therefore be a large contribution to the snow science community. Such a data portal would also benefit from societal inputs. The citizen driven REGOBS platform is a good example on how the public can be engaged in data collection as it improves avalanche prognosis for the region.

3 Knowledge trends, gaps and research needs

A bibliometric analysis was carried out to identify recent trends and possible knowledge gaps in snow-related research in Svalbard. The analysis was based on a survey of >205 peer-reviewed scientific articles published since Winther *et al.* (2003) last presented an overview of snow research in Svalbard. Figure 1 shows that field studies of snow/snowpack properties since 2003 have mostly been carried out near Ny Ålesund or Longyearbyen. These sectors are disproportionally represented relative to the remainder of the archipelago. Glaciers and lowland tundra environments are equally represented in field studies (~37 % of publications each), while snowpack properties on upland plateaus (above ~750 m a.s.l.) and on wetlands are, by comparison poorly studied. This reflects the predominance of glaciological and phenological research in the surveyed publications. Since the Winther *et al.* (2003) review, several new areas of snow-related research have also emerged, notably on snow-atmosphere and snow-soil chemical exchanges, and on microbial communities in snow (up to 5 times more publications between 2003-2018, relative to 1989-2003).

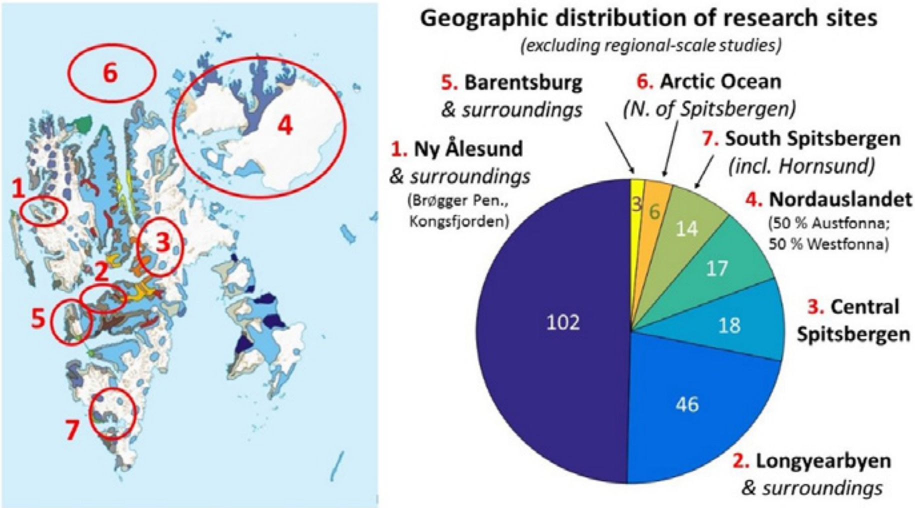

Figure 1: Spatial coverage of snow/snowpack studies in Svalbard published since 2003 (n = 205). Most studies were carried in one of 7 geographic sectors, the Ny Ålesund and Longyearbyen sectors being the most represented.

Based on this survey, and on a review of published literature, several knowledge gaps were identified that are recommended as priority targets for future monitoring-related activities in Svalbard. These gaps mainly relate to snow spatial variability on glaciers and tundra, the role of snow cover on terrestrial ecology, and the impacts, cycling and fate of snow contaminants. Although the N-ICE2015 expedition recently carried out extensive observations on the snow cover of sea ice north of Svalbard (e.g., Merkouriadi et al., 2017a,b), this aspect is not considered hereafter because sea-ice cover has been declining in Svalbard. This renders the development of regular snow-monitoring activities in this environment problematic (Hansen et al., 2013b).

3.1 Variability of supra-glacial snow cover

Since the snow regime on Svalbard has changed markedly over the past few years (van Pelt et al., 2016a), the development of modelling tools for all Svalbard glaciers requires monitoring data sets that capture both spatial changes in transient snow cover (Rotschky et al., 2011) and vertical changes in snow physical properties. There are particularly critical knowledge gaps in snow spatial variability representing glaciers in the southern, central and the eastern parts of Spitsbergen, for which data are almost completely missing. By contrast, there is a clear bias towards monitoring in West Spitsbergen, where the majority of surface mass balance observation networks are situated (Hagen et al., 2003). Despite the development of new observation techniques like Ground Penetrating Radar (GPR; Dunse et al., 2009), terrestrial laser scanning (Prokop et al, 2016) or satellite remote sensing, and the marked improvement in the modelling tools being applied to the entire Svalbard Archipelago (Aas et al., 2016; Lang et al., 2015; Østby et al., 2017; van Pelt et al., 2016b), field programs for monitoring the snow cover conditions on glaciers are still necessary in order to ground truth their outputs. Indeed, the size and location of the glaciers where regular field measurements are already being undertaken are not always optimal for ground truthing remote sensing products, and atmospheric or geomorphological corrections remain very challenging. Models particularly suffer from a lack of field validation for meteorological forcing (Schuler et al., 2013) and snow water equivalent measurements (i.e. precipitation). When snow contains water and ice lenses with different densities and optical refractive indexes, as frequently observed in Svalbard snow packs, absorption and scattering properties of the snow pack are modified. This has an impact upon the information retrieved using remote sensing and GPR. There is an urgent need to pursue research in this field to better calibrate the newly developed observational techniques (Gray et al., 2015), and in so doing, greatly improve the quality of data representing the entire Svalbard Archipelago.

Two actions that will improve the state of the science mentioned above include: i) undertaking repeat traverses to measure snow properties across larger, remote glaciers with a significant altitudinal range, and ii) the establishment of a denser network of meteorological data collection sites that better represent local conditions and can thus be used to validate or correct the data products used for larger-scale glacier modelling. Automatic weather stations should be deployed at remote targeted glaciers and measurements during the traverses should be sufficient for all important ground truthing purposes, as well as describing the critical physical and chemical properties beneath the snow surface. Defining the exact location is however slightly premature at present, as this should be coordinated with glaciological studies and other relevant groups interested in working in these areas.

3.2 Seasonal snow cover and terrestrial ecology

Observations of snow on bare ground and tundra ecosystems on Svalbard are even more scarce than on glaciers (see Table 1 above), and the spatial distribution of snow is hard to model (Liston, 2004). Consistent observations and simulations of temporal and spatial patterns of snow accumulation (Aalstad et al., 2018; Gisnås et al., 2014, Kępski et al., 2017) and possibly later melt water production are needed to assess climate change influences on terrestrial flora and fauna, as well as permafrost thermal regime. This also involves precipitation sampling (for which procedures are needed with respect to calibration, routines and timing). Melt water penetration in the snow pack and internal refreezing also needs to be improved due to the complexity of the processes involved and also the lack of field data (D'Amboise et al., 2017). The seasonal variability of snow also needs to be assessed, in terms of properties and duration because this sets the length of the potential growing season. Extreme warming events have been observed more frequently in the Arctic recently (Graham et al., 2017; Rinke et al., 2017, Vikhamar-Schuler et al. 2016), with observable effects on the snow pack (Gallet et al., 2017; Merkouriadi et al., 2017a,b), but observations are still limited. Basic snow properties (temperature, density, ice quantity) should be more consistently measured and recorded in standardised formats suitable for modellers. Wet snow processes are very complex and not fully understood, so development of a snow dedicated super-site network should be undertaken.

The variation among species and even among ecotypes as a function of snow amount and type is still poorly understood. For instance, intermittent mild periods and snowmelt during winter may be beneficial for some aspects, like the enhancement of heterotrophic processes and increased nutrient availability (e.g. Morgner et al., 2010), and detrimental for others, like damage and mortality of soil fauna and vegetation (Bokhorst et al., 2011a, b). The extent of wintertime microbial biomass production both within and under the snow pack as well as effect of snow change on the Arctic food chain and nutrient resources are topics that have rarely been studied. Ecosystem changes in the Arctic can be rapid and can directly affect life quality, in the same manner as the amount of contaminants in the snow (Forsström et al., 2009, Stohl 2006, Kühnel et al., 2011), which can also be transferred to the ecosystem (Björkman et al., 2014, Kozak et al., 2015) and the local population.

Actions to be undertaken are to determine the amount of snow and ice on the ground, in addition to basic parameters on the internal structure of the snow (snow hardness for example) in areas where observation of ecosystem parameters are being carried out. Linking the spatial and temporal scale between climate and ecosystem research is a very challenging question. We have to use the existing data, and engage discussion with ecologists in order to determine the best suitable field measuring protocols, and be in cooperation with projects such as COAT (http://www.coat.no/) in Svalbard, which is a part of SIOS.

Determining transfer functions between atmosphere and snow surfaces of aerosols and micro-organisms is a complex task for which field work is essential. Understanding the transfer of aerosols and micro-organisms from the atmosphere to the snow surface requires information on their atmospheric content, their properties, their interactions with clouds, deposition processes as well as post-depositional evolution once deposited on the snow pack. Developing a program to combine these various fields of research is essential and requires that atmospheric and snow bio-physical and chemical researchers collaborate. This is something that can be facilitated through SIOS. A strong atmospheric group is working and developing platforms in Svalbard, especially in Ny-Ålesund. Communication is essential in order to be able to link all research fields, especially in terms of area where the work would be developed, or the potential creation of a super-site where larger group will work together and develop a larger interdisciplinary program. A common platform to better describe and understand the process is necessary, but bearing in mind that protocols, background data, manpower, research facilities (laboratories) and large international expertise is needed.

3.3 Cycling, fate and impacts of contaminants in snow

Because of its relative proximity to the continental land mass, Svalbard is a receptor for long-range contaminants emitted from mid- to high-latitude source regions of Eurasia (Stock et al., 2014; Winiger et al., 2015; Dekhtyareva et al., 2016; Hung et al., 2016; Nawrot et al. 2016). These contaminants include BC, secondary aerosols derived from acidifying gases (SO_x, NO_x), trace metals and also complex, persistent organic pollutants (POPs) sourced from human activities. Emissions of some impurities from natural sources, such as forest fires, are also indirectly affected by anthropogenic climate warming, leading to potential future increases (Stohl et al., 2007; Yittri et al., 2014). Some air contaminants reaching Svalbard, such as BC, are in particulate form which, when deposited in the snowpack, affect its radiative properties (Warren, 1984). Others, such as toxic metals (e.g., Hg) and POPs, are bio-accumulative and can adversely affect the local fauna (e.g, Fenstad et al., 2014; Andersen et al., 2015; Goutte et al., 2015). Local sources of snow cover contamination include dust dispersion from mining activities, fuel and waste incineration, or transport (Eckhart et al., 2013; Abramova et al., 2016; Granberg et al., 2017; Kahn et al., 2017). Presently, many contaminants in air and precipitation are monitored by research installations in Ny Ålesund. There are, however, comparatively few systematic observations elsewhere across the Svalbard Archipelago.

The seasonal snow cover (on land or glaciers) is a convenient sampling medium for air contaminants where air or precipitation sampling is impractical. Knowledge of concentrations in late winter/spring snow is essential to assess the surface radiative impact of BC. For other contaminants, it is the total burden of contaminants in the snow pack prior to spring snowmelt that matters, because this is what can enter soils and waterways upon release by snowmelt. Several studies point to the existence of gradients of contaminant deposition in snow across the Svalbard Archipelago, either due to spatial heterogeneity of air transport patterns, and/or to precipitation gradients and orographic effects (e.g., Beaudon et al., 2013, Vega et al., 2015). Hence for some contaminants, fluxes measured at Ny-Ålesund may not be representative of deposition across the rest of the Archipelago. Also, while some POPs have been measured in snow (e.g,. Kallenborn et al., 2011, Xie et al., 2015, Abramova et al., 2016, Vecciato et al., 2018), the data have been disseminated piecewise, some in journal articles, other in government reports, such that an ensemble view is difficult to grasp. Furthermore, with the exception of a few case studies (e.g. Dommergue et al., 2010, Björkman et al., 2014), the fate of contaminants, once deposited in snow, remains poorly known. Finally, there is a growing recognition that biogeochemical transformations in the snow pack itself can impact the fate of contaminants deposited in snow, but the nature of these interactions is under-studied (e.g. Hodson et al, 2010; Larose et al., 2013a,b).

In view of the above, a set of research goals to be pursued in future snow research on Svalbard are: (1) better define and quantify regional gradients of contaminant deposition and accumulation in seasonal snow packs across the Svalbard archipelago; (2) identify the meteorological conditions (and other factors) that account for inter annual variations in contaminant accumulation in snow in different geographical parts of the archipelago; (3) determine the fate of contaminants in the seasonal snow pack by quantifying the fractions that actually enter soils and waterways upon snowmelt; (4) establish how future changes in snow cover phenology (e.g., rate of accumulation, frequency of winter thaws, timing of spring melt) will impact the release of contaminants from melting snow; and (5) investigate interactions between particulate organic matter, microbial communities, and contaminants (such as nitrates, BC or metals) within the snow pack thaw are relevant to the fate of these contaminants.

3.4 Snow, as a constituent in natural hazards and hydrology

Changes in snow temporal and spatial variability have a number of societal impacts on the economy (Bokhurst et al. 2016) including the cost of snow removal (Hanbali, 1994), maintenance and prevention costs of freezing damage infrastructure (Bjerke et al. 2015) and road and structure maintenance costs (Sosnovsky et al. 2014). Changes in the magnitude and timing of spring runoff also impact flood and reservoir management (Popova, 2011, Semenov, 2013). The landscape in Svalbard is high relief, largely without vegetation, with continuous snow cover for most of the year and wide plateaus with deep valleys that allow for snow drifting (Eckerstorfer & Christiansen, 2012). This makes it especially at risk for avalanches with detrimental costs for inhabitants.

Snow avalanche activity, which is often spontaneous but also caused by external loading, is linked to snow variability and weather conditions and their interactions with topography (McClung & Schaerer, 2006). The frequency, magnitude, seasonality, and typology of avalanche events are also variable, which makes them difficult to predict (Schweizer, 1999). Snow avalanches are defined as masses of snow or ice that move rapidly down a sloping surface. To understand their dynamics it is important to understand the processes resulting in the formation, growth, and degradation of snow crystals and how these processes affect the snowpack throughout the winter season (Schweizer et al. 2003). For example, powder snow avalanches generally occur after intense snow precipitation during cold winter conditions (Baggi & Schweizer 2009), while wet and dense flows often coincide with warm spells (Ancey & Bain 2015). The increasingly wetter and milder Arctic climate will likely increase the frequency of avalanches (Eckerstorfer & Christiansen 2012, Qiu, 2014). Increasing air temperature increases the shear deformation rate of snowpacks due to a rise in liquid water content, which favors increased strain at the interface of slab and/or weak layers, and ultimately, the release of wet snow avalanches (Ancey & Bain, 2015). The increase in the liquid water content of snow can also, in some cases, reduce friction once it begins moving, increasing avalanche runout distances (Naaim et al., 2013).

Although relationships between climate and snow avalanches remain unclear due to the general lack of long-term observations (Ballesteros-Cánovas et al., 2018), the ongoing warming and changes in precipitation will likely impact snow avalanche activity. Several actions will improve the state of the science and risk mitigation for hazards related to changes in snow regime: i) the establishment of a denser network of snow monitoring sites near infrastructure that are equipped with seismic sensors and infrasound arrays; ii) the use of radar (e.g. Radarsat-2, TerraSAR-X, and Cosmo-Skymed) to help predict and quantify avalanche events around Svalbard (Caduff et al. 2015); and iii) the establishment of coordinated actions to improve risk management of snow avalanches and disaster risk policies.

4 Summary and other suggestions

With respect to the above-mentioned gaps, we collected the crucial missing information regarding snow research in Svalbard and provide some recommendations on how to improve it in the frame of SIOS. The recommendations are listed in three main research thematic areas: snow on glaciers, snow on land and snow-atmosphere interactions, plus a last section regarding other strategic topics. Certainly more themes could be listed but these are the ones where current data have already been collected and monitoring programs are ongoing.

Supra-glacial snow coverage

1. Improve the spatial resolution of glaciers being monitored to include glaciers from central and eastern Svalbard. Set up glacier monitoring programs that engage with future and early career snow scientists (e.g. at Slakbreen).
2. Based on the traverse organized in Spring 2018, we can use existing infrastructure (e.g. Pyramiden, Barentsburg as science polygons of Russian Science Centre on Svalbard - RSCS) as a base to carry out glacier measurements, store and prepare samples to be sent to Longyearbyen or Barentsburg (chemical-analytic laboratory of RSCS) for analysis. The advantage is better safety, shorter field days and access to the central part of Svalbard.
3. Focus more on snow melt (including inside layer radiation melting), even during winter, and better quantify the ice amount in snow packs.
4. Utilize/develop new tools to better quantify wet snow properties, with a focus on remote sensing and model validation.

Seasonal snow on land

1. Promote scientific exchange among users of different research infrastructures.
2. Promote interdisciplinarity that links soil, snow and atmospheric research, and the effect of snow on biodiversity.
3. Funding for year-round monitoring commitments.
4. Using common and merged protocols to simplify field sampling but able to fulfil the goals.
5. Establish 2 to 3 super-sites with a holistic approach with measurements from the ground to the atmosphere throughout the year. This is logistically only possible on land, but would be more than interesting in bringing knowledge on winter snow conditions in Svalbard. Only permanently and annually functioning sites can then be concerned.

Impacts, cycling and fate of contaminants in snow

1. Need for coordinated studies of snow cover contamination at multiple sites across Svalbard, using standardized protocols and laboratory facilities.
2. SIOS can assist by being a central repository and clearing house for relevant data on snow properties measured across the archipelago.
3. Develop improved logistical solutions for transporting field samples to Longyearbyen or Barentsburg when specialized measurements cannot be performed in the field or at local field stations.
4. Promote catchment-scale studies (where feasible) that address the issue of the fate of contaminants released by snow melt.
5. Foster a closer cooperation and integration between the aerosol research community (largely focused Ny Ålesund) and the broader snow research community across Svalbard.

Other suggestions

Networking: in order to improve long term monitoring and also coverage, more nations working in Svalbard should be part of SIOS. SIOS could be a tool for improving communication among researchers by facilitating and organizing interdisciplinary snow workshops and by establishing working groups and programs. By focusing on programs with specific research focus in targeted areas, SIOS could enrol institutes and nations that have not been working much or at all together before, and create a synergy.

Snow data exchange platform: should be facilitated through SIOS and this is one of the main goals. However, beforehand discussion on data sharing and format would be recommended due to the different timing, type, geographical location and vertical structure of the snow data sets that could exist. Suggestions should be provided by SIOS. Data sets should include at least the type of the temporal resolution of the data of the most vital interest for a start for the SIOS project (depth, density, SWE and temperature). The data present in the exchange platforms, which is to be used by the entire research community, should be accessible in English.

Improve involvement: Involve UNIS and students from Norwegians Universities (as well from Europe and Russia) in basic snow and glacier monitoring programs (ex. April glaciology course with GPR and SWE, chemistry, microbiology, winter or summer field school on base of RSCS): SIOS would help in transferring knowledge, form the next generation of polar researchers, and make good use of the collected data for master and PhD students at UNIS, and by also helping researchers to use and publish the collected data.

Acknowledgements

The preparation of this report was support by the Research Council of Norway, project number 251658, Svalbard Integrated Arctic Earth Observing System - Knowledge Centre (SIOS-KC). The authors thank the arctic stations that contributed to the success of the project and the report. In particular we would like to thanks the AWIPEV arctic station, the CNR-Dirigibile Italia, Czech Arctic Station of Josef Svoboda, The Polish Polar Station Hornsund, the University of Svalbard (UNIS), The Russian Scientific Center on Spitsbergen (AARI) and the Svendrup Station. The authors are grateful for the support of the following research programs: for AS and MB, the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 657627, the European Union's Horizon 2020 research and innovation programme under grant agreement No. 689443 via project iCUPE (Integrative and Comprehensive Understanding on Polar Environments), the Swedish Research Council Formas grant agreement grant agreement No. 2016-01187. Research projects by CL and HWJ were performed at the AWIPEV Station supported by the French Polar Institute (IPEV), the Agence Nationale de la Recherche (ANR), and CNRS/INSU. HWJ acknowledges support by the Labex OSUG@2020. CL acknowledges support from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 675546. BL work was partially supported within statutory activities No 3841/E-41/S/2018 of the Ministry of Science and Higher Education of Poland. AU fieldwork during spring 2018 was supported by Research Council of Norway under Arctic field grant-2018 (No. 282630). The authors thank Christian Zoelly for logistic support.

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Temperature time-series in Svalbard fjords. A contribution from the "Integrated Marine Observatory Partnership (iMOP)"

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Keywords: Svalbard, fjords, mooring, temperature, observatory

Introduction

The environment of Svalbard is heavily dominated by its maritime location and many of the processes occurring in the region are strongly influenced by the state of the ocean and ice. It is located close to the major marine inflows and outflows for the Arctic Ocean in an area where important boundary fluxes (between atmosphere, ocean, and sea-ice) are occurring [*Ellis-Evans and Holmen*, 2013]. Long-term monitoring of key arctic ocean gateways have revealed important changes in the system [*Carmack et al.*, 2016; *Onarheim et al.*, 2014; *Polyakov et al.*, 2017] and it is important that the Svalbard Integrated Observing System (SIOS) contributes to those international efforts to monitor and report on decadal change in the ocean. This has relevance not only to marine processes but also the broader connections to the atmosphere and glaciological systems.

Many of the marine observations that are made on Svalbard are biased towards summer and the fall. Due to the intense seasonality in Arctic regions, this bias in observations can skew our understanding or, at worst, present a misleading picture of rates and processes that are active in the marine environment. Moored observatories have the capacity to make year-round measurements of key physical, geochemical and biological properties. In this report we define an observatory to mean an arrangement of sub-surface instrumentation mounted in the water column to examine physical, geochemical or biological parameters over timescales that span at least one season. Sometimes we abbreviate this to just the word "mooring".

Datasets from such moored observatories capture processes occurring on sub-hourly to decadal time-scales [*Nilssen et al.*, 2015] and when combined with complementary data are very powerful in determining the drivers and impacts of environmental change. Moored observations also enhance our predictive capabilities by acquiring data that can be used to support modelling work of the Arctic system – either to provide the essential boundary conditions to drive the model, or to provide robust in situ data for model calibration and validation [*Cottier et al.*, 2007; *Drysdale*, 2017; *Sundfjord et al.*, 2017; *Wallace et al.*, 2013].

Although often regarded as routine monitoring tools, moored observatories have opened up new frontiers of research. As little as a decade ago, it was not widely appreciated how active the winter marine ecosystem is. However, important winter observations of zooplankton migration revealed by acoustic instruments demonstrated that an important component of the marine ecosystem was active [*Berge et al.*, 2009a] which paved the way for new winter observations [*Berge et al.*, 2015; *Wallace et al.*, 2010]. The use of moorings in understanding polar night ecology has gone beyond single site observations on Svalbard and has been used in a fully pan-Arctic context to understand the response of zooplankton to moonlight [*Last et al.*, 2016].

Integration with complementary Earth System parameters is also well supported by moored observations. For example, glaciological time series, collected throughout the year with 11-day repeat satellite passes require a similarly resolved marine time series with which to interpret change. Such a combination of data has demonstrated highly significant geophysical correlations that allow us to understand glacier ablation [*Luckman et al.*, 2015]. Marine observations in Svalbard have also been used to derive decadal records of change. These are principally linked to the physical system [*Pavlov et al.*, 2013], but also aligned with records of the benthic ecology [*Berge et al.*, 2009b] and geochemical proxies of environmental change [*Ambrose et al.*, 2006; *Vihtakari et al.*, 2017].

Current Status of marine observatories

There have been many mooring deployments in Svalbard waters over the last decades and there exists a rich network of observatories around the Svalbard archipelago and adjacent shelf seas [*Hop et al.*, in press]. Historically, many were located within the fjord systems and were operated for just a few years. More recently, both coastal and offshore moorings have been established as part of more extensive observations networks and many have been maintained for multiple years providing key insights into interannual variability.

There have been a number of efforts to collate our understanding of long-term data series [Renaud and Bekkby, 2013] and collating information on marine observing activities through the Svalbard Science Forum Ocean Flagship [*Beszczynska-Moller and Sagen*, 2015; *Falk et al.*, 2016] and community workshops. Importantly, however, two of the moorings presented herein (outer Kongsfjorden and Isfjorden) are implemented in the Norwegian SIOS Infrastructure programme SION InfraNOR, which in effect will ensure that these two moorings will both be coordinated and in operation until 2026.

Methods

In this first edition of the SESS report, the iMOP project has focused exclusively on inshore observatories (within fjords). The work does not include all inshore observatories and does not consider any of the existing offshore time series observations. The criteria for inclusion in this report were as follows

- Observatories that are currently deployed in Svalbard fjords
- Observatories that have a minimum of three years of continuous operation
- Observatories which are likely to be maintained for another 2 years

With these criteria, we were then able to focus on time series that are likely to contribute to future SESS reports rather than short-term, process-oriented observations. The observatories that were considered are listed in Table 1.

Table 1: Summary of the four observatories that collected temperature data for this report. Precise distribution and the instrumentation on each mooring is documented within the cited literature.

Location	Start	Latitude*	Longitude*	Water Depth (m)	Institution and point of contact
Isfjorden	2005**	78° 03.64’ N	013° 31.44’ E	205	UNIS Ragnheid Skogseth
Kongsfjorden (inner)	2014	78.94°N	12.01°E	193	ESSO-NCAOR Divya David T
Kongsfjorden (outer)	2002	78° 57.75’ N	011° 48.30’ E	230	SAMS/UiT Finlo Cottier/Daniel Vogedes
Rijpfjorden	2006***	80° 18.08’ N	022° 17.44’ E	236	UiT/SAMS Daniel Vogedes/Finlo Cottier

* Positions are approximate as over the course of many years of deployment the moorings will have been in slightly different positions. Nevertheless, the positions are sufficiently similar to make realistic assessments of interannual change.

** No deployment between Feb. 2008 and Sep. 2010

*** No deployment between Sep. 2008 and Sep. 2009

Data processing was identical for each time series. Each data provider was responsible for sensor calibration and quality control of the data. Accuracy of the temperature data is typically better than 0.1°C. The data were collected from multiple temperature sensors, fixed to a vertical mooring line that extended from the seabed to within typically 20 m from the surface. The sensors had varying vertical spacing on the mooring line, but generally were more closely spaced in the upper 100 m, for example [*Cottier et al.*, 2005]. These data were interpolated on to a regular grid of 10m vertical resolution and 6-hour time resolution. Temperature data at each point in time were reduced to a single depth-average value. Water within the fjord can be warmed by either local heating through surface heat fluxes or advection into the fjord of warmer waters. It is anticipated that in summer months the local surface heating is limited to the upper 50m due to the formation of surface freshwater layers and a well-developed pycnocline [*Cottier et al.*, 2005]. To quantify the impact on water temperature through local heating the depth-averaged temperature was calculated for a) the full water column and b) the water column deeper than 50 m. The following metrics were then derived from each time series:

Monthly mean temperature: A single value representing the depth mean for each calendar month.

Maximum mean temperature: A single annual value representing the mean value for the months which climatologically show the warmest depth-mean temperatures (September/October/November).

Warmest 5-day temperature: An annual value for the warmest depth-mean temperature recorded across a series of 5-day periods.

