The Research Council
of Norway

# Changes in snow/ice and pollutants and their effects on terrestrial ecosystems

Workshop Report, February 2012
Svalbard Science Forum – SSF

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## The Svalbard Science Forum – added value through cooperation

The Svalbard Science Forum (SSF) promotes coordination of and collaborative efforts in research activities in Svalbard. This includes managing the “Research in Svalbard” (RiS) database which contains information relating to several thousand Svalbard-based projects.

The SSF also organizes workshops and administers funding schemes targeted towards the polar research community, while continuously working to minimize the environmental footprint of research activities.

The Svalbard Science Forum is administered by the Research Council of Norway.

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Report No. 1/2012

## SSF Cooperation Workshop No. 3:

# Changes in snow/ice and pollutants and their effects on terrestrial ecosystems

Based on the Svalbard Science Forum workshop 13-16 February 2012 in Oslo.
Editors: Halvard R. Pedersen, Elisabeth J. Cooper, Geir Wing Gabrielsen & Krzysztof Migala

*Participating institutions*
**Austria:** University of Innsbruck; **Canada:** Environment Canada; **Czech Republic:** University of South Bohemia; **Denmark:** Aarhus University; **Finland:** University of Helsinki; **Norway:** Norwegian Polar Institute, Norwegian University of Life Sciences, University Centre in Svalbard, University of Oslo, University of Tromsø; **Poland:** Polish Academy of Sciences, University of Silesia, Wroclaw University; **Russia:** Arctic and Antarctic Research Institute of Roshydromet (AARI), North-West Branch of Research and Production Association (Typhoon); **Sweden:** Swedish University of Agricultural Sciences, Umeå University; **Switzerland:** Paul Scherrer Institute; **United Kingdom:** Lancaster University

*Workshop goals*

1. Exchange of information about ongoing research activities (see appendix 1 and 2).
2. Presentation of activities planned for the near future (see appendix 1).
    - Incl. SSF foci: More coordination, new technology and reduced environmental footprint.
3. Identify knowledge gaps and topics of special interest (see chapter 2.2-2.4 and appendix 1).
4. Identify scientific areas of potential cooperation (see chapter 2.1).
5. Data sharing and project cooperation (chapter 2, and during presentations and discussions).

*Workshop planning group*

- Dr. Krzysztof Migala, University of Wroclaw, Poland (chair)
- Dr. Elisabeth J. Cooper, University of Tromsø, Norway
- Dr. Geir Wing Gabrielsen, Norwegian Polar Institute, Norway
- Halvard R. Pedersen, Svalbard Science Forum, Longyearbyen, Norway

*Workshop report*

- Part 1: Priorities and recommendations. The discussions in groups were structured around the three fields of science (snow/ice, ecology and pollutants), linkages between them and common ground for possible joint projects and collaboration in the future.
- Part 2 (appendixes): Abstracts from the presentations, input from other scientists not able to attend, workshop programme and list of participants.

*SSF Cooperation Workshops:*
No. 1 (2009): Pan-Svalbard Cooperation
No. 2 (2010): Geology of Svalbard
No. 3 (2012): Changes in snow/ice and pollutants and their effects on terrestrial ecosystems
No. 4 (2013): Zackenberg & Nuuk – What can we learn for Svalbard?

# Contents

**1 Summary** ........ **5**

**2 Conclusions, recommendations and priorities** ........ **7**

2.1 Prioritised cooperation projects ........ 7

2.2 Conclusions from the "snow & ice group" discussion ........ 13

2.3 Conclusions from the "terrestrial ecology group" discussion ........ 14

2.4 Conclusions from the "pollutants group" discussion ........ 16

**Appendix 1: Abstracts** ........ **19**

**Appendix 2: Input from other researchers** ........ **63**

**Appendix 3: Workshop participants** ........ **71**

**Appendix 4: Workshop programme** ........ **75**

**Workshop participants:**

From the left: Heikki Hänninen, Krzysztof Migala, Josef Elster, Piotr Glowacki, Elisabeth Cooper, Jan Kavan, Lennart Nilsen, Bronislaw Wojtuń, Sergey Vlasov, Åshild Pedersen, Elisabeth Isaksson, Irina Solovyanova, Anna K. Sinisalo, Margit Schwikowski (in the middle), Birgit Sattler, Terry Bidleman, Mark Hermanson, Mariusz Grabiec, Crispin Halsall, Bartek Luks, Stef Bokhorst and Kaj Mantzius Hansen.
Not present: Roland Kallenborn and Halvard R. Pedersen (photo)

# 1 Summary

Svalbard Science Forum (SSF) organises cooperation workshops aimed at creating new networks within and between scientific disciplines. SSF Cooperation Workshop No. 3, held at Voksenåsen Hotel in Oslo, Norway, on 13-16 February 2012, gathered together 24 experts working on topics related to snow & ice, ecology and pollutants. The participating scientists have acquired research expertise from their work in Svalbard and the Arctic as well as in other cold regions.

The researchers presented their own work and views on knowledge gaps and potential areas of cooperation during day 1 (see abstracts in appendix 1). During day 2 the workshop discussed priorities, links between the fields of research and possibilities for cooperation.

**Recommendations**

The tasks for the group discussions during day 2 were to prioritise the knowledge gaps revealed, link the different fields of research and suggest possibilities for cooperation. After discussions within the three fields, the outcome of the discussions were presented in plenary (see chapter 2).

The workshop decided on eight projects that would add value to current research by promoting increased cooperation and joint activities. Each of these has the potential to fill main knowledge gaps, combine different fields of research and generate more cooperation and collaboration. The recommended projects will be part of the *SSF priorities* relevant for strategic funding. The projects are (in non-prioritised order):

1. Identification of climatic parameters that have been recorded.
2. Spatial and temporal variability of snowpack properties in non-glaciated areas.
3. Meltwater release of pollutants to terrestrial ecosystems.
4. Local pollution vs. long-range transport: biomonitoring and source markers.
5. Impacts of winter stress events: Extreme winter weather and pollution shock on community development.
6. Spring: Changes in onset of spring and impact in terrestrial ecosystems.
7. Autumn: Date of onset of soil freezing and snow cover in the autumn.
8. SNOW.MELT - Impact of snowmelt on soil development.

During day 3 there were discussions in cross-disciplinary groups to start defining, describing and planning possible realisation of the eight suggested projects. See chapter 2.1.

**Conclusion**

The discussions clearly showed that there are many possible ways of combining these three fields of research in new and relevant projects that will advance all the fields in their research in Svalbard. The projects suggested have the potential to generate important knowledge through cooperative and more efficient research. They can also contribute to the *SSF Strategic Objectives*:

- increased and improved international and interdisciplinary research cooperation;
- more and open sharing of data collected in Svalbard;
- reduced environmental impact through coordination of logistics and activity, use of new technologies and efficient use of existing infrastructure.

The workshop has given rise to many fruitful discussions with very good input and helped to stimulate cooperation. The feedback from participants was that these cooperation-focused discussions were very useful, stimulating and inspiring - an effective way of thinking of new ideas and making cross-disciplinary contacts.

“The discussions broadened our perspective and awareness, and it appears that the workshop has created valuable synergies through more collaboration in upcoming joint projects.”

Elisabeth J. Cooper, member of the planning group

# 2 Conclusions and priorities

The workshop discussions were based on presentations by the researchers in attendance and focused on identifying areas of potential cooperation, data sharing and feasible projects that could fill identified knowledge gaps and combine the different fields of science. This chapter contains the conclusions and recommendations from the workshop discussions both within groups and in plenary.

## 2.1 Prioritised cooperation projects

The participants suggested eight prioritised projects that can provide an overview of existing investigations and data already collected, fill the main knowledge gaps and create more efficient research through closer cooperation. The recommendation also forms an integral part of the SSF priorities. The projects are:

### 2.1.1 Identification of climatic parameters that have been recorded

The main objective of the project is to create an inventory of archived and temporal meteorological measurements and climatological data for Svalbard. The project could be divided into two steps/deliverables:

1. Overview/paper of the existing records, measurements and "milestone" literature.
2. Free access database with detailed metadata, and raw data as well as published papers and references. The database could be applied to other environmental studies.

*Elements of database*

- Map of locations;
- Metadata: location, description of area, description of data and sensors, time of series, photos/detailed maps, responsible institution, etc.;
- Raw data;
- Satellite data (SST, sea ice, snow cover, cloudiness, NDVI etc.);
- Grid data from reanalysis;
- PDF files with archive tables, etc.;
- Paleodata (last 1000 years);
- Links to existing databases/online measurements, etc.;
- Library of climatological/bioclimatological parameters (animals, plants, human);
- List of references and milestone publications/records;
- Useful tools/links to these tools (back-trajectory analysis, etc.).

*Parts of database*

- Historical (Isfiord Radio, IGY3rd, etc.);
- Synoptic stations;
- Barentsburg, Longyearbyen, Ny-Ålesund, Hornsund;
- Data from international contributors, for example Polish scientific investigations.

*Open questions*

- Location of server;
- Updating procedures/responsibility/service;
- Search tool in the database, etc.

### 2.1.2 Spatial and temporal variability of snowpack properties in non-glaciated areas of Svalbard

The main objective of the project is to gather knowledge on the snowpack properties in Svalbard outside the glaciers. Main deliverable: Background paper on temporal and spatial variability of snow cover focusing on non-glaciated areas. The paper should include:

- Information on available long time series (Ny-Ålesund, Hornsund, Barentsburg, Longyearbyen);
- Short-term studies of snow cover from other sites;
- Data on snow depth, snow water equivalent, snow density, precipitation, air temperature;
- Data analysis (parameters dependencies/correlations);
- Data comparison between sites.

### 2.1.3 Meltwater release of pollutants to terrestrial ecosystems

Main objective: Consider the impacts of contaminant releases from meltwater in Svalbard. Ecosystems investigated will include both terrestrial (as sources) and aquatic (as impact sites). The impacts of meltwater runoff on aquatic ecosystems should be considered from glaciated and non-glaciated systems, in part to identify the effects of a warming climate in Svalbard.

Meltwater from glaciated systems has the potential to contain contaminants in long-term storage (since the 1950s for organic contaminants, longer for metals), while non-glaciated system meltwater is more likely to contain only seasonal (1-year) inputs. The discharge from glaciated systems likely will depend to some degree on glacial hydrology, which may require hydrological studies (which could be historic) or glacial modelling.

The ecosystems could include plants, insects, fish (more likely) which show body burdens of contaminants of interest (COI). Suggested COIs include pesticides (chlorpyrifos, trichlorfon), herbicides (dachthal), PCBs, PCNs, and trace metals. The COI list may also depend on inputs shown in available data sets from selected field sites. Potential field sites may include Revvatn near Hornsund, and Linnévatn, east of Barentsburg. Other lakes should also be considered.

In the first stage of the study, the first goal is to measure bioaccumulation of organic contaminants of interest in fish and zooplankton in spring because these are high-accumulation sites. Analysis of metals in muscle tissues from fish could be included.

### 2.1.4 Local pollution vs. long-range transport: biomonitoring and source markers

The main objective of the project is to conduct a systematic study that examines the “halo” and “reach” of pollutants from long-range transport. Svalbard is affected by local pollution sources associated with power generation and industrial/municipal activities, notably on the western side of Spitsbergen. The influence of this pollution on atmospheric studies, which tend to focus principally on long-range transport of pollutants/trace gases, is often referred to in the scientific literature. Studies of such sources are lacking.

Pollution “hotspots” are likely to occur around the major centres of Longyearbyen, Barentsburg, Pyramiden and Ny-Ålesund. To characterise or discriminate the sources of air pollutants, there is a need for a systematic survey in which chemical markers can be measured along spatial transects, extending through and beyond these populated centres. The transects would take advantage of biomonitoring – in this case the use of plant material to sequester and accumulate particles, metals and organic pollutants. Selected lichens and mosses/higher plants would serve as biomonitors and would be harvested and then subjected to chemical and physical analysis. This would complement snow surveys conducted along spatial transects during snow-covered periods. Specific chemical markers relevant to pyrolytic and petrogenic processes, industrial chemical markers, etc. will be identified. Diesel and coal combustion for energy generation – both point and mobile sources – could be distinguished by this technique.

The same plant material could be harvested from background sites (impacted only by long-range transport, LRT) to distinguish chemical patterns associated with LRT only. The long-term air monitoring station on Zeppelin Mountain, Ny-Ålesund, is an example of a background site and has the added advantage that the active air samples collected can be compared to the chemical pattern observed in nearby plant material. It is anticipated that local meteorology (inversions, local wind fields, etc.) could be used to model the transport and incursion of locally-derived air pollution to more remote sites and be compared to larger scale hemispheric transport of relevant pollutants, particularly persistent organic pollutants.

*Deliverables/novelty:*

1. Systematic survey (first!).
2. Biomonitoring (cooperation between chemists and ecologists).
3. Novel chemical markers, techniques
   (magnetic strength to distinguish Fe-containing minerals).

### 2.1.5 Impacts of winter stress events: extreme winter weather and pollution shock on community development

*Main objectives and deliverables:*

1. Establish a baseline data set on the historical occurrence of extreme winter warming events and ROS events for Svalbard. Proposed deliverable: A published paper.
2. Develop a theoretical model in which pollutants become bioavailable during an extreme winter warming event, and consequently could pose a threat to already stressed organisms. A theoretical model can be used in a paper and for a grant proposal, and later on be validated in experiments.
3. Obtain funding to run the extreme winter warming event simulations.

Climate change models indicate that the frequency of extreme weather events may increase. A higher frequency of unseasonal - extreme - weather increases the risk of mortality for many organisms, which can lead to unexpected knock-on effects throughout an ecosystem. For the Arctic winters these extreme weather events manifest themselves as unusual warm weather events that melt snow and expose the terrestrial ecosystem to warmer temperatures that can induce spring-like developments or affect freeze hardiness in many organisms. Upon return of the colder winter temperatures the plants and animals are no longer protected by the insulating layer of snow and experience many cold shocks and freeze-thaw cycles for the remainder of winter.

Instead of complete snowmelt, as in extreme winter warming events, partial snowmelt results in ice formation in the snowpack which can encase organisms in ice. This kind of ice formation also occurs when rain falls on snow, known as "rain on snow" (ROS) events. This ice encasement can lead to anoxic conditions, and due to the higher temperature conductivity of ice, organisms are exposed to much colder temperatures than if they were under a thick snow cover.

*Multiple stresses*

Both the extreme winter warming and ROS events cause considerable shock to terrestrial communities. As the snowpack in Svalbard is loaded with pollutants, which are scrubbed from the air during snow deposition, the melting of this snow results in a potential additional shock from the pollutants. The combination of extreme winter weather events and pollution stress is ideal for elucidating community resistance and resilience.

*Events*

- ROS (rain on snow);
- Extreme winter warming;
- Pollution shock - additional stress following the extreme events;
- Heavy snowfall/thick ice results in heavy grazing pressure during winter in the low snow areas;
- Interaction: snow fungi and extreme events.

*Response variables*

- Community resilience/resistance;
- Cold hardiness;
- Life history traits;
- Inter- and intra-specific plasticity in physiological trait responses;
- Follow pollutant through the ecosystem.

**Project plans**

*Data required*:

- Frequency and timing of extreme warming/ROS events during winter from long term meteorological data sets (temperature and snow depth).
    - Acquire data/Write paper on:
        - Temporal changes in snow depth throughout the year (long term monthly data values);
        - Icing events;
        - Freeze-thaw cycling at soil surface;
        - Thermal conditions of snow;
        - Snow water equivalent.

- Pollution loading in snow, which pollutants (water soluble or not).
    - Compare with marine organism responses to pollutants.
- Theoretical model of when pollution leaves the snowpack.
    - Early release of pollutants will result in runoff from the system before it is warmed (unlikely to have an effect on organisms);
    - Late release of pollutants from the snow will occur when vascular plants and cryptogams will be "activated" and be susceptible to the pollutants.

*Future plans*

- Obtain funding for pilot studies and write baseline papers (SSF).
    - Pilot on field extreme events;
    - Pollution loading on plants in the lab;
- Write research proposal (ERC grant).

### 2.1.6 Spring: Changes in onset of spring and impacts in terrestrial ecosystems

The main objective is to gather knowledge on changes in onset of spring and establish a baseline data set on the historical occurrences for Svalbard. An overview will also provide the opportunity to coordinate variability testing (same method statistically).

*Possible deliverables:*
- Sum-up of existing data sets (positions and periods) with focus on changes in variability.
- Review article based on existing data sets.

Plot level:
- Data on snowmelt and temperatures in summer and how that translates into plant development and seed production (EC).
- What are the main climatic parameters driving species development?

Meso-level:
- Monitoring data March-end spring: snow cover spatial distribution of snow and categorise snow (2000 and forward).

Data sets:
- Spring (date between snowmelt, very early period to first greening-up period).
- Dates of snowmelt –variation in snowmelt (timing and duration of snowmelt).
- Date of geese arrival.
- Dates of calving.
- Dates for ptarmigan (egg-laying).
- Greening up (NDVI data).
- Temperature data.
- Bulbils production and ripening – susceptibility of bulbils to fungal attack.
- Phenology of Bistorta and other species.
- Bulbils and flowers of Bistorta.
- Goose grubbing (Fragile, Speed studies, Svalbard Terrestrial).
- Soil – geese reduce seeds and bulbils.
- Day degrees (approximation of development).
- Variability between parameters between years or not?
- Is there a pattern in these parameters related to date of snowmelt, snow cover, temperature, early summer temperature?

### 2.1.7 Autumn: Date of onset of soil freezing and snow cover in the autumn

The main objective is to gather knowledge on the date of onset of soil freezing and snow cover in the autumn and establish a baseline data set on the historical occurrences for Svalbard.

*Deliverables:*
1. Sum up data available and write an overview.
    - Get access to e.g. Met data (1990s onwards) and Hornsund annual variation (large area/locally).
    - Air temperature: e.g. LYB airport, e.g. below -5 constantly, 1970s onwards.
    - Satellite NDVI data (Aug-Oct 2000 onwards): date of senescence, onset of snowfall.

2. What is the variation/trends in autumn length/duration?
    - Reindeer, ptarmigan benefit from absence of snow: sibling vole? Positive effect? Temperatures above freezing in autumn.
    - Plants/soil C negative increased temps and respiration.
    - Warm autumn may delay plant hardening (early phase may be photophase other spp temperature) also invertebrate cold tolerance.
    - Microbial activity temp enhanced - which become more abundant/bacteria/fungi- effect on pathogens in general.

### 2.1.8 SNOW.MELT – Impact of snowmelt on soil development

The main objective of this project is to investigate the impact of snow on the development of Arctic (alpine) microbial communities under conditions of changing water availability and temperature properties. The project will base on these facts:

- Snowpack is harbouring diverse microbial communities which contribute to the carbon budget, especially in newly developed periglacial ecosystems.
- These are pioneer communities in the primary succession of the terrestrial ecosystems (after glacial retreat) and extreme environments in mountainous areas, respectively.
- Spatio-temporal distribution of the snowpack is the determining factor for the development of the terrestrial ecosystem.
- Snow coverage is stabilising the ecological properties of underlying ecosystems.
- Snow is an “accumulator” for nutrients, particles, minerals which is made available to soil communities after snowmelt and microbial inoculum.
- Climate change implies changes in temperature and water availability.

*Hypothesis*
- Increased temperatures result in increased water availability which could enhance microbial production.
- Soil biological crust communities receive more organic carbon due to the fertilisation effect which helps to develop the crust communities.
- Expected shift in biodiversity from snow to soil ecosystem followed by changes in soil ecological properties.
- Increased snowmelt can minimise the N-limitation of soil crust ecosystem development.

