Nitrogen fixation rates in high-arctic dry heath and the influence of climate change and water additions

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Published in:
Zackenberg Ecological Research Operations

Publication date:
2011

Document version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Sørensen, P. L., Skovgaard, M. S., & Michelsen, A. (2011). Nitrogen fixation rates in high-arctic dry heath and the influence of climate change and water additions. In *Zackenberg Ecological Research Operations: 16th annual report 2010* (pp. 84). Aarhus University, DCE – Danish Centre for Environment and Energy.

ZERO

ZACKENBERG ECOLOGICAL RESEARCH OPERATIONS

16th Annual Report 2010

Aarhus University
DCE – Danish Centre for Environment and Energy

ZACKENBERG ECOLOGICAL RESEARCH OPERATIONS

16th Annual Report 2010

AARHUS
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FOR ENVIRONMENT AND ENERGY

Data sheet

Title: Zackenberg Ecological Research Operations
Subtitle: 16th Annual Report 2010

Editors: Lillian Magelund Jensen and Morten Rasch
Department of Bioscience, Aarhus University

Publisher: Aarhus University, DCE – Danish Centre for Environment and Energy
URL: http://dmu.au.dk

Year of publication: 2011

Please cite as: Jensen, L.M. and Rasch, M. (eds.) 2011. Zackenberg Ecological Research Operations, 16th Annual Report, 2010. Aarhus University, DCE – Danish Centre for Environment and Energy. 114 pp.

Layout and drawings: Tinna Christensen, Department of Bioscience, Aarhus University
Front cover photo: The new researcher house in Daneborg, August 2010. Photo: Henrik Spanggård Munch.
Back cover photos: Jørgen Skafte drilling through the ice on Sommerfuglesø. May 2010. Photo: Charlotte Sigsgaard.

ISSN: 1904-0407
ISBN: 978-87-92825-27-8

Number of pages: 114

Internet version: The report is available in electronic format (pdf) on www.zackenberg.dk/Publications and on www.dmu.au.dk

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Zackenberg Ecological Research Operations (ZERO) is together with Nuuk Ecological Research Operations (NERO) operated as a centre without walls with a number of Danish and Greenlandic institutions involved. The two programmes are gathered under the umbrella organization Greenland Ecosystem Monitoring (GEM). The following institutions are involved in ZERO:
Department of Bioscience, Aarhus University: GeoBasis, BioBasis and MarineBasis programmes
Greenland Institute of Natural Resources: MarineBasis programme
Asiaq – Greenland Survey: ClimateBasis programme
University of Copenhagen: GeoBasis programme
Geological Survey of Denmark and Greenland: GlacioBasis programme

The programmes are coordinated by a secretariat at Department of Bioscience, Aarhus University and financed through contributions from:
The Danish Energy Agency
The Environmental Protection Agency
The Government of Greenland
Private foundations
The participating institutions

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Summary for policy makers

Lillian Magelund Jensen and Morten Rasch

The year 2010 was a busy year at Zackenberg Research Station with a field season from 4 May to 2 November, 73 scientists visiting the station and the number of bed nights totalling 1869.

In mid-August 2010, the Danish Minister of Climate and Energy, Lykke Friis, visited Zackenberg Research Station together with a delegation from the ministry and a delegation from Aarhus University led by Rector Lauritz Holm-Nielsen.

A new researcher house was constructed in Daneborg. The house can accommodate ten scientists in double rooms, and has a kitchen, a living room and a modern bathroom. Besides, the house holds a storage room and a modern laboratory. The project was made possible through a generous grant from Aage V. Jensen Charity Foundation.

Zackenberg Research Station staff became involved in several larger international research projects. Greenland Ecosystem Monitoring (GEM) is co-leading and coordinating two work packages in the EU project 'International Network for Terrestrial Research and Monitoring in the Arctic' (INTERACT), and is leading a task concerning international cooperation in the EU project 'Svalbard Integrated Arctic Earth Observing System' (SIOS). INTERACT has a strong transnational access component, which from 2011 will allow scientists to visit the stations involved in the network free of charge. Zackenberg Research Station has been allocated approximately 1000 bed nights for transnational access during the period 2011-14.

Results from the Zackenberg Basic monitoring programme are continuously published in scientific papers and popular science articles. Data from the Zackenberg Basic programme is freely available and was in 2010 used for reporting purposes in a number of international fora and by a number of externally funded research projects. GEM (Zackenberg and Nuuk Ecological Research Operations) has also seen the development of two larger research initiatives related to some of its basis programmes. Substantial funding has been given to a Canada Excellence Research Chair (CERC) in Arctic Geomicrobiology and Climate Change at the University of Manitoba led by Professor Søren Rysgaard from Greenland Climate Research Centre and to a new Nordic Centre of Excellence, DEFROST, led by Professor Torben Røjle Christensen from Lund University, Sweden.

Late in 2010, a strategy for Greenland Ecosystem Monitoring 2011-15 was approved by the Greenland Ecosystem Monitoring Steering Committee.

During 2010, the Zackenberg Basic programmes had a turnover of approximately 9 million DKK.

Executive Summary

Charlotte Sigsgaard, Michele Citterio, Niels Martin Schmidt, Mikael K. Sejr, Lillian Magelund Jensen and Morten Rasch

Introduction

The year 2010 was a busy year at Zackenberg Research Station with a field season from 4 May to 2 November, 73 scientists visiting the station and the number of bed nights totalling 1869.

ClimateBasis and GeoBasis

The winter 2009/2010 had a long lasting continuous snow cover due to the very early build up of snow. Snow depth and the onset of snowmelt were, however, average compared to previous years. By 19 June, the snow had disappeared from the area around the meteorological station.

Mean monthly temperatures in February and March were the lowest measured ever, whereas the other months had average monthly temperatures. It was a very dry summer with only traces of rain in July and August resulting in a very low water table in the valley. Most of the rain fell in September, which was a very wet month, compared to earlier observations.