Minimum mean temperature: A single annual value representing the mean value for the months which climatologically show the coldest depth-mean temperatures (March/April/May).

Coldest 5-day temperature: An annual value for the warmest depth-mean temperature recorded across a series of 5-day periods. In many cases, this equates to the mean freezing point of the water and is not a unique value in the time series.

Note that we do not make reference to the terms 'summer' and 'winter' as these are a) generally defined inconsistently and b) the climatological extremes do not coincide with the perception of summer and winter being warmest, and coldest respectively.

Results

Analysis showed that there was rather little difference between metrics derived from the full water column and derived from waters 50m and deeper. For consistency, we just report the data from 50m and deeper. Key metrics were then represented as time series with simple linear regression analysis and are shown in Figure 1.

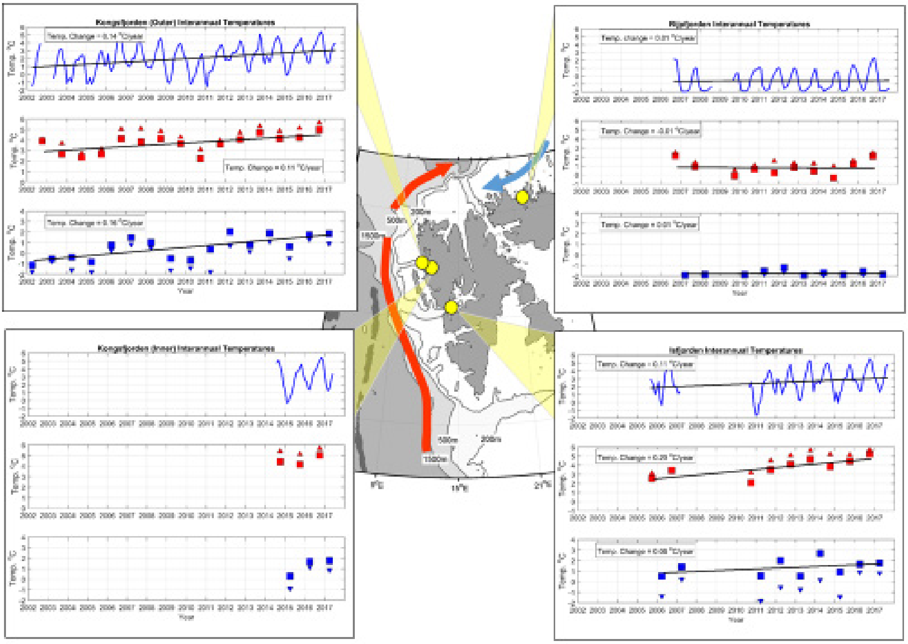

Figure 1: Time series of depth-averaged water column temperature (50m > bottom) at four locations in Svalbard: Kongsfjorden outer and inner basins, Isfjorden and Rijpfjorden. Each location data comprises three panels. Upper panel (blue line) monthly temperature values, middle panel (red markers) is warmest months (Sept/Oct/Nov) mean (square) and the peak temperature values in the season (triangle), lower panel (blue markers) is coldest months (March/April/May) mean (square) and the minimum temperature values in the season (triangle). Data series longer than 9 years are fitted with a simple linear regression model.

The key observation from these time series is the increase in water temperature (both the maximum and minimum temperatures) observed consistently for the west-facing fjords of Isfjorden and Kongsfjorden. The current rate of increase is of the order 1°C per decade. Perhaps most significantly we see consistent warming trend during the coldest months (March/April/May) In contrast, the temperatures (annually, warmest and coldest period) in Rijpfjorden show no increase and very little variation over a decade of observations.

Data accessibility

The data that forms the basis of the figures in this report is available at the Norwegian Infrastructure for Research Data (NIRD).

Discussion

The monthly temperature values (upper panel) for each location show a classic annual temperature cycle. The metrics for the coldest and warmest months provide a robust measure of the maximum and minimum temperature values for each year. It is apparent that data from the west-facing fjords (Kongsfjorden and Isfjorden) show a different response during the record period than the north-facing fjord (Rijpfjorden). The warmer water temperatures in the west-facing fjords can be attributed to both warming of the offshore West Spitsbergen Current and the regional wind stress [*Pavlov et al.*, 2013]. In the longer records of Kongsfjorden and Isfjorden we see some evidence for sub-decadal cycling within the time series, but the clear trend is one of increasing water temperature at a rate of the order 1-2 °C per decade. We note a similar sub-decadal variation (particularly in Kongsfjorden) for the coldest temperatures, suggesting a degree of correlation between successive warm and cold periods. Similarly, a clear warming trend is noted in the coldest periods at a rate of order 1-1.5 °C per decade. The clear implication of this warming is that there are now fewer years experiencing temperatures close to freezing point for the full water column – limiting the formation of sea ice. This change has been noted in satellite observations of sea ice cover over approximately the same period [*Muckenhuber et al.*, 2016].

The major difference between the mooring sites are the data from Rijpfjorden. Whilst the annual temperature cycle is clear, there is no significant increase in either the warmest or coldest temperatures. In particular, the coldest depth-averaged temperatures are always at or close to the freezing point such that the ice cover in Rijpfjorden is still able to form annually [*Wallace et al.*, 2010]. In the last three years in Rijpfjorden there has been a small increase in the warmest temperatures which may be linked to the increased presence of

Atlantic Water offshore [*Polyakov et al.*, 2017] which may become more prevalent on the northern Barents Sea shelf [*Lind et al.*, 2018]. Nevertheless, whilst the offshore changes in water temperature are increasingly well-documented, it will take more years of observation to show any robust trend in Rijpfjorden.

Future perspectives

In this report, we have only considered a subset of the inshore observatories and not considered the offshore time series at all. Future iterations of this report will look to provide a more consistent treatment of the data in terms of archiving, calibration and analysis. Further, many of these time series have records of ocean salinity – an important parameter in determining the timing and extent of ocean inflows to the coastal regions. Salinity will be another parameter to consider in future reports of interannual change.

A number of observatories have been used for investigating multiple, coupled parameters [*D'Angelo et al.*, 2018; *Venkatesan et al.*, 2016; *Wallace et al.*, 2010], and data from observatories have been linked to non-marine systems, e.g. glacial dynamics [*Luckman et al.*, 2015]. Future research opportunities exist by linking the existing time series of the fjord properties recorded by observatories with other marine time series around the archipelago [*Renaud and Bekkby*, 2013]. It is likely that we will see either immediate or lagged responses of the marine ecosystem to the observed trends in oceanic temperatures. Awareness of, and accessibility to, the marine time series data is critical for stimulating the research interactions between other Earth System Science groups operating in Svalbard. There are clear links to be made between marine, terrestrial, glacial and atmospheric processes. Cross-disciplinary investigations of the data series need to be supported.

In terms of developing the observation system, communication and coordination between the many groups operating marine observatories around Svalbard is of primary concern. Recent workshops have recognised that there is still a requirement to establish a cooperative group of mooring operators by which data can be identified and secured and planning can be coordinated to ensure that the Svalbard research community benefits from the best possible arrangement and access to infrastructure. It is often the case that a level of coordination and integration of data collection yields a more valuable insight into the system than single, stand-alone efforts. As a first step, a full audit of the mooring activity around Svalbard is required. One of the objectives of the iMOP project was to initiate a coordinating role for collating existing temperature data from marine observatories to produce consistent data series focused on ocean temperatures for inclusion in the first SESS report.

Looking ahead, it is clear that maintaining time series beyond the lifetime of research project funding is a challenge. Where resource exists to do this (for example through infrastructure funding) it must be applied with due consideration for the existing longevity of a time series, utility of data and logistical constraints to ensure continued monitoring.

Acknowledgements

The moorings have been supported financially by many funding agencies and projects and these are acknowledged individually within the publications cited by this report. In addition the authors thank the various organisations linked to mooring activities for providing in-kind support over the years, particularly UiT The Arctic University of Norway, UNIS and NPI. This work was supported by the Research Council of Norway, project number 251658, Svalbard Integrated Arctic Earth Observing System – Knowledge Centre (SIOS-KC).

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The Continuous Plankton Recorder Survey – Monitoring plankton in the Nordic Sea

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Keywords: CPR Survey, plankton, Calanus, diatom, copepod

Highlights

The warm-temperate calanoid copepod *Calanus helgolandicus* is becoming more common in the Nordic Seas with high records in 2016, which continued into 2017.

The Pacific diatom *Neodenticula seminae* (an indicator of trans-Arctic migration) was recorded off Svalbard in 2016, which is its most easterly record in the Nordic Seas.

Continuous Plankton Recorder monitoring

The Continuous Plankton Recorder (CPR) survey has been operating on a monthly basis using ships of opportunity from northern Norway to Svalbard for almost 10 years beginning in November 2008. Generally, the route operates every month from Tromso in northern Norway to Longyearbyen in Svalbard when conditions are favourable. Sometimes there can be reduced sampling during the winter period (Fig.1). The northern Norwegian routes were initially established due to the rapid changes to plankton and climate and the movement of plankton northwards observed over the last 50 years in the sub-polar Atlantic. These rapid changes in plankton were originally observed in the North East Atlantic where the majority of CPR routes operate with plankton northerly movement measured at a rapid ~ 23 km per year in this region (Beaugrand et al. 2009). To continue these observations of rapid biological movement and biodiversity changes it was considered crucial to establish more northerly CPR routes covering the Nordic Seas to continue to document these changes as well as to monitor for possible trans-Arctic migrations.

The CPR Survey is a long-term, sub-surface marine plankton monitoring programme consisting of a network of CPR transects towed monthly across the major geographical regions of the North Atlantic. It has been operating in the North Sea since 1931 with some standard routes existing with a virtually unbroken monthly coverage back to 1946. The CPR survey is recognised as the longest sustained and geographically most extensive marine biological survey in the world (Edwards et al. 2010). The dataset comprises a uniquely large record of marine biodiversity covering ~1000 taxa over multi-decadal periods. The survey determines the abundance and distribution of microscopic plants (phytoplankton) and animals (zooplankton including fish larvae) in our oceans and shelf seas. Using ships of opportunity from ~30 different shipping companies, it obtains samples at monthly intervals on ~50 trans-ocean routes. In this way the survey autonomously collects biological and physical data from ships covering ~20,000 km of the ocean per month, ranging from the Arctic to the Southern Ocean. The survey is an internationally funded charity (with operational funding from UK, USA, Canada and Norway) with a wide consortium of stakeholders. The Norwegian government directly funds the Svalbard CPR route through the Institute of

Marine Research in Bergen.

The CPR is a high-speed plankton recorder that is towed behind 'ships of opportunity' through the surface layer of the ocean (~10 m depth). Water passes through the recorder and plankton are filtered by a slow moving silk (mesh size 270 µm). A second layer of silk covers the first and both are reeled into a tank containing 4% formaldehyde. Upon returning to the laboratory, the silk is unwound and cut into sections corresponding to 10 nautical miles and approximately 3 m^3 of filtered sea water.

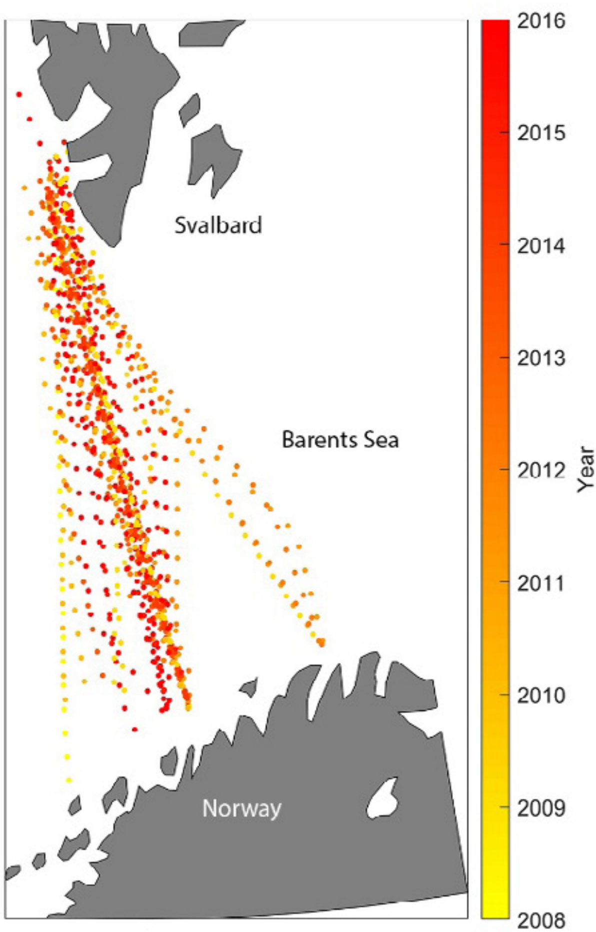

Figure 1: Distribution of CPR samples in the Barents Sea region between northern Norway and Svalbard.

There are four separate stages of analysis carried out on each CPR sample, with each focusing on a different aspect of the plankton: viz. (1) overall chlorophyll (the phytoplankton colour index; PCI); (2) larger phytoplankton cells (phytoplankton); (3) smaller zooplankton (zooplankton traverse); and (4) larger zooplankton (zooplankton eyecount) The phytoplankton colour of each section of the CPR silk is evaluated and categorised according to four levels of 'greenness' (green, pale green, very pale green and no colour) using a standard colour chart; the numbers are given a numerical value as a measure of 'Phytoplankton Colour Index'. Direct comparisons between the phytoplankton colour index and other chlorophyll *a* estimates including SeaWiFS satellite estimates indicate strong positive correlations. This is a semiquantitative measure of phytoplankton biomass; the silk gets its green colour from the chloroplasts of the filtered phytoplankton.

Phytoplankton cells are identified and recorded as either present of absent across 20 microscopic fields spanning each section of silk (representing ~1/10,000 of the filtering silk). Due to the mesh size of CPR silks, many phytoplankton species are only semi-quantitatively sampled owing to the small size of the organisms. There is thus a bias towards recording larger armoured flagellates and chain-forming diatoms and that smaller species abundance estimates from cell counts will probably be underestimated in relation to other water sampling methods. However, the proportion of the population that is retained by the CPR silk reflects the major changes in abundance, distribution and specific composition (i.e. the percentage retention is roughly constant within each species even with very small-celled species). Zooplankton analysis is then carried out in two stages with small (<2 mm) zooplankton identified and counted on-silk (representing ~1/50 of the filtering silk) and larger (>2 mm) zooplankton enumerated off-silk (see (Richardson et al. 2006) for further details on CPR methodology). The collection and analysis of CPR samples have been carried out using a consistent methodological approach, coupled with strict protocols and Quality Assurance procedures since 1958, making the CPR survey the longest continuous dataset of its kind in the world. Of particular relevance to the abundance of copepods around Svalbard, the CPR survey currently distinguishes between the species *Calanus finmarchicus* and *C. glacialis* by measuring the prosome length of adult specimens (for C. glacialis, prosome length of CV 3.0-3.5mm; Adult female prosome length 3.5-4.1mm) and therefore in some circumstances may underestimate the abundance of *C. glacialis* as the size ranges can overlap (see Choquet et al. 2018 for further details).

The addition of a water sampler onboard certain CPRs can provide information on the whole size-spectrum of plankton using molecular techniques from bacteria and viruses to flagellates and other taxa not normally identified using standard CPR analysis. In addition to this many CPRs currently have near-real-time sensors for variables such as conductivity, temperature and chlorophyll-a fluorescence from bespoke sensors that are being operated on CPR transects across some coastal to open ocean waters. The Tromso-Svalbard transect has deployed a CTD sensor on the CPR in the past and currently works in collaboration with Norwegian colleagues operating the Ferrybox installed on the vessel.

Plankton trends

Generally, the plankton sampled in the Barents Sea consists of a cold-boreal to an Atlantic assemblage with the occasional temperate species recorded particularly in the warmer waters of the North Atlantic current to the west and south of Svalbard. As the Barents Sea sits at the doorstep to the Arctic Ocean a number of boreal-arctic species are also found such as *Ephemara planamembranacea* and *Ceratium arcticum*. The Barents Sea region is a rich ecosystem with high biomass of phytoplankton and zooplankton leading to lucrative marine bio-resources particularly the fisheries.

The most commonly recorded phytoplankton in this region are the diatom groups *Chaetoceros* spp., *Rhizosolenia* spp. *Pseudo-nitzshia* spp. The dinoflagellate genus *Ceratium* are also very common particularly during the summer months. Calanoid copepods typically dominate the zooplankton assemblage particularly the boreal species *Calanus finmarchicus*. Euphausids and hyperids also contribute to high zooplankton biomasses. Annual trends in the most common phytoplankton and zooplankton species are shown in Fig.2. Over the course of the time-series a significant community shift was recorded in 2016 and may represent a recent change in the community structure. The spatial distribution of the most common zooplankton *C. finmarchicus* and its relatives are show in Fig 3 and 4. *C. finmarchicus* is most abundant off the northern coast of Norway with the more colder distributed species *C. glacialis* and *C. hyperboreus* found most abundant off the south-west coast of Svalbard and Storfjord Channel. Interestingly the warm-termperate species *C. helgolandicus* is also recorded on this route with highest abundances recorded off northern Norway. Rather surprisingly, the species has also been recorded off the coast of Svalbard itself. There is increasing evidence that temperate species are becoming more commonly recorded in the Barents Sea over the last few years. This is in line with the observed and rapid increase in temperatures recorded in the Barents Sea over the last decade (Lind et al. 2018).

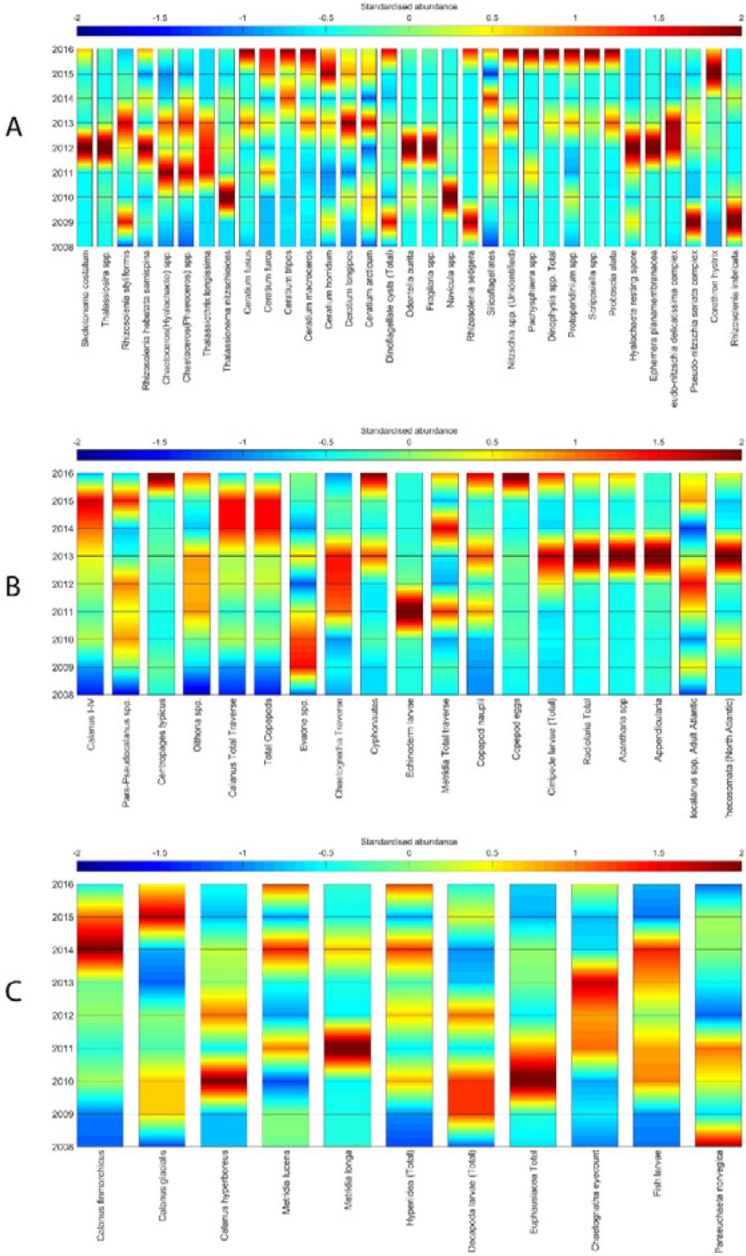

Figure 2: The average annual abundance of the most common plankton taxa recorded since 2008, (A) phytoplankton; (B) small zooplankton (C) large zooplankton. Standardised abundance, 0=mean. Aggregated data for the whole Svalbard transect.

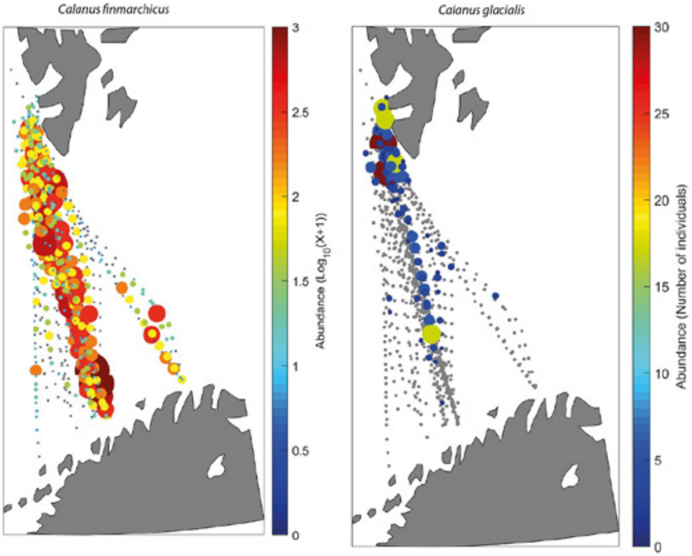

Figure 3: The spatial distribution and abundance of the calanoid species *Calanus finmarchicus* and *Calanus glacialis*. Colours represent abundances per sample.

Trans-Arctic invasive species

It has recently been highlighted that Arctic ice is reducing faster than previous modelled estimates and the seas around Svalbard continue to warm at an accelerated pace compared to other global regional areas. As a consequence of this the biological boundaries between the North Atlantic Ocean and Pacific may become increasingly blurred with an increase of trans- Arctic migrations becoming more common. The CPR survey has already documented the presence of a Pacific diatom (*Neodenticula seminae*) in the Labrador Sea since the late 1990s which has since spread southwards and eastwards (Reid et al. 2007). The diatom species itself has been absent from the North Atlantic for over 800,000 years and may itself be the first evidence of a trans-Arctic migration in modern times and be the harbinger of a potential inundation of new organisms to the North Atlantic (Reid et al. 2008) .

The species has been recently found in the Barents Sea north of Iceland and west of Svalbard and also on the ST route in the spring of 2016 at 77.387 N and 13.557 E which is currently its most easterly record. Independent of the CPR survey the presence of *N. seminae* has recently been recorded from sediment samples along the west Spitsbergen slope (Miettinen et al. 2013). It is possible we could witness more trans-Arctic exchanges in the near future if the ongoing warming trend and reduction of sea ice continues in the Arctic. Currently the consequences of such a change to the function and biodiversity of Arctic systems is not yet known.

Future recommendations

Within this region of the Nordic Seas, the CPR survey adds to and compliments other monitoring methods in this area by providing a larger spatial and temporal perspective as most other surveys are coastal or are sporadically sampled through time. In addition to this, the CPR survey data adds value by providing multi-decadal data at the Atlantic basin scale that can help disentangle and interpret changes observed in the Nordic Seas and help predict these changes over the next coming decades. For example, current Arctic systems will become sub-Arctic systems within the next 10 to 20 years (if not sooner) and the biological signals of change we see further south in Atlantic sub-polar systems now can be used to detect the early warning signs of change in the Arctic.

To develop the operation system further the CPR survey currently works closely with Norwegian scientists to coordinate its sampling on board this ship of opportunity. For example, the CPR survey coordinates its activity with the Norwegian ferrybox system on board this ship of opportunity to obtain further and complimentary information such as pCO_2. It is hoped in the near future that the CPR survey will form part of a more integrated observation system within these waters and improve its monitoring with an additional suite of biogeochemical and molecular sensors. It is also foreseeable in the future that additional CPR routes could be towed using other ship of opportunity in this region such as tourist vessels.

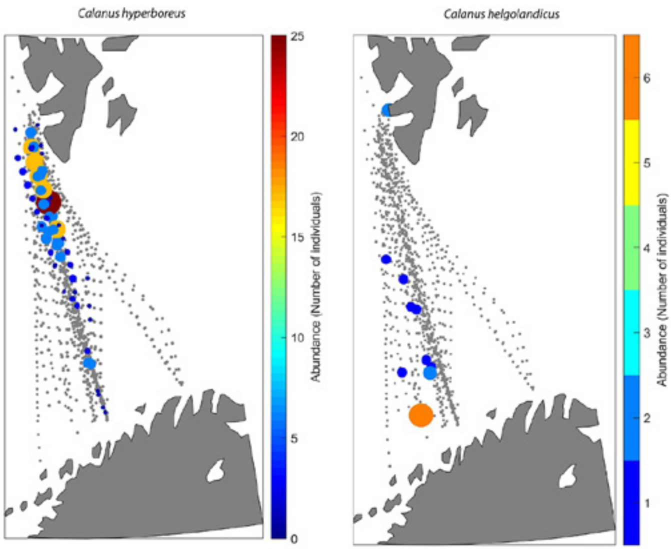

Figure 4: The spatial distribution and abundance of the calanoid species *Calanus hyberboreus* and *Calanus helgolandicus*. Colours represent abundances per sample.

Data accessibility

All data is freely available on request by contacting the Continuous Plankton Recorder Survey at the Marine Biological Association (MBA), United Kingdom. Data requests to the MBA Head of Data, Information and Technology (Dan Lear: dble@mba.ac.uk).

Additional CPR information: microplastics

In addition to recording upto 1000 taxa of plankton the CPR survey has also been recording for the presence of microplastics since 2004. Quantitative counts of microplastics have been recorded since 2016. The occurrence of microplastic in the Nordic Seas seems to be regular and echoes the normal frequency of occurrence in the North Atlantic

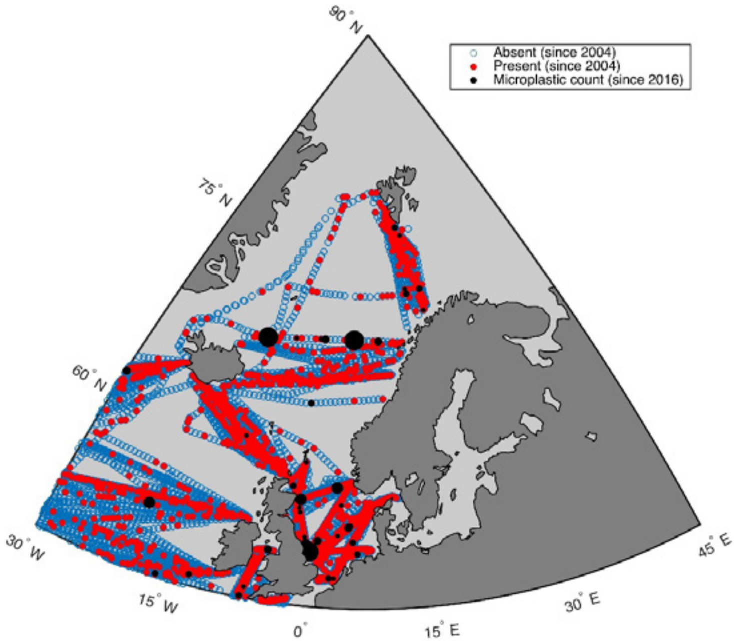

Figure 5: The distribution of microplastics on CPR samples since 2004. Red indicates presence on CPR samples and blue values indicate absence on CPR samples. Black values indicate quantitative counts of microplastics since 2016.