*Methodology:*
- Climatological timing (when is period of snowmelt/fall likely to occur).
- Characterisation of abiotic and biotic properties of the snow:
    - Physical-chemical properties (snow height, density, water potential, snow types, temperature, nutrients [anions, cations], dissolved organic substances, pollutants).
    - Description of snow and crust communities:
        - Quantification of bacteria, algae, cyanobacteria, invertebrates, fungi;
        - Qualification: molecular biological approaches (pyrosequencing, fingerprinting);
        - Productivity: primary [14C NaHCO3-incorporation], secondary production [3H-leucine] to calculate carbon in-/output;
        - Nitrogen cycle: nitrogenase activity;
        - Time before snowmelt, intensive sampling in parallels of snow plots.
- Compare development in snowpack and soil in glaciated versus non-glaciated surfaces.
- Manipulation: OTC to increase temperature and snow barriers ( tentative snow fields).

## 2.2 Conclusions from the "snow & ice group" discussion

1. Main knowledge gaps:
    - **Model development and validation.** Need for better meteorological input to snow models employing downscaling e.g. RCM model output. Model of orographic precipitation as an example.
    - **Consistent observations** and simulations of temporal and spatial patterns of snow accumulation and meltwater production. This also involves precipitation sampling (procedures needed: calibration, routines and timing). Meltwater penetration in snowpack - internal refreezing.
    - Snow distribution in **coastal areas** needed. Studies of glacial areas dominate today (side product of glacial mass balance studies).
    - **Spatial distribution**. Knowledge of certain areas such as southern and eastern parts of Spitsbergen missing completely. Regionalisation of precipitation lapse rates.
    - Denser network of **meteorological data**, more automatic weather stations in remote areas.

2. Possible use of and contribution to work done by the other researchers?
    - Meta database needed in order to gain an overview of existing data and identify gaps.
    - Contribute with suitable tools such as GPR (ground penetrating radar), develop models (e.g. snowpack models), specific instrumentation, knowledge about physical and chemical properties.

3. Possibilities for:

    *a. New technology and remote sensing:*
    - Establish new reference areas for validation of remote sensing data and models.
    - Laser scanning (e.g. near infrared).
    - Lidar investigations detecting volcanic dust, long-range transport.
    - Multispectral analysis of satellite images for snow cover monitoring.

    *b. Reduced environmental footprint:*
    - Overview of what has been done before, not reproduce what already has been done. Meta database important, digitise old data (e.g. Soviet data). Update knowledge through workshops and review papers.
    - Data sharing (e.g. automatic weather stations).
    - The SIOS project (Svalbard Integrated Arctic Earth Observing System).
    - Fieldwork coordination.

    *c. Common logistics:*
    - Double sampling.
    - Research database, metadata of measurements networks;
        - Calendar of common routine measurements.
        - Common sampling protocols.
    - Common lab establishment and data processing.

4. Potential international cooperation projects or workshops
    1. Database of research and monitoring – review of snow studies in Svalbard.
    2. Multidisciplinary pilot project in reference areas.
    3. Joint project with the European Space Agency (ESA) for remote sensing and validation of data.

## 2.3 Conclusions from the "terrestrial ecology group" discussion

1. Main knowledge gaps related to each Arctic season (autumn, winter and spring):

**Warmer autumn** (higher temperatures and later snow cover):

- Warmer autumn, higher temperatures, later snow cover (impacts on the ecosystem).
- Identify the length of the period between senescence and freezing (before/after the snow comes) and snow on ground. Is this period changing?
- Pathogens – autumn, winter temperature may be important for parasites.
- Pathogens – may affect plants, microbes, temperature in autumn.
- Factors determining plant hardening, de-hardening and plant senescence in the High Arctic (milder, warmer autumns). Become tolerant to winter cold by preparing themselves in autumn. Period of adjusting.
- Interaction between pollution and cold tolerance (ability for insects to survive, may also affect plants).
- What is driving the senescence in species?
- Influx of species (invasive species) – impacts on terrestrial ecosystems.
- Changes affected by time of snow and when snow falls.
- Difficulties defining autumn when using remote sensing, onset of autumn. Being aware of how we define the onset of autumn.
- Variation among species and even among ecotypes is still poorly understood. For instance intermittent mild periods and snowmelt during mid-winter may be beneficial for some species (e.g. due to activation of photosynthesis) and detrimental for others (e.g. due to damage during subsequent periods of frost).

**Winter** (and extreme events):
- Timing and frequency of events in relation to light and temperature and combination of these factors and snow-wetness, snow-depth, freeze-thaw.
- Snow-depth, snow-thickness, amount of water in the snow, snow cover, insulation capacity.
- Wetness of snow – how this affects the tropic relationship from microbes to higher levels.
- Snowpack properties and percolation.
- Spatial and temporal extent and variability of ground ice in the landscape.
- How much biomass can be produced in winter in the snowpack?

**Onset of spring:**
- Warmer spring, onset of spring starts earlier.
- Freeze-thaw cycling (fairly well understood).
- Trophic match-mismatch.
- Herbivores – key forage plants.
- Plants – insects and pollination.
- Snow-melting processes and amount of meltwater vary (still snowpack on the top) – affect various organisms differently.
- Snow cover in space and time (spring temperatures and amount of snow in winter [snow depth, snow accumulation]).
- Amount of nutrients on landscape scale and under which climatic conditions they are released from the snowpack (how will it affect tropic webs).

2. Possible use of and contribution to work done by the other researchers?

**Snow & Ice**

- Complete overview of climate parameters collected in Svalbard from all stations in a review article.
- List/overview/meta-database of climate parameters: Complete list of data with temporal and spatial resolution on snow depth, basal ice layer, note melting events in winter.
- Information from/about climate processes.

**Pollutants**

- Collaboration on level of pollutants in terrestrial organisms with chemists and ecologists.
- Pollutants in snow – scavengers of pollutants - if high levels are found, these species need to be targeted.
- Snow on land – how do pollutants in snowpack affect terrestrial organisms?
- Focus on plants first, then higher trophic levels.

3. Possibilities for new technology and remote sensing?

- Remote sensing (meso-scale – data from remote cameras), combine remote sensing with other data, ground checks.

4. Potential international cooperation projects

(Review articles, project applications, collaboration projects, follow-up workshops)

| | Theme | Keywords |
|---|---|---|
| **1** | Climate parameters | Review paper on relevant climatic parameters relevant for terrestrial ecosystems, cooperation between geophysicists and ecologists. |
| **2** | Autumn and Spring | Timing of snow deposition and melt impacts. |
| **3** | Remote sensing | Snow cover (space and time). |
| **4** | Extreme events | Multiple stressors on organisms. Timing and frequency of events (duration). |
| **5** | Water cycle | Timing, direction, nutrients, pollution (transport), moisture, content, snow-melt processes. |
| **6** | Biomonitoring | Experimental studies – baseline studies on plants (key forage plants for herbivores). |

## 2.4 Conclusions from the “pollutants group” discussion

1. Main knowledge gaps:

A. Quantification of local sources compared to long-range transport

- Investigate the impact of local sources of pollutants (POPs but also inorganics) on the Svalbard environment e.g. Barentsburg. Estimations of the quantity, composition of technical formulations of PCBs, DDTs and other OC “products”. “Halo” of contamination. Local sources should be examined more systematically – links into BC/EC work. There are several local sources: settlements, mines, cruise ships, snowmobile transport, etc. Svalbard may not be a “pure” background anymore?
- Deployment of a network of passive samplers and surface snow samples to identify local sources.
- Knowledge about local accidents (e.g. 2006 fire accident in Svea mine (2005) and Barentsburg mine (2006)).
- Waterborne local pollutants: ship discharges, waste water, runoff from mine activities (waste piles).
- Effects of increased oil exploration.
- The challenge we face is identifying sources of contaminants when researching Svalbard glaciers. While we know that most air masses moving towards Svalbard have come from the east or south, from Eurasia, few data are available regarding the use of compounds that we have analysed. Other key missing information is air data for these contaminants from the likely source regions, or between these regions and Svalbard. We also need more information about possible local sources of these contaminants in Svalbard.
- Use of ion chemistry of snow and ice, including black carbon, to discriminate pollution sources and strength to Svalbard: also distinguish local sources from LRT.

B. Meltwater

- Meltwater runoff and remobilisation of POPs – thawing permafrost and surface ice melting (ice caps and glaciers) have the potential to create a significant new source of contaminants release to the Arctic.
- Investigations in one or more Svalbard fjords (like those carried out in Greenland), e.g. Kongsfjorden, sampling ice on Kongsbreen and passive samplers in the fiord. Could also be conducted on a freshwater system such as Linnévatten close to Barentsburg or Revvatnet and Myrktjørnasjøen near Hornsund.

C. Impact of terrestrial ecosystem contaminant runoff on a stressed habitat

- Grow Arctic plants in a cold lab with clean and contaminated snow; see the effect on the development of the plant after snowmelt.

D. Climatic effects

- Understanding the fate and release of contaminants during freeze-thaw and spring melt, field studies in a well-defined catchment area coupled to hydrology.
- The role of summer precipitation (fog and rain) in delivering POPs/CUPs.
- The impact of the shortened snow season, greater rates of snow precipitation, and winter warming events on POPs’ delivery and fate.

E. Process studies

- Air-surface exchange processes within the Arctic. Different rates of exchange are apparent between different surfaces e.g. snow, soil and water, which may control the seasonal fluctuations in POP concentrations observed in Arctic air.
- Post-depositional loss from the snowpack for different chemical pollutants and the role of particles in delivering “new” POPs to the snowpack.
- Detailed studies into the association of POPs with snow crystals and the role of the quasi-liquid layer and derivation of snow-air partition coefficients. Related to point D: the investigation of chemical diffusion in the snowpack and the role of wind ventilation on chemical movement.
- Basic survey of POPs in Arctic soil. There is no knowledge at present.

F. Target compounds

- Mercury - Release into aquatic systems.
- PCNs. Found in the Arctic, in old Russian mixtures found in Barentsburg. Relevant for the Stockholm convention?

2. Possible use of and contribution to work done by the other researchers?

- Effects/impact studies of “pulse” releases from the melting snowpack on “stressed” habitats e.g. plant/soil communities.

# Appendix 1: Abstracts

## Snow & Ice

20: Krzysztof Migala: *Atmosphere boundary layer, local climate & snow*
22: Anna K. Sinisalo: *Multi-methodological approach in investigating the spatial and temporal variability of snow distribution on Svalbard*
24: Irina Solovyanova: *Snow distribution on Aldegonda and West Grønfjord Glaciers (Spitsbergen)*
25: Bartek Luks: *A comparison of two approaches to model snow cover dynamics at the Polish Polar station at Hornsund*
26: Mariusz Grabiec: *Snow cover distribution and structure on glaciers of Svalbard*
28: Elisabeth Isaksson: *Svalbard ice and snow as archives for climate and pollution*

## Terrestrial ecology

30: Elisabeth Cooper: *An overview of the effects of changes in winter climate on Arctic terrestrial ecosystems*
32: Stef Bokhorst: *Extreme winter warming in the sub-Arctic*
33: Heikki Hänninen: *Snow and overwintering ecophysiology of northern plants: Combining experimental studies with modelling*
35: Åshild Pedersen: *Svalbard's terrestrial ecosystem: Impact of snow and ice on the herbivore guild and their shared predator*
38: Lennart Nilsen: *Time serial studies of Arctic vegetation: Bridging the spatial scale from field sampling to satellite remote sensing*
40: Birgit Sattler: *Glaciers are becoming greener*
42: Bronislaw Wojtuń: *Polish ecological studies in Hornsund*
45: Josef Elster/Jan Kavan: *Czech research in Petuniabukta, Billefjorden, northern part of Isfjorden, Svalbard*

## Pollutants

47: Roland Kallenborn: *Remobilisation, Atmospheric distribution and meltwater runoff. Climate change and the presence of persistent organic pollutants in the Arctic*
49: Terry Bidleman: *Delivery of POPs to the Arctic: Transport and Air-Surface Exchange Processes*
52: Crispin Halsall: *The accumulation, behaviour and fate of POPs in the seasonal snowpack*
54: Kaj Mantzius Hansen: *Modelling the effect of snow of the fate of persistent organic pollutants*
56: Mark Hermanson: *Organic contaminants in ice cores from Svalbard*
58: Margit Schwikowski: *Recent pollution levels from Lomonosovfonna ice core, Svalbard*
60: Sergey Vlasov: *Organochlorines contamination in Barentsburg area, Svalbard, 2002-2011. Local sources*

# Atmosphere boundary layer, local climate & snow

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Snowfalls with accumulation and next amount of heat consumed on melting are primary factors forming arctic environment. Research carried out in the vicinity of the Polish Polar Station, SW Spitsbergen led to the conclusions that studied meteorological elements as well are formed by global changes with time but also vary with altitude, which is reflected in cryological/glaciological processes. The factor, which should be taken under consideration are properties of arctic ABL (atmospheric boundary layer). The arctic mixing layer is shallow and reaches maximum height of 300 – 350 m a.s.l. The depth of ABL and air temperature changes in vertical profile mark the border in dynamics of the processes concerned with clouds development and surface radiation budget In consequence. Structure of ABL modifies chemistry of precipitation and dynamics of other processes i.e. freeze/thaw cycles.

New experience with snow measurements turned our attention on to new questions and formed the basis to carry out studies concerned with:

- chemistry of snow cover and acidic snowfall
- extreme pollution events as markers in snow cover stratification
- local climate and vertical gradients of glaciological processes

Preliminary studies led to general conclusions:

- Snow properties have altitudinal gradients which are induced by atmospheric processes and chemistry (weather & climate)
- The key for study snow cover properties (stratification, spatial distribution) is intensity of warm air advections and fehn processes modified by local relief
- Altitudinal gradients modify cryochemical processes
- Monitoring of fresh snow chemistry in altitudinal profile of a glacier gives an opportunity to recognize extremal events in snow cover structure.
- Intensity of percolation & quality of the contaminants in snow cover divide the glacier on two parts (unglaciated slopes as well)
- The processes are differentiated locally as well they are modified by geometry and individual position of a glacier and properties of local climate (unglaciated valleys as well)
- Climate changes and interannual weather fluctuations have to be considered in the detailed snow studies

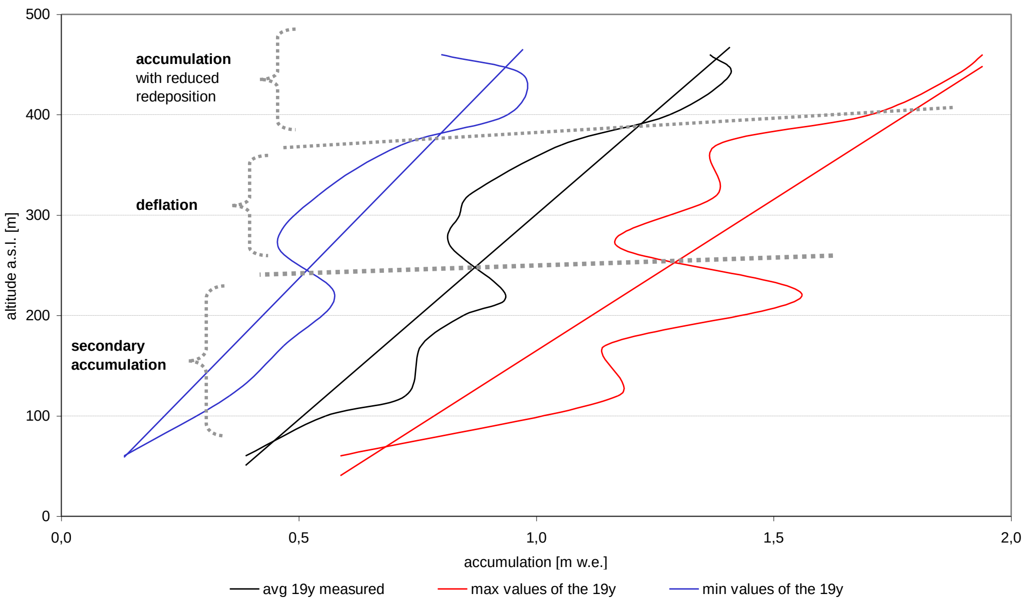

**Fig. 1.** Hypsometric zonality of snow accumulation on the Hans Glacier as the effect of wind and orography, in the years 1988-2007.

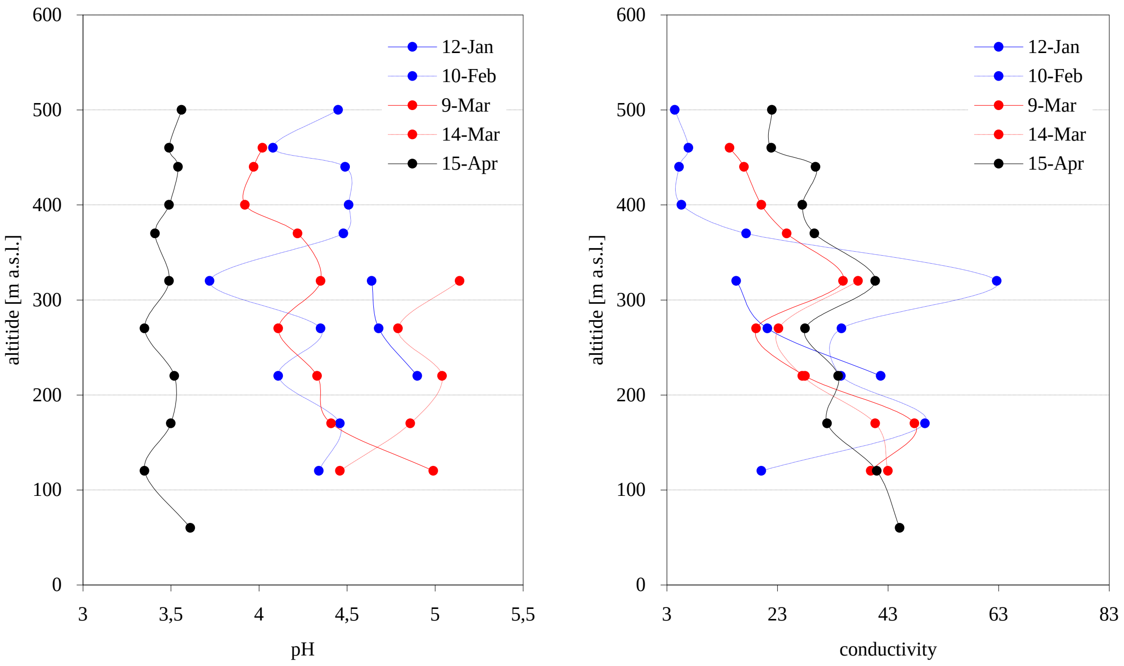

**Fig. 2.** Fresh snow pH and conductivity in the hypsometric profile of the Hans Glacier in the winter season 2005/2006.

# Measurements of the spatial and temporal variability of snow distribution on Svalbard

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## Introduction

Currently, the main research areas of the Department of Geosciences (University of Oslo) on Svalbard regarding snow studies are Austfonna ice cap and the area close to Ny Ålesund research station. Ground penetrating radar (GPR) measurements are used to investigate the spatial variability in snow accumulation (Dunse et al., 2009; Taurisano et al., 2007). Point measurements such as snowpit studies reveal accurate information on snow thickness, stratigraphy and physical properties of the snow cover. Furthermore, mass balance stake measurements and shallow cores provide information on the total surface mass balance, i.e. the sum of snow accumulation and ablation. Remote sensing and numerical models are applied to enhance the understanding of the physical properties of the snow and underlying key processes (Nuth et al., 2012; Rotschky et al., 2011; Schuler et al., 2007). The snow observations especially on Austfonna cover a large area and are suitable for validating climate models and reanalysis of the data.

## Spatial and temporal variability of snow distribution in Austfonna

On Austfonna, near-surface (>=10 m depth range) GPR measurements along fixed profiles were collected in 1998 and annually since 2004. These measurements indicate a stable spatial pattern of snow accumulation but display a large inter-annual variablity in the total amount of snow. Snow thickness, variable weather conditions, e.g. winter cold (recharging the cold content), the length and intensity of the summer melt period, and the frequent occurrence of rain events have an influence on the amount of water that can be retained in the snow by refreezing. The integral effect of all these processes is represented in the glacier facies, that we have monitored on Austfonna over 4 consecutive years, distinguishing between firn, superimposed ice and blue ice of the ablation area. However, the short time period does not allow to draw conclusions on the potential impact of a changing climate.