Episodes of freezing temperatures were observed in both July and August but diurnal average temperatures below 0 °C were not registered until 7 September and first after 29 September did the diurnal average temperatures stay below zero.

A thin snow cover started to build up in the valley from 3 October 2010 (first lasting snow) but when the station was left in early November the snow depth was still below 10 cm at the meteorological station.

Zackenbergelven broke up 30 May, when water started to run from several of the secondary streams in the eastern part of the drainage basin. Contribution from the main streams Lindeman and Store Sødal was not significant until 5 June. By the end of September, the river was again covered by ice and only a limited base flow persisted. The total runoff was 173 million m^3, which is within the average range for Zackenbergelven. The suspended sediment transport amounted to 23538 tonnes, which is also quite normal for years where no major flood takes place during the summer, as was the case this year.

In Young Sund/Tyrolerfjord the ice broke up around 7 July, and by 18 July, there was no longer ice present in Young Sund. The timing of the break up is close to the average of what have been registered so far. New ice started to form on the fjord in early October and by 12 October; the fjord was covered by a thin layer of fast ice.

Soil thaw in the two CALM plots (ZEROCALM 1 and ZEROCALM 2) took place from the moment snow disappeared and reached a maximum by the end of August. At both sites, the thickness of the active layer was close to previous years maximum.

Gas flux measurements between land and atmosphere continued in the fen and in the well-drained heath area. At the heath site measurements of exchange rates of CO_2 was initiated 5 May and lasted until 31 October. From 1 July to 14 August, there was a net uptake of CO_2 and within this period, the total accumulation of carbon amounted to 26.8 g m^{-2}. A maximum diurnal uptake of 1.14 g C $m^{-2}d^{-1}$ took place 15 July. During the entire period, the net CO_2 balance amounted to 5.0 g C m^{-2}, which results in 2010 being the first year where the heath system acted as a net CO_2 source since measurements started in 2000.

Due to instrumental problems, the 3D wind measurements at the fen site failed a week after they had started and left a gap in the time series from 16 May to 8 July. Therefore, a total accumulation of CO_2 is not available from this site. The maximum diurnal uptake of 5.15 g C m^{-2} d^{-1} was measured 15 July – on the same date as observed at the heath site but almost five times as high. At the fen site, the system shifted back to being a net source of CO_2 16 August –two days later than at the heath site.

Methane emissions from the fen were measured in chambers from 23 June to 2

November. Emissions peaked 7 July with 2.4 mg CH_4 m^{-2} h^{-1}. The early summer and mid-summer peak emissions were similar to those measured in 2009. Again, an increase in the methane emissions was registered during soil freeze-in in October although the fluxes were not as high as detected in 2007.

GlacioBasis

The GlacioBasis programme monitors the main outlet glacier of the A.P. Olsen Ice Cap in the Zackenberg river catchment (NE Greenland).

The existing infrastructure was established in 2008 and tasks carried out in 2010 were:

- a network of 14 ablation and displacement stakes, extended to 15 in 2010
- maintaining three automatic weather stations (AWS), two of which have satellite data-link to Denmark
- survey of snow depth by snow radar calibrated with manual probing and density profiles from snow pits
- survey of surface velocity and surface elevation by differential GPS
- workflow for data retrieval, validation and storage
- scheduling of on-demand acquisitions by the US-Japan ASTER instrument onboard the Terra satellite, with custom tuning of the satellite sensor settings to avoid saturation over high albedo surfaces

Fieldwork in 2010 was completed successfully in all planned components. All ablation and surface velocity stakes have been surveyed and maintained, with the exception of the stake in the crevassed area close to the ice-dammed lake, which was not approached for safety reasons. The first differential GPS survey of the stakes was carried out to serve as a reference for re-measurement in 2011 and the following years. More than 40 km of snow radar and differential GPS profiles of the glacier surface have been acquired and post-processed with reference to a temporary base station established at the terminus forefront. All three AWS have been visited and maintained and the calibration plan of the sensors is up to date. On 19 October 2010, satellite telemetry from the AWS3 close to the summit of the Ice Cap stopped in high wind conditions.

The bottom topography of the ice dammed lake responsible for the recurring glacier outburst floods into the Zackenberg River has been preliminary mapped from satellite laser altimetry and the water volume estimated to approximately 9-10 10^6 m^3.

BioBasis

Snow melt in 2010 was later than the extremely early year 2009, but still relatively early compared to previous seasons. The relatively early snowmelt resulted in earlier than average flowering in most plots compared to all previous seasons. However, despite the relatively early snow melt and flowering, not all plant plots had earlier than average dates of 50 % open seed capsules, and four of 14 plots had later than average dates. The number of flowers produced in the 2010 season was generally lower or close to average of the previous seasons, and with new minima in two arctic poppy, two arctic willow (male catkins), and one moss Campion plots. The mean landscape NDVI in the 2010 season was around the average of the previous season, but with relatively early peaks in the plot NDVI measurements. Also, the NDVI measurements along a fixed transect revealed that the pattern of vegetation greening was similar in the three altitude categories, and the NDVI levels in each altitude category was similar within all vegetation types but in the grassland, where higher NDVI values were observed with decreasing altitude. In the ITEX experimental warming plots, carbon flux measurements showed that the *Salix* heath was more productive than the *Cassiope* heath, which is in line with results from previous years. Both sites functioned as sinks for atmospheric CO_2 during summer, while during autumn they were small sources. Warming generally increased both ecosystem respiration (R_{eco}) and gross primary productivity (GPP) at both sites, though not consistently significant. For the net ecosystem exchange (NEE), warming significantly increased the loss of carbon during the autumn. In the experimental UV-B exclusion plots, the seasonal development and magnitudes of NEE, R_{eco} and GPP were similar to those recorded at the ITEX *Salix* site. However, there were no significant difference between treatment effects observed for NEE, R_{eco} and GPP. In the UV-B exclusion plots, the total leaf performance index (PI_{total}) was the most sensitive parameter in both *Salix* and *Vaccinium*. The PI_{total} was reduced by around 15 % in *Vaccinium* and around 20 % in *Salix* when comparing the filter treatment to reduced UV-B. In addition, in 2010, the ZERO line was re-examined, and data are being processes. With respect to the monitoring of northern limit species, the re-examinations revealed marked differences from previous years, with many plots exhibiting an increase in number of flowers and fruits, which contrast the conclusion of the comparison of the 2000 and 2005 data.