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Spitsbergen Oceanic and Atmospheric interactions – SOA

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Keywords: Fram strait, deep sea thermohaline variability, slope currents, wind-induced processes.

Introduction

The SOA (Spitsbergen Oceanic and Atmospheric interactions) project aims at contributing to the first SESS report released by SIOS in 2019. The main scope of the project was providing results from an integrated analysis of meteorological and oceanographic data collected in the south-western offshore Svalbard area within the period 2014-2016. The scientific objective of the project is to deepen the knowledge of the role of atmospheric forcing that can drive and influence the variability of the deep current flow and thermohaline properties below 1000 m depth along the continental slope west of Spitsbergen.

Circulation and long-term changes in the Fram Strait

The Fram Strait is the only deep passage linking the Nordic Seas and the Arctic Ocean. The northward transport of relatively warm and salty Atlantic water (AW) has a significant impact on conversion and circulation of water masses (Rudels et al. 2015) as well as on sea ice and atmospheric fluxes in the Arctic. AW is carried poleward by two branches of the Norwegian Atlantic Current (NAC), a baroclinic branch linked to the Arctic Front and a barotropic jet, following the Norwegian and Barents Sea shelf break (Mork and Skagseth 2010). Of the latter flow, one part turns eastward into the Barents Sea Opening, while the larger portion enters Fram Strait and continues northward as the West Spitsbergen Current (WSC, Gascard et al. 1995; Walczowski 2013). The eastern Fram Strait is characterised by a steep slope between the shelf and deep basin. The warm and salty AW is transported northward within the WSC core, a fast and confined current located above the shelf break and the upper slope west of Svalbard (Beszczynska-Möller et al. 2012). The West Spitsbergen Shelf (WSS) is a region where waters of Atlantic and Arctic origin converge, mix and exchange (Saloranta & Svendsen 2001). In the surface layer on the shelf, the Sørkapp Current transports cold and fresh Arctic-type water, advected from Storfjorden around the southern tip of Spitsbergen, to the north. It consists mostly of the Storfjorden surface water, a mixture of local meltwater, heated by solar radiation, and the Arctic Water, warmed already in the shallow Barents Sea and advected into Storfjorden by the East Spitsbergen Current (Haarpaintner et al. 2001; Skogseth et al. 2005). The Arctic-type water carried by the Sørkapp Current along the shelf and Atlantic water transported by the WSC above the shelf break are typically separated by a frontal zone, a part of the large Polar Front system in the Barents Sea and farther north (Loeng 1991; Walczowski 2013). The Polar Front west of Spitsbergen is characterised by a density gradient only in the 50 m thick surface layer, while beneath this layer the front is density compensated and manifested through strong temperature and salinity gradients (Saloranta and Svendsen 2001; Walczowski 2013).

Warm anomalies observed in the WSC are mostly advected to the region from the North Atlantic, where increased AW temperature and salinity has been observed since the 1990s (Holliday et al. 2008). They are modified along the way by ocean-atmosphere heat fluxes and variable strength of ocean currents (Årthun and Eldevik 2016; Wåhlin and Johnson 2009). Two warm AW anomalies passing through the Fram Strait were observed in 1999–2000 and 2005–2007 and statistically significant positive trends were found in AW temperature (0.06°C y^{-1}, Beszczynska-Möller et al. 2012) and salinity (0.003 y^{-1}, Walczowski et al. 2017) in the upper layer of the southern Fram Strait. At the same time, no significant trends in AW volume transport in the WSC have been observed (Beszczynska-Möller et al. 2012).

Dense water formation within fjords and on the WSS depends on the rate of cooling (heat loss to the atmosphere), homogenisation of the AW and upper waters, sea ice growth, and brine rejection. Strong and cold winds trigger the dense water formation and the shelf dynamics (Boyd and D'Asaro 1994; Skeie and Grønas 2000; Nilsen et al. 2016), by elevated heat loss to the atmosphere as well as sea-ice formation. The densest water is the brine-enriched shelf water (BSW) formed during intensive ice formation in winter in the coastal latent heat polynya in Storfjorden and wind forcing is crucial for preconditioning such events. BSW gradually fill the fjord to the sill crest and initiates a density-driven overflow (Schauer, 1995; Geyer et al. 2009). Density-driven currents move along the shelf and the continental slope reaching velocities as high as 0.6 m s^{-1} at the shelf break and sinking to deep layers according to their density anomaly and following bathymetric constraints (Wobus et al. 2013; Jungclaus et al. 1995; Fer and Ådlandsvik 2008). *Downslope cascading and evolution of dense water plumes as they propagate along the slope are however difficult to observe due to their intermittent and localized occurrence and to model due to challenges with parameterization of turbulent mixing and bottom friction in the bottom boundary layer*. A key question is *how recent climate changes have been influencing the dense water production and spreading along the WSS and what effects this had on the deep circulation in the Arctic Ocean and in the Fram Strait*.

State of the art of the measurements in the Fram Strait

In the Fram Strait, temperature and salinity profiles have been collected fairly regularly since 60' as part of the Norwegian monitoring around Svalbard (http://www.mosj.no) and international observing campaigns. Year-round observations with single or few oceanographic moorings have been collected since the early 70s to study the properties and dynamics of the Atlantic water inflow to the Arctic Ocean (e.g., Greisman 1976; Hanzlick 1983). Until the mid-80s, moorings were confined to the WSC and later years they were occasionally distributed in the entire strait. Since 1997, a sustained moored array has been established in collaboration between the Norwegian NPI (Arctic Ocean Outflow Observatory, http://www.npolar.no/framstrait) and German AWI (https://www.awi.de/en/expedition/observatories/

ocean-fram.html) across the entire northern Fram Strait at approx. 79°N. The array consists of between 14 and 17 oceanographic moorings with up to 5 levels of sensors measuring temperature, salinity and ocean currents covered the continental slopes west of Svalbard and east of Greenland, and the deep interior (Beszczynska-Möller et al. 2012). In addition, the deep-sea, long-term multidisciplinary observatory Hausgarten was established in the northern Fram Strait in 1999 to monitor environmental changes and deep-sea biodiversity near the Molloy Hole (Soltwedel et al. 2016). In 2014, the AWI oceanographic moored array and Hausgarten observatory were combined and extended into the FRAM (Frontiers in Arctic Marine Monitoring) observatory. Since 2012 the moored array north of Svalbard (at approx. 31°E) has been operated by Norwegian NPI, IMR, and Polish IOPAN under the A-TWAIN project (http://www.npolar.no/en/projects/a-twain.html) to monitor Atlantic water in the Arctic Ocean Boundary Current and its interactions with atmosphere and sea ice (Renner et al. 2018). While most of these observational activities were concentrated in the northern Fram Strait, a limited number of moorings were also deployed in the early 90s in the southern Fram Strait, in the Storfjorden region to investigate dense water formation and spreading (Schauer, 1995). Observations of brine production and Storfjorden outflow have been continued afterwards with single bottom moorings (Geyer et al. 2009; Skogseth et al. 2013) or ice-moored platforms (Jardon et al. 2014) complemented by ship-borne CTD sections. Single moorings were also deployed for one or more years in the vicinities of the West Spitsbergen fjords' outlets (e.g., Isfjorden or Hornsund) to monitor fjord-shelf exchanges. Four moorings were deployed for a period of one year (2010-2011) along the SW margin of Spitsbergen within the FP7-HERMIONE (Hotspot Ecosystem Research and Man's Impact on European Seas) project to investigate particle sources and downward fluxes under the influence of the WSC (Sanchez-Vidal et al. 2015). Two moorings have been deployed more recently (since 2014) in the southern Fram Strait by the Italian OGS and CNR in collaboration with UGOT and the Italian Navy (Hydrographic Institute), to study the deep flow variability (Lucchi et al., 2014; Bensi et al., 2017).

In addition to moored measurements, until the 90s hydrographic data were collected during regular Norwegian cruises and several international campaigns (e.g., MIZEX'84), usually along a few irregular sections and mostly during the summer period. A summary of early observations is given e.g. in Gascard et al. (1995). Since the 60s, the joint ecosystem surveys for fish stock assessments, including also oceanographic measurements, have been carried on in the Barents Sea and southern Svalbard region (Eriksen et al. 2017) by the Norwegian IMR and Russian PINRO. IOPAN has carried out regular summer cruises into the Nordic Seas and Fram Strait under the long-term monitoring program AREX since 1987 (Walczowski et al. 2017), measuring oceanographic and ecosystem parameters along several (10-15) repeated sections (the regular station grid established since the mid-90s). Since the mid-90s, the coast-to-coast hydrographic section in the northern Fram Strait, covering the entire width of the strait, has been repeated yearly by AWI and/or NPI to complement the moored array. Occasional oceanographic sections have been covered every year during international research cruises in the Svalbard area. In order to optimise a large number of observational activities, a large effort has been paid in the last decade by the scientific community to extend and integrate the observing systems in the Arctic and around Svalbard through several projects, programmes, and consortiums/networks. Among currently on-going activities, we can mention e.g., the H2020 project INTAROS (coordinated by Norwegian NERSC, https://www.nersc.no/project/intaros), the Norwegian programme Nansen Legacy (https://arvenetternansen.com/), the EuroGOOS regional system ArcticROOS (Arctic Regional Ocean Observing System, https://arctic-roos.org/), and SIOS (Svalbard Integrated Arctic Earth Observing System, www.sios-svalbard.org).

SOA - Summary of used data

In this section, we present briefly the data used and the results obtained from their analysis within the SOA project.

Atmospheric data

The atmosphere plays a fundamental role in the process concerning the dense water formation along the coast of Spitsbergen. Large-scale pressure fields are responsible for the general atmospheric circulation, whose patterns above the ground modify due to the strong influence of the complex local geographical features. As local observations cannot always be assumed as representative for large areas, they need to be analysed with reference to the general atmospheric circulation. Along the west coast of Spitsbergen meteorological stations are located in e.g., Kongsfjorden, Isfjorden, and Hornsund fjords (Fig. 1 and 2). They coherently revealed a positive trend of the air temperature. Wind measurements show different regimes due to different geographic position and elevation, as well as to the distance from the open continental margin. The climatological wind direction over the Svalbard archipelago during the fall-winter season is easterly. It is characterised by high nonlinearity (Skeie and Grønas 2000) and by strong topographic steering of the atmospheric flows across the Svalbard Archipelago. Cisek et al. (2017) highlighted significant differences between meteorological parameters at Ny-Ålesund and Hornsund. *For an integrated data analysis that includes both atmosphere and ocean to study the dense water formation, time and spatial scale of the processes, type of measurements, representativeness and homogeneity of the data have to be carefully taken in consideration. The comparison between wind data collected on land stations (e.g., the Arctic station Dirigibile Italia in Ny-Ålesund, http://www.isac.cnr.it/~radiclim/CCTower/) and those obtained from ECMWF (European Centre for Medium-range Weather Forecasts) show a large similarity (correlation > 0.84). Hence, to study significant atmospheric events we employed ERA-Interim wind dataset from the ECMWF, which covers both land and open sea areas on a* *regular grid. Data are available at 6-hour time intervals and regularly spaced at 0.25° latitude x 0.25° longitude over the entire Svalbard archipelago. We extracted ECMWF data at two locations close to the moorings S1 and ID2 (Fig. 2). Overall, the most energetic events occur coherently in the bottom current flow and in the wind speed* (Bensi et al. in preparation).

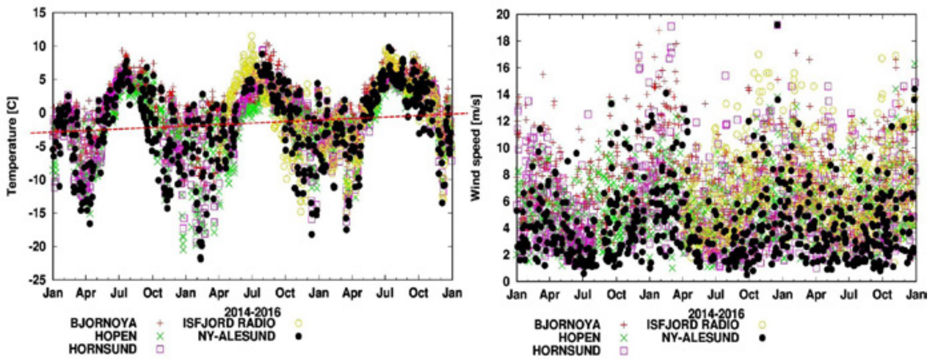

Figure 1: Air temperature (°C) and wind speed (m s^{-1}) at different meteorological stations in Svalbard (see the map in Fig. 2 for their locations).

Oceanographic moorings S1 and ID2 (South-west Spitsbergen margin)

With the aim of collecting multi-annual time-series in an area of potential interaction between the West Spitsbergen Current and dense water cascading along slope, two deep moorings (ID2, S1) were deployed in 2014 offshore southwestern Svalbard, at depths of ~1000 m (Lucchi et al. 2014; Bensi et al. 2017; Ivaldi et al. 2017). The moorings were designed to collect data (temperature, salinity, turbidity, dissolved oxygen, currents, sediment trap) in the near-bottom layer (100-150 m thick), in areas where two contourite deposits (Bellsund and Isfjorden sediment drifts, Rebesco et al. 2013) were detected. Mooring ID2 recorded data from June 2014 to June 2016 (and re-deployed in 2018), S1 from June 2014 to July 2018 and it is still active (the last maintenance was accomplished in July 2018 during the "*High North 18*" cruise, on board the Italian r/v Alliance). The most interesting feature revealed by these data is the high variability observed during the winter period. In particular, occasional intrusions of warmer (+2°C) and saltier (~35) water (resulting less dense than ambient water) often in concomitance with intense near-bottom currents, were detected (Bensi et al. in preparation). These intrusions modify the properties of the local bottom layer, occupied by the Norwegian Sea Deep Water (NSDW, $_{\theta}$~-0.90°C, S~34.90, σθ~28.07 kg m^{-3}). The comparison among 2-yrs long time series collected at S1, ID2, and at the observatories HAUSGARTEN and FRAM show a similar variability (Fig. 2). *These anomalies may be attributed to topographically trapped waves generated by barotropic* *oscillations modulated by atmospherics forcing (Nilsen et al. 2006) confined over the slope area. Enhanced currents at 1000 m depth, with a time delay of about 1 day (at S1) and 2 days (at ID2) with respect to strong wind events, took place mainly between October and April. A linkage between the variability of the deep currents and wind was found, with periodicities from diurnal (24 h) to 10 and 20 days. The diurnal signal of the variability connected to the cross-shore current component may be the result of propagating topographically trapped waves at 1000 m depth, similarly to what observed by Nilsen et al. (2006) at shallower depths (250 m) in the same area. It indicates that meteorological factors (winds) can modulate the current flow. We argue that this phenomenon protrudes into depth, where also occasional cascading of sediment-enriched shelf waters occurs.* Indeed, dense waters form over the shelf by the combined effects of cooling, strong evaporation, and brine rejection phenomena induced by cold and dry winds blowing over the whole archipelago. They are then able to descend downslope collecting sediment. However, the intrusion of less dense waters observed at S1 and ID2 is counterintuitive. A hypothesis is that high concentration of suspended sediment (SSC) can substantially contribute to increasing the kinetic energy and the density of the downslope flow (Fohrmann et al. 1998). Turbidity peaks at S1 appeared time delayed with respect to density ones (Fig. 2). We calibrated the turbidity sensor in a laboratory by using particles collected at S1 (sediment trap) to obtain the corresponding values of SSC. However, maximum values of SSC associated with episodes of density minima were about 16 - 18 mg L^{-1}, which are not sufficient to compensate the low density calculated solely from temperature and salinity. We cannot exclude that low values of SSC could depend also on the position of the instruments and further investigations are needed to better understand this phenomenon. Samples from the sediment trap at S1 revealed major peaks (0.65 g m^{-2} d^{-1}) in the total mass flux in late March and late May 2016 but also minor peaks in Dec 2015 and Feb 2016, coherently with data recorded by the turbidity sensor. Sanchez-Vidal et al. (2015) measured values of total mass flux 20 times higher (up to 11.6 g m^{-2} d^{-1}) in their station A (same location of S1) in Feb-Mar 2011. Total mass flux values at S1 were higher/lower when organic carbon content was lower/higher, respectively. Organic carbon content peaked, in late August 2015, in late April 2016, and at beginning of June 2016.

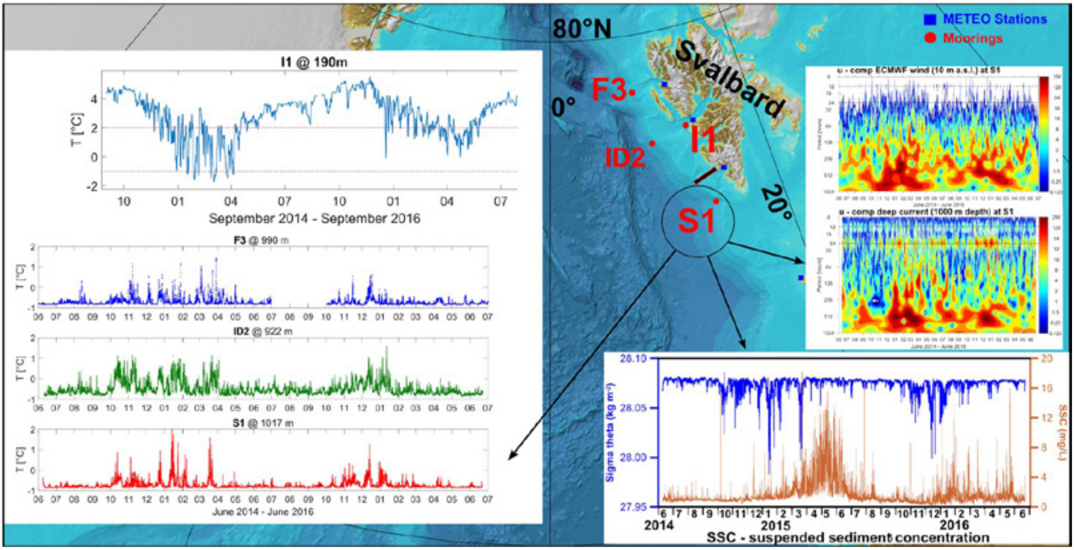

Figure 2: In-situ temperature, density anomaly, calculated SSC, and wavelet power spectrum of u-component from deep currents and wind at S1. Temperature at ID2, I1 (shelf), and F3 (von Appen et al. 2015, 2017) are also shown. The thick line on the WSS, north of Hornsund fjord, indicates the position of CTD profiles shown in Fig. 3. The bathymetry chart is taken from Jakobsson et al. (2012).

Oceanographic mooring I1 (West Spitsbergen Shelf)

To capture the AW intrusions into the Isfjorden, temperature, salinity, and current at several depths have been measured from moored instruments since 2010. The mooring is located at 78.068°N, 13.528°E at 203–214m depth and maintained yearly every September. It is equipped with three Aanderaa current meters with CTD sensors (either RCM9, RDCP or Seaguard) at ~50 m, ~100 m and ~190 m depths, three SeaBird SBE37SM MicroCATs at ~40 m, ~75 m, and ~150 m, and five evenly distributed VEMCO temperature loggers. The along-slope current velocities measured at 50 m and 190 m depths represent the upper and lower layer of the water column. In general, both the upper and lower layers cool during autumn and winter, but the cooling is often interrupted with intrusion or advection of warmer water. *This occurs every year, and in particular, during winter 2012 the temperature hardly dropped below 1 °C (Nilsen et al. 2016)*. These warm water intrusions during winter are due to inflow of AW triggered by air–ocean interaction processes as described by the shelf circulation model in Nilsen et al. (2016). *The along-slope velocities (towards Isfjorden) increase during the winter months (December–March). These are also the months when the along-coast wind stress and the wind stress curl on the southern WSS are strongly positive and negative, respectively (Nilsen et al. 2016)*. The amount of AW on the WSS varies annually, for instance in winter 2013-2014 the WSS outside Isfjorden was flooded with AW from bottom to the surface, while in winter 2014-2015 the

WSS was occupied with cold and fresh Arctic Water (Fig. 2). During winter 2015-2016 warm waters were observed again at I1 site.

Hydrographic cruises (West Spitsbergen margin)

IOPAN has been conducting repeated summer surveys (June-July) in the Nordic Seas and Fram Strait from RV Oceania since 1987 under the long-term monitoring program AREX (Walczowski et al. 2017). Hydrographic measurements cover the grid of regular CTD/LADCP stations (conductivity, temperature, depth, and current velocities measured from ocean surface to the bottom). In addition, the upper-ocean currents were recorded underway by the vessel mounted ADCP. The hydrographic sections (10 zonal and several meridional) are located in the eastern Greenland Sea, along the Barents Sea Opening, in the eastern Fram Strait and north of Svalbard and cover shelf, continental slope and deep basins. To complement the standard stations (~200 per year), high-resolution sections with a towed CTD system (operating down to approx. 300 m depth) are measured in a few locations across the shelf break, in Spitsbergen fjords and near the marginal ice zone north of Svalbard. The collected data enable analysing AW properties and long-term changes of the AW inflow in the Nordic Seas and Fram Strait towards the Arctic Ocean (Walczowski et al. 2017). *In 2013-2017 in the north-eastern Greenland Sea, the AW temperature slightly exceeded the long-term mean, while salinity was close to the long-term average. In the south-eastern part of the Fram Strait, near the South Cape, the AW temperature dropped below its long-term mean in 2013, becoming higher than the mean in the following years, while the salinity has remained constantly high since 2004, with no clear trend (González-Pola et al. 2018). The deep waters in the annually measured part of the Nordic Seas reveal a positive trend in temperature (as in other northern regions), and high interannual variability in salinity.*

UNIS student cruises carried out in April 2014 with R/V Lance and May 2015 with R/V Helmer Hanssen collected CTD profiles across the WSS north of Hornsund (Fig. 2). *Data revealed different conditions on the shelf between winters 2014 and 2015 (Fig. 3). In winter 2013-2014, the WSS was occupied with warm and saline Atlantic Water whereas in winter 2014-2015 the conditions were more "normal" with colder and less saline Arctic Water on the shelf and with a clear temperature-salinity front between Arctic and Atlantic waters at the shelf break.* I1 mooring data confirm the presence of colder water in January - April 2015.

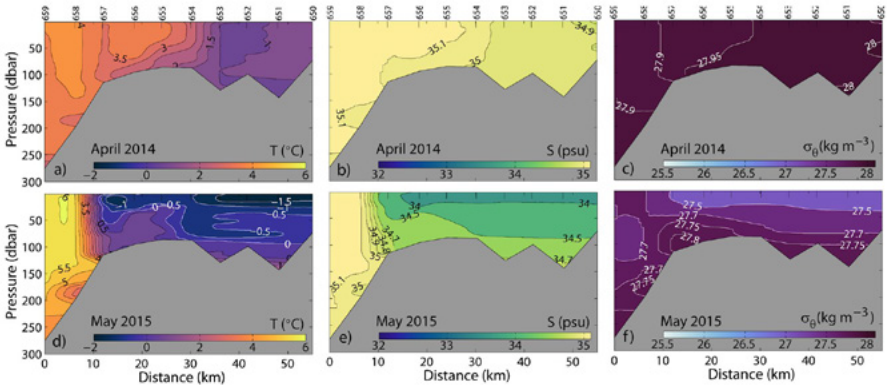

Figure 3 - Distribution of a)-d) in-situ temperature (°C), b)-e) salinity (psu), and c)-f) potential density anomaly (kg m^{-3}) across the WSS north of Hornsund fjord in a)-c) April 2014 and d)-f) May 2015. West side is on the left.

Geophysical and geological datasets (bathymetric constraints and insight into the past)

Seafloor topography controls the oceanic circulation and sedimentary processes, which in turn, reshape the seafloor morphology. The pathway of bottom currents is controlled by the topographic steering of the continental slope and affected by deviations of its direction causing perturbations of the flow. Moreover, dense water produced on the shelf fills the topographic depressions and spills over bathymetric sills to find its way towards the continental slope along troughs, gullies, and canyons. High-resolution bathymetry and morphological information are hence needed to identify the bottom-current related features (sediment drifts and corresponding bedforms) and to detect the path of episodic dense water cascading along the continental slope. In this way, it is possible to identify flow paths and direction and possibly infer a speed range. Moreover, this kind of data is needed to plan targeted measurements (mooring sites) and sampling (coring sites). Extensive multibeam bathymetry and sub-bottom profiles on the Storfjorden-Kveithola Trough-Mouth Fan system and partial coverage of Bellsund and Isfjorden sediment drifts have been collected during a series of scientific expeditions in the last 10 years (e.g., *Svais, Eglacom, Coribar, HighNorth*). These data already contributed to the International Bathymetric Chart of the Arctic Ocean (IBCAO, Jakobsson et al. 2012). *Sedimentary samples* and in particular two Calypso cores (19-17 m long) and three box cores were collected during the PREPARED cruise (June 2014) on the Bellsund and Isfjorden sediment drifts. They help to reconstruct the paleoclimate at centennial/millennial scales. In fact, surface geological data provide information on the characteristics of present and modern sediments deposited and shaped by bottom currents and/or cascading phenomena. Conversely, long piston/gravity cores enable extrapolating this kind of information to the past, when the climate conditions were different. Analysis of sediments deposited in geologic periods, when the atmospheric Carbon Dioxide concentration (and hence temperatures) were higher than today, allows predicting future scenarios connected to the present climatic change and global warming.

Data policy

To fulfil the SIOS Open data principles allowing free and open access to data gained through research around Svalbard to any person or organisation who requests them, the SOA project will make their datasets available in a timely manner. Participants of the SOA project will provide the metadata for their results either directly to the SIOS Data Management System (SDMS) or via the individual data centres of the participants involved in this study. In the latter case, the SDMS will connect these individual systems to a unified virtual data management system to make all the data visible in the SIOS catalogue. All metadata will then be available through a search interface integrated with the SIOS web portal. Some data may have access restrictions due to the policy of projects funding their collection (e.g., Italian S1 and ID2 moorings and hydrographic stations collected by IOPAN) and they will be handled accordingly by the responsible data centres. Generally, the metadata will be searchable and contain information on how to request access to the dataset.