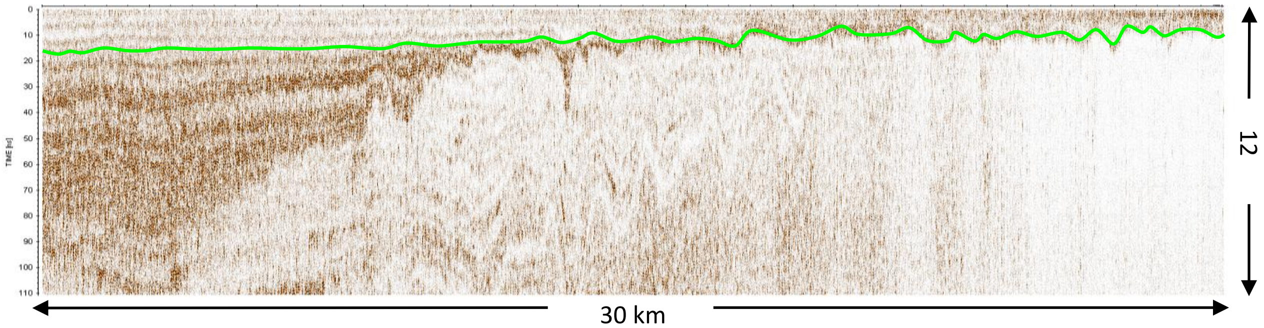

**Figure 1.** Spatial variability of snow depth (green line) along a 30km transect measured with a GPR on Austfonna (Dunse et al. 2009).

We can roughly estimate regional precipitation lapse rates from the measured snow depths on Ausfonna. These precipitation lapse rates display a complex pattern depending on exposition to the dominating moisture flux (Taurisano et al., 2007) and are best described by a horizontal gradient superimposed to a vertical gradient. Ongoing work using a model of orographic precipitation successfully reproduces this spatial pattern, thereby offering a promising opportunity to couple large scale atmospheric dynamics to regional scale precipitation (Schuler et al., 2010).

## Outlook

In addition to the spatial variability, the GPR measurements can be used to estimate the temporal variability of the surface mass balance by matching the radar layers with dated layers from shallow ice cores, such as Beaudon et al. (2011) and Isaksson et al. (2001) or the deeper ones, e.g. Isaksson et al. (2005). The ice cores give the temporal variability of surface mass balance at the point of drilling and the record can be spatially extended by a network of GPR profiles. In addition the surface mass balance measured in situ by GPR, stakes or snow pits can be modelled on a daily basis from meteorological input data (Schuler et al., 2007 and 2010; Nuth et al., 2012). The ground based measurements provide essential data for calibration and validation of larger scale models and remote sensing studies.

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# Snow distribution on Aldegonda and West Grønfjord Glaciers (Spitsbergen)

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The results of studies the dynamics of snow cover basic characteristics on glaciers around Barentsburg it was examined spatial patterns of distribution of the characteristics of snow cover over the period 2003-2011.

According to long-term an observation on the archipelago is about 480 mm of solid precipitation in a year; their share is about 80% of the annual amount. The average date of the snow cover formation is about 15th of September, a full descent of the snow cover observed about June 22. The duration of snow cover about 280 days. The average height of the seasonal snow line for this period is 500 m.

The snow cover on the surfaces of Aldegonda (Aldegondabreen) and West Grønfjord (Vestre Grønfjordbreen) Glaciers has a bimodal distribution, the first peak is equal to 170 cm, it is describe the state of snow cover on the subhorizontal sections of glaciers, the second peak is confined to the sloping parts of the catchment, where there is an increase in the snow heights of about 20-65 cm of the average glacier value. Statistically significant dependence of snow cover on the absolute height of the catchment is characterized by a coefficient of determination 0.76. Intensive processes of snowdrift help change the height of snow cover on glaciers within a small range depending on local conditions. Average heights are marked on relatively flat smooth slopes, the minimum on convex parts of glacial slopes. Maximum power of the snow cover is observed in circuses and near mountain ridges and slopes on the glacier surfaces.

It was marked the increase in the density of the snow cover to the headwaters of the glaciers from 0.29 g/cm3 to 0.46 g/cm3. The observed high values of snow density, primarily due to the presence in the snow large number of ice layers and icy crust, and metamorphosed snow streaks of various thicknesses. Number of ice layers in snow pits is about 8-10, and their thickness varies from 0.5 to 5 cm each, indicating unstable weather conditions, snow accumulation period, the frequency of warm periods and their intensity.

Maximal water reserves in snow contained in the rear parts of mountain frame glacial watersheds receiving additional feed by the avalanches from the surrounding slopes. Investigating the distribution of snow on the glaciers of Spitsbergen showed a clear dependence of the quantities of snow cover increase with increasing altitude areas, is sometimes violated at sites of ice divides. The snow gradient according our data, in the average is about 240 mm/100 m for glaciers on the west coast of the Nordenskjöld Land, which agrees well with data obtained by Norwegian scientists 237 mm/100 m, with an average gradient of snow cover for the archipelago is about 104 mm/100 m.

Inter annual variability of snow cover on the glaciers of the archipelago is essential. However, the analysis of multiyear data of snow observations on Aldegonda and West Grønfjord glaciers showed the presence of a positive trend on the average snow heights over the study period.

# A comparison of two approaches to model snow cover dynamics at the Polish Polar station at Hornsund

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We compare different approaches to model snow cover dynamics at the Polish Polar Station at Hornsund. In the first approach we applied physically based Utah Energy Balance Snow Accumulation and Melt Model (UEB). The model uses a lumped representation of the snowpack with two primary state variables: snow water equivalence and energy. Its main driving inputs are: air temperature, precipitation, wind speed, humidity and radiation (estimated from the diurnal temperature range). Those variables are used for physically-based calculations of radiative, sensible, latent and advective heat exchanges with a 3 hours time step.

The second method is an application of a statistically efficient lumped parameter time series approach to modelling the dynamics of snow depth, based on daily meteorological and snow depth measurements from the same area. A dynamic Stochastic Transfer Function (STF) model is developed that follows the Data Based Mechanistic approach, where a stochastic data-based identification of model structure and an estimation of its parameters are followed by a physical interpretation.
We focus on the analysis of uncertainty of the both model outputs. In the case of time series approach, the applied techniques also provide estimates of the modelling errors and the uncertainty of the model parameters. In the first, physically based approach the applied UEB model is deterministic. It assumes that the observations are without errors and the model structure perfectly describes the processes within the snowpack. To take into account the model and observation errors, we applied a combination of the Generalized Likelihood Uncertainty Estimation technique (GLUE). These techniques also provide estimates of the modelling errors and the uncertainty of the model parameters. The observed snowpack water equivalent values are compared with those simulated with 95% confidence bounds. The results show a good agreement with observations.

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# Snow cover distribution and structure on glaciers of Svalbard

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The winter snow cover on glaciers has great importance for their state and for processes occurring on the surface as well as inside the glaciers. Snow accumulation is the key element of glacier mass balance. Due to its high albedo, snow cover reduces melting rate during thaw periods and reduces the energy balance of glaciers. The insulating properties of snow influence the thermal state of glaciers. Water derived from melting snow cover plays a crucial role in glacial hydrology and increases basal sliding of glaciers.

The most extensive snow studies are carried out by our team on Hansbreen (S Spitsbergen) and its surrounding. This glacier is a well running environmental laboratory thanks to maintaining varied scientific equipment and proximity of year-round operating Polish Polar Station in Hornsund. The mass balance monitoring on Hansbreen delivers valuable information on snow thickness and accumulation lapse rate since 1988. Three automatic weather stations (AWSs) are operating on the glacier at ablation zone, equilibrium line and accumulation area and supplement standard weather station at Hornsund coast. The AWSs deliver valuable information in wide range of meteorological parameters (air/snow/firn temperature, radiation fluxes, surface albedo, wind direction and speed, etc.) crucial for understanding of snow cover development and internal structure. They also automatically record changes of glacier surface level that supply information on variability of snow cover thickness. The snow monitoring is supplemented by manual analysis of physical properties and internal structure of snow cover carried out every year when the snow thickness reaches its maximum. Measurements are conducted at several snow pits and much denser snow coring sites. Recently the spatial distribution of snow cover thickness is expanded by high frequency radio echo-sounding that supply also spatial information on snow stratigraphy. The spatial distribution of snow cover thickness in period 2006-2011 was wider studied on other glaciers of Southern Spitsbergen (Renardbreen, Amundsenisen) and Nordaustlandet (Vestfonna). The scientific facilities and experienced staff allow conducting high quality snow studies. The most important findings are:

- The snow accumulation is variable in space and time. The regional variability of snow thickness on Svalbard can be simply explained by availability of moisture and parameterised by distance to the open sea. Temporal changes of snow quantity are related to complex atmospheric processes. Those factors influence on difficulties in settling of the snow accumulation lapse rate. According to Hansbreen data from last 23 accumulation seasons the accumulation gradient is very changeable from season to season with average value 0.19 m on 100 m of elevation. Hence the accumulation lapse rate can be more universal when applying percentage gradient of the snow accumulation corrected by distance to open water factor (Grabiec 2005).

- Local topoclimatic conditions play an important role in precipitation distribution in scale of single glacial basin. The most distinct orographic effect is the increase of precipitation with altitude that reflects in snow accumulation gradient. However, topographic influence on the precipitation field is also related to location of orographic barriers in relation to the direction of humid air mass advection. When the snow is deposited on the glacier's surface it becomes the subject of wind redeposition that is one of the most effective processes of reshaping the initial precipitation pattern of snow distribution. The direction of redeposition is related to the direction of wind which is capable to transport the snow particles. The strongest eastern winds on Svalbard favour westward snowdrift (Grabiec *et al.* 2011).

- Processes that may effectively change the properties of snow density are mid-winter thaws and liquid precipitation. Both of them are thermally controlled and their influence decreases towards higher altitude. The effect of those processes on snow cover is also similar. Snow thickness may decrease slightly due to superficial ablation and densification, but water supplied by rain or melting refreezes forming ice crusts effectively protecting the surface against deflation. According to our data there are no evidences of diminishing snowdrift effects towards lower elevation as an effect of better snow cover protection by ice crusts (Grabiec *et al.* 2011). Due to progressing increase of winter temperature in last decades the ice crusts within snow cover are thicker and more frequent that may significantly change typical snow stratigraphy pattern and redistribution magnitude.

- Basing on the analysis of spatial changes of snow thickness on different type of Svalbard glaciers, the patterns of snow accumulation distribution have been distinguished: precipitation pattern, precipitation-redistribution, redistribution and complex pattern. The precipitation pattern assumes that the snow distribution on glaciers follows the altitudinal gradient. If the accumulation gradient is significantly modified by local factors like wind erosion and redeposition, or local variability of precipitation, the accumulation pattern turns into the precipitation-redistribution pattern. In the redistribution pattern, local factors play a crucial role in the spatial variability of snow depth. The complex pattern, however, demonstrates the co-existence of different snow distribution patterns on a single glacial object (glacier/ice cap/ice field).

New scientific challenges are focussing on physical modelling of processes determining the snow distribution and its internal structure under variable climate. To fill the gaps the local as well as regional climatic models are required. Wider employing of remote sensing methods and innovative tools (eg. radio echo-sounding) in snow research is recommended. Better understanding of the influence of chemical properties (eg. sea aerosols) and their concentration on the processes within snow cover is also needed.

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Grabiec M., Puczko D., Budzik T. and Gajek G. 2011. Snow distribution patterns on Svalbard glaciers derived from radio−echo soundings. *Polish Polar Research* 32 (4): 393–421

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## Svalbard ice and snow as archives for climate and pollution

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Over the last 15 years scientists from Norwegian Polar Institute together with colleagues from several other nations have retrieved ice cores, spanning several hundreds of years, from three major glacier-ice caps in Svalbard; Lomonosovfonna, Austfonna and Holtedahlfonna (Fig 1). Thus these cores are providing information on both the spatial variability component in addition to the temporal record. This is a summary of our main findings regarding climate and black carbon. The studies involving various contaminates will be presented by Mark Hermanson.

### Climate

We have used the $^{18}$O records from two of the Svalbard ice cores; Lomonosovfonna and Holtedahlfonna, to reconstruct the winter surface air temperatures (SAT) for Longyearbyen and Vardø in northern Norway. To our knowledge this is the first attempt to date to quantify in detail past temperature changes in Svalbard from isotopic ice core records. Our approach to reconstructing past winter SAT variations utilizes a technique called ‘scaling’. It refers to the equalization of the mean and standard deviation of a proxy time series (here ice core $^{18}$O) to the corresponding values of an instrumental temperature record over a common period of overlap. This approach rely implicitly on the simplifying assumption of a stable in time linear relationship between a “predictor” proxy and “predict and” climate series. As a target for reconstruction we utilize winter (December-January-February) SAT derived from the homogenized Longyearbyen monthly temperature record which starts in 1911 and Vardø series that has been now extended back to 1840. Analysis of the derived reconstructions suggests that the winter climate evolution of Svalbard and northern Norway of the last millennium can be divided in three major sub-periods. The cooling stage in Svalbard (ca. 1020-1800) is characterized by a progressive winter cooling of approximately 1 ˚C century$^{-1}$ (0.4 ˚C century$^{-1}$ for Vardø) and a lack of distinct signs of abrupt climate transitions. During the 1800s, which according to our results was the coldest century in Svalbard, the Little Ice Age –associated winter cooling was of the order of 4˚C (1.3˚C for Vardø) compared to the 1900s. The rapid warming at the beginning of the 20th century is already well documented in the instrumental data and was accompanied by a parallel decline of sea ice extent in the study area. One of the most striking features of the reconstruction is a lasting pre-1300 period of warm winters where DJF temperatures were comparable, within error, to those that were observed in Svalbard in the 1930s and in the most recent decade. The inference that climate conditions during that period were as warm as the present is indirectly corroborated by evidence stemming from the other types of proxy data from the Lomonosovfonna ice core. Repeated sampling at the drilling location on Lomonosovfonna during field campaigns of 2000-2007 have demonstrated that such a degree of melt, as was observed in the Medieval times, has been exceeded only in a very recent few years. In summary, both the reconstructed winter temperatures as well as indirect indicators of summer temperatures suggest the medieval period before the 1200s was at least as warm as at the end of the 1990s in Svalbard (Divine et al, 2011).

### Black carbon

Using different pollution data from the ice cores and additional shallow cores and snow pits we have been able to investigate links between atmospheric circulation, transport and deposition in snow/ice investigate the aerosol- temperature link through the ice cores proxies. Due to the recent large focus on black carbon (soot) in the scientific community it was natural for us to also include that in our work. As part of our regular field activities on various Svalbard glaciers we have collected snow samples for black carbon analyses from 2007 up to present. Black carbon concentrations from 81 snow samples taken around Svalbard in spring 2007 are low, and show large variation at each of the 6 locations (Fig. 2) (Forsström et al, 2009). The atmospheric transport of black carbon to Svalbard was studied by connecting atmospheric soot measurements to back-trajectory calculations, in order to understand the observed regional (100 km) scale variability in the snow pack. The samples at the eastern side present statistically significantly higher values than those at the western side. Linking the observed atmospheric equivalent black carbon BC concentration at the Zeppelin station, Ny-Ålesund with air mass trajectories, shows that generally higher concentrations are observed when the air comes from the east than from west. This could be one factor to explain why the measured black carbon content in snow in east Svalbard presented systematically higher values compared to the western side. The sampling from the years following 2007 is supporting the initial results (Forsström et al., in prep.).

An extremely useful addition to the spatial study of BC will be the 500 years high-resolution BC record from a 150 deep ice core drilled on Lomonosovfonna in March 2009 in collaboration with Margit Schwikowski from Paul Scherrer Institut (Switzerland).

Since 2000 we have been investigating various contaminants in ice cores and snow pits from sites on Austfonna, Lomonosovfonna, and Holtedahlfonna in collaboration with Mark Hermanson from UNIS. Studying the contaminants has given us insight into atmospheric transport, deposition and preservation in the snow pack thus also highly relevant for climate variability studies.

**Fig.1.** Ice core location on Svalbard.

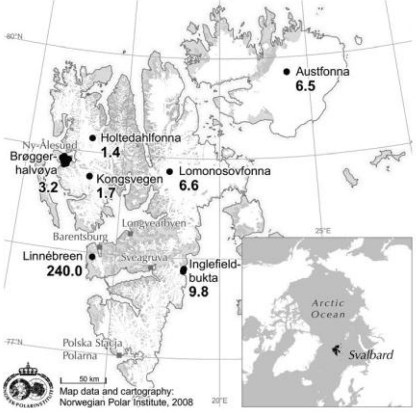

**Fig. 2.** Spatial variability of black carbon on Svalbard (Forsström et al., 2009)

### Main publications (see also abstract from Mark Hermanson)

Divine, D.V., E. Isaksson, T. Martma , Meijer, J. Moore, V. Pohjola, R.S.W. van de Wal, F. Godtliebsen 2011. Thousand years of winter surface air temperature variations in Svalbard and northern Norway reconstructed from ice core data. *Polar Research* 2011, 30, 7379, DOI: 10.3402/polar.v30i0.7379

Forsström, S., J. Ström, C. A. Pedersen, E. Isaksson, and S. Gerland (2009), Elemental carbon distribution in Svalbard snow, *J. Geophys. Res.,* 114, D19112, doi:10.1029/2008JD011480.

Isaksson, E., Hermanson, M., Hicks, S., Igarashi, M, Kamiyama, K., Moore, J., Motoyama, H., Muir, D., Pohjola, V., Vaikmäe, R., van de Wal, R.S.W., Watanabe, O. 2003. Ice cores from Svalbard - useful archives of past climate and pollution history. *Physics and Chemistry of the Earth*, 28, 1217-1228.

Isaksson, E., Kohler, J., Pohjola, V., Moore, J., Igarashi, M., Karlöf, L., Martma, T., Meijer, H.A.J,. Motoyama, H.,.Vaikmäe, R., and van de Wal, R.S.W. 2005. Two ice core □$^{18}$O records from Svalbard illustrating climate and sea ice variability over the last 400 years. *The Holocene,* 15 (4), *501-509.*

# An overview of the effects of changes in winter climate on Arctic terrestrial ecosystems

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**Main effects of changes in snow/ ice, effects on study organisms + higher trophic levels.**
I am putting together a review article on the effects of changes in winter climate in the arctic and the effect this will have on terrestrial organisms and ecosystems. There are several ways in which the climate is expected to change, outlined below.

1. Changes to winter temperature: Changes in air temperature will affect soil temperature and precipitation type-snow effectively insulates the soil from cold air in winter. This will affect all processes which are thermally sensitive.

2. Changes to snow depth: due to (a) increased/ decreased precipitation, (b) changes in proportion of precipitation falling as snow or rain (temperature dependant), (c) changes in autumn/ spring temperatures which determine length of snow lie.

3. Changes in date of snow melt: dependant on depth of snow in late winter, and air temperatures and precipitation in late winter/ spring. It determines the start of plant growing season and abundance of forage for herbivores.

4. Changes in timing of winter onset: Plant senescence is mostly determined by light quality (ratio of red: far red light), so that by the end of August, little photosynthesis is carried out, and plants have a lower nutrient content. If winter onset is delayed, plants and microbes will respire at higher rates than normal, negatively affecting their C balance and that of the tundra in general.

5. Changes in frequency of extreme warming events in winter: A mild period in an otherwise cold winter leads to melting of snow, flooding, freezing and the formation of an ice layer. Resultant widespread vegetation damage can have severe effects for herbivores the following summer. In addition, ice layers act as very effective barriers to winter forage for ungulates and their presence may cause mass starvation and population crashes.