Unfortunately, most of the arthropod samples collected during the 2010 season did not arrive in Denmark at the end of the field season, and its whereabouts at the time of the deadline for this report was unknown. Consequently, samples have not been sorted. We hope to be able to present the arthropod data for the 2010 season in the 2011 Annual Report.

The breeding bird census resulted in densities generally comparable to previous years, but with relatively high densities of sanderling and dunlin territories. For all wader species, nesting was early compared to previous years, and with extremely low nest success. The number of long-tailed skua territories was lower than average, and only one pair nested (unsuccessfully) in the census area. For barnacle geese, the mean brood size was low early in the season, but later in the season numbers were close to average.

In 2010, only 27 new collared lemming nests were recorded, which is the lowest number ever recorded. And as in the later years, not a single nest was found depredated by stoat. Musk ox numbers were lower than the average of previous years, and with high numbers only remarkably late in the autumn. Breeding of Arctic fox was verified in two dens, with a minimum of 11 pups. Arctic hare numbers were close to average for all available previous seasons.

With respect to lake ecology, the 2010 season was characterized by an early ice-off and a warm summer. Water temperatures followed the general trend of warming observed during the previous seasons. The phytoplankton communities were dominated by chrysophytes during most of the season in both lakes, while the zooplankton communities held large numbers of *Daphnia pulex* in the fish-free Sommerfuglesø, and while the species was absent in Langemandssø with fish. The recorded species composition as well as densities was within the range found for previous years.

MarineBasis

In Young Sund, the sea ice conditions play an important role for the physical, chemical and biological processes in the fjord. The duration of the summer period, where the fjord is without sea ice cover has been recorded since 1963. Until the late 1990s, the open water period was relatively stable around 90 days a year. The last 10 years we have observed increased variability with open water season increasing up to more than 130 days in 2002 and 2008. In 2010, the open water period was 99 days.

The importance of the ice conditions in the fjord motivated the instalment of two new ice-monitoring cameras during the 2010 season. Both cameras were placed on the top of Brisbane Bjerg and monitor ice conditions in the outer part of Young Sund and the Greenland Sea where we want information about the polynya extend and duration outside the fjord.

2010 was a successful season where all parameters were obtained according to the programme. All the autonomous equipment had recorded physical and chemical data through the winter as planned. The field season was conducted in calm and sunny conditions, which caused a well-stratified water column to develop with distinct vertical variation in physical, chemical and biological parameters. On August 9 strong winds lasted for less than 24 hours but it was enough to cause mixing of the surface water.

The stratification resulted in surface water that warmed up to above 8 °C and where salinity dropped below 25 due to fresh water input from land. In addition, the stratification resulted in depletion of nutrients in the surface water and the formation of a peak in fluorescence, which is an indicator of phytoplankton biomass at 25-30 m. In the water column, the composition of zooplankton community was characterized by low abundance of *Calanus* species and a dominance of smaller species such as of *Oncaea* spp. and *Oithona* spp. Compared to data from the onset of the programme, the relative distribution in abundance between the Arctic species *Calanus hyperboreus* and the Atlantic species *Calanus finmarchicus* remained low. The dominant species of the phytoplankton community was comparable to previous years as was the total number of species.

In 2010, two of the focus areas of the marine group working within Greenland Ecosystem Monitoring (GEM) were to 1) increase knowledge of the coupling between melting ice and fjord dynamics and 2) put the data obtained in Nuuk and Daneborg into a wider geographical perspective. This resulted in a very comprehensive measurement programme focusing on the Godthåbsfjord system combined with increased focus on comparing data between the two monitoring sites, between other study sites in Greenland and trying to compile data from Greenland for comparison to other Arctic regions. Using the monitoring programmes as a platform a number of research projects was initiated with funding from sources like Aarhus University Research Fund, the Nordic Council, EU's 7th framework programme and the Danish Energy Agency. This work is in progress and has already resulted in a number of scientific papers with more under way.

Research projects

Fifteen research projects were carried out at Zackenberg Research Station in 2010. Of these four projects were parts of the Zackenberg Basic monitoring programmes. Twelve projects used Zackenberg Research Station as a base for their activities and three projects used Daneborg.

1 Introduction

Morten Rasch and Lillian Magelund Jensen

The year 2010 was another busy year at Zackenberg Research Station. The field season started 4 May and lasted until 2 November. In total 73 scientists visited the station during that period, and the total number of bed nights was 1869.

1.1 International cooperation

In 2010, Zackenberg Research Station staff became involved in several larger international research projects. Greenland Ecosystem Monitoring (GEM) is co-leading and coordinating two work packages in the EU project 'International Network for Terrestrial Research and Monitoring in the Arctic' (INTERACT), and is leading a task concerning international cooperation in the EU project 'Svalbard Integrated Arctic Earth Observing System' (SIOS). INTERACT has a strong transnational access component, which from 2011 will allow scientists to visit the stations involved in the network free of charge. Zackenberg Research Station has been allocated approximately 1000 bed nights for transnational access during the period 2011-14. Further, INTERACT will contribute to the work at Zackenberg with three so-called joint research activities focusing on (i) development of intelligent data loggers and telemetry, (ii) improved measurements of climate change feedback mechanisms in arctic ecosystems, and (iii) data storage. A Station Managers Forum within INTERACT and with station managers from 36 research stations in the Arctic are led by the Greenland Ecosystem Monitoring Coordinator.