Unanswered questions and gaps in the knowledge

a. *What are the effects of the progressive warming and reduction of ice cover, induced by both natural and anthropogenic influences (e.g., CO_2 increase, black carbon on the snow), in the Arctic and around Svalbard archipelago on dense water production and their links to the global thermohaline circulation?*

b. *What triggers the thermohaline variability observed at depths exceeding 1000 m along the West Svalbard continental margin? Could that variability be linked to vertical fluctuations of the intermediate layer of Atlantic Water modulated by atmospheric events or to oscillations generated by internal waves/eddies?*

c. *Cascading events along the west Svalbard margin:* Which measurements are needed to have a better comprehension of the phenomena involved (*i.e., mixing and entrainment, sediment transport and deposition, temporal variation of event frequency*)? Turbidity measurements performed in the deep layer at mooring S1 revealed qualitative differences between the two deployment periods as well as between timings of thermohaline and turbidity peaks. This fact highlights the need for more extensive and reliable measurements to assess the role of sediment erosion and resuspension in cascading events and in the variability of the deep flow.

d. *Coupling between atmospheric and oceanic measurements*: there is a lack of meteorological data collected offshore.

e. *Katabatic wind*: is it composed only by a local or large scale (or both) component? The measurements gathered at Ny-Ålesund can try to answer at a local scale, as a case study to explore the possible link between the shallow sea and the atmospheric boundary layer above the sea.

f. *How can we optimise the future activities along the west margin of Svalbard?*

Requirements for addressing unanswered questions and fill the gaps in the knowledge

Overall, in order to address the *question related to the effects of progressive warming and reduction of ice cover on the sensitive Arctic marine environment we need to sustain integrated long-term time series (>10 years), both at sea and on land*. The collaboration among Nations and Organizations is the only way to provide long-term datasets. A limiting factor to sustain long-term ocean monitoring programmes is the access to icebreakers and research vessels capable of travelling around Svalbard, especially during the winter season. At the moment, the following nations are planning activities in the region: Norway, Germany, Poland, Italy, Sweden, GB, Korea. We need a collaborative framework within which the oceanographic mooring maintenance and the regular collection of hydrographic data could be guaranteed on the long term.

To address unanswered questions, we need the following actions and requirements:

- **a.** *To implement the number of moorings* and their payloads along the West Spitsbergen margin, shelf and deep sea (> 1000 m depth). Only by improving temporal and spatial data coverage we can have a better comprehension of the phenomena involving fjords, shelves, and deep sea areas.
- **b.** *To capture seasonal variability of the Atlantic Water* properties and of atmospheric and oceanographic forcing influencing shelf dense water formation and cascading.
- **c.** *To promote and sustain an adequate observational strategy for* monitoring source areas of dense water formation (e.g., Storfjorden and SW Svalbard margin) under the current conditions when the ice-cover is retreating;
- **d.** To fulfil a need for meteorological measurements at sea (e.g., Prins Karls Forland island) a solution could be to establish a connection with jcomm.info for the meteorological data availability from ships of opportunity and research vessels.
- **e.** To Perform oceanographic cruises during winter-spring along established transects; search for ship infrastructures available for the cruises (e.g., Norway, Germany, UK, Korea, etc.).
- **f.** To acquire additional high-resolution Multibeam data to better investigate the role of bathymetric constraints that influence shelf-slope dynamics. The Continental shelf area is well covered by Olex data (http://www.olex.no/). Conversely, continental slope and deep areas west of Svalbard Archipelago are only partially surveyed. Beside of Italian bathymetric data contributing to IBCAO, we are aware of extensive Russian and German datasets.
- **g.** To obtain additional multi-corer samples in key areas (e.g., around S1 and ID2 where sediment drift was found) to deepen the knowledge on the sedimentary record of the cascading.
- **h.** To collect biogeochemical data through autonomous platforms for studying specific

processes (e.g., shelf-deep sea carbon export, acidification, etc.).

i. To make available harmonized meteorological data from opportunity ships.

j. To promote collaborations and data sharing among research groups and international Institutions.

To move towards an optimisation of future activities along the west margin of Svalbard:

a. A constant effort has to be paid to bring scientific research to operational systems with particular attention to the accessibility of data and products.

b. The maintenance of moored observatories and the duration of time-series should be guaranteed to reach decadal scales in order to study inter-annual variability and possible climate change evolution.

c. Time series data with high temporal resolution have to be extended to more depths (upper, intermediate, and deep layers) also in the south-west offshore Svalbard area following the approach of the FRAM Observatory (http://www.fixo3.eu/observatory/fram/).

Long-term measurements of the physical parameters and particle fluxes along the Svalbard margin can be useful to investigate the temporal variability of the processes driving lateral and vertical particle advection. Such variability hints at possible environmental changes associated with both sea-bottom processes and sea-surface environmental conditions reflecting climate change (e.g., sea ice extension, phytoplankton shift). Long-term measurements can also provide information regarding the exchange of water and biochemical properties between fjords and offshore areas. This approach has been already applied to HAUSGARTEN (Soltwedel et al. 2016). Moreover, specific analysis focused on the microplastic pollution from sediment trap samples could provide useful information particularly on the environmental conditions affected by an anthropogenic factor.

At the present time (2018), two oceanographic moorings (S1 and ID2) are active on the continental slope (> 1000 m depth) in the southwest part of Svalbard. Other moorings arrays are active in the northern part of the Fram Strait and north of Svalbard, on the shelf (e.g., I1) and within Storfjorden, Hornsund, and Kongsfjorden. *A big effort to maintain and harmonize (in terms of measured parameters and protocols) the existing observatories is needed.* Ongoing collaborations strengthened, thanks to the SIOS initiatives, which would aim at planning future joint research activities focused on the scientific questions raised in this scientific report. For example, within the SOA project, we discussed the possibility to share instruments and mooring logistics, and provide complementary measurements in the next future.

Final recommendations

(I) It would be beneficial for the scientific community if SIOS could diffuse annual cruise plans and ship-based operations around Svalbard to make people aware of the possibility to collaborate and optimise the logistics at sea; (II) To address the question regarding the influence of anthropogenic forcing on the "*natural variability, particularly the interannual to multi-decadal modes of variability*", there is a need for effective implementation and harmonization of in-situ measurements (more observatories, more sensors) and for multidisciplinary numerical modelling.

Acknowledgements

This work was supported by the Research Council of Norway, project number 251658, Svalbard Integrated Arctic Earth Observing System - Knowledge Centre (SIOS-KC). Moorings S1 and ID2 were deployed in the framework of the FP7-EU/Eurofleets2 Programme *PREPARED* (PREsent and PAst flow REgime on contourite Drifts west of Spitsbergen) and maintained by the project *DEFROST* (DEep Flow Regime Off SpiTsbergen), funded by the Italian Ministry of University and Research through the National Programme of Research in Antarctic (PNRA), by the Italian *High North programme* (Italian Navy Hydrographic Institute), and thanks to international collaborations (AWI, IOPAN, UiT).

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The Lower Atmosphere above Svalbard (LAS): Observed long term trends, small scale processes and the surface exchange

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Introduction

All the components of the Arctic System must be observed across time and space to understand the scope and evolution of change. Understanding how the system functions and projecting future changes requires models developed or initialised using data. For the Svalbard region, these data should primarily come from the core Earth System Science (ESS) observations within SIOS. Long-term records of lower atmospheric variables are primarily available from six permanent observations sites in Svalbard: Longyearbyen, Barentsburg, Ny-Ålesund, Hornsund, Hopen and Bjørnøya. Bjørnøya has a climate distinct from the rest of Svalbard, and Hopen is not representative of large parts of the archipelago, either. The remaining sites are all at sea level, on or near the west coast of Spitsbergen, limiting our ability to understand spatial variability across the main parts of Svalbard. Among the long-term stations, by far the most extensive atmospheric observations are made in Ny-Ålesund. This report therefore focuses on the observations, results and needs in Ny-Ålesund, while also highlighting the challenges coming from the lack of broader geographical coverage.

One of the core aims of SIOS is to *combine model and observing strategies to achieve the most rapid and cost effective development of both and to maximize the understanding gained from the available information*. Data are limited in time and space, and a good way to fill the gaps is by means of theoretical and numerical models at different time and space scales. Data can then support tests and verify models, and models can identify areas where new measurements would most contribute to better understanding and predictability.

The present report addresses some of the major themes concerning atmospheric research in Svalbard: long-term measurements, the boundary layer and its interaction with snow, aerosols and clouds. The first topic is obviously important to link atmospheric research with programs in other disciplines, as both biology and glaciology are strongly influenced by climate change. Moreover, the long-term recording of key meteorological parameters is needed to constrain climate models running on a long time scale and to understand the pronounced warming in the European Arctic in a global context. The atmospheric boundary layer, especially under thermally stable conditions, is not fully understood. Hence climate models usually show the largest spread in the boundary layer. Aerosol, clouds, their feedbacks and the hydrological cycle remain the largest sources of uncertainty in climate models. The error bars in the radiative forcing by aerosol and clouds, according to the IPCC reports, are of the same magnitude as the anthropogenic CO_2 forcing. Therefore, it is not surprising that the different institutes performing research in Svalbard, while having slightly different perspectives on their own, all contribute to several of these four topics. Hence the atmospheric research in Svalbard and its international cooperation is most advanced in these topics. The four themes interact significantly with each other and are presented separately merely for convenience. Further studies and analysis should attempt to better understand these interactions, in addition to working within the individual themes.

Long-term trends in the lower atmosphere

Keywords: Temperature, humidity, wind field, atmospheric pressure, radiation budget, cloudiness

Observations of numerous parameters describing the basic thermodynamic state and composition of the atmosphere, meteorology, radiation, aerosols, clouds, greenhouse and trace gases, have been collected in Svalbard, with varying degrees of detail, for decades now. However, many aspects of multi-decadal trends and inter-annual, annual and seasonal variability of atmospheric conditions have not yet been well examined in the region. Important studies have been made based on the long-term observations performed at Ny-Ålesund, but much still needs be done to give a complete overview of Svalbard's environment and ongoing changes and a better interpretation of small-scale local processes and their interaction with large-scale conditions. A common sampling strategy between different research groups should produce more valuable, temporal and spatial, integrated data sets useful to reduce the measurement gaps and get a better data coverage over Svalbard.

Recent results

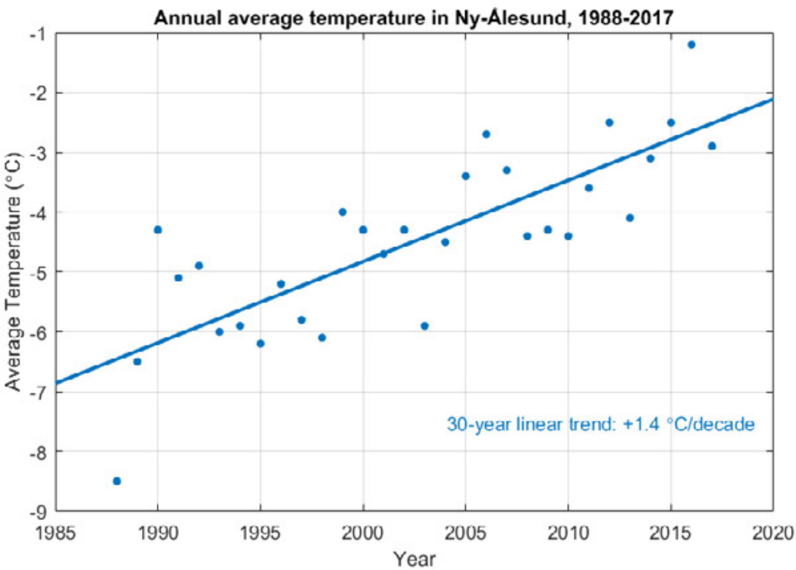

Figure 1: Annual mean air temperature measured at 2 m in Ny-Ålesund from 1988 to 2017 (dots). The linear regression (line) shows a trend of air temperature increase (+1.4 °C/decade) corresponding to about + 4.2 °C in 30 years.

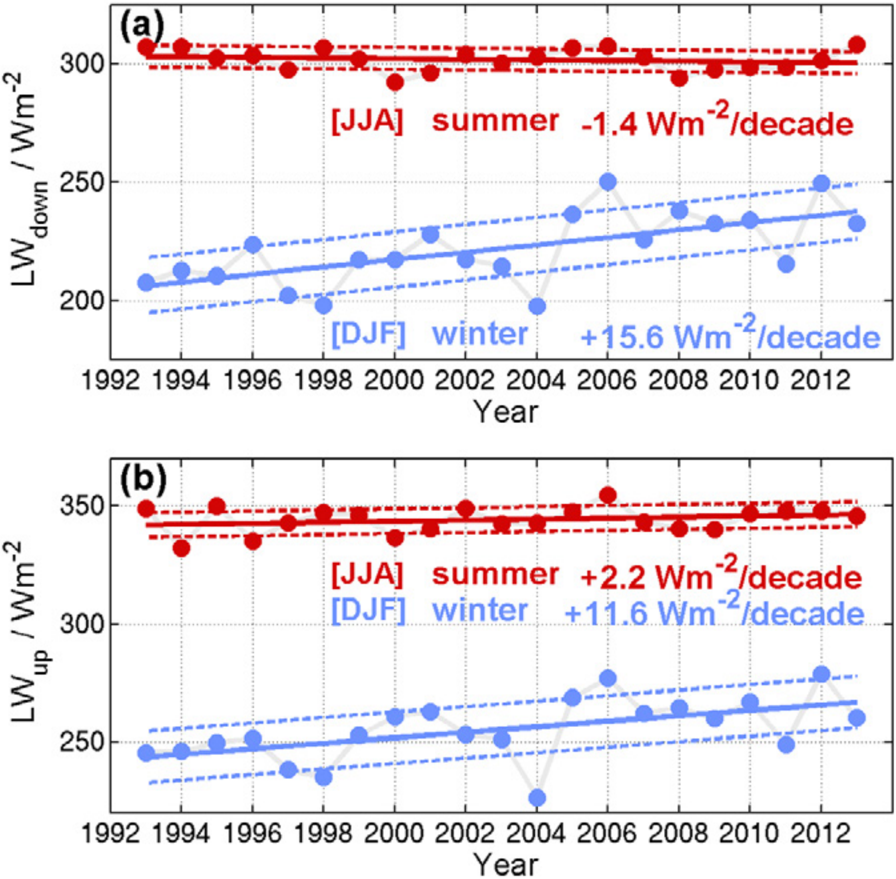

Figure 2: Seasonal mean downward (a) and upward (b) longwave radiation for summer (red dots) and winter (blue dots) in Ny-Ålesund. The continuous and dashed lines are the linear regression and regression uncertainty, respectively. No relevant changes are observed in the summer months (JJA) for downward and for upward longwave radiation. A considerable increase in winter months (DJF) is observed for downward and upward longwave radiation.

Maturilli et al. (2013, 2015) present long-term observations of meteorological and atmospheric radiation data. The annual mean temperature at Ny-Ålesund has risen by +1.3 ± 0.7 K per decade, with a maximum seasonal increase during the winter months of +3.1 ± 2.6 K per decade. Dahlke and Maturilli (2017) attempt to quantify the advective contribution to the observed atmospheric warming in the Svalbard area. Based on radiosonde measurements from Ny-Ålesund, a strong dependence of the tropospheric temperature on the synoptic flow direction was revealed. Kayser et al. (2017) provided statistics of temperature inversion characteristics, static stability, and boundary layer extent. During winter, when radiative cooling is most effective, they found the strongest impact of synoptic cyclones. Maturilli and Kayser (2017) showed that the humidity in the whole troposphere is rising. They indicate a strong seasonality of atmospheric surface layer warming and relate the changes to different radiation parameters. Winter is the season with the largest long-term changes in radiation, with an increase of +15.6 ± 11.6 W m^2 per decade in the downward longwave radiation. Mazzola et al. (2016) confirm these trends, discussing monthly and seasonal behaviour of meteorological parameters and radiation data that characterize the site as basic information to study the small scale processes, and their interaction with the other components of the system.

Unanswered questions

The reason for the rapid winter warming seen in Ny-Ålesund is not clearly understood. It cannot yet be addressed to what extent anthropogenic greenhouse gases, changing circulation patterns with more Atlantic impact (both from the atmosphere itself and the oceanic circulation), differences in cloud frequencies and properties and other factors have contributed. Furthermore, the representativeness of Ny-Ålesund, both for the rest of Svalbard and the wider Arctic, needs to be addressed in the future. By comparing data from Ny-Ålesund to those from other Arctic sites, the relative importance to the observed warming of long-lived greenhouse gases versus circulation or cloud changes, which probably act more on a regional scale, will become clearer.

Summary of existing data

Surface radiation measurements of up- and downward short- and longwave radiation have been made in Ny-Ålesund since August 1992 in the frame of the Baseline Surface Radiation Network (BSRN), complemented with surface and upper air meteorology since August 1993. The long-term radiation data set in Ny-Ålesund is available at https://doi.org/10.1594/PANGAEA.150000. The supplementary data set contains the basic BSRN radiation and surface meteorological data and is available at https://doi.org/10.1594/PANGAEA.854326. In addition, standard synoptic meteorological observations are available from the Norwegian

Meteorological Institute since 1969 (http://eklima.met.no), and non-BSRN radiation measurements are available from the Norwegian Polar Institute from 1974 until 2000 (https://data.npolar.no). Long-term vertical profile measurements of the atmospheric parameters are collected since September 2009 at the Climate Change Tower, between the surface and 34 m. Data are stored in the IADC database (http://mainnode.src.cnr.it/cnr/data.php). An overview of the existence, interoperability and accessibility of relevant databases and datasets should be provided for measurements at stations in Svalbard beyond Ny-Ålesund; the Research in Svalbard (RIS) portal will be starting point for this task.

Recommendations for SIOS

As all existing research sites are located at or close to the West coast of Spitsbergen, they probably share similar synoptic conditions but different micro-meteorology characteristics. Sites at the east coast of Spitsbergen and in northeast Svalbard would be influenced by a different (more Arctic) synoptic regime and hence be useful to separate local from regional and continental influences. Additionally, better observations from sites away from the coasts, especially on glaciers, would provide a more thorough understanding of the climate of Svalbard, considering its varied terrain and extensive glacier cover. An improvement of spatial distribution of measurement stations within Svalbard should be addressed and supported by SIOS.

Boundary layer meteorology

Keywords: Vertical profiles, turbulent fluxes, wind, air temperature, radiation budget

The atmospheric boundary layer (ABL) in the Arctic is one of the elements in the climate system that needs to be well understood to obtain a quantitative understanding of the exchange processes at the interfaces and to test the parameterization schemes for numerical modelling of weather, climate and chemical composition of the atmosphere. Due to the complicated orography of Svalbard, micrometeorological phenomena as well as the heterogeneity of the surface (type, albedo, and moisture) the measured fluxes of turbulence or trace gases that typically vary on scales of 100 m are normally not resolvable in climate models. The turbulent processes in the ABL drive the fluxes of energy and mass between the surface and the free atmosphere. The exchange of water vapour, aerosols and trace gases, in particular CH_4 and CO_2, are also controlled by such processes, as well as the long-range transfer of pollutants. The availability of long-lasting time series of turbulence measurements (first- and second-order moments of velocity and temperature) is allowing new and reliable re-evaluations of some classical expressions, mostly related to the application of Monin-Obukhov Similarity Theory (MOST), to identify critical aspects where the similarity theory fails, and in general to extend our knowledge of the ABL.

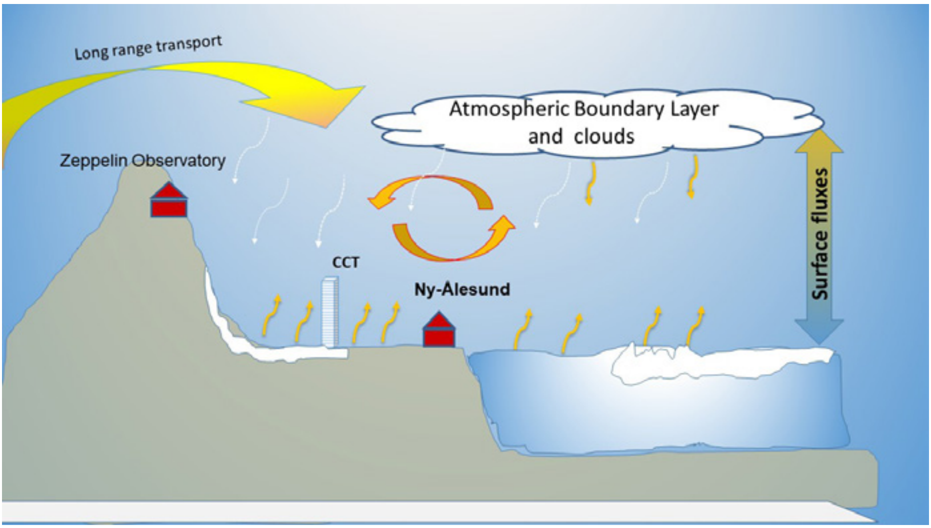

Figure 3: Conceptual model of the lower atmosphere above the fjord at Ny-Ålesund, Svalbard. All the components of the climatic system (sea, atmosphere, ice, snow, soil) interact, transferring energy and mass through the interfaces. The local conditions are also influenced by large-scale processes and long-range transport of mass and energy that contribute to amplifying the variability of the climatic system.

Recent results

The long time series of atmospheric measurements together with focused field experiments have allowed research into several aspects of the ABL structure, from the interaction of the local processes with synoptic circulation, to case studies of singular events like the solar eclipse. They have also provided good statistics on the behaviour of the ABL in different stability conditions, and allowed for evaluating and improving the parameterizations for modelling. Schiavon (2015) described the wind profiles in the lowest tens of metres of the stably stratified atmospheric boundary layer using the data collected at the Climate Change Tower in Ny-Ålesund. Investigation into the vertical structure of the atmospheric stable boundary layer (SBL) is presented by Mazzola et al. (2016) using sonic anemometers and low-frequency thermo-hygrometers and anemometers deployed in a vertical array on the Climate Change Tower in Ny-Ålesund. They show that both the traditional and upside-down SBL cases can occur. The general turbulent characteristics of the boundary layer in Ny-Ålesund under different stability conditions are analysed by Tampieri et al. (2016). They highlight the behaviour of the vertical mixing in quasi-neutral, low-wind conditions, examine the properties of the similarity scaling in unstable conditions and analyse the vertical profiles of the mean velocity and momentum and heat fluxes, also for stable cases. Observations of the ABL over larger areas using controlled meteorological (CMET) balloons have been shown to be valuable in Svalbard (Roberts et al. 2016).

Schulz et al. (2017) discussed the response of fluxes and temperature to the variation of the sunlight during a total solar eclipse that occurred in spring 2015 at Ny-Ålesund with stable atmospheric conditions and a snow covered surface. Kral et al. (2014) analysed, for seasonal variability and differing fetch conditions, measurements of turbulent fluxes of momentum and sensible heat using only a sonic anemometer and slow-response instruments on a tower on the coast of Isfjorden. Jocher at al. (2015) analysed the fluxes of a one-year data set from 3 different eddy sites around Kongsfjorden. The eddy covariance method and a hydrodynamic model approach (HMA) were compared and analysed with respect to season and mean wind direction. They found a clear distinction between 3 prevailing regimes (which have influence on the flux behavior), mainly caused by the topography at the measurement site. Concerning the fluxes, they found a good agreement between the methods in cases of turbulent mixing in summer but deviations are found for stable conditions. Less recently, Di Liberto et al. (2012) showed the possibility to estimate the PBL height by using lidar observations, radiosoundings, and a zero-order one-dimensional model. Jocher et al. (2012) presented the impact of gravity waves on eddy covariance measurements at a site on Kongsvegen glacier and the impact of the main wind direction on the observed fluxes.

The surface energy balance at the Svalbard Archipelago was simulated at high resolution with the Weather Research and Forecasting (WRF) Model by Aas et al. (2015) and compared with measurements of energy fluxes from a site near Ny-Ålesund and several other sites around Svalbard with more limited observations. For surface air temperature, a good agreement between model and observations was found at all locations, but the model overestimated both sensible and latent heat fluxes in most seasons. An interesting work by Schulz et al. (2017) shows the interaction between synoptic and local influences on the ABL height and stability over Ny-Ålesund using a combination of measured conditions during an intensive observational campaign and conditions simulated by a WRF model. Kilpeläinen et al. (2012) compared the vertical structure of the ABL, simulated with the mesoscale model WRF and with its optimized version Polar WRF, to tethered balloon soundings and mast observations taken in March and April 2009 from two Arctic fjords in Svalbard.

Summary of existing data

The Climate Change Tower is an important piece of scientific infrastructure in Ny-Ålesund that has been contributing to the long-term observations of meteorological parameters, turbulent fluxes at different levels and snow layer physical characteristics since November 2009. Due to the different sampling rate of the different sensors, mean values were computed based on a 30-minute average for low response (thermo-hygrometers and propeller anemometers) and fast response (sonic anemometers) sensors. Collected data are stored in the Italian Arctic Data Centre digital infrastructure (http://mainnode.src.cnr.it/cnr/data.php) and can be visualized and downloaded upon request. Since 2012 at the Atmospheric Observatory, a Microwave Radiometer has been running to provide atmospheric profiles of temperature and relative humidity, along with column values of liquid water path and integrated water vapour every 20 minutes. Moreover, a wind lidar has been running to provide 3D wind field profiles every 10 minutes. Data are stored at AWI Potsdam and are available upon request. Three Eddy Covariance (EC) systems set up at different times have been deployed at different sites within the Ny-Ålesund area. The first "Bayelva" is located 2 km W of the Atmospheric Observatory, in Bayelva valley, and has run continuously since 2008, measuring turbulent fluxes, surface temperature and soil temperature profiles (cfr. glaciology flagship). The second "Ny-Ålesund" is located 300 m SSW of the observatory and has run continuously since 2012, measuring turbulent fluxes, temperature and wind profiles in the lowest 2m, surface temperature, snow height and radiation. The third "old pier" is 100 m N of the observatory, just off the coastline at the end of old pier, and has run continuously since 2016, measuring turbulent fluxes and sea surface temperature. Data are stored at AWI Potsdam and currently under evaluation. Vertical profiles of meteorological parameters (pressure, wind, temperature and humidity) by tethered balloon system have been collected on a campaign basis, mostly in spring, since 2009 at the Atmospheric Observatory site. Data are stored at AWI in Potsdam and are available upon request.

Unanswered questions

The local features of the surface layer (the first few metres of the atmosphere) are not systematically related to the features of the upper part of the ABL and/or the free troposphere. Integration of conventional soundings, tower data and covariance measurements near the ground is necessary to fully observe the system. Ground-based remote sensing techniques with sodar to depict the thermal structure of the boundary layer depth or with lidars to estimate the aerosol stratification in the boundary layer could improve the observation of the vertical structure of the boundary layer, though not for all conditions. A rational approach (based on measurements and models) to link all these evaluations could lead to a substantial increase of understanding. A closure of exchange processes should include measurements at the air-sea/sea-ice interface.

Recommendations for SIOS

Evaluate the state of scientific infrastructure and data collection in Svalbard, beyond Ny-Ålesund, and provide support for new installation and/or repositioning of meteorological stations, EC systems and remote sensing systems at other sites outside Ny-Ålesund to build a distributed observation network on land, glaciers and sea. In particular, support should be provided by SIOS to establish and improve the network of measurements at the sea surface. Finally an effort should be devoted to increase the links between all the scientific components present in Svalbard for sharing information, data and facilities.