6. Changes to interspecific interactions: changes in climate may also affect the ways in which organisms interact, both in a competitive and inter-trophic manner. New complex interactions may arise.

**Key Gaps**
- Are ungulates and ptarmigan affected by changes in winter OTHER than snow/ ice as a barrier to forage? e.g. Does milder winter air temperature promote survival or does it enable disease to be more prevalent?
- Presence/ increase / role of pathogens with changing winter climate.
- Microbial dynamics and changes with season/ temperature/ freeze-thaw patterns.
- Interactions between organisms/ trophic levels- synergy/ mismatch.
- Interactions between active layer deepening /permafrost melting and C storage/fluxes/vegetation.
- Growing season length effects on plant biomass and reproductive success (and effects on herbivores).
- Factors determining plant hardening, dehardening and plant senescence in the High Arctic.
- The effect of a warmer autumn/ prolonged onset of winter- on all study organisms and interactions therein.

- Winter climate change effects on plant community composition+ processes of change.
- Effect of changing winter climate on predators and the regulatory effect on their prey.
- Immigration of new species from southern/warmer latitudes, and their ecological interactions.
- Interaction between pollution and cold tolerance.

**Key Scientists regarding Arctic Winter Climate Change Effects:**

- Soil-plant ecosystem: J. Welker (Alaska Uni), P. Sullivan (Alaska Uni), B. Elberling (Copenhagen Uni), E. Cooper (Tromsø Uni), M. Sturm (Alaska Uni), G. Liston (Alaska Uni), L. Klemedtsson (Gothenburg Uni), R. Bjørk (Gothenburg Uni), J. Schimel (Alaska Uni) Microbes: ?
- Invertebrates: S. Coulson (UNIS), J. Jepsen (NINA), M. Holmstrup (Aahus Uni), H-P Lainaas (Oslo Uni)
- Plants: J. Olofsson, T. Saarinen (Helsinki Uni), H. Hänninen (Helsinki Uni), S. Bokhorst, J. Bjerke (NINA), G. Phoenix (Sheffield Uni), E. Cooper (Tromsø Uni), S. Wipf (Davos), R. Baxter (Durham Uni)
- Birds: geese: M. Loonen (NL), J. Madsen (Aahus Uni) ptarmigan: Å. Pedersen (NP)
- Rodents: R. Ims (Tromsø Uni), N. Yoccoz (Tromsø Uni)
- Ungulates: E. Post, M. Forchhammer, B-E. Sæter (NTNU)
- Predators: Arctic fox: E. Fuglei (NP)

**Some relevant Scientific papers**

Aanes, R., Sæther, B-E. Smith, F**.M., Cooper, E.J.,** Wookey, P.A. & Øritsland, N.A., 2002. The Arctic Oscillation predicts effects of climate change in two trophic levels in a High Arctic ecosystem. *Ecology Letters* 5: 445-453.

Ávila-Jiménez M.L., S.J. Coulson, T. Solhøy, and A. Sjöblom 2010. Overwintering of terrestrial Arctic arthropods: the fauna of Svalbard now and in the future.. *Polar Research 29,* 2010 127–137

Björkman, M.P., Morgner, E., Björk, R.G., Cooper, E.J., Elberling, B., and Klemedtsson, L. 2010. A comparison of annual and seasonal carbon dioxide fluxes between sub-arctic Sweden and high-arctic Svalbard. *Polar Research* 29: 75-84

Bockhorst S.F., J.W. Bjerke, H. Tømmervik, T.V. Callaghan, G.K. Phoenix, 2009. Winter warming events damage sub-Arctic vegetation: consistent evidence from an experimental manipulation and a natural event, *Journal of Ecology.* 97: 1408-1415.

Cooper, E.J., 2010. Introduction to a special section: winter terrestrial ecology in Arctic and alpine tundra. *Polar Research* 29: 36-37.

Cooper E.J., S. Dullinger, and P. Semenchuk, 2011. Late snowmelt delays plant development and results in lower reproductive success in the High Arctic. *Plant Sci.* 180: 157-167.

Mallik, A., Wdowiak, J, and Cooper E.J., 2011. The effect of increased snow depth on the growth and seed production of a dominant High Arctic tundra heath plant, *Cassiope tetragona. Arctic Antarctic and Alpine Research* 43 (3) 404-409.

Morgner E., B. Elberling, D. Strebel, E.J. Cooper, 2010.The importance of winter in annual ecosystem respiration in the High Arctic: effects of snow depth in two vegetation types, *Polar Research.* 29: 58-74.

Olofsson, J.; Ericson, L.; Torp, M.; Stark, S. and Baxter, R., 2011. Carbon balance of Arctic tundra under increased snow cover mediated by a plant pathogen. *Nature Climate Change*. doi:10.1038/nclimate1142.

Schimel J.P., C. Bilbrough, J. A. Welker, 2004 Increased snow depth affects microbial activity and nitrogen mineralization in two Arctic tundra communities, *Soil Biology & Biochemistry*. 36: 217-227.

Wipf S., C. Rixen, 2010. A review of snow manipulation experiments in arctic and alpine tundra ecosystems, *Polar Research.* 29: 95–109.

# Extreme winter warming in the sub-Arctic

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Extreme weather events can have strong negative impacts on species survival and community structure when surpassing lethal thresholds. Extreme, short-lived, winter warming events in the Arctic rapidly melt snow and expose ecosystems to unseasonably warm air (for instance, 2-10°C for 2-14 days) but upon return to normal winter climate exposes the ecosystem to much colder temperatures due to the loss of insulating snow. To quantify the impact of these extreme winter events we simulated week-long extreme winter warming events -using infrared heating lamps and soil warming cables- for three consecutive years in a sub-arctic heathland dominated by dwarf shrubs (*Empetrum hermaphroditum, Vaccinium vitis-idaea* and *V. myrtillus*) and cryptogams (*Peltigera aphthosa* and *Hylocomium splendens*).

Dwarf shrubs were considerably damaged by the extreme winter warming events leading to considerable declines in standing biomass (±30%) and reductions in reproductive output (±75%). Lichens were much less affected by the events while the moss *H. splendens* showed reduced (±50%) photosynthesis and growth following the events. Belowground a community shift occurred among the soil invertebrates with a decline in the smallest soil animals and relative increase of larger sub-surface living animals.

Following a ‘natural’ extreme winter warming event during the winter of 2007/08 similar damage to the vegetation was observed in the field as in our experimental plots. On a regional scale the damage to the dwarf shrubs resulted in a 26% decline of NDVI across 1400 km$^2$ of northern Scandinavian heathland. The similarity in plant response to the winter warming events between our simulations and the ‘natural’ event strongly suggest that the biological responses observed in our simulations can occur at much larger scale if these events will increase in the near future.

Overall, the extent of damage was considerable, and critically plant responses were opposite in direction to the increased growth seen in long-term summer warming simulations and the ‘greening’ seen for some arctic regions. Given the Arctic is warming more in winter than summer, and extreme events are predicted to become more frequent, this generates large uncertainty in our current understanding of arctic ecosystem responses to climate change.

# Snow and overwintering ecophysiology of northern plants: Combining experimental studies with modelling

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## A hypothetico-deductive modelling approach to plant overwintering

We study the effects of warming winters on northern plants, using a hypothetico-deductive (HDM) approach where experimental studies in the field and in growth chambers are combined closely with ecophysiological modelling. Model simulations are carried out not only for examining the plant overwintering in any given environmental conditions, such as the warming winters projected for high latitudes, but also for planning informative set-ups for experimental studies. The HDM approach has been applied for decades with forest trees, but more recently we have started to apply it with other plant growth forms as well. So far we have modelled the effects of air temperature on the annual cycle of photosynthetic capacity in lingonberry (*Vaccinium vitis-idaea* L.) and the bud dormancy release and growth onset of several field layer species.

## Snow as a key environmental factor affecting plant overwintering

Similarly to several other pieces of earlier empirical work, our experimental studies have revealed the importance of snow for the overwintering of northern field layer plants. For instance, even if the photosynthetic capacity of lingonberry is retained under snow, photosynthesis is impaired when the shoots are suddenly exposed to high light levels due to snow melt (Fig. 1). On the other hand, winter-time respiratory losses are greater at a sheltered microsite under a thick snow cover than at an exposed site with little or no snow cover (Fig. 2). Most previous studies on the snow ecology of high-latitude plants focus on the effects of snow thickness on overwintering, but our results highlight the importance of the physical properties of snowpack as an essential ecological factor as well. Our former post-doc and current collaborator Sirpa Rasmus is a geophysicist specialised in snow research. She is modelling the effects of climate change on amount and properties of snow, so her simulation studies provide us snow scenarios to be used as input in our ecophysiological modelling studies.

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**Questions to be answered (ecology):**

1. *What are the main effects of changes in snow/ice (amount, spatial/temporal distribution) in your field? How does this affect your study organisms? Further effects in higher trophic levels?*
    a. Numerous effects on the ecophysiology of overwintering plants, such as increased incidence of frost damage, or increased photosynthetic production; and their subsequent effects on growth and development during the growing season.
    b. It is obvious that effects on higher trophic levels are involved, but we are not addressing them in our research.

2. *What are the key gaps in snow/ice-ecological relationships in your field?*
    a. Not only the thickness of snow but also its physical properties are expected to change due to warming winters. The effects of changes in snow properties on the overwintering and subsequent phenological development of plants is still poorly understood. Both experimental and modelling studies are needed here.
    b. Variation among species and even among ecotypes is still poorly understood. For instance intermittent mild periods and snow melt during mid-winter may be beneficial for some species (e.g. due to activation of photosynthesis) and detrimental for others (e.g. due to damage during sub-sequent periods of frost).

3. *Who are the key scientists working on snow/ice-ecological relationships in your field (in Svalbard, other Arctic areas or in alpine areas)?*
   These two scientists are among the leading ones in our field:
   a. Dr Elisabeth Cooper, University of Tromsø, Norway.
   b. Dr Juergen Kreyling, University of Bayreuth, Germany.

4. *Please list the scientific papers most relevant for snow/ice in your field.*
   The key publications are too many to be listed here.

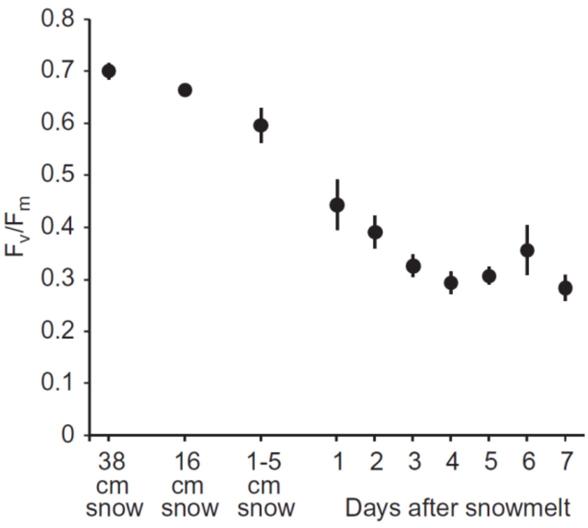

Fig. 1. The potential photochemical efficiency of photosystem II ($F_v/F_m$) in leaves of *Vaccinium vitis-idaea* before and after snow melt on an artificial snowmelt transect in Kilpisjärvi, northern Finland. (Lundell et al. 2010, *Plant Ecology & Diversity* 3: 121-130).

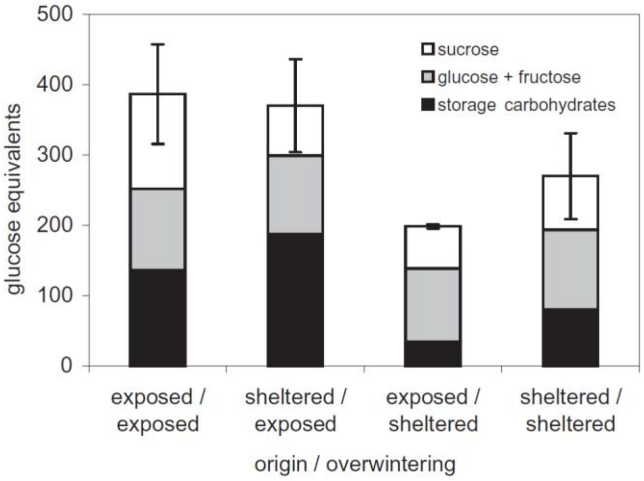

Fig. 2. Mean non-structural carbohydrate contents ($\mu g$ glucose equivalents $g^{-1}$ dry weight) of the leaves of *Vaccinium vitis-idaea* in a reciprocal transplant experiment in two sub-arctic microhabitats (exposed = thin snow cover, sheltered = thick snow cover) in Kilpisjärvi, northern Finland. (Saarinen & Lundell 2010, *Polar Research* 29: 38-45).

# Svalbard's terrestrial ecosystem: Impact of snow and ice on the herbivore guild and their shared predator

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## General background – main effects from snow and ice

Climate change in the Arctic is expected to alter climate throughout the year, change the season length (snow cover and spring thawing processes), and increase the frequency and intensity of extreme climatic events (e.g. 'rain-on-snow' [ROS]) (Førland et al. 2009). These changes can have strong effects on key species and their ecosystem functions (Post et al. 2009). Increased temperature and shifts towards earlier springs and extended summer seasons are expected to have direct effects on plants, causing increased primary production and changes in plant community structure (e.g. Chapin et al. 1995, Hudson & Henry 2009). Climate driven changes in onset of spring and plant productivity are likely allow herbivore populations to increase (e.g. through more available nest sites for geese [Madsen et al. 2007]; higher food availability for reindeer [Tews et al. 2007]). However, earlier springs may also reduce reproductive success as the change may influence the seasonal match between herbivore reproduction and the availability of limiting resources (Post & Forchhammer 2008). In winter more frequent ROS events that leads to icing, will influence herbivore survival and population dynamics (i.e. Svalbard reindeer; see Hansen et al. 2011, Kohler & Aanes 2004) and space use (Hansen et al. 2010, Stien et al. 2010), with likely cascading effects on ecosystem structure and function (Ims et al. 2008, Gilg et al. 2009).

In the high arctic archipelago of Svalbard the only resident vertebrates are the generalist predator arctic fox (*Vulpes lagopus*) and the endemic herbivores, the Svalbard rock ptarmigan (*Lagopus muta hyperborea*) and Svalbard reindeer (*Rangifer tarandus plathyrynchus*). In summer this ecosystem is supplemented by a large numbers of migratory geese (*Anser brachyrhynchus, Branta leucopsis*). ROS in winter, causing icing and inaccessible pastures, is a main climatic driver in the population dynamics of the Svalbard reindeer (Hansen et al. 2011), and studies have suggested that the balance between positive effects of increased primary production and negative effects of more frequent and extensive icing events will determine the future of the sub-species (Tews et al. 2007, Hansen et al. 2011). The population of the pink-footed goose (*Anser brachyrhynchus*) have increased significantly over the last decades, and climate change has been suggested as one of the major driver (Madsen and Williams 2011). Opportunities for breeding and reproductive success in Svalbard, are higher when snow melt is early (Madsen et al. 2007), suggesting further population growth in response to climate change. During the last decade increasing signs of the impact of foraging pink-feet on tundra vegetation in Svalbard has been observed elevating the potential for competitive interactions for key forage plants with other herbivores. Currently there is limited research on the population dynamics of Svalbard rock ptarmigan (but see Pedersen et al. 2011, Steen & Unander 1985, Unander & Steen 1985) Pedersen et al. 2011), however, recent research on the population dynamics of ptarmigans and other arctic ground nesting birds suggest that the viability of the Svalbard rock ptarmigan population will be affected by both direct climatic effects on ptarmigan reproductive rates (Wang et al. 2002), indirect effects of climate through effects on the timing of the availability of key food plants (Ludwig et al. 2006) and through competitive and predation effects of climate impacts on the other key herbivores in the ecosystem (Madsen et al. 1992, Fuglei et al. 2003, Gilg and Yoccoz 2010). Arctic fox population densities and reproduction are related to the density of Svalbard reindeer carcasses in the late winter (Fuglei et al. 2003), Eide et al. 2011) and the reproductive success of geese is low after winters with high densities of reindeer carcasses (Fuglei et al. 2003).

## Identification of key gaps

In this high-Arctic terrestrial ecosystem there are key knowledge gaps related to (1) how climate change, in terms of snow-cover and spring thawing processes, may cause mismatches in the food web and intensified inter-and intra specific competition by changes in herbivore space use and (2) how climate change, in trems of increased frequency (time) and extent (space) of ROS combined with changes in length of summer seasons, will impact the Svalbard reindeer population dynamics. Key knowledge gaps regards the relationship between the temporal and spatial extent of ice and population dynamics, and to what degree amount of rain, snow-depth, ground- and air temperatures before and after ROS events, play a role in determining the extent of icing. We depict three pathways (Fig. 1) through which climatic drivers (onset of spring, snow-cover and ROS) may affect herbivore reproduction and their shared predator, Arctic fox: (A) a trophic mismatch in time between plant development and herbivore reproduction (i.e. ptarmigan and key forage plants *Bistorta vivipara* and *Salix Polaris*), (B) effects on competitive interactions between herbivores (geese, ptarmigan and reindeer) and (C) effects on predation through changes in the availability of reindeer carcasses due to winter mortality.

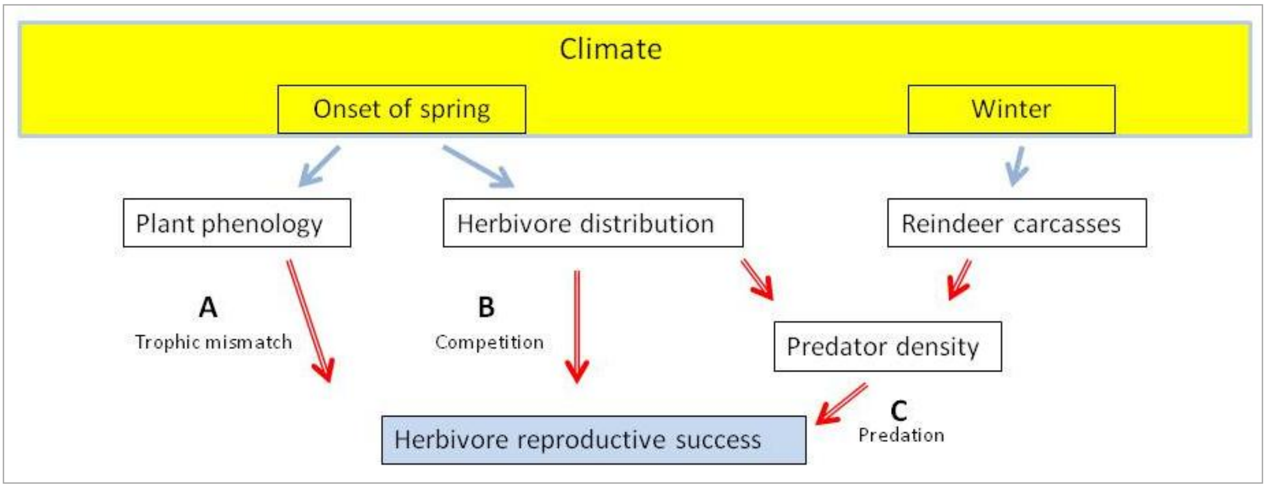

**Figure 1.** A conceptual model depicting the pathways through which climatic drivers (yellow boxes) may affect herbivore reproductive success (blue box).

## Key scientists and current projects

Presently there is a new ongoing research initiative within the Terrestrial Flagship research program *Effects of climate change on terrestrial ecosystems, landscapes, society and indigenous people* by the authors *Svalbards terrestrial ecosystem - climate impacts and trophic interactions* which target aspects related to the potential for mismatches in the food web and inter-and intra specific interactions among the herbivore guild (point 1 above). The project is still in an initial phase where pilot studies are conducted and is not financed on long-term basis. Recently one RCN funded research project REINCLIM *Predicting effects of climate change on Svalbard reindeer population dynamics: a mechanistic approach* where started and will provide results related to point 2 above (2012-14; project leader Brage B. Hansen, Norwegian University of Science and Technology ). This project investigate in a mechanistic and predictive way the impacts of climate change on Svalbard reindeer population dynamics through changes in the frequency of ROS in winter, and changes in plant primary productivity caused by changes in growth season length and summer warming. The reference list includes citations to other key scientists within the relevant field.