In both INTERACT and SIOS, GEM is responsible for international cooperation including linkage to other research and monitoring networks, programmes and projects.

A research group from Lund University led by Professor Torben Røjle Christensen has received a grant to establish a Nordic Centre of Excellence from the Nordic Council of Ministers to work with greenhouse gas balance and climate change feedbacks in arctic ecosystem. This project has the two Greenland Ecosystem Monitoring field sites at Zackenberg and Nuuk among its most important study areas.

Substantial funding was also given to a Canadian Excellence Research Chair (CERC) in Arctic Geomicrobiology and Climate Change at the University of Manitoba led by Professor Søren Rysgaard from Greenland Climate Research Centre.

1.2 Visit by the Danish Minister of Climate and Energy

In early August 2010, the Danish Minister of Climate and Energy, Lykke Friis, visited Zackenberg Research Station together with a delegation from the ministry and a delegation from Aarhus University led by Rector Lauritz Holm-Nielsen. Zackenberg scientists including Professor Søren Rysgaard (Greenland Climate Research Centre), Professor Torben Røjle Christensen (Lund University), senior scientist Andreas Ahlstrøm (Geological Survey of Denmark and Greenland) and scientific leader at Zackenberg Morten Rasch (Aarhus University) introduced the two delegations to the work at Zackenberg Research Station. The delegation spent two days at Zackenberg, and several possible developments of research activities in the area were discussed by the delegations.

1.3 New researcher house in Daneborg

In 2010, a new researcher house was constructed in Daneborg. The house can accommodate ten scientists in double rooms, and has a kitchen, a living room and a modern bathroom. Besides, the house holds a storage room and a modern laboratory. The house is situated next to the boathouse in Daneborg. The construction of the house was carried out during approximately three weeks in August 2010 by construction workers from Venslev Enterprise helped by logisticians from Aarhus University. The project was made possible through a generous grant from Aage V. Jensen Charity Foundation. With the new improved facilities in Daneborg, it is expected that Zackenberg Research Station will be able to attract more marine scientists in the future. The house is ready for use from the beginning of the 2011 field season, and it is already booked for a large part of the summer.

1.4 Greenland Ecosystem Monitoring Strategy 2011-15

Late in 2010, a strategy for Greenland Ecosystem Monitoring 2011-15 was approved by the Greenland Ecosystem Monitoring Steering Committee. The strategy includes thirteen different research questions to be addressed during 2011-15. The strategy is available on www.zackenberg.dk and www.g-e-m.dk. In 2011, the Greenland Ecosystem Monitoring Coordination Group will produce a working programme for Greenland Ecosystem Monitoring 2011-15 to describe in more details how the goals of the strategy will be achieved.

1.5 Zackenberg Secretariat

After the closure of the Danish Polar Centre 31 December 2008, National Environmental Research Institute (now Department of Bioscience) at Aarhus University has accommodated the Secretariats for Zackenberg Research Station, Zackenberg Ecological Research Operations (ZERO), Nuuk Ecological Research Operations (NERO) and Greenland Ecosystem Monitoring (GEM).

Kirstine Skov (GeoBasis) introduces the two delegations to the work at Zackenberg Research Station. From left: Henrik Sandbech, Thomas Egebo, Lauritz Holm-Nielsen, Lykke Friis and Kirstine Skov. Photo: Sofus Rex.

1.6 Further information

Further information about Zackenberg Research Station and the work at Zackenberg are collected in previous annual reports (Meltofte and Thing 1996, 1997; Meltofte and Rasch 1998; Rasch 1999; Canning and Rasch 2000, 2001, 2003; Rasch and Canning 2003, 2004, 2005; Klitgaard et al. 2006, 2007; Klitgaard and Rasch 2008, Jensen and Rasch 2009, 2010) and in a book about the first ten years of monitoring and research at Zackenberg (Meltofte et al. 2008). Much more information is available at the Zackenberg website, www.zackenberg.dk, including the ZERO Site Manual, manuals for the different monitoring programmes, a database with data from the monitoring programmes, up-to-date weather information, a Zackenberg bibliography and an extensive collection of public outreach papers in PDF-format.

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The new researcher house at Daneborg. Photo: Jøgen Skafte.

2 Zackenberg Basic

The ClimateBasis and GeoBasis programmes

Charlotte Sigsgaard, Kisser Thorsøe, Magnus Lund, Kirstine Skov, Morten Larsen, Dorthe Petersen, Per Hangaard, Julie Maria Falk, Birger Ulf Hansen, Mikhail Mastepanov, Torben R. Christensen and Mikkel P. Tamstorf

GeoBasis and ClimateBasis provide long-term data of climate, hydrology and physical landscape variables describing the environment at Zackenberg. This includes climatic measurements, seasonal and spatial variations in snow cover and local microclimate in the Zackenberg area. Furthermore, water balance of Zackenbergelven's drainage basin, the sediment and solute transport of Zackenbergelven, the carbon dioxide (CO_2) and methane (CH_4) fluxes from a well drained heath and a fen area, the seasonal development of the active layer, temperature conditions and soil water chemistry of the active layer, and the dynamics of selected coastal and periglacial landscape elements. For a map of the main study sites, see figure 2.1.

GeoBasis is operated by the Department of Arctic Environment, National Environmental Research Institute, at Aarhus University, in collaboration with Department of Geography and Geology, University of Copenhagen. In 2010, GeoBasis was funded by Danish Ministry for Climate and Energy as part of the environmental support programme DANCEA – Danish Cooperation for Environment in the Arctic. ClimateBasis is run by Asiaq – Greenland Survey, who operates and maintains the meteorological station and the hydrometric station. ClimateBasis is funded by the Government of Greenland.