Atmosphere-snow interactions

Keywords: Snow depth, precipitation, aerosol deposition, snow reflectivity, heat transfer

The role of snow in the interactions between atmosphere, land and ice is a key question in understanding Arctic variability, but snow is particularly difficult to quantify and monitor over time, so again the models are currently not effectively simulating snow in all its aspects. Part of the problem is the technical challenge of using isolated point measurements to assess snow depth distribution on appropriate horizontal scales to fit into current models. On the other hand, from a local point of view, the variability of the snow characteristics are hard to parameterize. There is a need to understand snow structure and composition in relation to the atmosphere, so new technical approaches, new technologies and more extensive networks of measurements are required to better evaluate and understand this critical variable and its relevance to other variables. Snow cannot be considered an independent variable and the study of the physico-chemical characteristics of the snow must integrate knowledge with the atmospheric conditions, aerosol characteristics, energy fluxes, albedo and radiation budget at the surface.

Recent results

Most of the recent works concerning snow are still far from considering the role of snow in the interactions with atmosphere, land and ice as key questions in understanding Arctic variability. Merkouriadi et al. (2017) show that snow depth is a major uncertainty in predicting ice thickness, using remote sensing algorithms. They examined the winter spatial and temporal evolution of snow physical properties on first-year and second-year ice during the Norwegian young sea ICE (N-ICE2015) expedition. To our knowledge, in Svalbard not many studies have been analysing the impact of snow on the climate system variability. Most of the important studies on snow relay what the snow contains and not how it contributes to such variability. Snow is mainly considered as medium where the emissions of natural and anthropogenic activity transported by the atmosphere are collected. In this frame, size distribution of black carbon (soot, BC) in the snowpack has been measured by Sinha et al. (2018) at two sites at Ny-Ålesund in April 2013. The BC size distributions did not show significant variations with depth in the snowpack, suggesting stable size distributions in falling snow. Nawrot et al. (2016) analysed the chemical properties of precipitation, monitoring snow cover and fresh snow at the Hornsund Polish Polar Station and in an elevation profile on the Hans Glacier. Meteorological data from the coast and the glacier helped to examine in detail the impact of atmospheric processes on snow cover contamination. Ianniello et al. (2016) performed measurements of atmospheric concentrations and fluxes of reactive nitrogen above the snow surface at Ny-Ålesund, where significant emission fluxes of NO and NO_2 were observed. Deposition fluxes of HNO_3 and fine and coarse particulate NO_3^- were also observed, reaching peak values during snowfall events. Measurements of surface snow provided experimental data of dry deposition. However, wet deposition in falling snow seemed to be the major contribution to the nitrate input to the snow.

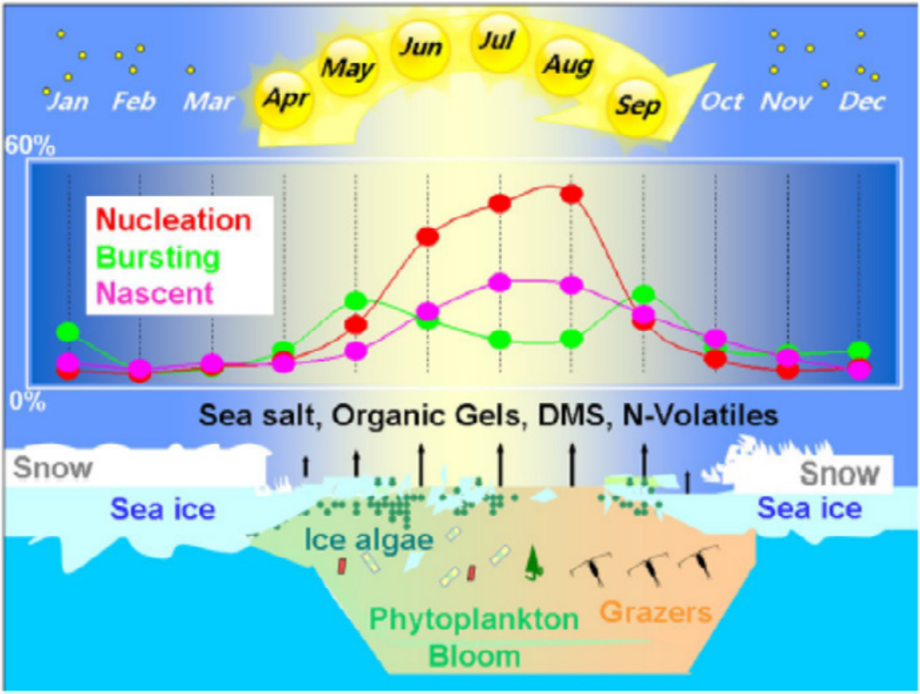

Figure 4: Schematic illustration of seasonal cycle of sea-ice, microbiota, sea-to-air emission and ultrafine aerosols in the Arctic. Aerosol size ranges are 10 ± 2 nm (nucleation aerosols), 32 ± 12 nm (bursting aerosols) and 50 ± 11 (nascent ultrafine aerosols). Both bursting and nucleation aerosol categories contribute to new particle formation events.

Unanswered questions

Snow is an important medium to measure the quantity and the property of atmospheric constituents falling at the surface. However, many aspects of its interaction with the overlying atmospheric layer, in terms of radiation and mass, chemical and energy fluxes, are still poorly understood. There is a need to find better parameterizations for representing snow and its role in the broader climate system in numerical models. Modelling of the ABL should aim to include the mass fluxes into and from the snow, which would provide a better simulation of both atmospheric and snow properties. However, deposition and exchange processes are not yet well enough understood to develop reliable parameterizations, so there is a need for more detailed coincident observations of atmospheric constituents, turbulent fluxes and the concentrations of the same constituents in precipitation and in snow on the ground.

Clouds and Atmospheric Aerosol

Keywords: Microphysics, clouds, aerosol, nucleation, long range transport

Arctic clouds are critical in influencing energy exchange between ocean and cryosphere surfaces. Water vapour is a major greenhouse gas, and changes in the moisture content of the global atmosphere modifies Arctic climate through transport of water vapour into the Arctic from mid-latitudes, causing changes in cloudiness and thus the radiation balance. The individual cloud droplets started their lives as aerosol particles. At the most fundamental level, understanding the processes that determine cloud properties from microscale to global scale requires understanding which particles actually form cloud droplets under various different conditions. These aerosol particles are mostly transported to Svalbard over long distances in the atmosphere. The resulting atmospheric aerosol concentration, size distribution, chemical and optical properties in the Arctic show a very strong repeating seasonal cycle controlled by seasonal variations in the general circulation, by varying strength of natural and distant anthropogenic sources, and last but not least, by changing efficiency of aerosol removal by clouds and precipitation. The seasonal variation in aerosol properties is not only a boundary layer phenomenon, but also occurs throughout most of the troposphere. Understanding aerosol-cloud interactions and the role of atmospheric dynamics and circulation is among the most important scientific challenges. Many pollutants and atmospheric constituents that are transported over long distances to the Arctic have been monitored for many years in Ny-Ålesund, including aerosol, greenhouse gases and short-lived climate forcers such as black carbon (soot). These influence snow albedo and cloud properties. Ny-Ålesund is well equipped with state-of-the-art aerosol measuring systems, both in-situ and from remote sensing. For this reason, the site should be a key validation point for climate models with interactive aerosol and trace gases to analyse the questions: what are the pollution pathways, the aerosol secondary formation processes, sources and sinks and the interaction between aerosol and clouds in the European Arctic. To answer these important, general questions the different aerosol measurements need to be combined, also considering vertical profiling, the interaction between aerosol and the boundary layer and the combination between in-situ and remote sensing information. Some of the recent work already points into this direction.

Recent results

Markowicz et al. (2017) used a combination of aethalometer measurements on a tethered balloon and lidar measurements to show that BC concentrations are normally low and their vertical concentration is not related to the backscatter in the lidar. Ritter et al. (2016) provided a statistics for the Haze season 2014 from a lidar perspective and height-resolved optical properties of aerosol during the iAREA campaign on aerosol in Spitsbergen. Tomasi et al. (2015) described an overview of photometer measurements at different polar sites and typical, lidar-based optical properties from Ny-Ålesund. In the paper of Stock et al. (2014) long-term aerosol optical depth (AOD) data are presented and interpreted via air back-trajectories and EOF patterns of surface pressure, and they found high AOD loads over Ny-Ålesund for air masses from the central Arctic, with less aerosol from Europe. Hoffmann et al. (2012) showed how lidar data from an Arctic haze event has been inverted to obtain a size distribution that showed reasonable agreement to a size distribution by SMPS at the Zeppelin Observatory. However, experiments like this need to be repeated for various aerosol conditions, as sometimes remote sensing instruments seem to overestimate and in-situ aerosol measurements to underestimate extinction (e.g. Tesche et al. 2014). Stock et al. (2011) showed that lidar and photometer data collected during an Arctic Haze event and a biomass burning case showed similar optical properties. Hence the maximum information content from remote sensing data needs to be revised. Hoffmann et al. (2012) analysed an aerosol layer of volcanic origin in the lower troposphere, which sporadically and unpredictably can enter the Arctic. Udisti et al. (2016) evaluated the seasonal pattern of sulfate, as a key component of the Arctic haze that presents a strong seasonality, with mean spring concentration about 1.5 times higher than that measured in summer. Giardi et al. (2018) presented, at high temporal resolution, a large atmospheric concentrations dataset of metals in Arctic particulate matter and used this to distinguish between local and long-range transported dust. Ferrero et al. (2016) and Cappelletti et al. (2016) demonstrated the possibility to measure vertical profiles of atmospheric BC and aerosol properties by tethered balloon. In particular Cappelletti et al. (2016) improved the capability of measuring at the same time aerosol light scattering, absorption coefficients and size distribution, which is very promising for deducing the aerosol optical properties as a function of height along the probed atmospheric column. Important results related to source apportionment, annual cycle and hygroscopic properties have been achieved using data from the Zeppelin Observatory. Strong evidence of role of marginal ice zone and biogenic sources in new aerosol particle formation in the Arctic was shown (Dall'Osto, 2017). Microphysical aerosol properties observed at Ny-Ålesund were studied together with 4 other sites in the Arctic and all sites show that similar processes and seasonal cycle is present on pan-Arctic scale (Freud et al., 2017). Seven years of observations of cloud condensation nuclei also show a repeating annual cycle closely linked to atmospheric aerosol and interplay between natural and anthropogenic sources of CCN (Jung et al., 2018). Specific to cloud research, among other types of measurements, cloud radars have been employed within the last 3 years by groups from Japan and Germany. Currently the cloud net algorithm is tested for Arctic clouds. Research that analyses cloud properties in relation to the synoptic wind is currently being performed. Further, a radiative transfer model to better understand the forcing of clouds and aerosol is currently being applied, but this important work will need to continue into the future as well.

Unanswered questions

As mentioned by Tesche et al. (2014), the combination of different aerosol measurements can lead to inconsistent results. More indications for this exist (L. Ferrero, private communication based on 2011 data and J. Lisok, private communication based on 2014 data). Combined aerosol measurements from the sites at Gruvebadet and Zeppelin, together with those from a tethered balloon and a lidar can be used to systematically improve our understanding of the aerosol properties. Aerosol properties in relation to relative humidity have already been studied on Mt. Zeppelin. However, due to the broad variety of the chemical composition of aerosol and the complex boundary layer structure in Kongsfjorden, this will probably remain an open topic for the near future. One of the challenges in future research is to understand the impact of changing atmospheric dynamics, water vapour distribution and aerosol properties on tropospheric cloud formation. The ultimate question we would like to answer is: To what extent are the changes in tropospheric cloudiness linked to perturbations in atmospheric dynamics and to aerosol effect on clouds?

Summary of existing data

Sun-photometers are very important sensors to estimate the AOD: one is located at the BSRN site and runs continuously (mid-March to early Oct) since 2003, and another runs continuously (mid-March to early Oct) since 2010 at Zeppelin Observatory. Both work at 10 wavelengths with 1-minute resolution. A Star-photometer at the Atmospheric Observatory works with 10 wavelengths and 6-minute resolution; it runs sporadically (mid Oct to end March) since 1996. To measure backscatter, extinction, depolarization and water vapour (night time) profiles from a Raman Lidar “KARL” with 7.5-m / 2-minute (maximal) resolution, runs on clear sky days since 2000. Data are stored at AWI Potsdam and are available upon request. Ground based measurements of aerosol are provided at Zeppelin Observatory and at Gruvebadet Aerosol laboratory. To observe cloud height and microphysical properties, a micropulse lidar has measured backscatter from clouds since 2002, with depolarization data since 2013, and a cloud radar has measured cloud reflectivity since 2013, with all data stored at NIPR. More recently, in-situ observations of cloud phase and droplet size distribution (data stored at U. Tokyo) and cloud condensation nuclei (data stored at KOPRI) have been made at Zeppelin Observatory.

Science Summary

Svalbard is located in a region in which North Atlantic and high Arctic conditions are mixing, and even though it is not representative of the whole Arctic it is a very important region in the Arctic where rapid warming has occurred. Moreover the region provides particular opportunities to tackle major questions, such as vertical and horizontal coupling of relevant variables, that are not easily addressed elsewhere. With the help of appropriate modelling, these results could be extended within and around the archipelago. The geographical position and the geomorphological structure allow Svalbard to be considered a natural laboratory for studies concerning climate change in polar regions as well as feedbacks on the other areas of the planet. *What occurs in the arctic does not remain in the Arctic!*

The low atmosphere is the part of the atmosphere directly influenced by processes occurring at the surface. The incoming solar energy is distributed to all the components of the climate system: atmosphere, cryosphere, land and sea, and the themes concerning the low atmosphere are strongly interconnected with all components of the climate system.

Long-term trends in Svalbard indicate that the climatology of wind, temperature, precipitation and cloudiness has changed during the last decades and that these changes can be attributed to the global increase of greenhouse gases, but also to the variation of the atmospheric composition and dynamics. Focusing more on the lower atmosphere, it is widely acknowledged that global climate change is substantially anthropogenically driven, but it is far from clear how much the remarkable changes observed in the Arctic are driven primarily by external processes (including Sun-Earth connections) or due to internal Arctic System processes, such as local and regional variations and feedbacks.

For example, melting of sea ice due to global warming causes an accumulation of heat into the sea contributing to the so-called Arctic amplification and driving an increase of evaporation, aerosol production, nucleation processes and, consequently, cloud formation. These processes are not independent from each other as they interact with other components of the climate system. Long-range transport, from mid- and low latitudes, contributes to the high variability of atmospheric conditions in the Svalbard region.

Some "hot current questions" are currently studied in Svalbard, and in particular in Ny-Ålesund, by several research groups from different scientific institutions, but definite answers have not been yet achieved.

Important results have been obtained in the atmospheric boundary layer studies. These results are mainly based on observations, and a huge amount of data has been collected over several years by the observatories and during specific field campaigns. The AWI observatory, the Zeppelin Observatory, the Gruvebadet laboratory, and the numerous other infrastructures have contributed to building such a database. For long-term trends in the lower atmosphere, the questions concern the dramatic increase of temperature, in particular in wintertime, and the trends in trace gases. Study of atmosphere-snow interactions is providing accurate precipitation measurements, estimation of the trends, measurements of Black Carbon and accurate measurements of physical and chemical properties of snow. Clouds and atmospheric aerosol studies focus primarily on the stability and occurrence of mixed-phase clouds, the hygroscopic growth of aerosol and aerosol-cloud interactions. An important study is attempting to achieve aerosol closure and to identify the forcing constraints of aerosol and clouds.

The validity of theories being applied to the observations still needs to be verified. In such a complex region, theory can fail and modelling cannot correctly reproduce the observations. This can be particularly true for the boundary layer vertical structure, atmospheric stability, stratification, fluxes of energy and mass, aerosol characterization and vertical distribution, cloud formation and cloud coverage. Moreover, the local observations must be coupled and integrated with the large-scale atmospheric and oceanic processes to get a complete overview of the phenomenology.

Main scientific gaps

From the open scientific questions, it can be seen that processes linking aerosol, clouds, boundary layer, and how they interact are still not sufficiently understood. In this respect, atmospheric research in Ny-Ålesund is not isolated but faces the same challenges as elsewhere e.g. Gimeno (2013), Boucher et al. (2013). Once some scientific progress is achieved, a state-of-the-art Large Eddy Simulation (LES) model for the Kongsfjord region could potentially bring all the existing measurements on aerosol, clouds, ABL and snow together for a closer look at the deficits or peculiarity of individual measurements, the micrometeorology of the complex terrain and deficits and shortcomings in the model. Generally, Ny-Ålesund is handicapped by a complicated orography. Moreover, the West coast of Spitsbergen is influenced by the interaction between the water and air masses of Atlantic and Arctic origin. On the long term, even with a better understanding of the micrometeorology in Kongsfjorden and closer cooperation with other existing stations in Svalbard, it might be necessary to consider permanent measurements at least of some key variables in the eastern part of the archipelago and at elevation, away from the coasts. The advantages of Ny-Ålesund are the relatively cheap and quick travel conditions and the comfort it provides. Moreover, more and more existing data sets will become "long-term" in the near future. Further, Ny-Ålesund is located in the region of most dramatic temperature increase. In fact, during the next decade the annual average temperature may rise above 0°C which will cause dramatic effects on the glaciers and the ecosystem. Nevertheless, its dramatic orographic influence poses a challenge in the interpretation and representativeness of the observations. However, a combination of LES modelling and different data sets of key meteorological quantities at different locations in Kongsfjorden and Svalbard may provide a strategy to differentiate between local and synoptic conditions. In this respect the measurements in Ny-Ålesund can also contribute to ESM modelling, as each meteorological profile from each site will be influenced by unique small scale disturbances.

Cross cutting themes

The seasonal variation in aerosol properties is not only a boundary layer phenomenon, but also occurs throughout most of the troposphere. Understanding aerosol-cloud interactions in a frame of atmospheric dynamics and circulation is among the most important scientific challenges. Aerosol research in Svalbard has a very long tradition, both in-situ and by remote sensing. In Ny-Ålesund, the cooperation between the different research groups is already strong. Research on boundary layer and clouds has been evolving quickly over about the last 7 years. So far, as stated above in the current research questions, each topic has its own, well-defined questions. Naturally, with evolving knowledge, in the end those topics will merge together. The communities have been gaining good experience by performing joint measurement campaigns. A common calibration facility is on the way, and it will be improved. Upcoming projects like the EARTHCare satellite mission will surely intensify the cooperation among the atmospheric community.

The Ny-Ålesund atmospheric community is already represented prominently in many high-level scientific organizations. Data are regularly uploaded in databases like BSRN, GRUAN, Fluxnet, to name just a few. SIOS promotes an open data policy and the natural exchange and external use of the data collected in Ny-Ålesund and in Svalbard data should be improved by a higher transparency through which each institution stores the data in in a well-documented, interoperable format. In this sense, common and interoperable systems should be supported to increase the data discovery and access. Open Data Policy should also sustain common procedures for maintenance of instruments and data processing information. Everyone knows that data management is complicated, also because of gaps when changing of the recording instrument occurs. Each scientific community has its own history in managing the data. In some case this can hard to modify, but a common procedure to access the data information (Metadata) should be achieved. Procedures must be user friendly, reducing the administrative requirements. A list of which PI is responsible for which data might introduce hardly any new administrative work, but would strengthen the cooperation among the research institutions. The Ny-Ålesund Atmosphere Flagship works to maintain such a list for relevant datasets there, and Research in Svalbard is a start towards that goal for the whole of Svalbard.

Summary of recommendations for SIOS

- Evaluate the state of scientific infrastructure and data collection in Svalbard beyond Ny-Ålesund
- Better coordinate the observations at existing sites between the different research fields
- Improve of spatial distribution of measurement stations within Svalbard
- Establish high quality, long-term observations at geographically diverse sites around Svalbard
- Build a distributed observation network on land, glaciers and sea
- Make the information on data (metadata) and data available, exchangeable and accessible.
- Improve the modelling to guide, improve and expand observations in the region

Data accessibility

Institution	Metadata and data URL
PANGEA – GERMANY	http://dx.doi.org/10.1594/PANGAEA. 150000/ 854326
IADC- ITALY	http://mainnode.src.cnr.it/cnr/data.php
NMI – NORWAY	http://eklima.met.no
NPDC–NORWAY	https://data.npolar.no
NILU – NORWAY	https://www.nilu.no/Miljoovervakning/tabid/186/language/en-B/Default.aspx
NIPR – JAPAN	https://scidbase.nipr.ac.jp/modules/metadata/index.php?cat=arctic
KOPRI – KOREA	https://kpdc.kopri.re.kr/metadata/?rid=KPDC_2018_0162

Table 1: List of data centres which host data for atmospheric studies in the Svalbard region.

Acknowledgements

The authors wish to acknowledge Hans Christen Hansson and Roland Neuber in encouraging submitting a proposal for SESS report to SIOS. The authors thank also Angelo Lupi and Mauro Mazzola for the fruitful suggestions during the preparation of the report. Last but not least the authors wish to thank all personnel of the SIOS Knowledge Centre for the technical, administrative, and logistic support provided. This work was supported by the Research Council of Norway, project number 251658, Svalbard Integrated Arctic Earth Observing System - Knowledge Centre (SIOS-KC).

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Clouds

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Observations of the solar UV irradiance and ozone column at Svalbard

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Keyword: Arctic environment, solar UV irradiance, ozone column, ozone profiles, Arctic upper atmosphere

Introduction

Solar UV radiation reaching the Earth's surface (from about 295 to 400 nm) is able to impact the chemical reactions in the troposphere, and all biological cycles (Bischof et al. 1998; Björn 2002; Cadet et al. 2005; Laglera and Van Den Berg, 2007; Raso et al. 2017). Since the intensity of the UV-B irradiance (wavelengths less than 315 nm) observed at the ground strongly depends on the ozone column, the behaviour of these two parameters is usually jointly studied. Due to its absorption capacity the ozone significantly affects the thermal regime of the stratosphere, where the concentration of this component reaches maximum values (Brasseur and Solomon 2005) and hence, the variations in ozone column can be considered as an important indicator of stratospheric dynamical processes. On the other hand, the atmospheric ozone acts as a reliable shield for all life on the Earth, protecting the organisms from harmful UV-C (100 – 280 nm) and a fraction of UV-B (280 – ~315 nm) irradiance. Svalbard is located in a region where the typical harsh polar climate is disturbed by the Gulfstream, which transports warm water masses from the tropics. As a result, the role of dynamical processes in the atmosphere tends to enhance the variability of the atmospheric transmittance and thus, the variability of the solar radiation reaching the surface. In this context, the study of solar UV irradiance and ozone column behaviour in the region of Svalbard could contribute to our knowledge about the Arctic environment and lead to deeper understanding of climatic variability.

Figure 1. The geographic position of the stations measuring solar UV irradiance and ozone column at Svalbard. The pink dashed curves outline a sector over which the distribution of the daily erythemal doses were reconstructed from the measurements performed at the stations (see Fig. 6).

Instrumentation and summary of existing data and achieved results

Irregular observations of ozone column in Svalbard (74° – 81°N, 10° – 35°E) have been performed since 1950 (either Longyearbyen or Ny-Ålesund, see Fig. 1) and continuously since 1991 in Ny-Ålesund (78°56'N, 11°55'E). Most of the historical ozone observations by means of Dobson spectrophotometer #8 between 1950 and 1968 were re-evaluated and the results were published in the recent past (Vogler et al. 2006). The 1985-1993 Dobson measurements in Longyearbyen are not usable for long-term trend studies due to insufficient quality-control routines, and only in 1995, the Dobson spectrophotometer was moved to Sverdrup Station in Ny-Ålesund, and observations under controlled conditions continued until 2005. Ozone profile measurements by means of ozone sondes were started in Ny-Ålesund by Alfred Wegener Institute in 1988 and are still continuing on a weekly basis. In 1991, a SAOZ UV/Vis spectrometer working on the basis of the Differential Optical Absorption Spectroscopy (DOAS) technique and providing total ozone around sunrise and sunset, was taken into operation in Ny-Ålesund to observe the ozone column behaviour from mid-February until early May and from August to end of October. The SAOZ instrument excellently complements the standard total ozone observation techniques (Dobson, Brewer photo-spectrometers, multi-wavelength filter instruments) which rely on solar zenith angles (SZA) typically less than 80° and it is especially suited to detect stratospheric ozone destruction in later winter/early spring at high latitudes (e.g., Pommereau et al., 2013). In 1995, researchers from Norwegian Institute for Air Research (NILU) established a 5-channel filter instrument (GUV-541, Biospherical Instruments, San Diego) at Sverdrup Station in Ny-Ålesund to monitor UV irradiance and total ozone with 1 min temporal resolution at SZA < 75°. A team from the Italian Institute of Atmospheric Sciences and Climate at the National Research Council (ISAC-CNR) has performed combined UV/ozone measurements since 2008 (with two major gaps in 2011 and 2013) by means of the own-made UV-RAD radiometer aimed to work in the harsh conditions of the polar regions (Petkov et al. 2006; Vitale et al. 2011). In 2005, Italian researchers from the Institute of Acoustics and Sensors "Orso Mario Corbino" (IDASC-CNR) started also operation of a Brewer spectrometer at Ny-Ålesund (Rafanelli et al. 2009). The last two instrument calibrations were in 2015 and 2018, respectively, while regular observations supervised by ISAC-CNR commenced in spring 2017.

At the Polish Polar Station in Hornsund (77°00'N, 15°33'E, see Fig.1), operated by the Institute of Geophysics, Polish Academy of Sciences, solar irradiance measurements, including UV were started in 1996, using an own-made radiometer very similar to Robertson Berger UV meter SL501 A and continued until 2002. In 2005, the instrument was replaced with a Kipp & Zonen UVS-AE-T UV radiometer, supplied by a CM11 pyranometer; these instruments have continued observations until present. In 2017, a new K&Z UVS-E-T UV radiometer was taken into operation, to take over from the old instrument after an adequate overlap time.

At the Russian station in Barentsburg, a filter ozonometer M-124, operated by a research team from the Main Geophysical Observatory, St. Petersburg, Russia, carries out ozone column measurements. At the beginning of March 2018, a recently developed UFOS spectroradiometer, providing the solar UV spectral irradiance was established at the station.

A K&Z UVS-E-T UV radiometer was set up at the new Czech Research Station (Julius Payer House) in Longyearbyen (78°13'N, 15°39'E) in the summer of 2017 to observe the erythemally weighted solar irradiance.

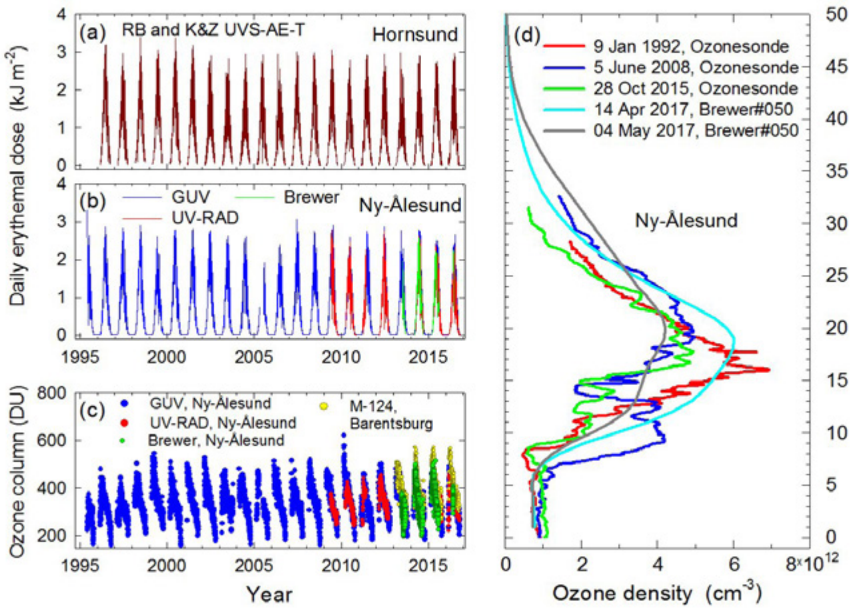

Figure 2. Data-sets, available from the measurements performed at Svalbard. Panels (a) and (b) show time patterns of the daily erythemal dose observed at Hornsund and Ny-Ålesund respectively, while the ozone column behaviour is shown in (c). Several profiles of the ozone density registered over Ny-Ålesund are given in (d). The instruments providing the corresponding data are indicated in each of the panels.