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# Bridging the temporal scale from winter to summer and the spatial scale from ground plot sampling to satellite remote sensing

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## Ecosystems are open

Even though scientists divide and study ecological systems as separate units or at distinct seasons such as summer or winter, natural ecosystems are open and not bound to a particular timer or spatial scale. What happens during winter time can greatly influence outcome of ecological processes during summer time. Especially polar ecosystems should be studied with great awareness of the link between the long and environmental severe winter season and the short and intensive summer. Likewise we need to link scientific studies at different spatial scales. A tremendous amount of satellite data are continuously gathered by many polar orbiting satellites at spatial scales typical ranging from 10 to more than 1000 m. At the same time lots of field studies have been initiated recording biotic and abiotic data at the plot level ranging from a few cm to more than a square meter. It is however difficult to directly relate processes and changes at these large scales to what is happening at the small spatial scale which satellite sensor operate. Further more frequent and prolonged periods with sea fog and cloudy condition makes it difficult to record satellite images on a regular basis for studying phenology or other time serial related events during the year.

## A sketch on how to bridge temporal and spatial scales

The core system is a ground mounted digital camera surveying a study area at an oblique angel, operating within the optical and near infrared part of electromagnetic radiation spectre. This solution is ideal for mapping limited ecosystem and fine-scale landscape characteristics. As the camera operates near ground, cloud cover is not a problem and high spatial resolution of images is achieved. Likewise images can be automatically recorded at regular intervals all year around. Study area can be delineated into land cover units such as plant communities or habitats based on manual mapping or some automatic classification techniques conducted on a per-pixel basis or in an object orientated (segmentation) fashion. This allows for a bridge down to the ground control plots as they can be linked to the mapped landscape features. Projects based on this framework already exist on Zackenberg, Greenland and has proven successful in monitoring seasonal changes in snow cover and vegetation characteristics. Next step is to bridge the land cover units with the satellite remote sensing data at the upper spatial scale. This can happen through application of satellite data with some intermediate pixel resolution (20-250 m) such as LANDSAT ETM+, SPOT or MODIS Terra.

Both camera and web service technology have made large progress, and today image data from several study sites can be made available through a web-based geographical information system (GIS) like e.g. ArcGIS for Server. This is a GIS developed to manage, produce, and exploit large numbers of raster data (images).

During my presentation I will outline the framework of this study design, present some alternative methods and illustrate some practical challenges using a pilot study from Adventdalen, Svalbard.

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**Questions to be answered (ecology):**

1. *What are the main effects of changes in snow/ice (amount, spatial/temporal distribution)? How does this affect your study organisms? Further effects in higher trophic levels?* Changes in snow and ice distribution along with changes in frequency and duration of such events can have profound effect on biophysical parameters such as NDVI, LAI, NPP or vegetation cover. Changes in these indices are likely to reflect changes in condition or quality of ecosystems or biodiversity.

2. *What are the <u>key gaps in snow/ice-ecological relationships</u> in your field?*
   We need a long-term monitoring and analysing system designed to bridge the gap between the large scale, field based plot study and data gathered by polar orbiting satellites. We also need to link and analyse how extreme winter events influence vegetation performance during growth season. The system must be designed to gather data at high spatial and temporal resolution in order to be relevant for phenology studies and satellite data calibration.

3. *Who are the key scientists working on snow/ice-ecological relationships in your field (in Svalbard, other Arctic areas or in alpine areas)?*
   - Dr. Stein Rune Karlsen (Northern Research institute - NORUT, Norway)
   - Dr. Jørgen Buus-Hinkler (Danish Meteorological Institute, Denmark)
   - Dr. Daniel Joly (Université de Franche-Comté, France)

4. *Please list the scientific papers most relevant for snow/ice in your field.*

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## Glaciers are becoming greener

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### Glaciers harbour distinct and active living communities in supra-, en- and subglacial habitats

Once thought to be barren of life, icy environments as glaciers are home to rich microbial communities including photosynthetic cyanobacteria (Priscu et al. 1998; Psenner and Sattler 1998; Psenner et al. 1999; Sattler et al. 2004; Priscu and Christner 2004). Aeolean transport deposits dust particles on icy surfaces containing both humic material and microbial life (Psenner 1999; Sattler et al. 2001). Melting of the ice surface promotes increased levels of microbial activity via the creation of unique and ideal life-habitats (e.g. cryoconite holes which are considered “hot spots” for primary productivity and biogeochemical cycling upon the surface of glaciers throughout the Earth´s cryosphere). The assemblage is soon covered by a new icy surface as the surficial portion of the melt freezes (Tranter *et al.* 2004). However, where the ice contacts the warmer humic material, an unfrozen layer of water around the particle provides a liquid water and nutrient microfilm sufficient to support a microbial community (Priscu *et al.* 1998; Price 2007). These accumulations, first called cryoconites (from the Greek kryos, “icy cold”; and konia, “dust”) by the Swedish explorer A.E. Nordenskjöld, in 1870, (Miteva, 2008) range in scale from detritus surrounding massive boulders to small grains a few millimeters to micrometers in diameter (Takeuchi et al., 2001). Cryoconite microbial composition exhibits significant variety, but appears dominated by important photosynthetic primary producers (Tranter et al. 2004; Hodson et al. 2005; Foreman et al. 2007; Hodson et al. 2008), particularly cyanobacteria (Säwström et al. 2002; Anesio et al. 2009). By an increase of temperature they are capable of altering the Earth’s carbon budget by contributing significantly to the annual availability of new organic carbon, which in turn supports higher forms of life or subsequent habitats like the glacier forefield and the fjord, respectively.

Colonization of these niches subsequently leads to further darkening of the ice surface. The result is enhanced absorption of solar radiation, promoting further melt and providing yet more water for microorganisms, which are then dispersed to other parts of the ice surface and the glacier forefield. The quote of co-author Alexandre Anesio says it all: “Glaciers are becoming greener” – this definitely implies the following: With continued global warming, the ability to monitor organic carbon availability and to quantify cryosphere microbial growth is of critical importance.

### Gaps and ways out for measuring the greening effect

To assess the seasonal supraglacial metabolic processes a temporal and spatial distribution of sampling points with high resolution is required. By using standard methods this requirement is hampered due to patchy sampling due to difficult logistics, manipulation of the samples resulting in change of in situ conditions and low temporal and spatial resolution. The need for an *in situ* non-invasive, non-destructive technique to detect, localize, and sample cryosphere biomass in the field is of considerable importance. A promising new tool could be provided by *Laser-Induced-Fluorescence-Emission (L.I.F.E.).* To ensure a data frequency with high resolution we apply a laser scanning technique due to surface communities of glaciers are highly autotrophic (i.e., where net carbon fixation rates are higher than respiration for the whole glacier on average) fixing carbon on an annual basis. Advances in laser-induced fluorescence emission (L.I.F.E) imaging and spectroscopy make it possible to detect photoautotrophic microbes. We found that 532nm green lasers excite critical photopigments in cyanobacteria and produce multiple fluorescence signatures between 550nm and 750nm - depending on species and metabolic state, Storrie-Lombardi & Sattler, 2009, Sattler & Storrie-Lombardi, 2009) which would enable a non-invasive in-situ measurement.

**Key scientists working in this field:**
(Co-)Authors of this abstract, Andy Hodson, Buford Price, John Priscu, Nozomu Takeuchi, Christine Foreman, Marek Stibal

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## Polish ecological studies in Hornsund

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### *Sanionia uncinata* as bioindicator of metal pollution in Hornsund region

Concentrations of the elements Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, N, Na, Ni, P, Pb, S, V and Zn in moss were measured in West Spitsbergen. Samples were collected at different distances from the seashore in wet moss tundras**,** moderately wet moss-herb tundras, dry epilithic and terricolous tundras. Some of these sites were strongly influenced by the *Alle alle*, *Branta leucopsis* and anthropogenic impacts of the Polar Station.

Compared to the background values for mosses from unpolluted areas [2, 3] (limits indicated in parentheses in mg kg $^{-1}$ d.w.), the concentrations of Cd (<0.2), Cr (0.9-3), Cu (4.5), Fe (150-400), Mn (110), Pb (5.7), Zn (25) and V (1.4-1.8) were higher. The upper concentrations of elements in *S. uncinata* from this investigation were also higher than in mosses of Spitzbergen (5.2 Cu, 1240 Fe, 14 Mn, 1.7 Ni, 5.8 Pb, 8.3 Zn) [1]. Also concentrations of elements in *S. uncinata* (0.41-0.82 Cd, 2.1-15 Cu, 1.6-8.9 Ni, 2.4-16 Pb, 1330-1626 S, 12.4-27 Zn) collected in the same area [4] were mostly lower as compared to our investigations.

Separate group of *S. uncinata* consists of sites under influence of little auk and barnacle geese colonies. Concentrations of elements in *S. uncinata* from these sites were significantly higher for N, P, K, S and all metals (Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, V, Zn). *S. uncinata* from sites influenced by anthropogenic impact contained significantly higher concentrations of Ni, Cr, Fe, Zn, Pb and V. So it can be concluded that examined ecosystems/sites may be recognized as affected by toxic metals.

The PCCA ordination revealed that *S. uncinata* from sites the most close to the seashore, the most distant and in between were differentiated by concentrations of Cd, Co, Cr, Cu, Fe, Pb and V. This moss growing in sites situated the most close to and the most distant from the seashore was differentiated by concentrations of Na, Ni and Mn. The established model points that Na, Mn, Cu, Ni and Zn were accumulated by *S. uncinata* mostly from sea spray.

### Question to be answered: Pollutans

In our opinion there are four main pathways what trace elements may follow: long range atmospheric transport, sea spray, sea as a source of food for birds and local sources (polar stations/tourism).

There is a shortage of recent investigations and data concerning metal concentrations in the terrestrial ecosystems of Svalbard. Background values for metals in plants and other organisms collected from areas in Svalbard relatively free from pollution should be established.

### Description of tundra types and vegetation map of Fuglebekken basin

The main purpose for creating a classification of vegetation in this area is to provide a basis for further ecological investigation. The criteria for the tundra type’s classification are based on:

- dominant life forms: dwarf shrubs, herbs (forbs and graminoids), bryophytes, lichens, cyanobaceria
- predominant components: dominant species in percentage ground cover
- physiognomic criteria: vertical structure of plant cover (layering)
- ecological conditions: impact of seabird colonies, ground moisture, snow cover duration, successional stage, patterned ground

- parent material: bedrock, gravel, arctic soils, organic material

The vegetation of Fuglebekken basin can be classified into twelve main tundra types. The most common are epilithic lichen crustose tundra and moss-lichen tundra and among terricolous: lichen tundra with *Cetrariella delisei*, lichen-moss tundra, lichen-dwarf shrub tundra, wet moss tundra, geophytic initial tundra, cyanobacteria-moss tundra and ornithocoprophilous tundra.

## The ecological significance of nitrogen sources for differentiation of terrestrial types of arctic tundra

The understanding of the nitrogen cycle and determination of its main sources in various tundra types is a key issue in recognition of arctic ecosystems significance in the global carbon balance and in consequence their possible influence on the global climate.

The aim of this project is to quantify the influence of various nitrogen sources and forms on a different tundra types and amount of other macroelements in main components of the phytocenosis. Five major nitrogen sources will be studied: 1. mineral ($NH_4^+$, $NO_3^-$) originated from decomposition of organic matter, 2. fixed by free cyanobacteria, 3. mineral from precipitation, 4. deposited by sea birds, and 5. soluble organic. These sources are characterized by clearly different nitrogen stable isotope composition ($\delta^{15}N$). For instance following values are characteristic: -5‰ for products of organic matter decomposition; *ca* 0‰ for nitrogen fixers; +5 to +10‰ for birds faeces. The uptake of amino acids is characteristic of some arctic nitrogen-limited plants. The $\delta^{15}N$ value for this group of compounds depends notably on a degree of decomposition, amount and an initial composition of organic matter (*ca* +5‰). The $\delta^{15}N$ of plant tissue reflects isotope composition of dissolved ions available for plants ($NH_4^+$ or $NO_3^-$) due to low fractionation during uptake, and in consequence reflects $\delta^{15}N$ values of an initial substrates and process enabling its mobilization (mineralization, $N_2$ binding).

High diversity of tundra types of the Fuglebekken basin allows selection of the habitats representing main N sources, corresponding to pathways of N inflow (numbers 1-5 correspond to nitrogen sources): 2 and 1. cyanobacteria-mosses tundra of snow-beds and polygonal structures; 3. lichen-dwarf shrub tundra, terricolous lichen tundra, initial tundra of lateral moraine; 4. and 1. ornithokoprofilic tundra, and 5. wet moss tundra. The samples of predominant species will be analyzed for the $\delta^{15}N$ and N, P, K, Ca, Mg and Na. In order to determine the magnitude and chemical composition of nitrogen pools, the soil cores will be analyzed for various N forms ($NH_4^+$, $NO_3^-$, total and soluble organic) as well as major ions (P, K, Ca Mg, Na), pH, organic matter content and moisture. The organic matter deposition rate will be determined using radiocarbon dating, whereas degree of conservation will be assessed using C/N, $\delta^{15}N$ and $\delta^{13}C$. Moreover, precipitation waters and snow will be subject to the stable isotope and chemical analysis, as a reference samples, and for determination of the amount of nitrogen coming form that sources.

## Question to be answered: Ecology

The analysis of meteorological data 1978–2006 from Hornsund [5] showed: statistically significant trends in: (1) temperature increase, (2) decrease of snowfall, (3) increase of precipitations during the winter, (4) snow depth decrease, and (5) not statistically significant trend toward earlier snow-cover disappearance in spring. What are the most important possible implications for terrestrial ecosystem functioning?

Alterations to surface energy and hydrological budgets may induce earlier dry up of surface which in consequence negatively affects biotic processes of vegetation and soils. An understanding of (1) how may decreased snow cover/depth affect plant phenological development, and (2) how will snow depth with the accompanying increased soil temperatures affect of nitrogen cycling, is a major future research priorities.

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# Czech research in Petuniabukta, Billefjorden, northern part of Isfjorden, Svalbard

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In 2008, the Czech Republic established the Centre for Polar Research. On the basis of this action, Arctic and Antarctic research initiatives were introduced into the research infrastructure of the Czech Republic. To date, several academic institutions, working across several research topics, participate in the programs of polar science. On the basis of these activities, a new research project is supported by the Czech Government: „CzechPolar – Construction and Operational Expenses“. The aim of this project is construction and operation of a Czech Arctic research station in Svalbard (University of South Bohemia in České Budějovice - http://polar.prf.jcu.cz) and providing a long term ecological research.

Hydrological, limnological, glaciological and climate research includes the following monitoring systems and observations:

- Hydrological measurements on 4 water streams
- Bathymetry, water physico-chemical parameters including long term temperature monitoring in lakes
- Sea environment monitoring
- 7 automatic weather stations
- Soil water content and temperature measurements
- Station for snow depth monitoring
- Complex monitoring of Bertil glacier dynamics

Discharge measurement in several water streams has been carried out during the summer season 2011 and finally four of them has been chosen for long-term monitoring. Water level sensors were installed to monitor these four experimental catchments on the western shore of Petuniabukta, Billefjorden. The purpose of these measurements is to describe hydrological regime and response to climatic forcing in catchments with different level of glaciation. Measuring profile downstream of the Bertil glacier serves also for mass balance study held on this glacier. Ferdinand and Elsa glacier catchments are an example of fast retreating glaciers and last catchment has no permanent ice cover anymore.

Different types of lakes have been identified in the area with predominance of recent lakes on newly deglaciated moraines. Some older lakes with high amount of organic matter sedimentation were found as well. About 20 lakes in total has been mapped in the area. Detailed bathymetry mapping has been made on 6 of them. Physical and chemical parameters were measured on the beginning and at the end of the season. Temperature sensors have been installed in 6 lakes of different types and on different localities to cover their spatial heterogeneity, age and origin of lake ecosystems. Temperature sensors are operating during freeze as well, hence allowing us to monitor changes in freezing and melting date.

Very basic study on the sea environment has been done as well. Water level sensor was installed to monitor tidal movements and temperature regime near the shore.

7 automatic weather stations are currently operating in the area. All of them measuring basic parameters such as temperature and relative humidity. The main meteorological station is equipped also with pyranometers measuring incoming and reflected radiation, which allow us to calculate changes in albedo strongly related to seasonal changes in snow cover.

Soil water content and temperature measurements are taken on 4 sites. This measuring system is focused on monitoring changes in hydrological and temperature regime of shallow soil environment. The main station measures these parameters in depth profile down to 1,5 m, thus reflecting changes in permafrost active layer.

Station for snow depth monitoring has been established in 2011. This one is equipped with ultrasonic snow depth sensor together with 3 temperature sensors in 5,20 and 50 cm from ground.

Complex monitoring of Bertil glacier dynamics has been established during 2011 season. Ablation stakes were drilled into the glacier covering both the accumulation and ablation zones. Mass balance measurements were initiated by stake readings and snow surveying. The position of the stakes was measured using static GPS measurements. In addition, the stakes were surveyed using a reflecting prism and an infrared rangefinder of a total station fixed on the lateral moraine. The observations of glacier motion started using 48 observational points placed at the glacier surface. In addition to 22 bamboo stakes, 26 wooden stakes were placed in the ablation zone of the glacier to better constrain the flow rate. The melt water runoff is measured nearby the glacier front with water level sensors. This study has been coordinated with team of Adam Mickiewicz University (Poznan, Poland) – Jakub Malecki. They carry out similar study on Sven glacier (aprox. 500 meters north over a mountain ridge). Final comparison of the dynamics of these two glacier with rather different physical characteristics could be one of the greatest benefits of this study.

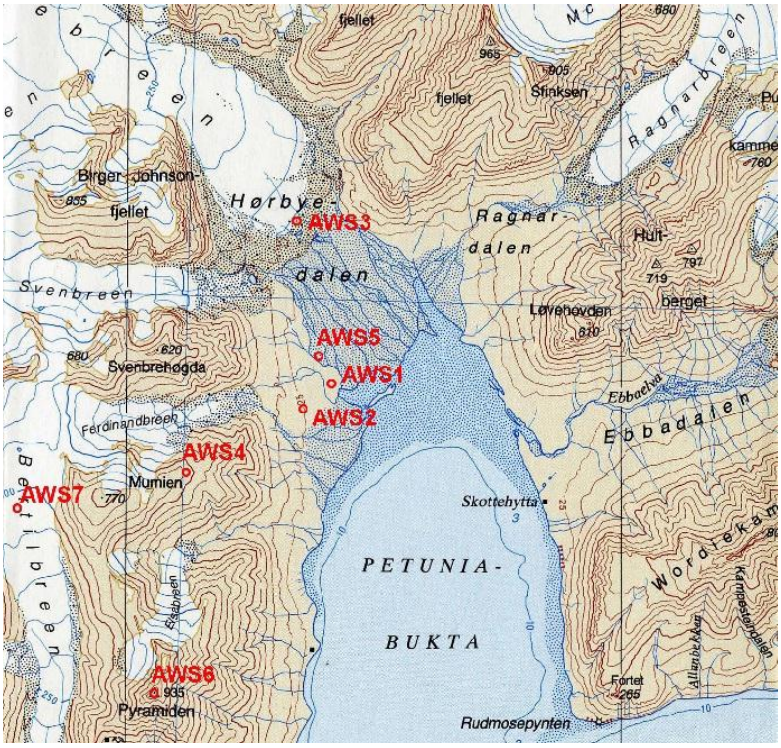

**Figure 1.** Automatic weather station (AWS) network in Petuniabukta.

# Remobilization, Atmospheric distribution and melt water Run-off. Climate change and the presence of persistent organic pollutants in the Arctic

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## Background and motivation

Arctic environments are expected to undergo dramatic changes within the coming decades (AMAP 2011). These expected environmental changes will mainly be triggered by the continuous and rapid loss of the Arctic cryosphere (decrease marine ice coverage, loss of permafrost, glaciers and ice caps). These expected cryospheric changes are comprehensively documented and assessed in the recent report on "Snow, Water, Ice, Permafrost in the Arctic" (SWIPA; AMAP, 2011). This cryospheric changes are expected to result in considerable change in fate and behaviour of pollutants stored in the Arctic cryosphere also in the terrestrial environmental compartments.