More details about sampling procedures, instrumentation, locations and installations are given in the GeoBasis Manual and the ClimateBasis Manual. Both can be downloaded from www.zackenberg.dk. Validated data from the monitoring programmes are also accessible from this website. However, GeoBasis data are currently not being updated in the public database due to implementation of a new data handling and validation tool. For updated validated GeoBasis data please contact Mikkel Tamstorf (mpt@dmu.dk) or Charlotte Sigsgaard (cs@geo.ku.dk). For matters, concerning ClimateBasis please contact Kisser Thorsøe (kit@asiaq.gl).

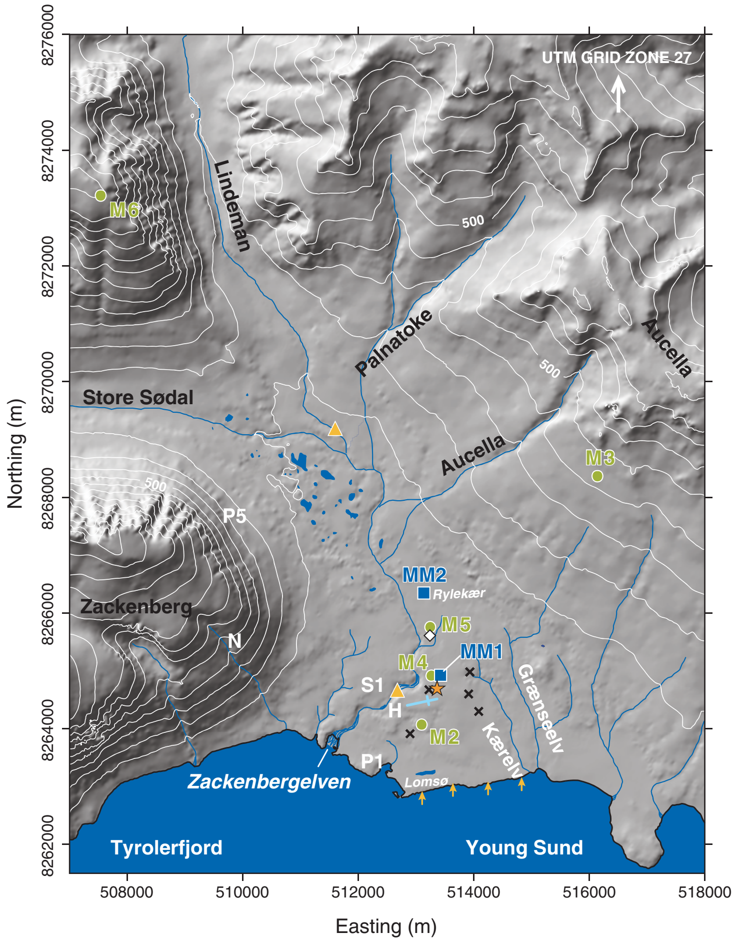


Figure 2.1 GeoBasis and ClimateBasis plots. Asterix=Meteorological station. H=Hydrometric station. Rectangles=Eddy towers. Circles=Snow and micrometeorological stations. Triangles= Water sample sites. N=Nansenblokken (photo site). Crosses=Soil water sites. Square=Methane site. Arrows= Coastal cliff recession.

2.1 Meteorological data

The meteorological station at Zackenberg was installed during summer 1995. Technical specifications of the station are described in Meltofte and Thing 1996. Once a year the sensors are calibrated and checked by Asiaq - Greenland Survey. In 2005, a satellite modem was installed on the eastern mast from which data are transferred once a day. Due to problems connecting to the modem it was planned to replace the system during the annual visit to the station. Unfortunately, it was not possible and therefore data has not been transferred daily in 2010.

Data was collected from the climate stations 2 November, just before the research