Figure 2 presents the available data-sets together with some examples of ozone profiles provided by ozone sondes and Brewer spectrophotometer (Umkehr measurements); these data were subjects of different studies performed by the corresponding research teams. The NILU Annual reports summarise measurements of surface UV radiation and ozone column at Ny-Ålesund (e. g. Svendby et al., 2017), while the observations performed at Hornsund were presented by Sobolewski and Krzyścin (Krzyścin and Sobolewski, 2001 and Sobolewski and Krzyścin, 2004-2005). Weather variability at Svalbard as a parameter strongly impacting surface UV radiation was examined by Láska et al. (2013). Large short-period ozone column variations characterised by hourly time-scales were observed at Ny-Ålesund and were a subject of an in-depth study (Petkov et al., 2012) to exclude the hypothesis that they could be a result of measurement errors. In addition, it was concluded that these short-period oscillations can be a manifestation of the evolution of a 6-dimensional stationary chaotic system (Petkov et al., 2015), that assumes a deterministic character of the ozone variations, and hence, the possibility to predict them within daily time intervals.

The impact of strong ozone depletion events observed in the Arctic on ozone column at lower latitudes were studied (Hansen et al., 1997; Hansen and Chipperfield, 1999; Petkov et al., 2014), and the results indicate that the processes in polar areas are able to affect UV radiation over highly populated lower-latitude regions. The variability in ozone density, air temperature and wind velocity over Svalbard were investigated by examining the 21-year data-set of ozone sonde measurements performed at Ny-Ålesund through the principal component analysis applied to two data-sets representing short-period (composed by harmonics with periods $P < 1$ year) and long-period ($P > 1$ year) oscillations (Petkov et al., 2018). The obtained Empirical Orthogonal Functions (EOF), which were assumed to represent the vertical profiles of amplitudes attributed to specific harmonics composing both kind of variations exhibited layered structure expressed by wave-like forms up to 25 km altitude. One of the important features of the EOF height distributions was the extremely low tropospheric values of the amplitudes characterising the long-period harmonics, composed by the Quasi-Biennial Oscillations, El Niño-Southern Oscillations etc. that usually are detected in the behaviour of atmospheric parameters over the world. These findings depict the Svalbard troposphere as being a comparatively closed system with respect to these global variations. The wave-like behaviour of some EOF components that compose the short- and long-period variations in the studied parameters was characterised by fluctuations from negative to positive values, whose changes in the amplitude sign were interpreted as changes in the phases of the corresponding components. This occurrence assumes height levels where the amplitudes of some spectral harmonics become close to zero and hence, the corresponding variations vanish. In addition, a response of the short-period ozone variations to particular atmospheric events, like the strong ozone depletion over Arctic in the spring 2011 and solar eclipses, was registered and such a response was expressed by modifications in the amplitude frequency characteristics of the corresponding oscillations.

Recent activity on harmonisation of UV and ozone studies at Svalbard.

The above presented results led to the idea of uniting the efforts of different research teams active in UV irradiance and atmospheric ozone research, and integration of the existing Svalbard stations in a network that would be able to provide more comprehensive information for scientists working on climatic and biological issues in the Arctic and for validation of satellite data. The project "UV Intercomparison and Integration in a High Arctic Environment (UV-ICARE)" (RIS 10871, https://www.researchinsvalbard.no/project/8626) aimed at making the first step toward the creation of such a network, starting with an intercomparison campaign of the instruments from 17 to 23 April, 2018. Considering the Brewer spectrophotometer as a reference device, it was found that the values of erythemally weighted solar UV irradiance provided by the different instruments agree within ±3% deviation for SZA < 75°, within ±5% for 75° < SZA < 80° and ±7 – 10% for SZA > 80°. With regard to ozone column measurements, the GUV, UV-RAD and Brewer radiometers showed less than ±3% differences between each other. These results demonstrate a satisfactory agreement between the different devices, bearing in mind that they are characterised by quite different spectral selection techniques and electronic equipment.

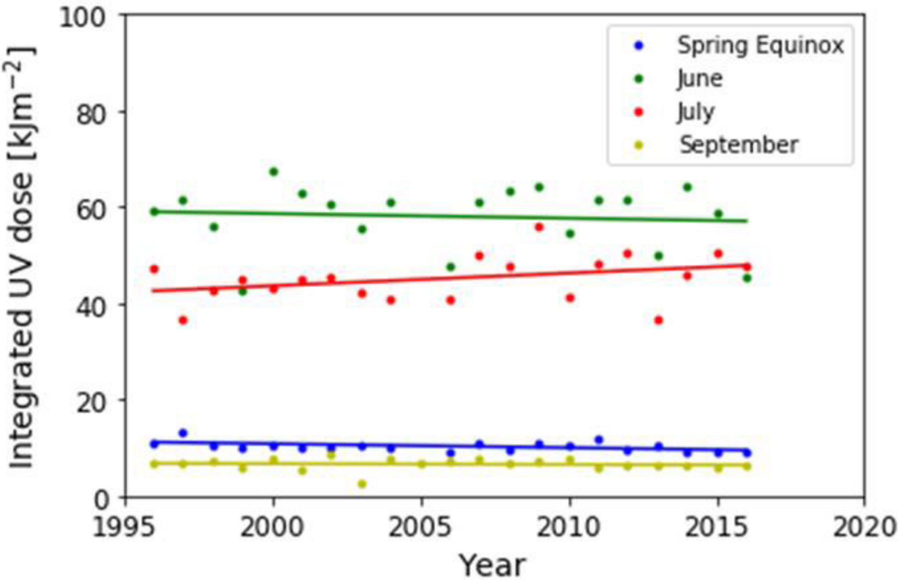

Figure 3. Integrated UV doses from Ny-Ålesund during selected periods: spring equinox±10 days (blue), monthly doses from June (green), July (red) and September (yellow). June and July values for 2005 are missing.

Another important task for the establishment of the new network was a re-analysis of the available data-sets that would help us to outline better the long-term features of the observed parameters and hence, to have a realistic idea about their evolution. As a part of such studies the trends derived from the GUV erythemal dose data series from 1996 to 2016 (except 2005 due to missing observations during summer) has been investigated, both on an annual basis (including days 60 to 285), and on a monthly and seasonal basis (G. Hansen, personal communication). During these two decades, the annual dose decreased by 1.6%, but the trend is not significant at a 2-s level. Figure 3 shows the trends for selected sub-sets exhibiting a negative trend in most of the months and seasons with an exception. The strongest negative trend of -8.1%/decade was found around spring equinox (±10 days), while in June the trend presented a lower negative value of -1.7%/decade followed by clearly positive trend of 5.8 %/decade in July. The September trend again is negative,with a value of -2.5 %/decade. As one does not see similarly large trends in the total ozone data, the cause has to be hidden in the other parameters: cloud cover and albedo (snow coverage). It is imaginable that a reduced snow cover during spring and autumn may explain the decrease of UV doses in these two seasons, while the marked increase in the summer must be due to reduced cloud coverage, possibly also decreased turbidity (less aerosols). Such a hypothesis should be investigated in detailed studies of these parameters.

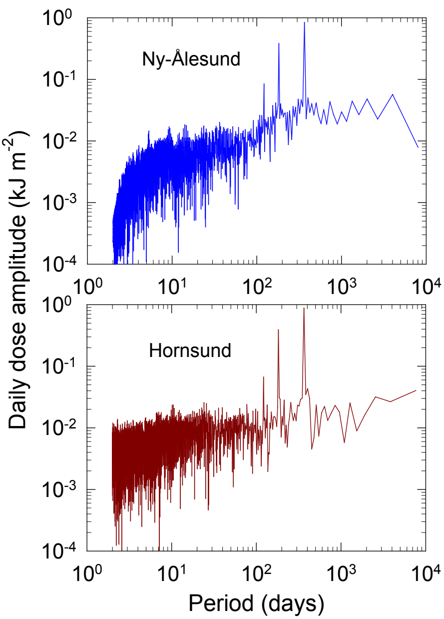

Figure 4. Spectra of the GUV and UV-RAD erythemal daily doses time patterns given in Fig. 2 (a) and (b), respectively.

Two erythemal dose data series registered at Hornsund and Ny-Ålesund (by GUV radiometer), which are shown in Figs. 2 (a) and (b) respectively, cover more than 20-year observational period. Assuming that the two partial series yielded by Robertson Berger and Kipp & Zonen radiometers at Hornsund within different periods are optimally homogenized, the two sequences offer the opportunity for a statistical long-term comparison. Figure 4 exhibits the spectra of the two time-series derived through the Lomb-Scargle periodogram approach (Lomb 1976; Scargle 1982). These spectra indicate very similar features: (i) both time-series are dominated by annual, semi-annual and 4-month harmonics, which are assumed to be modulated by the variations in the incoming solar radiation and (ii) both spectra contain a continuum-like band of harmonics with periods P < 120 days that are assumed to express the impact of the local environ-

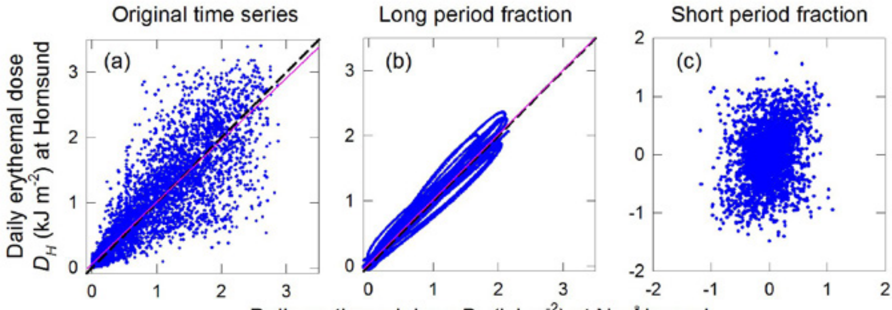

Figure 5. Comparison of daily erythemal doses (left panel) and their long-, and residual short-period components (middle and right panels, respectively) observed at Hornsund and Ny-Ålesund. Diagonals (black dashed lines) and regression lines (in pink) are shown for measured and long period values. Analytical regression dependencies with the corresponding coefficient of determinations R2 are given below.

mental conditions (cloud cover, aerosol loadings, surface albedo etc.) on the atmospheric transmittance. These findings led to the idea to separate both long-period (P > 120 days) and short-period (P < 120 days) spectral components and compare to each other all three time series: originally measured, short- and long-period fractions, obtained at each of the stations. Figure 5 shows scatter plots of these three datasets demonstrating that the values, which correspond to the long-period series (Fig. 5 (b)) are highly correlated with an axis offset of about 1%, a slope of 0.99, and a correlation coefficient of 0.98 that confirms the intuitively assumed circumstance about the similar effects of the incoming solar radiation, stratospheric ozone field and seasonal effects (snow cover) on the measurements at both stations. In contrast, the scatter plot of erythemal dose values representing the short-period time series (Fig. 5 (c)) exhibits a lack of linear dependence. It is seen that the short-period components reveal a larger variability at Hornsund than at Ny-Ålesund and, at the same time, they spread as much as the long-term component, varying within a ±2 kJ m^{-2} interval, which emphasizes the great influence of local conditions. The comparison between originally measured time series at both stations demonstrated in Fig. 5. (a) shows a good correlation and high significance that assumes a dominant role of the long-period component.

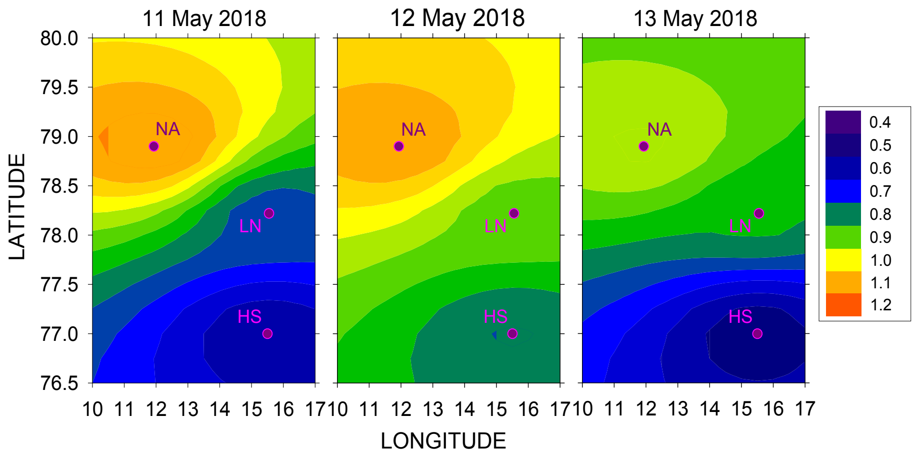

Figure 6. Erythemal dose distribution over the sector shown in Fig. 1 and obtained through the interpolation procedure presented in the text. The colour scale indicates the daily erythemal dose in kJ m-2 and the positions of the three stations, Ny-Ålesund (NA), Longyearbyen (LN) and Hornsund (HS), whose data were used for the reconstruction are also indicated.

The above results led to the idea for a reconstruction of the erythemal dose distribution over a region of Svalbard. Since the measured doses at two points placed at a distance of 230 km, like Hornsund and Ny-Ålesund are highly correlated, according to Fig. 5 (a), it can be assumed that an interpolation of the data from several stations over a grid covering an area around these stations so that the distance of each grid point to the closest station does not exceed 200 km, could give a realistic surface distribution of the doses. To perform such an interpolation, the sector outlined by 76°30'N – 80°00'N and 10°00' – 17°00'E that is shown in Fig. 1 by pink curves was covered by a grid with 15' resolution along the latitude and 30' along the longitude. The interpolation was performed by applying the Shepard (1968) approach that determines the erythemal daily dose D_{ij} at each grid-point (*i,j*) located at latitude *i* and longitude *j*, as weighted average using the inverse square of the distance d_{ij}^{s} between the grid-point (*i,j*) and station S as weight:

$$D_{ij} = \frac{\sum_{S} D_S \left(d_{ij}^{s}\right)^{-2}}{\sum_{S} \left(d_{ij}^{s}\right)^{-2}}$$

where D_S is the dose measured at station S. The distance d_{ij}^{s} (in km) was determined by applying the Lambert (1942) formula to the World Geodetic System 1984 spheroid (WGS84, 2000). A similar approach was applied by Petkov et al. (2014) to study the effect of the 2011 Arctic ozone depletion on the mid-latitude ozone column. Figure 6 shows three examples of dose distribution maps obtained for 11, 12 and 13 May 2018, respectively, over the chosen sector using the measurements performed at Ny-Ålesund, Hornsund and Longyearbyen. This example indicates that the Northwest part of Svalbard was exposed to more intense solar UV irradiance than the Southeast areas during the 3-day period considered.

The observations performed on Svalbard allow also us to gain information about the altitude characteristics of the variations in the ozone density. Besides ozone vertical profiles derived from ozone sondes, which were already presented above displaying features of ozone variation up to 25 km, the Brewer Umkehr measurements give the possibility to extract the vertical ozone distribution up to 50 km altitude as Fig. 2 (d) shows, though with less vertical resolution. Such an enlargement of the observational range, together with the satellite measurements allows a more profound study of the effects produced on the upper atmosphere by the solar particle fluxes, which are much more intensive over the polar areas (Jackman and Fleming 2000; Randall et al. 2005; Damiani et al. 2008; Mironova and Usoskin 2014). Figure 7 exhibits ozone density time series at different heights for the period March – May 2017 extracted from the Umkehr measurements at Ny-Ålesund. It can be seen that in the upper stratosphere the ozone was characterised by a comparatively deep minimum occurring in the middle of April, while below about 30 km, where the maximum of ozone density is usually registered (about 20 km), such a minimum occurred nearly two weeks later.

The achieved results help to outline the main features of the surface UV irradiance and ozone behaviour at Svalbard but, on the other hand, they assume a variety of unanswered questions that need additional study in the future. Some of these issues are:

The trends in the erythemal doses and ozone evolutions need to be studied in-depth including all available data-sets and compared with results found in other atmospheric parameters by other research groups working at Svalbard.

In the discussion of Figs. 4 and 5 it was mentioned that the short-period variations in the erythemal doses registered at Hornsund and Ny-Ålesund are strongly affected by the impact of local or regional environmental conditions. A detailed study of these variations, taking into account the measurements performed at other Svalbard stations, is expected to provide important information about the intensity of the atmospheric processes in the archipelago. Figure 4 indicates that the spectra of these variations follow a power law behaviour that reveals a complex nature of the dynamical system containing the erythemal dose as a component. The main features of this system could be outlined by examining the dose variations together with the evolution of other environmental factors.

- The dose distribution maps should be examined more carefully considering large observational data-sets that could help to find possibly typical patterns giving information about the exposure of Svalbard to solar UV radiation. This information would be important for biological and chemical studies. In addition, a comparison with satellite data provided by operating space-borne devices like Ozone Monitoring Instrument (OMI), Global Ozone Monitoring Experiment 2 (GOME-2) or completed missions like Michelson Interferometer for Passive Atmospheric Sounding (MIPAS), should be performed in order to have an idea about the reliability of the applied method and obtained results.
- The variations in ozone density observed in the upper stratospheric layers through the Umkehr Brewer measurements is considered to provide an important information about stratospheric processes and combining our efforts with those made by the research teams studying the upper atmosphere could outline a more comprehensive picture of the Svalbard middle atmosphere dynamics. Moreover, these data could be of great use in satellite validation efforts concerning both running instruments like OMI and GOME-2, and devices included in future space missions as well.
- A comparison of the achieved results about UV irradiance and ozone column with those obtained at other locations could indicate features that are particular for Svalbard that, in turn will outline the specific environmental features. The team presenting this report is also working on measurements of UV and ozone in other geographical regions such as Norway that ranges from Svalbard in the north to less than 60°N latitude, central and south Europe (Czech Republic and Italy) and also in Antarctica. In addition, data from adjacent regions can be also provided for comparison.

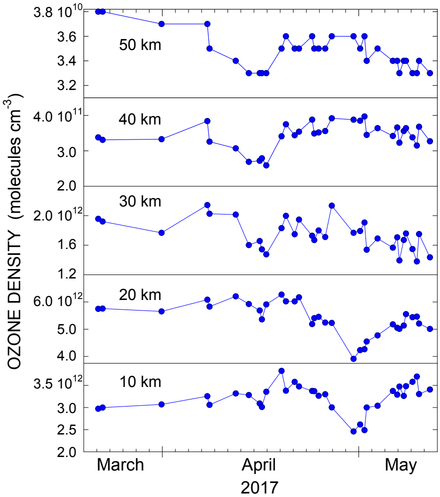

Figure 7. Time patterns of the ozone density derived from the Umkehr Brewer measurements at different altitude levels indicated in each of the panels. The blue circles correspond to the times when the ozone profiles were retrieved.

Data used and data providers / acknowledgements

The Norwegian ozone and UV measurements at Ny-Ålesund are funded by the Norwegian Environment Agency and the Ministry of Climate and Environment. The GUV instrument calibration is performed by the Norwegian Radiation Protection Agency.

The ozone sonde data at Ny-Ålesund were provided by the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, and were partly funded from the European Community's Seventh Framework Programme (FP7/2007 - 2013) under grant agreement № 603557 (StratoClim).

The observational activity at Longyearbyen was supported by the Ministry of Education, Youth and Sports of the Czech Republic, № LM2015078 - CzechPolar2, № CZ.02.1.01/0.0/0.0/16_013/0001708 - ECOPOLARIS and by the institutional long-term research plan № RVO 67985939 of the Institute of Botany CAS References, and by a support of NILU - Norwegian Institute for Air Research, № 270644/E109.

The ozone data from Barentsburg were provided by the Laboratory of Ozone Layer Control at Voeikov Main Geophysical Observatory, St. Petersburg, Russia

The measurement activity at Hornsund is partially supported within statutory activities No 3841/E-41/S/2018 of the Ministry of Science and Higher Education of Poland.

The UV-RAD and Brewer measurements are the result of the ISAC-CNR activity at Ny-Ålesund, supported by CNR and partly by a Great Relevance project funded by MAECI in the frame of the Executive Cooperation programme Italia-Quebec 2017-2019. Data analysis and presented results received support also by the Horizon 2020 European project iCUPE (Integrative and Comprehensive Understanding on Polar Environments), a project of The European Network for Observing our Changing Planet (ERA-PLANET), Grant Agreement n. 689443.

The local network that is currently being established at Svalbard provides space for collecting all above data in a server, which will be integrated with the SIOS database. At the moment, such a storage that contains the data of the different instruments in the format determined by the above providers is accessible via secure copy protocol (scp) at the address uv-icare@skyrad.bo.isac.cnr.it, after identification via password provided under request. A unification of the format allowing more compact data storage and an easier access is one of the aims for the near future.

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Grand Challenge Initiative – Cusp: rockets to explore solar wind-driven dynamics of the top side polar atmosphere

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Keywords: aurora, geospace, polar ionosphere, magnetosphere, reconnection, solar wind forcing, wave-particle interaction, particle acceleration, heating, oxygen outgassing, turbulence, space weather, rockets

Introduction

The Grand Challenge Initiative (GCI) - cusp is a gigantic sounding rocket program that counts 12 sounding rockets of which the major part will be executed in 2018 and 2019. The investigations will cover the altitude range from 100 km to 1000 km for solar minimum conditions. The scope of GCI-cusp is to study the solar wind forcing of the upper polar atmosphere and the atmospheric response to it. The dynamics of the upper atmosphere is largely controlled by the geospace interactions with the solar wind and the Interplanetary Magnetic Field (IMF). The physical phenomena which couple the various regions of the magnetosphere, ionosphere, upper and lower atmosphere have a multi-scale nature. In the auroral zone, it is of particular importance to understand the details of the small-scale mechanisms that significantly affect the ionized and neutral atmosphere, and the way in which they couple into larger-scale processes which control the global system (e.g. Kelley, 2009; Kintner and Seyler, 1985]: The most obvious phenomenon in this region is turbulence in the ionized and neutral components of the polar atmosphere. Plasma processes of a widely diverse nature couple forces spanning scales from 1000 km to tens of cm, i.e. 8 orders of magnitude in spatial scales. While ground-based observations can nowadays provide information about the medium and large scales, detailed in situ measurements are required to study the smallest scales [Moen et al. 2002].

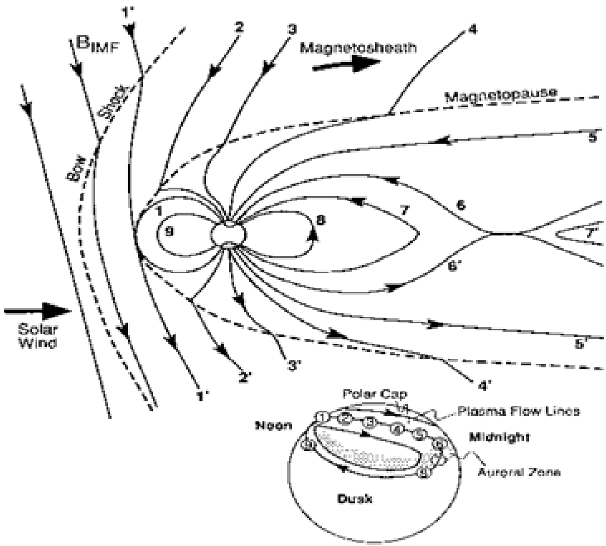


Figure 1: Illustration of how magnetic interactions between the interplanetary magnetic field (IMF) and the Earth magnetic field give rise to a twin cell circulation pattern in the polar cap ionosphere [Kivelson et al. 1995].

Above 100 km, the polar atmosphere is strongly forced by the solar wind, as visualized through e.g. the Aurora Borealis phenomenon. The solar wind drives a twin cell circulation pattern in the polar cap, which transports ionized matter (the ionosphere) across the polar cap from day to night [e.g. Dungey, 1961; Foster, 1984; Weimer, 1995; Cousins and Shepherd, 2010]. Momentum from this movement is transferred to the neutral atmosphere (the thermosphere) by collisions [Skjæveland et al., 2017 and references therein]. We have a reasonably good description of the dynamics of the large scale system, including the large scale currents systems [Kivelson et al., 1995]. Over the past couple of decades we have studied in quite detail the ionospheric signatures of Flux Transfer Events (FTEs) by ground-based and satellite measurements; these are ascribed to transient coupling of the interplanetary magnetic field (IMF) to the Earth magnetic field. In the auroral ionosphere, FTEs are associated with poleward moving auroral forms (PMAFs) [*Sandholt et al*., 1990], ion upflows [*Moen et al*, 2004], flow channels [*Rinne et al*, 2010], formation of polar cap patches [*Carlson et al*., 2006], and are also associated with radio wave scintillation events [*Carlson et al*., 2007; Jin et al, 2015; Oksavik et al. 2015] taken as an indicator of plasma turbulence [Moen et al, 2013, Spicher et al. 2015].

The study of auroral signatures, precipitating energetic particles, plasma convection from dayside reconnection, and global plasma instabilities associated with substorms represent important challenges in Solar-Terrestrial Physics that have profound effects on the ionosphere/thermosphere [e.g. Kelley, 2009]. Traditionally, the thermosphere was thought to be an inertial background of stable, slowly varying density, winds and temperature. However, recent papers identify an appreciable "meso-scale structure" (a few hundred kilometres wide, and few tens of minutes duration) [e.g. Moen, 2002; Oksavik et al. 2004, 2005, 2011; Rinne et al., 2007; Moen et al., 2013]. These have huge implications for the energy dissipation in the neutral atmosphere, because neutral winds driven by ion drag are significantly overestimated and heating rates are underestimated [Skjæveland et al., 2017]. The thermosphere is probably not a passive load on the magnetosphere; thermosphere dynamics also plays an active role in magnetospheric processes, but we do not know how. The unsatisfactory performance of existing atmospheric models is mainly a consequence of poor data coverage in this highly dynamic and structured region. It is necessary to consider the atmosphere as a whole, from the ground to the interactions with the solar wind, in order to understand the dynamics and behaviour of the coupled system.

The need for in-situ small-scale 3D measurements of waves, structures and turbulence in the altitude range 40-120 km by a structured program of sounding rockets is emphasized in the SIOS Optimization report, as it will be essential to make progress on understanding the vertical transport of energy and mass flow dynamics, including the role of meteor components [Ellis-Evans and Holmen, 2013]. However, in the auroral oval, the solar wind executes a strong heating and, probably, a structuring of the thermosphere. Hence the solar wind driven energy input into the ionosphere thermosphere system may probably not be neglected in global atmospheric models.