It has long been known that global warming can affect contaminant pathways simply through physical and chemical properties (e.g., vapour pressure, Henry's Law constants). If we consider the globe to be warming on average, then the time a contaminant spends in the air will increase, and seasonal thermal forcing will have greater effect on contaminants that undergo multiple hops (e.g., DDT, PCB, Hg). Every step along the transport and redistribution pathways to and within the Arctic can be influenced by climate change operating on processes because reactivity, adsorption, air-sea exchange, and precipitation, all depend on temperature.

Perhaps one of the greatest ways in which cryospheric change can manifest itself in contaminant pathways is by altering the size of storage reservoirs. This is particularly important for classical contaminants that have been loaded heavily into the environment during the recent anthropocene.

## Remobilisation and atmospheric transport

Recently, the atmospheric monitoring program at the Norwegian atmospheric research station "Zeppelin mountain", Ny-Ålesund, Svalbard (Norway), revealed increasing atmospheric levels of volatile POPs and inparticular hexchlorobenzene (HCB; Hung et al. 2010), the monitoring date revealed a continuous increase of concentration levels since 2004. This increase coincide with changes in oceanographic patterns in the Fram Strait and the strong inflow of "warm" North Atlantic surface waters into the Western Arctic leading to virtually ice-free fjords along the western Svalbard coast during winter (Slubowska-Wodengen 2007). However, not all POPs with similar volatility follow this pattern in the air monitoring data from the Zeppelin station. For HCB continous contribution from primary sources may be assumed, thus additional increased emissions from secondary source will eventually result in an increasing temporal trend (MOSJ 2012). However, for $\alpha$-HCH (similar volatility as HCB) , were the primary sources are regulated since the early 2000s, still decreasing trends are observed (MOSJ 2012, Hung et al. 2010). A current modelling study based on a combination of monitoring and IPCC scenario assessment revealed, that through statistical evaluation, that also for these compounds an increasing emission from ice-free water surfaces is occurring. However, this increased trend is masked by absence of primary sources and the obvious changes in equilibrium for the water surface/ air interface in the Arctic (Ma et al. 2011). The thorough valuation of future scenarios (based upon IPCC models) revealed that the increased re-emission are expected to continue for decades before the remissions will level off (dependent on compound specific physico-chemical properties).

### Melt water run-off and remobilisation of persistent organic pollutants

The accelerated thawing of permafrost and surface ice melting (ice caps and glaciers) has the potential to create a significant new source of contaminant release in the Arctic. Furthermore, partitioning and deposition may lead to contaminant concentrations in the upper layers of the snowpack significantly higher than in the overlying km of atmosphere. Thus, surface wastage of permanent snowpack may lead to a considerable pulse of persistent contaminant concentrations into the ambient air (troposphere) or the water, depending on the exact circumstances of melting. Recent temporal trend studies conclude that glacial ice contains considerable amounts of POPs, including currently used pesticides (Hermanson et al. 2005,Kwok et al 2010).

A recent study using chemical indicators (OCP = organochlorine pesticides) for the hydrological characterisation of surface water in a Greenland fjord (Godhåbfjord, Nuuk), during spring time melt revealed that the melting of the Greenland ice cap has the potential to release considerable amounts of OCPs previously deposited and stored the ice surfaces for the past5 5 to 6 decades (Carlsson et al. 2012).

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# Delivery of POPs to the Arctic: Transport and Air-Surface Exchange Process

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## Introduction

Atmospheric transport of persistent organic pollutants (POPs) to the Arctic is well known (1), and in recent years it has become recognized that persistent and relatively water soluble compounds can also be delivered by ocean currents (2-4). Air concentrations of most “legacy” PCBs and organochlorine pesticides at arctic air monitoring stations have declined by 50% or more over the last two decades, although some compounds have declined more slowly, remained stable, or even increased in recent years (1). Declines are thought to result from legislative controls on production and usage which have specifically been linked to observed trends for lindane (5) and technical HCH (6), while lack of decline has been observed for some chemicals that are in current use or controlled only recently (e.g., endosulfan and PBDEs) (1). It is clear that arctic air concentrations are influenced not only by production and usage (i.e., “primary” emissions) but also by “secondary” emissions from environmental surfaces (soil, ice, snow, vegetation), and by meteorological and climatic factors. Ratios among compounds in arctic air provide evidence for secondary sources of chlordanes (probably from soil emissions) (7-10), while the amount and proportion of DDT compounds might be influenced by release from vegetation during forest fires, seasonal air transport from different regions and use of DDT-contaminated dicofol (9). Release of stored POPs from melting alpine (11) and glaciers has been observed, resulting in higher concentrations in downstream sediments (12), and DDT sources from melting glaciers was implicated in its lack of decline in Adélie penguins on the western Antarctic Peninsula (13) .

The role of air-surface exchange processes *within* the Arctic has been less well studied. The increase in some POPs, or reduced rates of decline, in air at Svalbard were linked to rising temperatures and reduced ice cover, suggesting that POPs are being remobilised from the ocean into the atmosphere (14). Ice and snow exert profound effects on atmospheric levels of POPs. Snow is generally a more efficient scavenger of POPs from the atmosphere than rain (15), but once deposited, POPs are revolatilised through diagenesis of the snowpack which results in loss of surface area (16,17). Long-range transport models which include snow scavenging and exchange with the snowpack in winter and soil in summer give realistic simulations of POPs behaviour (18-20). Different rates of exchange with snowpack and soil and possible oxidation on arctic soil surfaces during summer has been predicted to account for observed seasonal profiles of endosulfan and its transformation product endosulfan sulphate in arctic air (20). Rates of release to terrestrial and aquatic ecosystems during snowmelt depend on the physicochemical properties of the chemical and partitioning between particulate and dissolved phases (21). In the marine environment, the ice and snowpack can interact with the atmosphere through deposition and revolatilisation, and also by upward intrusion of brine from seawater (22). Below we give two examples of air-surface exchange process studies from our own work in the Canadian Arctic, which constitute most of the presentation at SSF.

### Influence of ice cover on the sea-air exchange of α-HCH

Investigations in the Canadian Archipelago have shown that concentrations of α-HCH within the lower air boundary layer increase abruptly after ice breakup in spring-early summer (23,24). This evasion from the ocean was traced by the changing proportions of α-HCH enantiomers. The α-HCH from long-range air transport is racemic, enantiomer fraction EF = (+)α-HCH/[(+)α-HCH + (–)α-HCH] = 0.5, while seawater contains non-racemic α-HCH which is depleted in the (+) enantiomer due to microbial degradation. The increase in airborne α-HCH after ice breakup was accompanied by a drop in its EF in air, as non-racemic α-HCH volatilised from seawater mixed with racemic α-HCH from long-range transport (Figure 1).

**Chlordane compound ratios in arctic air: photochemistry or microbiology?**

Ratios of *trans*-chlordane/*cis*-chlordane (TC/CC) in arctic air undergo seasonal cycles, higher in winter and lower in summer (1,7,9,10). This phenomenon was noticed in the late 1980s by Oehme (25), who hypothesized that the *trans*- isomer is more susceptible to photochemical degradation. This hypothesis has been repeated so often (1,7,9,10) that it is usually accepted as true. But is it? We have examined the EFs of TC in air from Alert, Canada over the period 1994-2000 and found that a there is a summertime lowering of EF that accompanies lower $F_{TC}$ = TC/(TC+CC) (Figure 2). This suggests that the seasonal cycle of TC/CC may not be caused by photodegradation of TC, but by selective microbial processing of TC at environmental surfaces, perhaps soil, vegetation or water. Possibilities will be discussed.

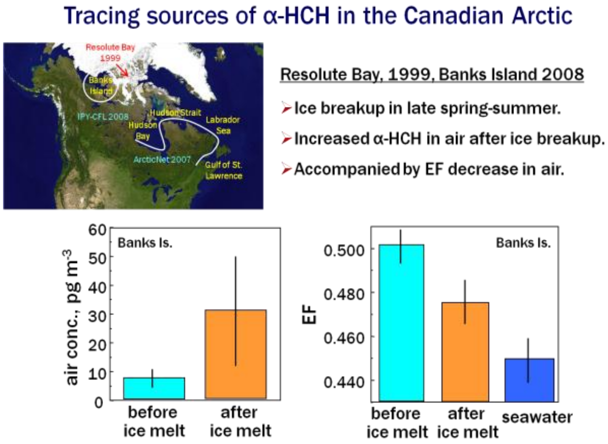

**Figure 1.** α-HCH concentrations and enantiomer fractions (EF) in air at Banks Island before and after ice breakup in 2008 (24). Similarly at Resolute Bay in 1999 (23). Nonracemic α-HCH was also found over open water of Hudson Bay and the Labrador Sea (24).

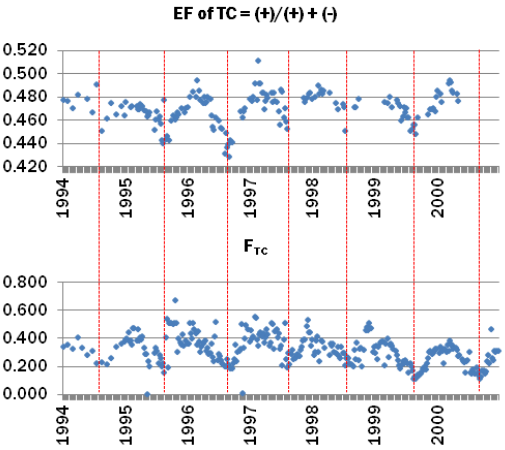

**Figure 2.** *trans*-chlordane/(*trans*- + *cis*-chlordane) = TC/(TC+CC) and enantiomer fraction (EF) of TC in air at Alert, Canada. Note summertime dips of TC coincide with lower EFs, suggesting a link to a microbial depletion mechanism.

**Knowledge gaps regarding air-surface exchange and secondary sources**

Many data gaps and recommendations for research regarding POPs sources, exchange processes exposure of wildlife and humans, ecotoxicology and human health impacts have been stated in the UNEP/AMAP report, “Climate Change and POPs, Predicting the Impacts” (26). Knowledge gaps and research recommendations regarding the cryosphere in general are documented in the SWIPA report (27). These lists are too long to reproduce in this abstract, but we should be aware of these recommendations during our discussions.

**Key references**

References for this abstract are listed below, and these can also be considered some of the “key papers” in the context of the request from the SSF organisers. There are many more relevant papers on transport to and air-surface exchange within polar and alpine regions. Except for our two papers on HCHs, I have left out references to air-water gas exchange, and no papers on ice photochemistry have been included. These omissions were made simply for lack of space.

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## The accumulation, behaviour and fate of POPs in the seasonal snowpack

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### Overview

Falling snow is an efficient scavenger of both vapour and particle-bound semi-volatile contaminants from the atmosphere. Washout or scavenging ratios have been measured in the range $10^3$-$10^5$ (e.g. Pucko et al. 2011) and are predicted to be $\geq 10^6$ depending on the ambient temperature and the surface area presented by the snowflakes (Lei and Wania, 2004). As a result the seasonal snowpack, particularly fresh snow layers, serve to concentrate organic contaminants, with the snowpack providing a temporary but significant repository of atmospherically derived pollutants (Meyer and Wania, 2008). For areas where the seasonal snowpack contributes significantly to catchment hydrology such as upland/Alpine regions or remote northerly catchments, then contaminant deposition and subsequent diffusive entry to first and second-order streams can be significant. For example, Bergknut et al. (2010) studied a remote boreal catchment in northern Sweden, where the surface water hydrology was dominated by seasonal snowfall, and found that diffusive entry in the upper catchment from melt contributed significantly to levels of PCBs and selected dioxins observed further downstream. Similarly, in a recent study conducted in the Italian Alps (Vaj et al. *in preparation*), perfluoroalkyl acids (PFAs) were measured in the snowpack, glacial streams and river water (both the upper and lower catchment). The snowpack and glacial stream displayed relatively high concentrations of PFAs, particularly for the shorter-chain compounds e.g. perfluorobutanoate ($C_4$,PFBA): snow: 500-908 pg/L; stream: 93-767 pg/L). Levels of PFAs in the upper catchment appear to provide a baseline upon which point sources downstream add to. To fully understand the importance and role of the snowpack in accumulating and contributing organic contaminants to surface waters then the following areas present research challenges or knowledge gaps which need to be addressed; particularly in light of climate change which is altering snowfall patterns, snow intensity and the timing and rates of melt.

### Post depositional loss

Following snowfall, fresh snow layers undergo compaction with a general increase in snow density and reduction in specific snow surface area. As result there is a loss of vapour-sorbed chemicals through volatilisation and this can be aided by wind ventilation. This process can greatly reduce the load of certain chemicals within the pack (e.g. hydrophobic OC pesticides and lower chlorinated PCBs) and this loss has been observed in several field-based Arctic studies (e.g. Herbert et al., 2005; Pucko et al. 2011). For other chemicals, with lower vapour pressures e.g. particle-bound compounds and ionisable chemicals (e.g. PFAs) then volatilisation losses are likely to be negligible. However, post-depositional fate and repartitioning within the snowpack needs further study particularly to reduce uncertainty when the snowpack is incorporated into regional or global chemical fate models (e.g. Hansen et al., 2008).

### Chemical release during melt

Release of organic contaminants from the melting snowpack has received attention through both modelling and laboratory-based studies (e.g. see Plassman et al. (2011)). This is a complicated process though and dependent on the physical-chemical properties of the chemical and the characteristics of the snowpack (snow depth/layering, rate of melt, particle content etc). While initial melt may result in an early release of relatively water soluble contaminants, more hydrophobic or particle-bound chemicals are likely to be released during later stages of melt. Ultimately this will affect the timing and loading of contaminants to nearby water courses. To illustrate differences in chemical behaviour, Figure 1 shows the concentrations of perfluorooctane sulfonate (PFOS) and perfluorooctanoate (PFOA) measured systematically in the melting snowpack in northern Sweden over a 12 day period in early spring (Codling et al. *in preparation*). Differences in their behaviour, marked in this case by a marked decline of PFBA (and to a lesser extent perfluorooctanoate (PFOA)) and an increase (or retention within the diminishing pack) for perfluorobutane sulfonate (PFBS) and perfluorooctane sulfonate (PFOS). Models and laboratory studies do not always replicate this behaviour and field studies are urgently required to explore and quantify contaminant release and subsequent loading into catchment waters.

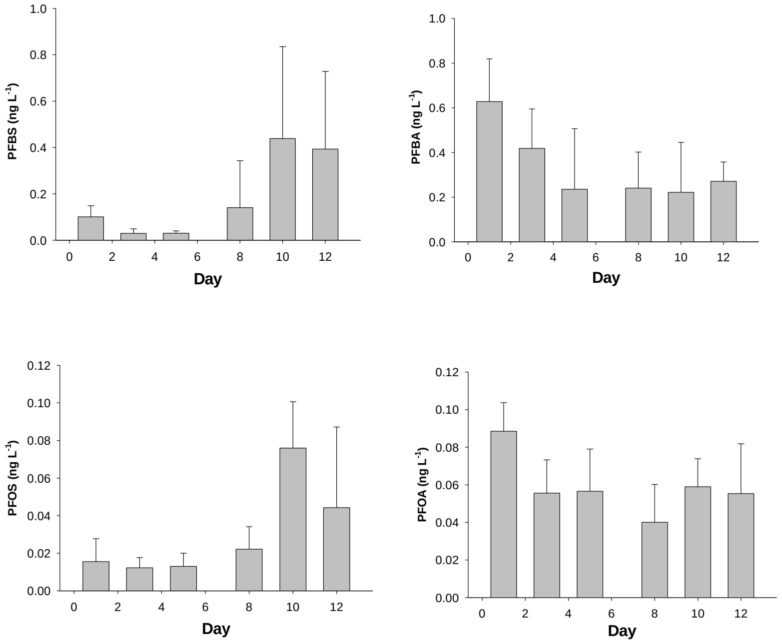

**Figure 1.** Concentration time-series of selected PFAs in a melting snowpack in northern Sweden (April-May 2009).

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# Modelling the effect of snow of the fate of persistent organic pollutants

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## Snowpack model

We have developed a model which describes the uptake and air-surface exchange of selected Persistent Organic Pollutants (POPs) in a snowpack. The snowpack is described using a dynamic physical-based model, with chemical sorption to snow surfaces as the major component. The snowpack is regarded as one homogeneous layer, effectively describing the different stages of snowpack evolution: accumulation, settling, and melting. Meteorological data (temperature, wind speed, and precipitation) as well as changing physical aspects of the snowpack drive the model. Important physical and chemical parameters include the total surface area (TSA) of snow, as well as the chemical specific interfacial-air partition coefficient (Kia). Empirical relationships between SSA and density and for the decrease of SSA with time are utilised to age the snowpack following snowfall events. The chemical input to the snowpack is through both wet and dry deposition of gas-phase and particle-bound chemicals. Instantaneous mixing of both physical parameters and chemical concentrations is assumed for each time step to maintain snowpack homogeneity. The exchange of gas-phase chemicals is described with a two-film resistance model and accounts for both deposition and re-volatilisation from the snowpack. As the surface area of snow decreases, repartitioning of the snow-sorbed chemical into pore-space air occurs and re-volatilisation from the snowpack increases (Hansen et al., 2006).

## The effect of snow on the modelled fate of POPs

The model was included in the Danish Eulerian Hemispheric Model (DEHM), a dynamic high-resolution 3-D atmospheric chemistry-transport model covering the Northern Hemisphere, in order to predict the distribution and fate of POPs in the polar environment. The effects of the snowpack on the fate of alpha-hexachlorocyclohexane (α-HCH) were investigated by making simulations both with and without the formation of a snowpack. The model results were compared to data from 21 air monitoring sites. The fit between modelled and observed α-HCH air concentrations for the winter and spring seasons is generally improved with the snowpack module included in the DEHM model.

The model results indicate that the modelled snowpack in DEHM acts as a fast-exchanging temporary storage medium for α-HCH, as significant fractions of deposited α-HCH were rapidly re-volatilized back into the atmosphere following deposition with snowfall. Relatively high air concentrations observed between March and May at several high latitude monitoring stations are also predicted by the model. These high concentrations are associated with the re-volatilization of previously deposited chemical from the snowpack, following a reduction in the capacity of the snowpack to retain α-HCH with increasing temperatures toward the end of the winter period, rather than the actual melting of the snowpack (Hansen et al., 2008).

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## Questions to be answered (pollutants)

1. *What are the levels and changes of pollutants (in air, snow/ice, soil, water, vegetation and biota) that you have investigated?*

We have primarily studied modelled air concentrations of legacy POPs (HCHs and PCBs). The levels of legacy POPs are decreasing in air (e.g. Hung et al., 2005) as well as in other environmental media as a result of decreasing emissions due to regulations. Results from the DEHM model show that the levels of relatively volatile gas-phase persistent pollutants in snow are very variable and can change on short time scales (Hansen et al., 2008). This is supported by measurements (Herbert et al., 2005).