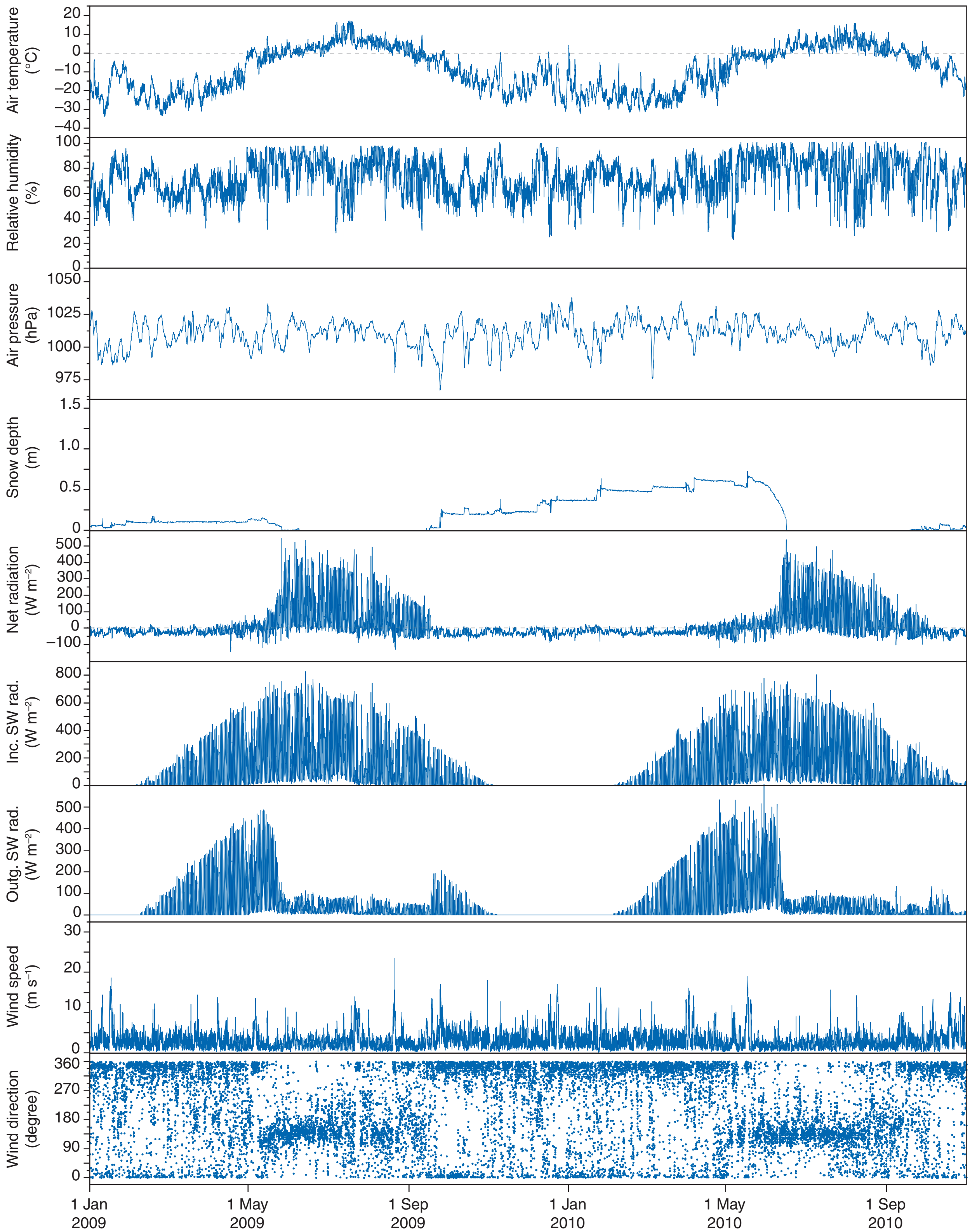


Figure 2.2 Variation of selected climate parameters during 2009 and 2010. Wind speed and direction are measured 7.5 m above terrain; the remaining parameters are measured 2 m above terrain. Data for November and December 2010 has not been retrieved yet. No precipitation data for the period 22 January to 7 April.

station was closed for the winter. As data for the last two month of 2010 has not been retrieved yet, a thorough presentation of data from 2010 will be presented in the 2011 Annual Report, but data for 2009 and until 1 November 2010 are shown in figure 2.2 and monthly mean values of climate parameters for 2009-2010 are shown in table 2.3. Furthermore, annual values for selected parameters for 1996 to 2009 and mean wind statistics have been updated in tables 2.1 and 2.5.

Table 2.1 Annual mean, maximum and minimum values of climate parameters for 1996-2009. No data for 2010 are shown as data from November and December 2010 has not yet been retrieved. Some figures differ from earlier publications due to re-evaluation of data.

Year	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Annual mean values														
Air temperature, 2 m above terrain (°C)	–9.0	–10.1	–9.7	–9.5	–10.0	–9.7	–8.6	–9.2	–8.5	–7.7	–8.1	–8.7	–8.1	–9.4
Air temperature, 7.5 m above terrain (°C)	–8.4	–9.3	–9.1	–8.9	–9.4	–9.2	–	–8.7	–7.9	–6.9	–7.6	–8.2	–7.9	–8.6
Relative air humidity 2 m above terrain (%)	67	68	73	70	70	71	72	71	72	71	72	69	72	71
Air pressure (hPa)	1009	1007	1010	1006	1008	1009	1009	1008	1007	1008	1007	1006	1008	1010
Incoming shortwave radiation ($W m^{-2}$)	113	104	101	100	107	112	105	104	99	101	107	107	107	104
Outgoing shortwave radiation ($W m^{-2}$)	52	56	55	56	52	56	54	49	42	43	54	45	52	38
Net radiation ($W m^{-2}$)	16	9	6	4	14	13	–	8	–	–	10	13	8	13
Wind velocity, 2 m above terrain ($m s^{-1}$)	2.7	3.0	2.6	3.0	2.9	3.0	2.8	2.6	3.0	2.9	2.8	2.6	2.9	2.6
Wind velocity, 7.5 m above terrain ($m s^{-1}$)	3.1	3.4	3.2	3.7	3.3	3.4	3.3	3.1	3.6	3.5	3.4	3.2	3.5	3.2
Precipitation (mm w. eq.), total	223	307	255	161	176	236	174	263	253	254	171	178	202	169
Annual maximum values														
Air temperature, 2 m above terrain (°C)	16.6	21.3	13.8	15.2	19.1	12.6	14.9	16.7	19.1	21.8	22.9	16.4	18.4	18.1
Air temperature, 7.5 m above terrain (°C)	15.9	21.1	13.6	14.6	18.8	12.4	–	16.7	18.5	21.6	22.1	15.6	18.2	17.7
Relative air humidity 2 m above terrain (%)	99	99	99	99	100	100	100	100	100	99	99	99	99	101
Air pressure (hPa)	1042	1035	1036	1035	1036	1043	1038	1038	1033	1038	1038	1037	1043	1034
Incoming shortwave radiation ($W m^{-2}$)	857	864	833	889	810	818	920	802	795	778	833	769	747	822
Outgoing shortwave radiation ($W m^{-2}$)	683	566	632	603	581	620	741	549	698	629	684	547	563	488
Net radiation ($W m^{-2}$)	609	634	556	471	627	602	–	580	–	–	538	469	565	594
Wind velocity, 2 m above terrain ($m s^{-1}$)	20.2	22.6	25.6	19.3	25.6	20.6	21.6	20.6	22.2	19.9	20.8	27.6	24.5	20.5
Wind velocity, 7.5 m above terrain ($m s^{-1}$)	23.1	26.2	29.5	22.0	23.5	25.0	25.4	23.3	25.6	22.0	22.8	29.6	28.9	24.4
Annual minimum values														
Air temperature, 2 m above terrain (°C)	–33.7	–36.2	–38.9	–36.3	–36.7	–35.1	–37.7	–34.0	–34.0	–29.4	–38.7	–33.9	–35.3	–33.9
Air temperature, 7.5 m above terrain (°C)	–31.9	–34.6	–37.1	–34.4	–34.1	–33.0	–	–32	–32.1	–27.9	–37.2	–32.5	–33.9	–33
Relative air humidity 2 m above terrain (%)	20	18	31	30	19	22	23	21	17	22	21	18	24	25
Air pressure (hPa)	956	953	975	961	969	972	955	967	955	967	968	969	963	967
Incoming shortwave radiation ($W m^{-2}$)	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Outgoing shortwave radiation ($W m^{-2}$)	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Net radiation ($W m^{-2}$)	–86	–165	–199	–100	–129	–124	–	–98	–	–	–99	–99	–104	–146
Wind velocity, 2 m above terrain ($m s^{-1}$)	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wind velocity, 7.5 m above terrain ($m s^{-1}$)	0	0	0	0	0	0	0	0	0	0	0	0	0	0