The GCI – Cusp is going to investigate the nature of magnetic coupling to the solar wind during quasi-steady IMF conditions. We are going study in detail the various wave-wave and wave-particle interactions and acceleration mechanisms downward for auroral precipitation and upward acceleration of oxygen particles escaping the gravitational bound, and there will be rockets to study ion flow channels and neutral wind flow. The Norwegian ICI series of rockets that has been developed to investigate the dynamics of the cusp ionosphere at finer scales [Lorentzen et al., 2010; Moen et al., 2012; Oksavik et al., 2012; Moen et al., 2013] will be further developed to perform 3D in-situ measurements of plasma turbulence. The auroral zone and the polar cap is a region with sheared flows, particle beams, unstable plasma gradients and is rich in waves, instabilities and turbulence phenomena [e.g. Kelley, 2009; Kintner and Seyler, 1985]. Plasma turbulence processes represent one of the outstanding major challenges in classical physics, where fundamental problems have not yet been adequately understood [e.g. Tsinober, 2009]. Turbulent, anomalous resistivity is likely to be an essential constituent in the description of the full ionospheric and magnetospheric current circuit, which may have a large impact on the energy transfer from the solar wind to the thermosphere.

Sounding rockets were prioritized in the Norwegian prioritization report of SIOS, because of the high science potential this technique has in combination with radars and optical instrumentation. Svalbard is in fact the only place in the world where these three techniques can be used simultaneously to observe the solar wind – upper atmosphere interactions. This first SESS report on the SIOS sounding rockets will provide an: i) overview of the gigantic GCI-Cusp sounding rocket program, ii) a rather detailed description of the motivation and the performance of the SIOS InfraNor ICI-5 sounding rocket, and three NASA rocket missions to be launched in the winter of 2018/2019, the plan for developing and sharing data through the SIOS rocket data base, and then a brief summary.

Grand Challenge Initiative – Cusp rocket program

The GCI-Cusp program is a large-scale international collaboration for targeting advancement in specific, fundamental issues in space and Earth science. The GCI concept idea was initiated in 2012 by the University of Oslo (UiO) and the Andøya Space Center (ASC). The idea was simply to umbrella several individual rocket missions in one bigger program with six rockets or more. The GCI-cusp concept was then further developed in close collaboration with the National Aeronautics and Space Administration, (NASA), and the Japanese Aerospace Exploration Agency, JAXA. In 2016, it culminated in the first GCI program - "GCI-Cusp" - to determine the multi-scale physics of heating and precipitation in the ionosphere specific to the geomagnetic cusp region [http://spa.agu.org/spa-section-newsletter-volume-xxiii-issue-23/].

The GCI-Cusp program is an open initiative that has received great attention in the science community. The strategy is to advance the common understanding of the fundamental physics of Solar-Terrestrial interaction in the magnetic cusp by coordinated experimental and theoretical research using ground-based instruments, modelling, sounding rocket investigations, and satellite-based instruments.

Open data access between the collaborating teams is a prerequisite in order to develop efficient collaboration between many international teams. NASA, JAXA, SIOS, and UiO signed a joint venture agreement in Tokyo 6 April, 2017 stating that all partners will share equally the combined database produced by GCI-Cusp [https://www.uio.no/om/aktuelt/pressemeldinger/2017/international-campaign-to-explore-auroral-cusp.html].

Figure 2: Dr. Ole Jørgen Lønne (Interim Director, SIOS), Dr. Saku Tsuneta (Director General, ISAS/JAXA), Dr. Elsayed Talaat, Heliophysics Division Chief Scientist, signed for Mr. Steven Clarke, Director Heliophysics Division, Science Mission Directorate, NASA, and Prof. Ole Petter Ottersen (Rector, UiO). The signing ceremony was observed by the Norwegian ambassador to Japan, Erling Rimestad. Photo Yngve Vogt, University of Oslo.

Table 1. Overview of the rocket missions currently included in the GCI-cusp program. VISIONS-2 successfully launched 7 December 2018, and TRICE-2 successfully launched 8 December 2018 (up to date 12 December 2018)

Mission name	#rockets	Launch Site	Time	Lead nation	Co-Nations	Main Objective
TRICE-2	2	ASC	DEC2018	US	NO, UK	SolarWind-Magnetosphere coupling
VISIONS-2	2	Svalrak	DEC2018	US	NO,CA, UK	Ion upflow
CAPER-2	1	ASC	JAN2019	US	NO	Magnetosphere-Ionosphere coupling
G-Chaser	1	SC	JAN2019	US	NO, JP	Student rocket
AZURE	2	ASC	2019	US		Neutral&plasmadynamics
SIOS ICI-5	1	Svalrak	DEC2019	NO	US,CA	Plasma turbulence
C-REX 2	1	ASC	DEC2019	US		Neutral&plasmadynamics
CHI	1	Svalrak	DEC2019	US	JP	Neutral&plasmadynamics
SS-520-3	1	Svalrak	JAN2020	JP	NO	Ion upflow

Student participation in plasma model development and a dedicated student rocket is an essential aspect of the GCI concept. NASA has provided a full-size two-stage rocket for students to become part of the gigantic GCI-cusp rocket program. This rocket named G-CHASER is scheduled from Andøya in January 2019. Strategic use of public outreach, particularly via the tool of social media, is also a vital component of the GCI-Cusp program.

The rockets will be launched from Andøya Space Center and from Ny-Ålesund, Svalbard. The GCI-cusp program currently comprises twelve rockets listed in **Table 1** The core GCI-Cusp observational activities will be conducted in the high northern latitude region surrounding the Svalbard archipelago from late 2018 to early 2020.

Just before Easter 2017 a delegation from the University of Oslo and SIOS travelled to Japan to sign

a joint venture agreement with the American space agency, NASA, and the Japanese Aerospace Exploration Agency, JAXA. Their aim is to understand more about what happens when violent solar storms hit the Earth.

SIOS ICI-5 Rocket experiment

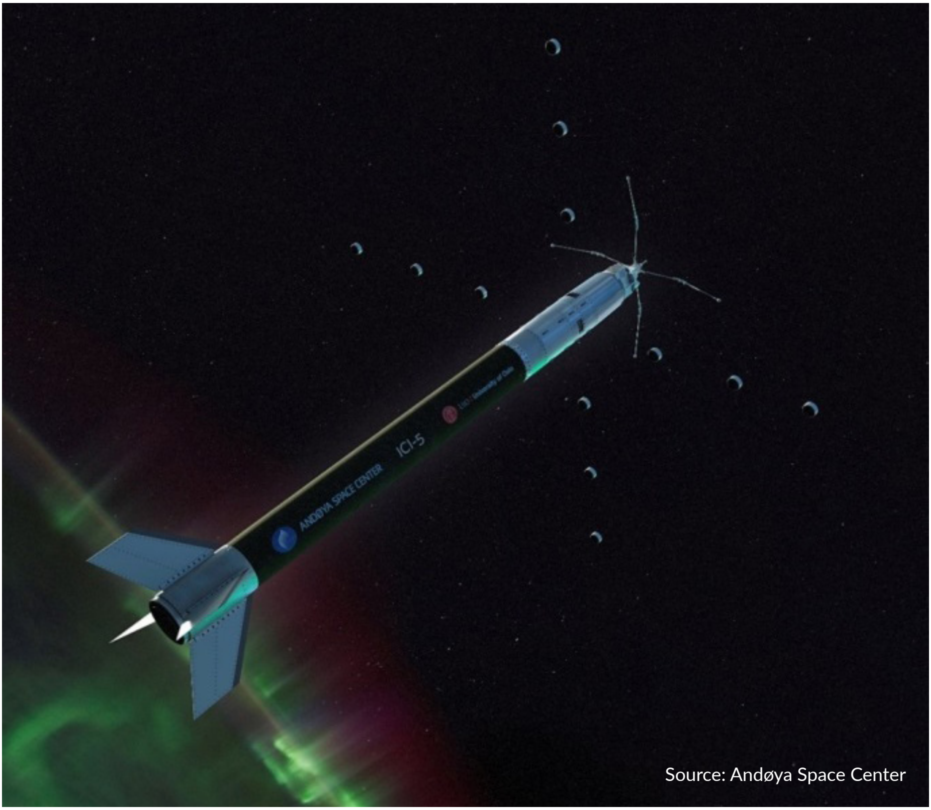


Figure 3: The envisioned ICI-5 rocket flight through aurora, with 12 daughters deployed from the 4DSpace module (Credit: Trond Abrahamsen, ASC).

The first SIOS sounding rocket, Investigation of Cusp Irregularities (ICI-5) is part of the SIOS InfraNor infrastructure project. The main objective of the SIOS rocket program is to study *Vertical coupling processes in the atmosphere from ground to space.*

Vertical coupling in the atmosphere is a complex interplay of processes over a wide range of spatial (cm to hundreds of km) and temporal scales (seconds to months), some of which, in addition, involve large-scale horizontal transport processes. We will investigate processes that are crucial for vertical coupling. Characterizing the evolution of ionospheric irregularities/turbulence and the transfer of energy between the different scales can be regarded as a study of fundamental plasma physics from a theoretical point of view, and is critical in order to understand energy transport and deposition in the ionosphere. SIOS rockets will also provide key knowledge for ionosphere space weather forecast models, as turbulent plasma regions interfere and distort trans-ionosphere satellite signals.

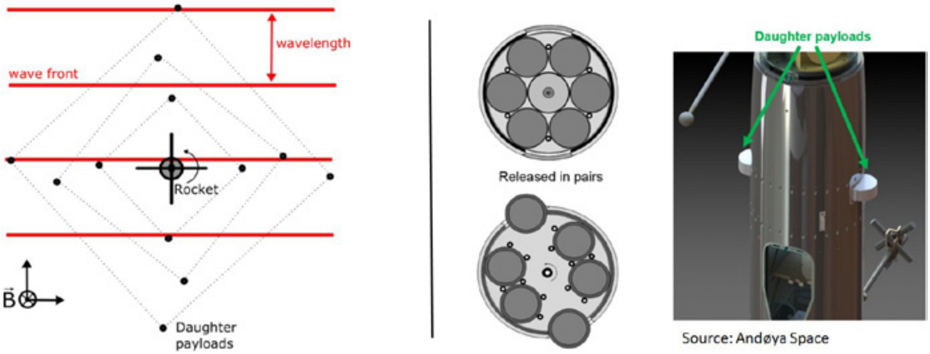
The ICI-5 main objective is to explore the physical properties of plasma turbulence in the F-region cusp ionosphere. In order to achieve this we need to develop a 3D in-situ measurement technique for ICI-5. From the multi-point measurements by the 12 daughter configuration we will determine the spatial scales of the turbulent structures (eddies), explore the 3D nature of the turbulent structures in the F-region cusp ionosphere, and examine the drivers of turbulence/plasma structuring in the auroral cusp.

Turbulence: Characterizing turbulence (both in fluids and in plasmas) remains a grand challenge as central issues are not yet adequately explained [Kintner and Seyler, 1985; Tsinober, 2009; Petrosyan et al, 2010; Bruno and Carbone, 2013]. Significant progress has been made for the characterization of solar atmosphere/wind turbulence [see reviews from Petrosyan et al., 2010; Bruno and Carbone, 2013]. However, for the high latitude ionosphere, where turbulence is common [e.g. Kelley, 2009], our knowledge about the nature of the turbulence is still very limited. There are indications that part of the fluctuations observed could be described by electrostatic fluid-like turbulence theory [Kintner and Seyler, 1985], but many questions remain to be solved, including(1) which models do best describe the turbulence? (2) Are the observed structures due to linear superposition of decoupled normal modes (waves), or due to turbulent interactions across a wide range of scales caused by plasma instabilities? (3) How is the energy distributed between the scales? To address such questions, investigations of the spatial and temporal evolution of the irregularities are crucial, **which require multi-point measurements**. For making progress in the study of high-latitude F region turbulence with space weather impacts, theoretical work and novel experimental concepts are thus necessary.

In general, the development of turbulence and irregularities occurs when free energy is redistributed through some instability mechanism and, consequently, both the source of energy and the instability are coupled processes [Treuman and Baumjohann, 1997]. In the classical view, three sources of free energy are believed to be dominant in the Polar regions: the density gradients and associated polar cap patches, flow shears and the particle precipitation [e.g. Keskinen and Ossakow, 1983; Tsunoda, 1988; Carlson et al., 2012; Moen et al., 2013]. Associated with them are macro-instability processes, with the gradient drift instability (GDI) [e.g. Linson, 1970] and the Kelvin-Helmholtz instability (KHI) [Keskinen et al., 1988] believed to be dominant mechanisms.

Major challenge: UiO has invented a multi-Needle Langmuir Probe System (m-NLP) [Bekkeng et al., 2010; Jacobsen et al. 2010] to make high-resolution density measurements along the rocket trajectory. However, as these measurements are one-dimensional, they do not allow us to determine the spatial extent of ionospheric plasma irregularities, nor do they provide any unambiguous answer whether the observed structures are due to the linear superposition of decoupled normal modes (waves), or due to turbulent interactions across a wide range of scales caused by some plasma instability. The former are propagating waves with dispersion relations that are known, whereas the latter are simply varying structures convected and distorted by the larger-scale flow of the system. In the case of linear superposition of different wave modes, the dispersion relation is expected to follow a theoretical expectation depending on the wave mode [e.g Narita et al., 2003; 2011; Hnat et al., 2016]. Hence, a key for characterizing the ionospheric irregularities observed by the m-NLP along the rocket is to calculate the dispersion relation from the data. To achieve this unambiguously, simultaneous multi-point data are necessary [e.g. Pinçon et al, 2000; Narita et al., 2010]. In general, the spatio-temporal ambiguity for the dynamics of one-dimensional structures may be removed using two spacecraft. At least four spacecraft arranged in a tetrahedral configuration measuring fields and flows in three dimensions are necessary for determining the motion of three-dimensional structures [Pinçon et al., 2000]. In the high-latitude ionosphere at F region altitudes, fluctuations in density are accompanied by motions which are essentially perpendicular to the magnetic field. The turbulent structures are thus expected to be almost two-dimensional, as the correlation length along the magnetic field is much larger than across it [Similon and Sudan, 1990]. We will thus launch a sounding rocket with 12 "daughter" payloads in a plane perpendicular to the magnetic field, and make use of this quasi-2D property to explore the nature of turbulence in the cusp ionosphere. While the ICI-5 experiment is specially designed to make the first 4D measurements of turbulence in the cusp, it is worth mentioning that recent sounding rocket missions have performed multi-point in-situ measurements elsewhere in the ionosphere, for example the Cascades 2 (The Changing Aurora: In-Situ and Camera Analysis of Dynamic Electron precipitation Structures-2) [e.g. Mella, 2011; Lundberg, 2012], and the Leewaves experiment measuring between about 70 km and 100 km altitude [Sjolander et al. 2015].

Choice of method: During the ICI-5 sounding rocket flight, 12 daughter payloads separated over two stages will be released from the rocket, each carrying a m-NLP instrument. The daughter payloads will be ejected 4 by 4 in two perpendicular directions (making three squares around the rocket) and travel at approximately m/s relative to the main rocket body, perpendicular to the main rocket axis and hence at right angle to the background magnetic field. A sketch illustrating the configuration is shown on the left side of Figure 4. The functionality of the ejection of the daughter payloads and the communication to the main rocket was successfully tested for the first time on 27 September 2018, on the Nammo Nucleous hybrid rocket test flight from Andøya Space Center [Kolbjørn Blix, private communication]. The rocket is shown from above and the dots represent the daughter payloads. The red lines represent wave fronts. The images on the right side in Figure 4 show the modules and their location on the rocket. Assuming that the daughter payloads are released after 150 s of flight and that they provide ionospheric data for about 300 s, we can expect a final separation between the daughter payloads and the rocket of a few km. This will allow to explore whether there are evidences of dispersion relations at different scales, as well as the nature of the plasma turbulence at the explored scales [e.g. Narita, 2011].



Source: Andøya Space Center

Figure 4: The principle of 4DSpace multi-point measurements Cf. text for explanation.

For this, data analysis techniques for multi-point measurements applicable to the ICI-5 will be necessary. Such techniques are generally challenging [De Wit, 2003], and we will approach the analysis of the ICI-5 and daughter payloads data based on previous methods which have shown successful results for multi-satellite experiments such as Cluster [Escoubet et al., 2001, Pinçon et al., 2008; Horbury and Osman, 2008].

According to our knowledge, the auroral cusp is highly structured [e.g. Jin et al., 2015]. We will thus launch ICI-5 to intersect the auroral cusp. We have successfully done this with both ICI-2 [Lorentzen et al., 2011] and ICI-3 [Spicher, 2016] (note that ICI-4 had different scientific objectives). With ICI-5 we aim to meet an additional requirement. We want solar EUV ionized plasma to enter the polar cap through the cusp inflow region. Therefore, we will centre the four hours launch window on 11 LT = 10 GMT = 13 Magnetic Local Time (MLT).

Svalbard is the only place in the world to conduct simultaneous ground-based and sounding rocket observations in the cusp ionosphere. The SuperDARN CUTLASS HF radar, which continuously monitors HF backscatter over Svalbard, is a crucial tool to determine the launch conditions. The 32-meter steerable dish of EISCAT Svalbard (ESR) in Longyearbyen is ideal to observe flow channel boundaries and to map and track the movement of solar EUV ionized plasma/formation of polar cap patches. Finally, the ground-based optics from the Kjell Henriksen Observatory (KHO), Longyearbyen, and Sverdrup Station, Ny-Ålesund, will be used to locate the cusp and Birkeland current arcs. We will make use of the ACE spacecraft to provide IMF conditions, giving us one hour lead time information about the solar wind stimuli of the cusp. We will also access data from the GPS scintillation receiver network at Ny-Ålesund, Longyearbyen and Bear Island.

ICI-5 instrument payloads

The ICI series of rockets makes use of the 356 mm cross section, 2915 mm long payload, mounted on a VS30+Improved Orion motor configuration. With a payload weight of ~130 kg the rocket will reach an altitude of 350 km which is ideal for our investigation. The rocket is spin-stabilized at a rate of 3 rps.

For our science objective, it is critical for us to measure the plasma velocity, plasma density and the electron precipitation. Below is a brief description of our instrumentation:

i) 4-Needle Langmuir probe (4-NLP, University of Oslo) for high-resolution (m-scale) absolute electron density measurements. The experiment consists of four identical needle probes with a diameter of about 0.5 mm and a length of 5 cm. The probes are biased to typically +3V to +7V with respect to the rocket potential in order to measure the saturated electron currents. The Langmuir probes are mounted on the electric field booms in the front of the payload. The instrument's dynamic range is from nA to µA, with 16 bits resolution. Automatic gain control can also be enabled.

ii) The 4DSpace daughter payload module (4DSpace, University of Oslo) is containing six daughter payloads. ICI-5 will accommodate two 4DSpace sections, i.e. 12 daughters. The daughter payloads will be deployed pair-wise from each module. Each daughter will be equipped with a smaller, special version of the UiO-mNLP. This will give a multi-dimensional measurement of the electron density. The daughter payloads communicate with the rocket, and the data is fitted into the main PCM data stream.

iii) Electric Field Wave Experiment (EFW - University of Oslo). The ICI payload has two crossed (orthogonal) double probes in front. The quasi-static electric field is assumed to be perpendicular to the magnetic field and can be determined from two double probes spinning with the rocket. The probes are spheres with 3 cm diameter separated by more than 2 m. The electric field measurements have 16 bits resolution, and with the selected dynamic range this corresponds to a resolution of about 5µV/m.

iv) The Bifocal Sensor (BSM-Iowa University) probes the electron distribution function in the energy range 1eV-20keV, with a nominal operating energy range of 10-2000eV tailored for ICI-5 science. The sensor is a top-hat electrostatic analyzer with deflecting optics that define two entrance apertures – one with coarse (~10°) angular resolution and one with fine resolution (~1.75°). Voltages on the outer electrodes allow electrons through one of these apertures, after which they pass through two concentric toroids which select electrons by energy, with an intrinsic energy resolution $\Delta E/E$ ~15%. The voltages on the electro-optical surfaces are swept to cover the desired energy range from 100 eV-1 keV. Electrons within the selected energy window at each step impact a micro-channel plate, producing a measurable charge pulse of ~2M electrons per incident electron, which impact a segmented anode that registers the incident electron azimuthal velocity angle. With a 180° field-of-view, the azimuthal resolution is 22.5°. The intrinsic time resolution is 16 msec/ 16 energy steps (or 32 msec/ 32 energy steps).

v) Sounding Rocket Attitude Determination System, version 3, (SRADS3-University of Oslo). SRADS3 consists of a low-cost and miniaturized system for sounding rocket three-axis attitude determination. The system makes use of a three-axis gyro, two digital Sun sensors (using a pinhole camera; the trajectory will be sunlit above about 100-200 km depending on launch time) and two three-axis magnetometers. One magnetometer is mounted internally in the payload and an optional one is mounted externally on one of the E-field booms. Finally, a three-axis accelerometer is completing the system. The data from these sensors are combined with mathematical models of the sensors, the Earth magnetic field and the position of the Sun. This data fusion (post-processing) is done by an extended Kalman filter (EKF) and smoother, in order to reconstruct the spacecraft attitude.

Sounding rocket missions in the winter 2018/19

In this section we will briefly describe the NASA sounding rockets mission to be launched in December 2018 and January 2019. They are both of high relevance to SIOS. That is **T**win **R**ocket **I**nvestigation of **C**usp **E**lectrodynamics **2 (**TRICE-2; PI: Craig Kletzing, Iowa University) and **VIS**ualizing **I**on **O**utflow via **N**eutral atom **S**ensing-2 (VISIONS-2; PI: Douglas Rowland, NASA Goddard Space Flight Center), and **C**usp **A**lfven and **P**lasma **E**lectrodynamics **R**ocket **2** (CAPER-2: PI : Jim Labelle). University of Oslo will fly the multi-Needle Langmuir Probe (m-NLP) on all these rockets.

TRICE-2 was already planned when the GCI-Cusp program was agreed with NASA and JAXA in 2016. The VISIONS-2 proposal was the first mission to take advantage of the added value being under the GCI-Cusp umbrella. TRICE-2 and VISIONS-2 consist of two rockets each, and TRICE-2 will be highly complementary to VISIONS-2.

The TRICE-2 main objective is to investigate whether the magnetic reconnection at the magnetopause is steady or pulsed. As magnetic reconnection is the major external driver for vertical dynamics in the auroral zone atmosphere, this is a key Earth system science question. Magnetic reconnection is anticipated to modulate the thermosphere as well as the ionosphere.

With a single rocket or satellite it is not possible to unambiguously distinguish between steady state reconnection from multiple reconnection sites and pulsed reconnection. The TRICE-2 approach will be to fly two sounding rockets simultaneously from Andøya over Svalbard, one high-flying and one low-flying, both at the same magnetic coordinates. Except when they are on the top of each other, there will always be one lagging behind the other, allowing to assess whether the magnetic reconnection process is a steady state or time varying.

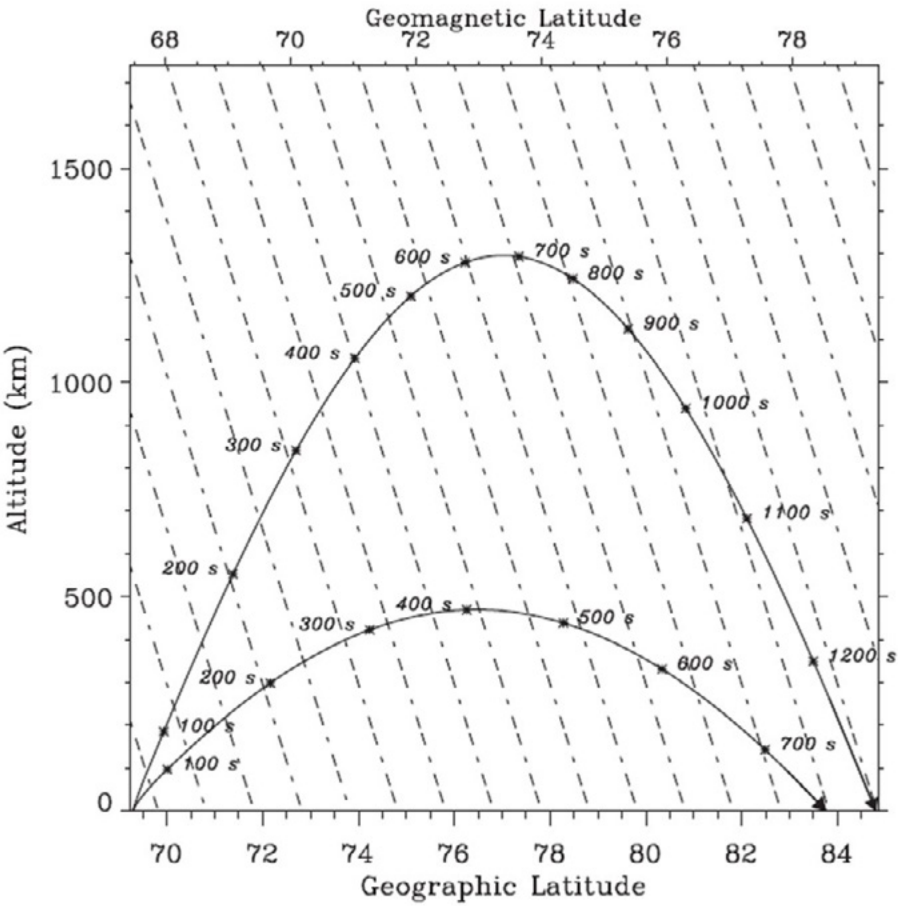


Figure 5: Range vs. altitude of the two payloads as function of time since launch of each payload. The Earth's magnetic field lines have been added to illustrate how the two payloads map from one altitude to the other (Courtesy: Craig Kletzing).

The two rockets are nearly identically instrumented and equipped with electric/magnetic field and wave package, particle spectrometer for electron and ion particle fluxes and the UiO multi-needle Langmuir probe system. This allows us to measure Electromagnetic Energy (Poynting) flux and Alfvén waves in accelerating electrons that may carry these currents and may be triggering plasma instabilities/turbulence, i.e., the electromagnetic and particle energy input heating essential to model the thermosphere effect. TRICE-2 is planned to fly from Andøya Space Center, Norway, in December 2018, through the cusp over Svalbard.