2. *What are the pathways and exchange of pollutants in your field (between the atmosphere, snow/ice and soil/vegetation and biota)?*

The Atmosphere is the major transport pathway of POPs to cold environments. Snow is an efficient scavenger of POPs from air (Lei and Wania, 2004), The snowpack acts as a fast-reacting temporary storage medium for the relatively volatile POPs with the overall effect of enhancing the atmospheric transport of volatile POPs (Hansen et al., 2008). The less volatile POPs will be removed from the snowpack with melt water and end up in the aquatic environment or the terrestrial environment. Once in the abiotic environmental surface compartments they can be taken up by biota.

3. *What are the key knowledge gaps in your field?*

POPs are associated with the surface of the snow crystals (Lei and Wania, 2004). However, the mechanisms of how POPs are associated with the surface are not known, i.e. are they sorbed onto the snow crystal surface or dissolve into a quasi-liquid layer. Of the same reason, the present air-snow partition coefficients are highly uncertain, which complicates modelling studies of the processes in the snowpack. Another process not well known but of high importance for studying the fate of POPs in snow is diffusion of POPs within the snowpack. Climate change will change the extent and distribution of snow. The effect of this on the environmental fate of POPs is also uncertain (Armitage et al., 2011, Ma et al., 2011).

4. *Please list the scientific papers most relevant from your field.*

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# Organic contaminants in ice cores from Svalbard

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### *Levels and changes of organic contaminants in Svalbard ice cores*

Since 2000, we have measured organic contaminants in 5 general groups in 4 ice cores drilled from 3 glaciers (Austfonna (740 masl), Holtedahlfonna (1150 masl), Lomonosovfonna (1250 masl)) on Svalbard. The contaminant groups are halobenzenes (HBZ), PCBs, current-use pesticides (CUPs), brominated flame retardants (BFRs), and perfluorinated compounds (PFCs). We have analysed 316 compounds in these 5 groups, most of them PCBs. The core from Holtedahlfonna (2005) is the most analysed to date.

The analysis of cores allows us to identify the input histories of contaminants reaching these high-elevation ice sheets through the atmosphere. Because of large volume requirements for 4 of the contaminant groups (halobenzenes, PCBs, CUPs, BFRs) the dating resolution is 6- 10 years. For PFCs, which have small volume requirements, the resolution is ~3 years. We are also measuring core contaminant burdens (pg cm$^{-2}$) which enable us to make comparisons between contaminants and sites over the time of accumulation. The burdens we have measured from Hotedahlfonna (HBZs, PCBs, CUPs, BFRs) cover 1953 – 2005; burdens for PFCs are from Lomonosovfonna from 1976 – 2009. The top two burdens in each compound class are shown in Figure 1.

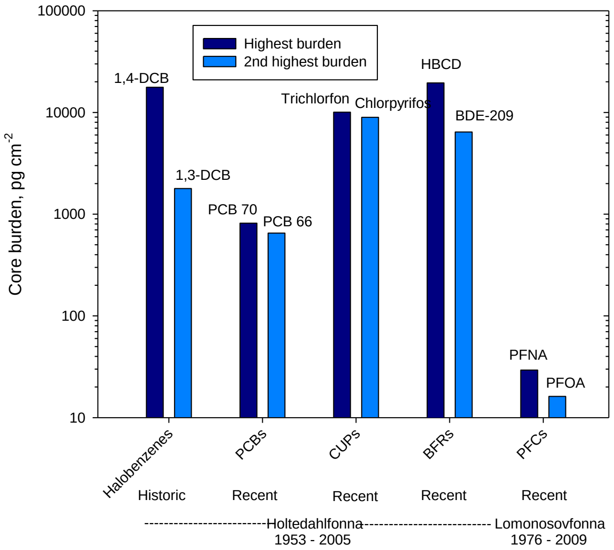

**Figure 1.** The two greatest contaminant burdens from 5 classes are shown. Most of the results are from Holtedahlfonna. The greatest burden is HBCD and is recent ((1996-2005). Second greatest is 1,4-dichlorobenzene; its burden is 10x greater than 1,3-DCB; neither was not found after 1988. CUP burdens include trichlorfon and chlorpyrifos; the former was not observed after 1995, the latter peaked 1996 – 2005. PCBs are comparatively low; major congeners are 66 and 70, both tetra-CBs. ΣPCB burden (not shown) was 6900 pg cm$^{-2}$, about the same as BDE-209. The PFCs have comparatively very low burdens (not > 30 pg cm$^{-2}$ and only cover the period from 1976 – 2009. The majority of PFC burdens accumulated between 2006 and 2009.

Our PCB analysis from Holtedahlfonna included 125 congeners (87 actually observed). Comparison of congener concentrations profiles permits us to identify changes in congener makeup over time. In the two surface samples (1988 – 1995, 1996 – 2005) we have noticed a nearly 2x increase in the flux of ΣPCBs, and a shift in congener pattern to lower molecular mass congeners, shown in Figure 2. The suggestion is that after 1995, the PCBs reaching Holtedahlfonna through the atmosphere were coming from a different source at least part of the time.

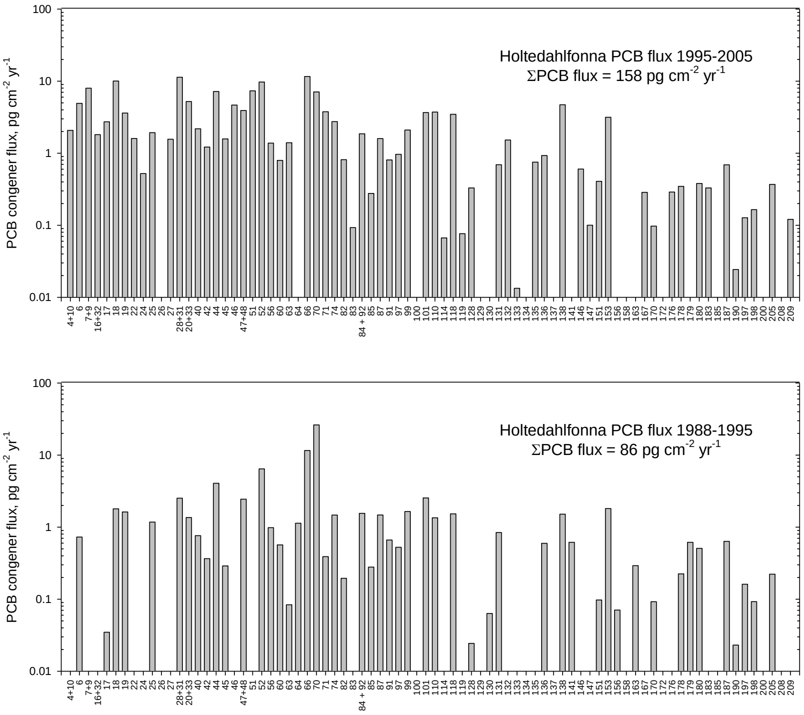

**Figure 2.** PCB congener profiles for the upper 2 samples from the ice core drilled at Holtedahlfonna in 2005. The upper segment covers 1996-2005, the lower 1988 – 1995. The ΣPCB input peaked at 275 pg $cm^{-2}$ $yr^{-1}$ in the segment from 1980 – 1988 (not shown). In the 1988 – 1995 segment, the input is about one-third the peak value, which increases in the top segment with a shift towards lower MM congeners. The increased input to the top segment and the distinct congener shift suggest that a new PCB source is impacting western Svalbard. All segments of the core up to 1995 are dominated by PCB 66 and PCB 70. In the top segment, PCBs 66 and 70 are still prominent, but other congeners, including PCB 28 and 52, are nearly as great.

## Pathways and exchange of contaminants

Our ice cores are from high elevations on Svalbard; the contaminants observed are net deposition from the atmosphere. Our analysis of air mass back trajectories shows that air masses reaching ice coring sites on Svalbard are from the east or south. We have observed shifts in trajectory pathways over time. During the summer some surface snow normally melts with formation of an ice layer. Exchange with the atmosphere will have ended below the ice layer; contaminants in the ice at that time will remain in place. Once an ice layer has formed, there is no downward movement of contaminants.

## Key knowledge gaps in research on contaminants in Svalbard ice cores

The challenge we face is identification of sources of contaminants reaching Svalbard glaciers. While we know that most air masses moving to Svalbard have come from the east or south, in Eurasia, few data are available regarding use of compounds that we have analysed. Other missing key information is air data for these contaminants from the likely source regions, or between these regions and Svalbard. We also need more information about possible local sources of these contaminants on Svalbard.

## Scientific papers most relevant

Hermanson, M. H., Isaksson, E., Forström. S., Teixeira, C., Muir, D. C. G., Pohjola, V., van de Wal, R. Deposition history of brominated flame retardant compounds to an ice core from Holtedahlfonna, Svalbard, Norway. Environmental Science & Technology 2010, *44,* 7405-7410

Ruggirello, R. M., Hermanson, M. H., Isaksson, E., Teixeira, C., Forström. S., Muir, D. C. G., Pohjola, V., van de Wal, R., Meijer, H. A. J. *Current-use and legacy pesticide deposition to ice caps on Svalbard, Norway.* Journal of Geophysical Research – Atmospheres 2010, *115*, D18308, doi:10.1029/2010JD014005

Hoferkamp, L., Hermanson, M. H., Muir, D. C. G. *Current use pesticides in Arctic media; 2000-2007.* Science of the Total Environment 2010, *408,* 2985-2994.

# Recent Pollution levels from Lomonosovfonna ice core, Svalbard

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## Pollutants/Geophysics (snow/ice)

Black carbon (BC, the absorbing component of soot) can significantly contribute to climate change by altering the Earth's radiative balance. BC in the atmosphere absorbs light and causes atmospheric heating, whereas BC deposited on snow and ice can significantly reduce the surface albedo, hasten melting, and trigger albedo feedback (Flanner et al., 2009). BC is estimated to have 55% of the radiative forcing effect of $CO_2$ (Ramanathan and Carmichael, 2008), yet BC remains one of the largest sources of uncertainty in analyses of climate change. Records of BC mass concentration and spatial and temporal distribution in the atmosphere are therefore needed to determine the role of BC in climate change. Recently, BC was suggested to be responsible for a large fraction of the Arctic warming and a faster retreat of glaciers (e.g. Shindell and Faluvegi, 2009; McConnell et al., 2007).

Since no ice core BC record exists from Svalbard, an ice coring expedition was conducted in March 2009 to drill a new core from that ice cap. We collected two ice cores of 149 m and 37 m depth, respectively, at the Lomonosovfonna (1202 m asl, 78°49'24.4" N; 17°25'59.2"E). At 149 m the drill got stuck and was released by applying antifreeze, thus bedrock at about 215±15 m was not reached. The 149 m ice core is being analyzed for BC concentration and a variety of other components related to climate variability and pollution. We estimate that it covers roughly the last 1000 years.

In Svalbard BC originates from local or long-range sources. Local sources include mining activities, coal and diesel power plants as well as vehicles. Long-range transport of BC occurs from sources in Europe and Russia. The major ion snow chemistry is dominated by sea salt species since the archipelago of Svalbard is surrounded by ocean. To study the geographical distribution of BC and major ion concentrations, samples of the 2009/2010 winter snow pack were taken at Foxfonna, Tellbreen and Lomonosovfonna glacier. The first two are located in the vicinity of Longyearbyen (12-15 km), the biggest settlement on Svalbard, and close to the ocean (11-15 km). They have an altitude between 500-800 and 300-750 m asl, respectively. In contrast, Lomonosovfonna is a remote site, located far from any settlement (~75 km to Longyearbyen), situated at an altitude of ~1200 m asl and ~20 km distance from the ocean. The study revealed that the geographic location plays an important role for the ion as well as the BC concentrations. The lowest values for the sea salt tracers sodium and chloride as well as for BC were found at Lomonosovfonna, confirming the remote location of this glacier that makes it suitable for the study of long-range transported species.

In order to determine the BC concentration in ice a single particle soot photometer (SP2, Droplet Measurement Technologies, DMT, Boulder, USA) is used. Within this instrument, single BC particles are heated to their boiling point (~4000 K) by a Nd:YAG-laser. At that temperature the BC particles emit incandescent light which then is detected by two photomultiplier tubes. The intensity of that light beam is proportional to the BC mass in the particle, independently of particle morphology and coatings with light scattering material (Kaspari et al., 2011). However, BC values obtained in the snow pack study are lower than those published in previous studies from Svalbard but also from Greenland. On the one hand this is explainable by different methods applied. On the other hand this study only represents one year of winter snow. Nevertheless, before starting the BC analysis of the new Lomonosovfonna ice core, we are optimizing the SP2-method. Previously an ultrasonic nebulizer (U5000AT$^+$, CETAC Technologies) was used to transform the liquid sample, i.e. the melted ice, into a dry aerosol. However, there are indications of losses of BC particles in the nebulizer. Therefore, a new set-up, including a jet nebulizer (Apex Q, Elemental Scientific Inc.), was tested and shown to be more effective, especially in transporting larger BC particles. Since large particles contain most of the mass, those are particularly important in climate concerns.

Due to the geographic location of Svalbard, the ice core ion chemistry is mostly influenced by sea-salt species (about 80%). Based on correlation analyses using the ion concentrations, chemical species were classified into four groups corresponding to their main sources: (1) sea salt: sodium, chloride, potassium, magnesium, sulphate (2) anthropogenic pollutants: ammonium, nitrate, sulphate (3) dust: calcium (4) marine biogenic: methanesulphonic acid. Concentration records of all chemical species tend to peak in winter/early spring. This was already observed for ambient aerosols in Svalbard (e.g. sea-salt species, sulphate) and explained by a higher frequency of storms, an enhanced transport efficiency, and Arctic haze pollution in the cold season. However, methanesulphonic acid aerosol clearly peaks in summer. Here, ice core maxima in winter can most probably be explained with percolation effects during melting processes. Trace species related to anthropogenic pollution such as ammonium, nitrate, and sulphate show a strong temporal trend with maxima around the mid 20th century. Since then concentration levels decreased significantly approaching pre-industrial levels (Figure 1).

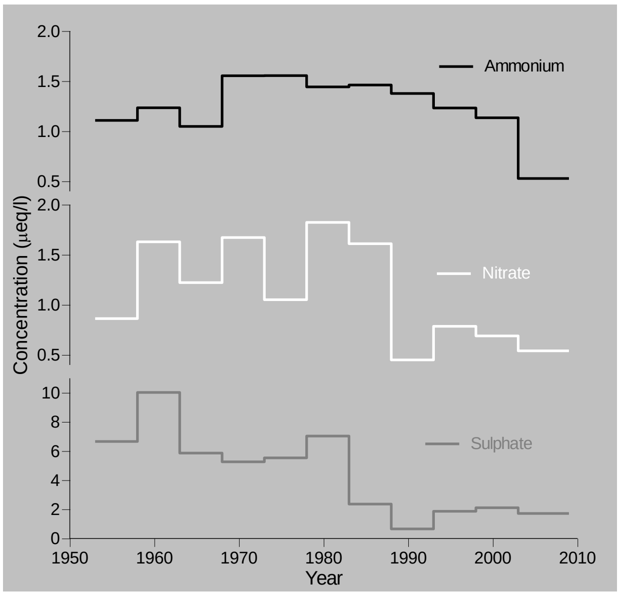

**Figure 1.** 5-year concentration averages of anthroponic pollutants ammonium, nitrate, and sulphate from the Lomonosovfonna 2009 ice core for the time period 1952-2009, representing the upper 30 m weq.

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D. Shindell and G. Faluvegi, *Climate response to regional radiative forcing during the twentieth century*, Nature Geosci. **2**, 294 (2009).

# Organochlorines contamination in Barentsburg area, Svalbard, 2002-2011. Local sources

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The Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet) has developed the Program of operations and scientific studies at the archipelago for 2002-2011, also including an assessment of environmental pollution levels in the area of Barentsburg settlement. The aim of the work was to obtain comprehensive information on the levels of pollution of environmental components in the amount necessary for an annual assessment of the existing ecological situation, and for investigating an inter-annual trend. Generalization of available materials was finished in 2011 and at present time the manuscript is in print.

One of the objectives of the environmental monitoring program was to try to establish the sources of PCBs found in samples of snow near the settlement of Barentsburg, and find out what kind of role in the contamination of the area under study are local sources rather than long-range transport, which was considered a long time the main source of PCBs in Svalbard area.

Over the years, have repeatedly observed a situation where in some samples of snow cover (spring period) and in soil (autumn period) concentrations of PCBs were unexpectedly high. Average sum PCBs concentration in the snow was at the level of 10 ng/kg (Seven Dutch, $PCB_7$), the concentration ten-forty times higher -100-400 ng/kg were observed in some samples.

In 2008, the State Administration of Geological Survey of Norway implemented the PCBs contamination in the settlements on the archipelago, in which economic activity is carried out. As a result of studies a significant local source of PCBs have found, it was the old paint coatings. A range of $PCB_7$ content is varied from <0.35mg/kg to 96 mg/kg for exterior paint in Barentsburg that are most relevant sources of income of the PCBs in the environment. The mean value of PCBs was approximately 11 mg/kg, the median value of - 0.82mg/kg (Report-2008). Analysis of these data suggested that the highest concentrations of PCBs found in old paint coatings of defective buildings out of use.

Nine samples of paint from old buildings of the Barentsburg were sampled and analyzed in 2011. Data on the content $PCB_7$ presented in Table 1.

**Table 1.** *$PCB_7$ contents (mg/kg) in old paint coatings of the buildings in Barentsburg.*

| Min | Average | Mediana | Max |
|---|---|---|---|
| **0.4** | **11.2** | **4.2** | **55.0** |

Samples of modern paint coatings on buildings in the Barentsburg, analyzed for comparison contained less than 0.1 mg/kg of PCBs. Thus, we conclude that the old paint coatings are vary greatly in content of PCBs, while the absolute values of PCBs in them exceeds the normal value established by Norwegian SFT (0.01 mg/kg) and are hundreds or thousands times higher. In one case observed concentrations are even exceed the value established by “Prescription for Waste” (2004) for hazardous waste - 50 mg/kg.

It is significant that it is near the old abandoned buildings covered PCBs-containing paint, observed the highest PCB levels in the snowpack (up to 110 ng/kg) during the spring period and in the soils (up to 5000 ng/kg) in autumn 2011 observations. Profile of PCBs (**Fig. 1)** constantly shows the maxima for the congeners #105, #118, #138, which is closest to the profile of such products as Arohlor1254 and Chlofen A-50, except that some samples contained less chlorinated PCBs #101, and #52.

Samples with a high content of PCBs as a rule contain significant amounts of DDT, including its isomers, byproducts and metabolites. This is true for samples of paint, and for samples of snow, soil and vegetation, and to understand the reasons for such organochlorines behavior more research is needed.

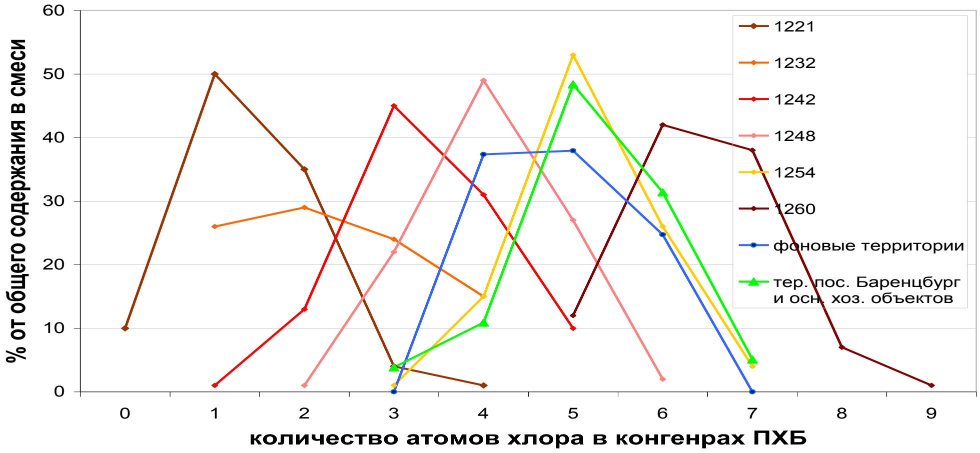

**Figure 1**. Profile of PCBs congeners in mixtures of "Aroclor", paint coatings and in samples of snowpack taken at background areas nearby Barentsburg

In 2008-2009, the “Akvaplan-niva”, the Geologucal Survey of Norway and the NW branch of RPA “Typhoon” took part in the intercalibration exercises, in which the sampling techniques and chemical-analytical methods used by these organizations were compared. These exercises showed the Norwegian and Russian results to be quite comparable, although there are some differences in the sampling methodology and analytical equipment (Evenset & Ottesen 2009).