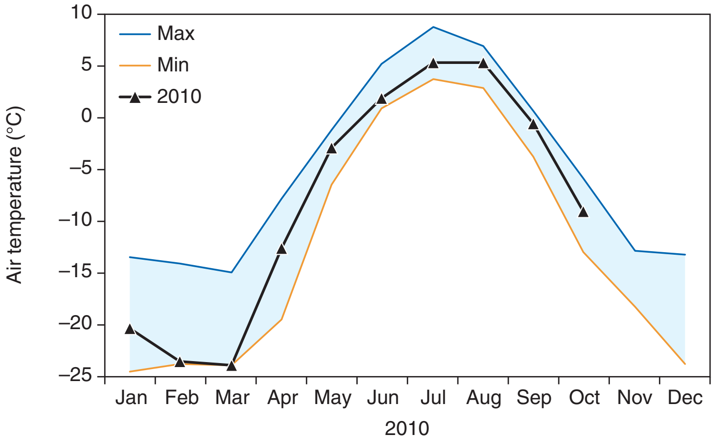


Figure 2.3 Monthly mean air temperatures 2010. Min and max are lowest and highest monthly mean air temperatures from 1996-2010.

The winter 2010 was cold; February was the second coldest month and March was the coldest month registered since measurements began, whereas the mean monthly temperatures until November was average (figure 2.3). The first positive temperatures in 2010 were measured 6 May and by 18 June, the temperature for the first time exceeded 10 °C. The maximum temperature was 16.1 °C (8 August). Monthly mean values of selected climate parameters for June, July and August from 1996-2010 are shown in table 2.4. The sum of positive degree-days during 2010 was a little less than average for the last 15 years (table 2.2). Episodes of night frost were registered in both July and August but the first negative diurnal mean temperature was not measured until 7 September.

After two years with relatively high summer precipitation, 2010 was very dry. With only 16 mm, the summer was among the years with lowest precipitation (table 2.4 and figure 2.13a). In June, most of the precipitation fell as snow whereas the precipitation in July and August was extremely sparse. Most rain fell in September during a very wet period from 9-13 September. Even as late as 27 September there was a rain event, which resulted in large icings as the bare ground was below freezing. All precipitation values in this section are actual amounts registered at the meteorological station. Values have not been adjusted for wind induced under catch or wetting loss.

2.2 Climate gradients, snow, ice and permafrost

In order to increase the spatial resolution of meteorological data and to describe the gradients (both altitudinal and coast/inland), several smaller weather stations have been installed in the area. In 2003, the station M2 was installed in the valley and the station M3 installed halfway up Aucellabjerget (Rasch and Caning 2004). M6 was installed at the top of Dombjerget in 2006 (Klitgaard et al. 2007) and M7 was installed in 2008 in the area just west of Store Sø in Store Sødal (Jensen and Rasch 2009). Three automatic weather stations were installed on the A. P. Olsen Glacier and data from these are reported in the GlacioBasis section.

Monthly mean temperatures from the four weather stations are shown in figure 2.4. Here it is very clear that the lower lying stations have larger annual variations than the higher lying stations. Especially during the winter months, the valley sta-

Table 2.2 Positive degree-days calculated on a monthly basis as the sum of daily mean air temperatures above 0 °C. Calculations are based on air temperatures from the meteorological station.

Degree days	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
January										1.5		3.6			
February															
March															
April								0.2	1.1		2.9				
May	1.1	1.3	0.1	3.6	0.5	0.5	18.2	3.3	4.1	5.4	3.1		10.0	12.3	0.4
June	63.7	74.6	32.5	52.9	71.8	68.2	81.8	74.2	73.9	84.6	37.2	99.7	155.0	64.6	73.3
July	181.0	115.4	147.36	192.7	164.4	152.0	175.6	237.2	222.2	214.7	205.3	182.2	270.8	265.6	165.6
August	140.5	154.2	143.6	89.2	127.3	181.2	152.5	203.2	169.4	141.5	171.5	204.5	213.7	141.3	164.3
September	15.3	4.5	11.3	19.7	5.7	31.1	41.2	42.5	41.4	17.7	15.7	10.1	63.1	8.9	29.6
October		1.5				0.3	1.8								
November															
December															
Sum	**401.7**	**351.5**	**334.8**	**358.0**	**369.7**	**433.2**	**471.1**	**560.6**	**514.8**	**466.4**	**435.7**	**500.1**	**712.6**	**492.7**	**433.2**

Table 2.3 Monthly mean values of climate parameters from 2009 and 2010. Some figures differ from earlier publications due to re-evaluation of data. Data for November and December 2010 has not yet been retrieved.