VISIONS-2's main objective is to investigate upward acceleration of ions along the magnetic field lines in order to understand the wave-particle interaction that accelerates oxygen ions above 10eV to escape the Earth gravitation. Upflowing ions were mapped to the auroral oval by satellites in Shelley et al. [1976], and the initial upflow acceleration above 300 km altitude was attributed to magnetic reconnection cusp-auroral events [Moen et al., 2004]

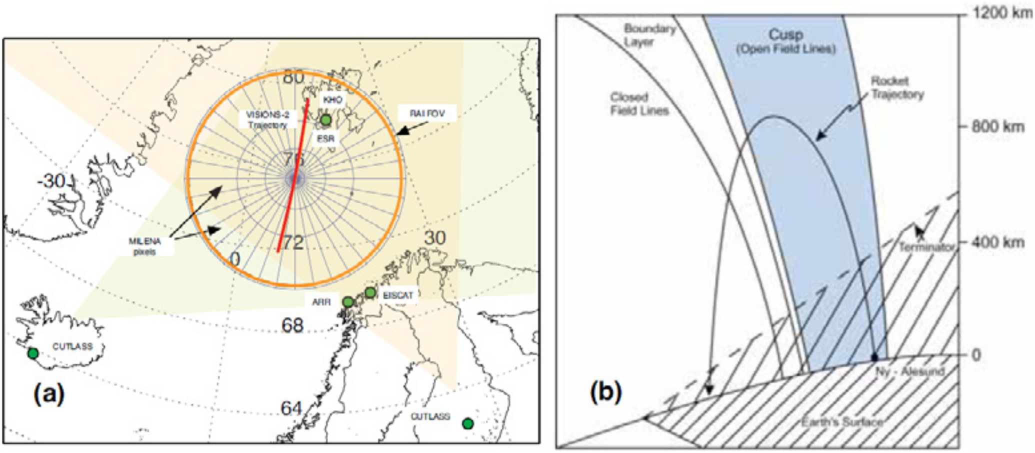


Figure 6: The VISIONS-2 experiment combines rocket and ground-based instrumentation to measure the nature and extent of ion outflow in the cusp. (a) The nominal trajectory, showing launch from Ny-Ålesund, and the radar fields of view; (b) a side view, showing the altitude / latitude extent of the trajectory, along with realistic magnetic field geometry, and a typical terminator for mid-December. (Courtesy; PI. Douglas Rowland)

VISIONS-2 will be the first mission to combine ENA imaging of cusp ion outflow with direct measurements of the drivers, including multispectral optical imaging of aurora, corresponding to regions of electron and proton precipitation, as well as direct in-situ measurements of fields and particles that provide very strong constraints on the remote sensing inversion and modelling. VISIONS-2 will fly from Ny-Ålesund, Norway, in December 2018, through the magnetic cusp, to an apogee near 800 km. During the flight, it will remotely sense ion outflow and its drivers over a region approximately 1000 km in diameter, providing critical information about the patchiness and burstiness of cusp ion outflow, as well as detailed information about the mechanisms that drive this outflow, leading to a new understanding of the mechanisms that couple the magnetosphere:

1) What is the total low-altitude (<1000 km) ion outflow at energies > 10 eV from the cusp under typical Bz south conditions?
2) How spatially and temporally variable is this outflow?
3) How is the outflow tied in detail to drivers and sources of free energy (e.g. auroral electron precipitation, convection, Joule heating)?

CAPER 2 is dedicated to explore the physical nature of magnetosphere-ionosphere (MI) coupling in terms of waves and acceleration processes. There are at least two separate electron acceleration processes of broad significance to space plasma physics: acceleration in electrostatic electric fields and in time-varying electromagnetic fields associated with Alfvén waves. In addition, a host of microscopic wave modes play a role in redistributing energy from the resulting electron beams to the thermal plasma, including most ubiquitously Langmuir waves. While many previous rocket experiments have probed nightside processes such as polar substorms, the proposed CAPER-2 will make significant advances in understanding electrodynamics associated with MI coupling in the cusp.

In particular, direct measurements of Alfvén waves associated with electron acceleration, via their electric and magnetic fields, have not been explored in the cusp, and the detailed interaction of the electron beam with Langmuir wave electric fields, as well as statistics of the resulting complex structure in the fields remains to be studied. The CAPER-2 instrument package includes the first ever wave-particle correlator measurements in the cusp.

Critical Ground based Observations

The large-scale context of the detailed rocket measurements will be mapped by a suite of ground-based instruments, including the EISCAT and SuperDARN radars, as well as with optical measurements from Ny-Ålesund and the Kjell Henriksen Observatory (KHO) near Longyearbyen. The cusp is often thought of as a dayside feature, but during the northern hemisphere's winter season, the cusp's ionospheric footpoint is often in darkness and directly over Svalbard. This enables the use of optical imaging for cusp studies.

SIOS rocket data base

From experience, old sounding rocket data are difficult to get a hand on. Such data are often stored on the private computers, and the focus has been on exchanging within the team of each rocket mission and not to provide easy access for external research teams. For example, it would be a big effort, if at all possible, to gather all the electron density altitude profiles that have been obtained over several solar cycles since the 1960s. This has made it difficult for the sounding rocket science community to provide added value to others across research disciplines and, thus, to reach a broad community. A key vision for the GCI-CUSP project is to reverse this tendency and to create standardized, long-lived datasets accessible to a broad community. Bringing observations together in a coherent, integrated and sustained program is indeed one of the backbones of the GCI-CUSP program, as mentioned in section 2.

The idea is that all the GCI-Cusp partners should share equally their data in a combined database accessible through the SIOS Data Management System (SDMS) [https://sios-svalbard.org/SDMS]. Each PI and his team coordinate their own dataset which has been standardized according to conventions agreed upon, and SDMS establishes a virtual data centre offering unified access to the relevant data. In particular, the (meta)data should be findable, accessible, interoperable and reusable. This will increase the efficiency in exchanging and comparing data between experiment teams.

Actions towards the creation of standardized GCI-Cusp datasets have already started. This was done through a GCI – CUSP data workshop in Santa Fe, New Mexico, USA, during the CEDAR meeting (24 June, 2018). During this workshop, several strategies were addressed, comprising the use of common metadata convention and data formats (CDF/netCDF), and the procedure for making the data available. It has been agreed upon that standardized calibrated data (SI units) should be made available to the community after the first scientific article has been published. In particular, for the multi-needle Langmuir probe systems, articles about the data, its quality and the extraction procedure will be written. It is also planned to use the data from the VISIONS sounding rocket (from 2013) as a precursor for GCI-Cusp dataset to check how well this standardization works, and discover any hiccups/challenges. From late autumn 2018 (October), teleconference meetings will be organized monthly to coordinate data sharing actions.

Summary

The GCI-cusp program is a game changer in providing sounding rocket infrastructure for science. Instead of individual rocket teams working separately, the GCI-cusp program umbrellas 9 missions that consist of 12 rockets. In this way, by multi-lateral collaboration, resources and results are combined and shared in an unparalleled capacity building to attack and close grand challenge questions of solar wind driven dynamics of the polar atmosphere, that is: the time-spatial variability in magnetopause reconnection, the wave-particle physics and acceleration processes of magnetosphere-ionosphere interaction, and the resulting vertical and horizontal coupling dynamics of the ionosphere and the thermosphere.

The participating research teams fund their own research on selected topics. University of Oslo, for example, that is in charge of the SIOS ICI-5 mission, flies the multi-Needle Probe instruments on 6 out of the 12 rockets (Figure 7), and will take part in the data analysis across five GCI-Cusp missions.

We aim to adapt the SIOS Data Management System (SDMS). Standardized data formats, and provision of SI unit data values will be crucial in order to stimulate efficient collaboration across teams, including the ground-based instrument research community, space plasma physics and atmosphere modellers. To bridge space science to Earth System Science is a SIOS goal.

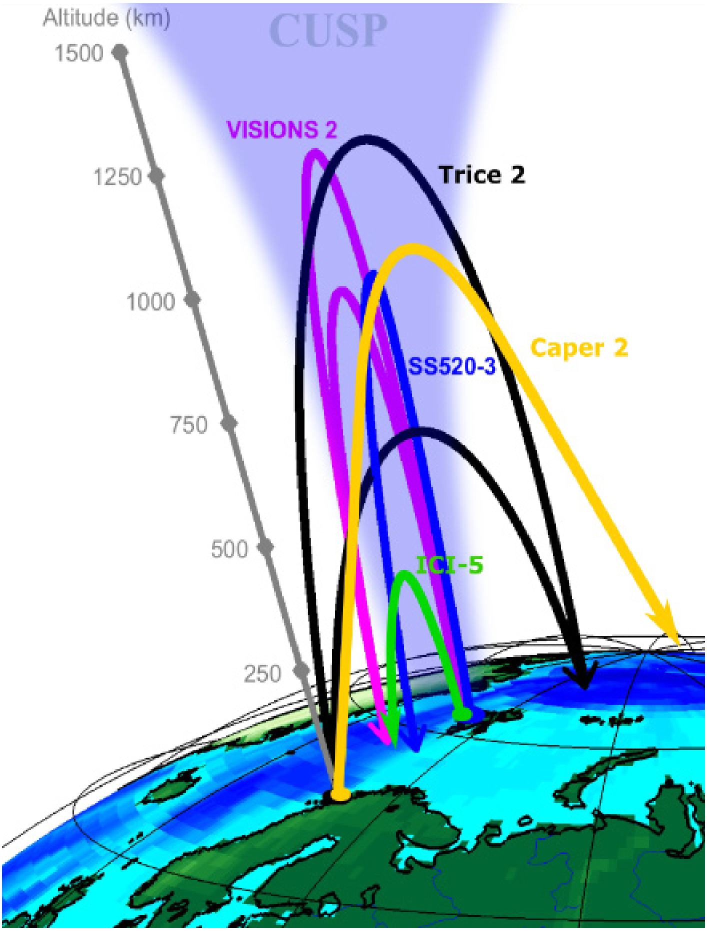


Figure 7: Trajectory of the GCI-Cusp rockets with the m-NLP fom UiO onboard.

Acknowledgement

The Norwegian contribution to the Grand Challenge Initiative- Cusp program is funded by grants from the Research Council of Norway and the Norwegian Space Center. Thanks to the SIOS staff for their assistance, and a particular thank to Kolbjørn Blix at Andøya Space center who has played a major role in developing the GCI-cusp strategy.

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Frequently Asked Questions

CHRISTIANSEN ET AL: PERMAFROST THERMAL SNAPSHOT AND ACTIVE-LAYER THICKNESS IN SVALBARD 2016-2017

What is permafrost?

Permafrost is a ground thermal condition occurring in cold regions, and is defined as ground (soil, sediment, or rock) that remains at or below 0°C for two or more consecutive years.

What is the temperature of the permafrost in Svalbard?

Mean annual ground surface temperatures during the 2016-2017 hydrological year (1 September 2016 to 31 August 2017) ranged from -1.0°C to -4.1°C; mean annual temperatures at the permafrost surface ranged between -0.5°C and -4.0°C, and permafrost temperatures, at or close to the depth of zero-annual amplitude (typically from 10-20 m depth), varied from -2.3°C to -5.2°C, all observed in boreholes at the five permafrost study sites in Svalbard.

What is the active layer and how thick is it in Svalbard?

The active layer is the layer above the permafrost which thaws during summer and re-freezes during winter. The thickness of the active layer, as measured in autumn 2017, varied from 49 to 300 cm, but generally fell within the range of 100 cm to 200 cm. Thinnest active-layers are reported from blockfields at higher elevations and in sediments. Thicker active-layers are encountered in bedrock settings.

What is the freeze-back duration and why is it important?

The freeze-back is the amount of time it takes for the active layer to re-freeze during the late autumn and early winter. If this lasts long there will be less time for the permafrost to cool during the remaining part of the winter. In the particularly warm winter 2016-2017 freeze-back only started in November, and lasted from December to April for the studied sites, causing relatively high permafrost temperatures in the top permafrost.

MALARD ET AL: MICROBIAL ACTIVITY MONITORING BY THE INTEGRATED ARCTIC EARTH OBSERVING SYSTEM

How do microorganisms influence climate?

Microorganisms can influence climate through the production and/or decomposition of climate-active gases such as carbon dioxide, methane and DMS.

Can microorganisms influence weather patterns?

Yes, as they possess proteins that act as ice condensation nuclei. When water condenses on these condensation nuclei, clouds form, which can influence a region's albedo.

Can we influence microorganisms in the environment?

Yes, we can fertilise to encourage growth, or inhibit their growth, depending on the required effect.

What proportion of climate-active gas flux is attributable to microorganisms?
It has been measured at about 10%, though is likely highly variable depending on geographic location and context.

By microorganisms, do you mean bacteria?
Predominantly, yes, though pico-eukaryotes, fungi, viruses and archaea all play a role.

GALLET ET AL: SNOW RESEARCH IN SVALBARD: CURRENT STATUS AND KNOWLEDGE GAPS

Will the ongoing climate change influence the snow?

Yes, the amount, distribution and duration of snow cover in Arctic regions will change. Warmer climate conditions bring humidity and more precipitation, including snow, although rain now occurs more frequently in winter. The spatial distribution of snow will change, meaning that some areas will get less snow, while others get more. When the winter snow disappears earlier in spring, the ground absorbs more solar energy due to albedo feedbacks, lengthening plant growing seasons and feeding times for animals.

What are the consequences of changes in snow cover and snow properties in the Arctic?

Snow is a good insulator. It protects glaciers from melting in the summer, but also keeps the temperature of the ice higher. Rain events during winter affect vegetation and wildlife since they result in thick ice layers. Grazing conditions for herbivores become difficult and plants can suffocate and grow slower when encapsulated in ice, or even die. Changing winter precipitation patterns are also expected to influence the avalanche hazard for humans and structures in Svalbard.

Should the focus for snow studies be on small or big glacier systems in the Arctic?

In terms of climate mechanisms, the focus on glaciers and snow has been oriented towards the larger ice sheets of Greenland and Antarctica. However, when it comes to the annual snow cover and its responses to climate and influence on the Arctic, we need to include many systems: larger ice caps, small glaciers, mountain regions, tundra areas, etc. The reason is that the smaller glaciers generally respond faster to warming.

Why are long-term monitoring programs for snow essential?

Climate change research is by definition a long-term process and requires appropriate long-term perspectives for monitoring and data legacy. We need to have data that span over a long enough period to filter stochastic effects from weather events in general. For example, climate scientists define the "normal" climate as the average over a 30-year period. So to generate adequate data for any climate evaluation, the monitoring programmes need to be on a long-term basis.

Can we use chemical, physical and microbial signatures of the snow to evaluate the rate of change in the Arctic?

Yes. The snow pack composition can reflect atmospheric chemical signatures and processes and can be used as a tracer for changes in atmospheric transport of pollutants, for example. The physical properties of snow are a good indicator of the winter conditions in the Arctic (warm, moist or windy). Snow is not only a reservoir but also an ecosystem for micro-organisms and their genomes could be used to provide signatures of the environment they live in and how it is changing.

COTTIER ET AL: TEMPERATURE TIME-SERIES IN SVALBARD FJORDS. A CONTRIBUTION FROM THE "INTEGRATED MARINE OBSERVATORY PARTNERSHIP (IMOP)"

Why does the report only concern 4 moorings around Svalbard, I thought there were many more than that?

Many moorings have been placed in the waters around Svalbard over the years. Some have just been short term deployments to support a science project. Others have been in place for a number of years. The moorings in the current SESS report have focused on four moorings where we could readily access temperature data, which had been deployed for at least three years, and which are planned to be maintained in the future. Further development of this report might include offshore moorings.

How do I find out about moorings that have been deployed in Kongsfjorden?

The most up-to-date review of mooring activities in Kongsfjorden is: Hop, H., F. Cottier, and J. Berge (in press), Autonomous marine observatories in Kongsfjorden, Svalbard, in The Ecosystem of Kongsfjorden, Svalbard, Advances in Polar Ecology, edited by H. Hop and C. Wiencke, Springer.

Do the moorings measure the temperature of the surface waters?

In general, the moorings are deployed with a gap of around 20m between the top of the mooring and the water surface. This due to the risks posed by ice and passing vessels. Therefore, there are few measurements of temperature shallower than 20m.

What other instrumentation is on the moorings?

Each mooring will generally have its own specific set and arrangement of instruments. An exception is the pair of moorings in Kongsfjorden and Rijpfjorden (operated by UiT/SAMS) which have deliberately been designed to provide complementary datasets. Each mooring is operated by a different institute for different purposes and with access to different instruments. This means that a wide variety of parameters are measured from the marine moorings around Svalbard. Temperature and salinity are probably the only core parameters available on all moorings.

EDWARDS ET AL: SVALBARD AND NORDIC SEA PLANKTON MONITORING BY THE CONTINUOUS PLANKTON RECORDER SURVEY

Why study plankton?

Plankton are highly sensitive to environmental changes and are excellent indicators of the state of the environment. As plankton are at the base of the food-web, by monitoring changes in the plankton we can also understand changes to other animals and trophic levels such as fish and seabirds.

How long has the Continuous Plankton Recorder Survey been operating?

The CPR survey has been operating in the North Sea and North Atlantic since 1931 and is one of the most geographically extensive and oldest continuous marine biological surveys in the world. It has been operating in Svalbard waters since 2008.

Are there any plans for the future?

It is hoped in the near future that the CPR survey will form part of a more integrated observation system within these waters and improve its monitoring with an additional suite of biogeochemical and molecular sensors.

BENSI ET AL: SPITSBERGEN OCEANIC AND ATMOSPHERIC INTERACTIONS

What is the status of the arctic water cycle?

To the best of our knowledge, the Svalbard water cycle is speeding up. We see more glacier melting and more precipitation – and as a consequence, more freshwater input. Monitoring these processes is fundamental and calculating the water budget from the models and data is required.

What are the most important feedback mechanisms for amplification, and are they specific to the arctic system?

Atlantic Water variability (from seasonal to yearly and long-term variation) influences how much the sea ice cover is reduced, which in turn affects the albedo. Polynyas (patches of consistently open water in otherwise ice-covered waters) are a source of heat and moisture to the atmosphere, so they modify the weather in surrounding areas.

What is the relative importance of anthropogenic forcing for Arctic change, especially on the regional and local scales?

This is an open question. There is broad scientific consensus that anthropogenic forcing is the primary driver of ongoing global warming. However, the climate system is highly non-linear and the feedback processes between the individual components are not sufficiently understood, meaning that attribution of specific regional changes remains a challenge.

Why are many aspects of arctic change amplified compared to global conditions?

Focusing exclusively on aspects related to shelf-slope processes, we know that small temperature and salinity variations in polar areas have strong feedback effects on environmental conditions (e.g. sea ice formation/melting). Changes in the transfer of heat, oxygen, and nutrients to the deep-sea environment affect benthic (bottom-dwelling) communities, with important impacts on biodiversity and ecosystem functioning. In addition, palaeooceanographic evidence shows that if the trends of density decrease in the abyssal waters continue, the deep circulation will be negatively affected, thus forcing the climate to change.

VIOLA ET AL: THE LOWER ATMOSPHERE ABOVE SVALBARD: OBSERVED LONG-TERM TRENDS, SMALL-SCALE PROCESSES AND THE SURFACE EXCHANGE

Vertical Coupling: What controls changes in the vertical structure of the arctic atmosphere?

Changes in the vertical structure may arise from different causes: changes in the large scale circulation; altered heating from the surface (e.g. due to oceanic circulation); change of atmospheric boundary layer stability or properties; shift in cloud cover, cloud properties or altitude; or increased concentrations of long-lived greenhouse gases. Many of these important questions are already under investigation in Ny-Ålesund by a well linked international research community. However, the lowest 2.5 km of the atmosphere is heavily influenced by Ny-Ålesund’s mountainous terrain, hence an answer to this question cannot be given only from observations done in Ny-Ålesund.

What is the significance for Arctic climate of the substantial natural variability and feedbacks associated with high latitude winds?

The melting of sea ice will lead to a stronger meandering of the jet stream. This will cause more frequent blocking events – large and persistent north-south variations in the jet stream. Naturally, a precise picture of high latitude winds cannot be obtained from measurements done at only one spot in the Arctic. Broader international cooperation beyond Svalbard is required to answer questions about how these winds behave, as are more model studies and validation.

To what extent are emissions of short lived greenhouse gases and aerosols (e.g. methane and 'black carbon') outside the Arctic affecting Arctic change?

Trace gases have been measured for many years in Ny-Ålesund and their increase is well documented. Black carbon concentrations are normally low and the vertical distribution of these particles is generally complicated. Future climate models with active aerosol and trace gas chemistry will give a better answer to this question, which is quite uncertain currently, as the impact of aerosol also depends on the surface albedo, cloud cover, possible aerosol layers at higher altitudes, solar zenithal angle, atmospheric stability and possibly more. So far a study by Acosta Navarro et al. (2016) suggests that the sulfur emission reductions in Europe in the 1990s actually contributed to Arctic warming.

How are the patterns and sources of long-range transported pollutants changing over time?

Stock et al. (2014) showed the difficulty of addressing the origin of Arctic aerosol. This is mainly due to a lack of meteorological measurements. Air back-trajectories that are reliable over weeks in central Europe become uncertain in the Arctic after about 5 days, which is normally not long enough to determine a precise origin of aerosol. Identifying sources of aerosol based on finding well suited markers in chemical analysis, as suggested by Udisti et al. (2016) might, over time, resolve this important question.

Why are many aspects of arctic change amplified compared to global conditions?

The Arctic Amplification is probably caused by a combination of several factors. If it were caused by a simple feedback, such as the ice-snow albedo feedback, or a direct driver, such as anthropogenic greenhouse gases, we would have seen the same amplification over Antarctica and Tibet (and no regional differences within the Arctic), which is not the case. Instead, it involves the complex interaction of many processes and feedbacks, including changes to atmospheric stability, radiative properties and moisture transport, surface-atmosphere exchanges, oceanic and atmospheric heat transport, among others. It is really important to obtain a better understanding of all relevant processes in the atmosphere, e.g. boundary layer properties, aerosol and clouds and trace gas concentrations, and derive from that information the forcing, the large scale circulation and the hydrological cycle.

Will natural variability, particularly the interannual to multi-decadal modes of variability, be affected by anthropogenic forcing in the future?

The current models still have difficulties reproducing the Arctic climate change of the past and the current rapid sea-ice decline. A coupling between anthropogenic and natural factors is likely. However, no prediction beyond seasonal scales exists.

PETKOV ET AL: OBSERVATIONS OF THE SOLAR UV IRRADIANCE AND OZONE COLUMN AT SVALBARD

What is the nature of the solar ultraviolet radiation?

Solar ultraviolet (UV) radiation is the fraction of the solar light at the ground which is characterized by wavelengths shorter than 400 nm. This spectral band has energy sufficient to impact chemical processes and, moreover, to affect DNA molecules in the cells of living organisms, potentially causing a dangerous disease like cancer. Fortunately, wavelengths up to 290 nm are stopped in the atmosphere due to the strong absorption by ozone, which acts as a shield for living organisms. A small fraction of UV radiation, from 290 nm to 400 nm is able to reach the earth's surface and studying how this fraction behaves is very important for in understanding various chemical and biological problems.

Which factors influence the intensity of UV radiation at ground level?

The most important influencing factor is the total ozone column, which solar UV radiation has to penetrate on its way to the earth's surface. While the most energetic and harmful part of the UV spectrum (UV-C) is absorbed completely and contributes to forming ozone from oxygen in the atmosphere, the medium-energetic, but still harmful part (UV-B) is only partially absorbed by ozone. Other important factors are cloudiness and particle content of the atmosphere (turbidity/visibility), which may reduce the intensity of incoming solar light in general. However, surface properties such as the elevation and the reflective properties of the ground also play an important role. For example, UV intensity is much higher at a mountainous, snow-covered site than at a low-lying, bare-ground place. Changes in cloudiness and especially in ice and snow coverage in the polar regions will have a strong impact on these regions' UV climate.

How is the ozone content in the atmosphere quantified?

The density of the atmosphere decreases exponentially with altitude, reaching 1/1000 of the surface pressure at about 50 km and 1/1,000,000 at about 90 km. If we imagine that it was possible to compress the atmosphere so it would have the same density at all altitudes, this atmosphere would be about 8 km thick. Let us now also assume that there was some way to separate all the gases composing the atmosphere into different layers. In this case nitrogen, which makes up 78% of the atmosphere, would occupy a layer about 6.2 km thick. Oxygen, which makes up slightly less than 21% will occupy 1.7 km. The remaining 100 m of this imagined atmosphere with homogeneous density would be dominated by the noble gas argon (more than 90 m), while the last 10 m would contain trace gases including ozone, which takes up only 3-5 mm. This thickness multiplied by 100 is the commonly accepted measure for total ozone content in the atmosphere. This measure, the Dobson Unit (DU) is named after Gordon Miller Bourne Dobson, who made great contributions to the study of atmospheric ozone. Hence, 420 DU means that we have a total ozone content equivalent to a layer 4.2 mm thick in the (hypothetical) homogeneous atmosphere.

Is the total ozone content in the atmosphere constant?

The total ozone content – the ozone column – varies both geographically and seasonally, usually from nearly 300 DU to about 500 DU. Levels are low at low latitudes (near the equator) and during autumn at higher latitudes, where levels also reach their maximum during the spring. Since the early 1980s, a strong decrease of the ozone column below climatological values for the season was observed. The most extreme case of this phenomenon during Antarctic spring was popularly named the "ozone hole". Ozone depletion episodes are periodically observed over Antarctica, where in austral spring (September – November) total ozone could reach values below 150 DU. Less dramatic ozone depletion can occasionally occur also over the northern polar regions. In March 2011, for instance, the ozone column dropped to about 230 DU, whereas long-term means are around 400 DU. These regular seasonal ozone depletion episodes have been found to be caused by chemical reactions between ozone and trace gases emitted by humankind. Brief ozone depletion events lasting 1-3 days and colloquially called "ozone mini holes" can occur anytime in mid- and high-latitude areas; these are caused by dynamical processes in the stratosphere (the part of the atmosphere with the highest content of ozone). In these cases, all living organisms are subject to high stress from exposure to solar UV radiation.

GRAND CHALLENGE INITIATIVE – CUSP: ROCKETS TO EXPLORE SOLAR WIND-DRIVEN DYNAMICS OF THE TOP SIDE POLAR ATMOSPHERE

Why rockets to study the Northern Lights?

We need detailed measurements within the aurora itself to explore the aurora-related energy transfer mechanisms and their effects on the atmosphere.

Where may I see "cusp aurora"?

"Cusp aurora" is Northern Lights in daytime. Svalbard is only place on Earth where rockets can be launched and flown through the cusp aurora. It is also the only land area where cusp aurora can be seen with naked eye; you can see it in December and January when the sun is below the horizon 24 hours a day.

What causes the Northern Lights?

Particles from the solar wind collide with oxygen atoms and nitrogen molecules. The energy absorbed due to collisions is emitted as light. Each type of molecule and atom emits light with its own specific colours. The Northern Lights occur at altitudes between 100 and 500 km.

Why should we bother to study the top side atmosphere?

It is part of the earth's climate system. The polar cap atmosphere is strongly driven by the solar wind and has to be taken into account to understand the energy flows and dynamics. Did you know that up to 300 tons of oxygen may disappear from the earth every day?

Is there any practical use for auroral research?

There is a need for space weather models to predict the quality of GPS signals. GPS signals are degraded due to some turbulence processes. During auroral activity the temperature near the auroral forms may be several thousand degrees Celsius, and the atmosphere expands. This gives rise to atmospheric drag on satellites that may shorten their life-span if the amount of fuel needed has been poorly estimated.

How much does one single rocket cost?

The Norwegian rocket SIOS ICI-5 costs NOK 16 million. This covers the payload section, two motors and launch operations. In addition, there are costs for the development and building of the instruments and the participation of scientists and engineers in the rocket campaign to collect data.

SIOS
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ISSN 2535-6321
ISBN 978-82-691528-0-7