## References

Evenset, A. & R.T. Ottesen 2009. Norsk og russisk overvåking av PCB-forurensning ved bosettinger på Svalbard: Sammenligning av felt- og analysemetoder og resultater. Akvaplan-niva rapport 4330-1. 31 s.

NGU Rapport 2008.073

# Appendix 2: Input from other researchers

## Snow & Ice

62: Friedrich Obleitner (Innsbruck University, Austria)

## Terrestrial ecology

63: Steve Coulson (UNIS, Norway): *Inverts*
65: Maarten Loonen & Jouke Prop (University of Groningen): *The impact of pollutants and snow melt patterns on the life history of arctic-breeding geese*
67: Niels Martin Schmidt (Aarhus University): *Biobasis Zackenberg*

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*E-mail: friedrich.obleitner@uibk.ac.at*

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**Questions to be answered (Ecology):**

1. *What are the main effects of changes in snow/ice (amount, spatial/temporal distribution) in your field? How does this affect your study organisms? Further effects in higher trophic levels?*
   Working mainly on glaciers so far, snow has a main effect on surface reflectivity, thereby affecting the energy and mass balance of glaciers. Secondary effects are related to surface roughness (affecting e.g. turbulent heat and vapour exchange with the atmosphere), low heat conductivity (affecting depth of seasonal temperature signals), melt water retention or runoff (affecting mass balance). Snow structure also affects accumulation/dilution of chemical compounds deposited on snow (black carbon, interpretation of ice cores)

2. *What are the key gaps in snow/ice-ecological relationships in your field?*
   Glaciers and forelands: consistent observations and simulations of temporal and spatial patterns of snow accumulation and melt water production. Need for better knowledge on development snow structure depending on atmospheric factors. Need for better meteorological input to snow models employing downscaling e.g. RCM model output.

3. *Who are the key scientists working on snow/ice-ecological relationships in your field (in Svalbard, other Arctic areas or in alpine areas)?*
   Rolf A. Ims, Eric Post, Gilles Gauthier, Donald Reid, Nils C. Stenseth, Mads C. Forchhammer, Olivier Gilg, Mikkel Tamstorf, Niels M. Schmidt.

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**Questions to be answered (Pollutants):**

1. *What are the levels and changes of pollutants (in air, snow/ice, soil, water, vegetation and biota) that you have investigated?*
   We did not really focus on that so far, but some recently performed snow structure measurements by the Norwegian Polar Institute have a potential in that direction.

2. *What are the pathways and exchange of pollutants in your field (between the atmosphere, snow/ice and soil/vegetation and biota)?*
   Atmospheric turbulence and runoff.

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**Questions to be answered (Geophysics)**

1. *What are chemical properties of snowfalls and snow cover? Do we observe spatial variability and changes in time scale?* We did not focus on that so far, but some recently performed snow structure measurements by the Norwegian Polar Institute have a potential in that direction. Time series of snow height are measured at several glacier sites since about 10 years.

2. *Do we observe changes of snow physical properties and changes of snow distribution/snow conditions due to climate changes?* Time series of snow height are measured at several glacier sites since about 10 years. Must be more systematic and complemented by enhanced atmospheric observations.

3. *Do we know local/regional differences of precipitation lapse rate? Do we know real lapse rate values?* No, these are really important but weak points. Much has to be done there on the observations and modelling side.

## Inverts

**Steve Coulson**(1)
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**Questions to be answered (Ecology):**

1. *What are the main effects of changes in snow/ice (amount, spatial/temporal distribution) in your field? How does this affect your study organisms? Further effects in higher trophic levels?*
   Main effects:- changes in the amount of snow will potentially change the insulation. Deeper layers will increase the potentially increase the insulation against low winter air temperatures. However, snow depth is also a function of wind strength and direction (especially in Svalbard where most snow is drifts). Climate projections indicate that there is a likely increase in winter precipitation and air temperature. This may increase average snow depths but only if a) precipitation is as snow and not rain, b) the wind does not result in the extra snow being blown away and c) higher temperatures do no significantly increase evaporation of snow during the winter.

   A critical influence of snow is the influence it has on the subsequent summer period. Deep snow in general requires longer to melt than shallow snow. The result being that animals and plants under deep snow have a shorter summer period. This has consequences on the local distribution of species. Changes in duration of snow lie also has the potential to disrupt synchrony between invertebrate emergence and breeding of insectivorous birds

   Snow also influences soil invertebrates (and plants) through providing water source during melt period.

   During snow melt pollutants accumulated during the winter are released in a short period. These can potentially have effects on the invertebrate fauna. Many species of invertebrate have their reproductive period at this time. Such a "pollutant shock" impact newly hatched Collembola for example. Further, interactive synergistic effects between pollutants and invertebrate stress tolerance are becoming clear.

   Holmstrup M., Aubail A., Damgaard C. 2008. Exposure to mercury reduces cold tolerance in the springtail *Folsomia candida*. *Comparative Biochemistry and Physiology Series C 148*, 172–177.)

2. *What are the key gaps in snow/ice-ecological relationships in your field?*
   Very little work has been undertaken in Svalbard and relatively little in the Arctic. This is peculiar given the extreme biodiversity (outstripping other taxa) but is likely related to the logistical difficulty. There are some studies on increased freeze thaw cycles in the Norwegian mountains but in general freeze thaw cycles in the soil during the melt period do not occur in Svalbard (midnight sun is present after snow melt with little diurnal temperature swing and positive temperatures). However, freeze thaw events do occur in the autumn. This has not been investigated as far as I am aware.

   Effects of icing on the soil fauna. Suspected to be deleterious (Coulson et al 2000). However, how deleterious or how such a surface ice layer acts is unknown. Given the increased rain events being observed, and projected to increase, this is an important stressor to better understand.

   Coulson, S.J., Leinaas, H.P., Ims R.A. & Søvik G. (2000) Experimental manipulation of the winter surface ice layer: the effects on a High Arctic soil microarthropod community. *Ecography* 23; 299-314

3. *Who are the key scientists working on snow/ice-ecological relationships in your field (in Svalbard, other Arctic areas or in alpine areas)?*
   Most are working in the summer.  However, Martin Holmstrup, and his group in Denmark, is a leading international figure in invertebrate cold tolerance. See http://www.dmu.dk/en/aboutneri/departments/terrestrialecology/section_of_soil_fauna_and_ecotoxicology/sofar_ii/martin_holmstrup/.

4. *Please list the scientific papers most relevant for snow/ice in your field.*
   There are relatively few. Most of the papers describe the importance of snow for small mammals and plants. I have therefore just included three of my own:

Ávila-Jiménez M.L & Coulson S.J. (2011) Can snow depth predict the distribution of the high Arctic aphid *Acyrthosiphon svalbardicum* (Hemiptera: Aphididae) on Spitsbergen? *BMC Ecology* 11:25

Ávila-Jiménez, M. L., Coulson S.J , Solhøy T. & Sjöblom A. (2010) Overwintering of Arctic arthropods; the case of the invertebrate fauna of Svalbard now and in the future. *Polar Research* 29;127-137.

Coulson, S.J., Leinaas, H.P., Ims R.A. & Søvik G. (2000) Experimental manipulation of the  winter surface ice layer: the effects on a High Arctic soil microarthropod community. *Ecography* 23; 299-314

These two detail important potential soil temperature changes in the Arctic and the interactve effects of pollutants and cold tolerance:

Isard S.A., Schaetzl R.J. & Andresen J.A. 2007. Soils cool as climate warms in the great lakes region: 1951–2000. *Annals of the Association of American Geographers 97*, 467–476.

Sjursen H., Michelsen A. & Holmstrup M. 2005. Effects of freeze–thaw cycles on microarthropods and nutrient availability in a sub-Arctic soil. *Applied Soil Ecology 28*, 79–93.

# The impact of pollutants and snow melt patterns on the life history of arctic-breeding geese

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## Questions to be answered (Ecology):

1. *What are the main effects of changes in snow/ice (amount, spatial/temporal distribution) in your field? How does this affect your study organisms? Further effects in higher trophic levels?*
For a successful reproduction, Arctic-breeding geese as barnacle geese *Branta leucopsis* intersperse incubation with brief bouts of foraging on tundra vegetation. The availability of suitable food is determined by the area of snow-free tundra, and as a consequence recession of snow from the tundra is a prime factor determining reproductive success (Figure 1). In more recent years, the advantage of early snow melt seems to have lost, and even in early snow melt years goose production is low. Currently, we are investigating the cause of this remarkable shift by exploring the role of changes in pollutants (or more general pathogens), predator behaviour, and snow melt patterns. The consequences of a depressed productivity on the ecosystem are large by negative effects on Arctic foxes (goslings are a main summer prey).

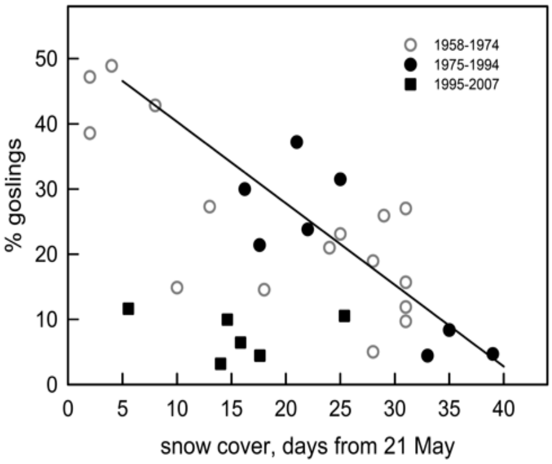

**Figure 1.** Relationship between the percentage of young in flocks of barnacle geese and the duration of snow cover (number of days from 21 May that at least 75% of the tundra was covered by snow). The close relationship between goose production and snow melt pattern disappeared after 1995, indicating a sudden change in the tundra ecosystem (from Drent & Prop 2008).

2. *What are the key gaps in snow/ice-ecological relationships in your field?*
The short-term effects of snow cover on biomass and quality of forage plants during summer and the long-term effects of snow cover on vegetation composition.

3. *Who are the key scientists working on snow/ice-ecological relationships in your field (in Svalbard, other Arctic areas or in alpine areas)?*
René van der Wal, http://www.abdn.ac.uk/biologicalsci/staff/details/r.vanderwal.

4. *Please list the scientific papers most relevant for snow/ice in your field.*

**Prop, J.** & de Vries, J. 1993. Impact of snow and food conditions on the reproductive performance of barnacle geese *Branta leucopsis.* Ornis Scandinavica 24: 110-121.

Van der Wal, R., Madan, N., van Lieshout, S., Dormann, C., Langvatn, R. & Albon, S.D. 2000. Trading forage quality for quantity? Plant phenology and patch choice by Svalbard reindeer.

Van der Wal , R., van Lieshout, S.M.J. & **Loonen, M.J.J.E.** 2001. Herbivore impact on moss depth, soil temperature and arctic plant growth. Polar Biology 24: 29-32

Drent, R.H. & **Prop, J.** 2008. Barnacle goose *Branta leucopsis* survey on Nordenskiöldkysten, west Spitsbergen 1975–2007: breeding in relation to carrying capacity and predator impact. Circumpolar Studies 4: 59-83.

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**Questions to be answered (Pollutants):**

1. *What are the* <u>*levels and changes*</u> *of pollutants (in air, snow/ice, soil, water, vegetation and biota) that you have investigated?*
   We explored in which way barnacle geese reacted to different levels of pollutants or pathogens in the terrestrial environment. We did this by measuring the activity of the immune system of the geese while on the Svalbard tundra. We chose three areas in Svalbard where we expected different levels of instantaneous pollution or pathogen pressure: close to a dense human settlement, close to a small settlement, far from any human source. The immune system was most active in geese close to a dense settlement and least active far from human settlements. This suggests a large flexibility in geese to cope with varying amounts of pollutants or pathogens. Preliminary results show costs for young by a retarded development and possibly a lower survival. As we suspect that biological pathogens play a crucial role in inciting the immune response by geese, we are now working on refined methods to measure bacterial loads in the environment.

2. *What are the* <u>*pathways and exchange*</u> *of pollutants in your field (between the atmosphere, snow/ice and soil/vegetation and biota)?*
   Don't forget pollutants already present in the soil and the effect of permafrost melting on the release of these pollutants.

3. *What are the key knowledge gaps in your field?*
   Impact of pollutants on herbivore populations.

## Biobasis Zackenberg

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**Questions to be answered (Ecology):**

1. *What are the* *main effects of changes in snow/ice* *(amount, spatial/temporal distribution) in your field? How does this affect your study organisms? Further effects in higher trophic levels?*
   At Zackenberg in NE Greenland the amount of snow precipitation has been declining since the mid-1990's. In recent years, however, this negative trend has been replaced by a large inter-annual variation in snow precipitation. Both the negative trend and the increased variability may impact the high arctic organisms and processes markedly. For instance, at Zackenberg snow cover is a major determinant of plant phenology (Høye *et al.* 2007), shrub growth (Schmidt *et al.* 2006), arthropod emergence (Høye *et al.* 2007), shorebird nest initiation (Meltofte *et al.* 2007), lemming dynamics (Schmidt *et al.* 2008), and ungulate foraging behavior (Forchhammer *et al.* 2005). The observed responses to the changing snow conditions are likely to cascade onto adjacent trophic levels, such as the pollinator community, the herbivore and predator guilds with implications for the functioning of the entire tundra ecosystem.

2. *What are the* *key gaps in snow/ice-ecological relationships* *in your field?*
   Snow is not just snow. Our knowledge on the various aspects of snow (e.g. cover, depth, density, thaw-events and ice-layers) and their linkage to key ecosystem compartments and processes is currently limited, and we need to expand our knowledge on these issues.

3. *Who are the key scientists working on snow/ice-ecological relationships in your field (in Svalbard, other Arctic areas or in alpine areas)?*
   Rolf A. Ims, Eric Post, Gilles Gauthier, Donald Reid, Nils C. Stenseth, Mads C. Forchhammer, Olivier Gilg, Mikkel Tamstorf, Niels M. Schmidt.

4. Please list the scientific papers most relevant for snow/ice in your field.

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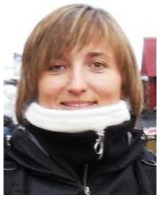

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# Appendix 4: Workshop programme

| DAY 1 - **Talks** | **Tuesday 14 February** |
|---|---|
| 08:30 – 08:45 | **Welcome, introduction, background & practical information**<br>Halvard R. Pedersen (SSF) and the Planning Group |
| **Session Snow & Ice** | Chair: Krzysztof Migala |
| 08.45 – 09.00 | Piotr Glowacki: **Last summary and paper concerning snow in Svalbard (2003) - new goals, tasks and direction** |
| 09.00 – 09.15 | Krzysztof Migala: **Atmosphere boundary layer, local climate & snow** |
| 09.15 – 09.30 | Anna K. Sinisalo: **Multi-methodological approach in investigating the spatial and temporal variability of snow distribution on Svalbard** |
| **09.30 – 10.00** | Coffee break |
| 10.00 – 10.15 | Irina Solovyanova: S**now distribution on Aldegonda and West Grønfjord Glaciers (Spitsbergen)** |
| 10.15 – 10.30 | Bartek Luks: **A comparison of two approaches to model snow cover dynamics at the Polish Polar station at Hornsund** |
| 10.30 – 10.45 | Mariusz Grabiec: **Snow cover distribution and structure on glaciers of Svalbard** |
| 10.45 – 11.00 | Elisabeth Isaksson: **Svalbard ice and snow as archives for climate and pollution** |
| **11.00 – 11.30** | Coffee break |
| **Session Terrestrial ecology** | Chair: Elisabeth Cooper |
| 11.30 – 11.45 | Elisabeth Cooper: **A n overview of the effects of changes in winter climate on Arctic terrestrial ecosystems** |
| 11.45 – 12.00 | Stef Bokhorst: **Extreme winter warming in the sub-Arctic** |
| 12.00 – 12.15 | Heikki Hänninen: **Snow and overwintering ecophysiology of northern plants: Combining experimental studies with modelling** |
| 12.15 – 12.30 | Åshild Pedersen: **Svalbard's terrestrial ecosystem: Impact of snow and ice on the herbivore guild and their shared predator** |
| **12.30 – 13.30** | **Lunch** |
| 13.30 – 13.45 | Lennart Nilsen: **Time serial studies of arctic vegetation: Bridging the spatial scale from field sampling to satellite remote sensing** |
| 14.00 – 14.15 | Birgit Sattler: **Glaciers are becoming greener** |
| 14.15 – 14.30 | Bronislaw Wojtuń: **Polish ecological studies in Hornsund** |
| 14.30 – 14.45 | Josef Elster/Jan Kavan: **Czech research in Petuniabukta, Billefjorden, northern part of Isfjorden, Svalbard** |
| **14.45 – 15.15** | Coffee break |
| **Session Pollutants** | Chair: Roland Kallenborn |
| 15.15 – 15.30 | Roland Kallenborn: **Remobilization, Atmospheric distribution and melt water Run-off. Climate change and the presence of persistent organic pollutants in the Arctic** |
| 15.30 – 15.45 | Terry Bidleman: **Delivery of POPs to the Arctic: Transport and Air-Surface Exchange Processes** |
| 15.45 – 16.00 | Crispin Halsall: **The accumulation, behavior and fate of POPs in the seasonal snowpack** |
| 16.00 – 16.15 | Kaj Mantzius Hansen: **Modelling the effect of snow of the fate of persistent organic pollutants** |
| **16.15 – 16.45** | Coffee break |
| 16.45 – 17.00 | Mark Hermanson: **Organic contaminants in ice cores from Svalbard** |
| 17.00 – 17.15 | Margit Schwikowski: **Recent Pollution levels from Lomonosovfonna ice core, Svalbard** |
| 17.15 – 17.30 | Sergey Vlasov: **Organochlorines contamination in Barentsburg area, Svalbard, 2002-2011. Local sources** |

| DAY 2 – **Discussions and work groups** | **Wednesday 15 February** |
|---|---|
| 09:00 **–** 09:30 | Info / Logistics and SSF fundings |
| 09.15 – 12.00 | **SESSION 1: Discussions within the research groups (snow/ice, ecology, pollutants)**<br>Leaders and rapporteurs: [Name1], [Name 2], [Name 3] |
| **12.00 – 13.00** | **Lunch** |
| **13.00 – 14.30** | **Workshop Walk** |
| 14.30 – 15.30 | **Presentations in plenary: Conclusions (session 1)** |
| 15.30 – 16.00 | **Coffee break** |
| 16.00 – 16.30 | **Group discussions on the suggestions from SESSION 1: Linkage between fields and priorities** |
| 18.00 – 19.00 | **Presentations in plenary and discussion: Suggestions for linked and prioritised projects** (continue day 3) |
| 19.00 | **Dinner** |

| DAY 3 – **Sum-up and conclusions** | **Thursday 16 February** |
|---|---|
| 09:00 - 09:10 | Info / Logistics (checkout..) |
| 09.15 – 11.00 | **SESSION 2: Discussions in mixed work groups: Project ideas, titles and description** |
| 11.00 – 12.00 | **Presentations in plenary, conclusions and closing the workshop**<br>Elisabeth Cooper, Halvard R. Pedersen |
| **12.00 – 13.00** | Lunch |

Working in groups at day 2, discussions within the fields ecology (upper left), pollutants (upper right) and snow & ice (bottom). Photos: Halvard R. Pedersen

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