Year	Month	Air temperature (°C)		Rel. humidity (%)	Air press. (hPa)	Net rad.[1)] ($W m^{-2}$)	Shortwave rad.[1)] ($W m^{-2}$)		Wind velocity ($m s^{-1}$)		Dominant wind dir.
		2.0 m[1)]	7.5 m				In	Out	2.0 m	7.5 m	7.5 m
2009	Jan	–17.0	–15.9	69	999.9	–20	0	0	3.3	3.9	NNW
2009	Feb	–23.8	–22.5	66	1012.3	–25	7	6	2.5	3.0	NNW
2009	Mar	–21.8	–21.1	62	1011.4	–24	66	51	2.6	3.1	NNW
2009	Apr	–15.9	–15.5	65	1014.5	–15	169	129	2.1	2.6	NNW
2009	May	–1.1	–1.2	82	1006.2	38	252	145	2.1	2.7	SE
2009	Jun	1.9	1.5	85	1013.6	134	257	32	2.2	2.6	SE
2009	Jul	7.9	8.1	71	1014.6	103	233	30	2.8	3.3	SE
2009	Aug	4.4	4.9	81	1010.0	48	145	18	2.3	2.8	SE
2009	Sep	–2.2	–1.3	73	998.3	–3	89	24	2.9	3.6	NNW
2009	Oct	–13.0	–11.4	64	1011.5	–33	19	15	3.1	3.8	N
2009	Nov	–18.1	–16.4	68	1005.3	–23	0	0	2.4	2.9	NNW
2009	Dec	–15.0	–13.6	71	1016.7	–24	0	0	3.3	3.9	NNW
2010	Jan	–20.3	–18.8	71	1007.9	–18	0	0	2.7	3.2	NNW
2010	Feb	–23.5	–21.5	69	1019.4	–26	6	5	2.4	3.0	NNW
2010	Mar	–23.9	–22.0	65	1015.3	–26	67	51	2.5	3.1	NNW
2010	Apr	–12.7	–11.6	72	1012.7	–15	156	126	2.8	3.5	NNW
2010	May	–2.8	–2.2	80	1016.5	1	236	177	2.9	3.5	SE
2010	Jun	1.9	2.1	85	1011.1	98	272	95	1.7	2.0	SE
2010	Jul	5.3	5.4	80	1004.8	123	264	40	2.2	2.6	SE
2010	Aug	5.3	5.9	74	1010.3	58	164	27	2.0	2.6	SE
2010	Sep	–0.6	0.2	80	1011.2	3	61	11	2.0	3.0	NNW
2010	Oct	–9.0	–7.8	70	1010.0	–28	14	9	3.2	4.5	NNW
2010	Nov	–	–	–	–	–	–	–	–	–	–
2010	Dec	–	–	–	–	–	–	–	–	–	–

tions have much lower temperatures than the stations in the mountains. This is due to less shadowing and the effect of cold air sinking down.

Inversions where temperature increases with altitude are very common in Zackenberg but not evenly distributed over the year. In general, the highest occurrence of inversions is observed during the winter months (especially February and March). This happens when the sun angle is low and there is more shadow in the valley than higher in the mountains. September had the lowest occurrence. In 2010, inversion occurred 93 % of the time in February and only 13 % of the time in September based on diurnal mean temperatures from the meteorological station (38 m a.s.l.) and M3 (420 m a.s.l.). There is a similar seasonal pattern when comparing temperatures between M3 and M6 (1278 m a.s.l.) even though, inversions occur less frequent between these elevations (67 % of the time in January and only 3 % of the time in August). However, one has to take into account, that there are 400 m between M2 and M3 and 800 m between M3 and M6. On an annual basis, inversion prevails approximately 50 % of the time between the meteorological station and M3 whereas it is 25 % of the time between M3 and M6.

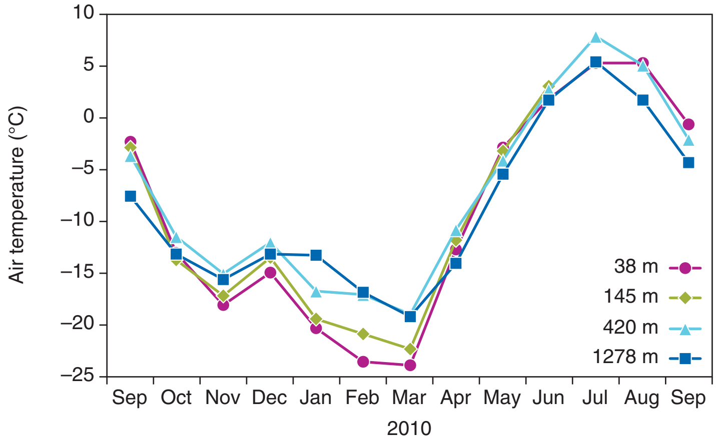


Figure 2.4 Monthly mean temperatures from automatic weather station M2 (17 m a.s.l.), M3 (420 m a.s.l.), M6 (1282 m a.s.l.), and M7 (145 m a.s.l.) during the period 1 September 2009 to 30 September 2010.

Table 2.4 Climate parameters for June, July and August 1996-2010. 1) Wind velocity, max is the maximum of 10 minutes mean values.

Year	Month	Shortwave rad. ($W\ m^{-2}$)		Net rad. ($W\ m^{-2}$)	PAR ($mmol\ m^{-2}\ s^{-1}$)	Air temperature (°C)			Precipitation (mm)	Wind velocity ($m\ s^{-1}$)		Dominant wind dir.
		mean in	mean out	mean	mean	mean 2 m	min. 2 m	max. 2 m	total	mean 7.5 m	max[1] 7.5 m	7.5 m
1996	Jun	332	133	113	–	1.9	–3.7	13.6	4	1.8	9.9	ESE
	Jul	238	24	145	–	5.8	–1.5	16.6	7	2.7	12.1	SE
	Aug	162	23	74	–	4.4	–4.0	14.1	2	2.9	12.5	SE
1997	Jun	222	111	85	–	2.2	–4.4	12.0	23	2.4	14.1	ESE
	Jul	225	23	130	–	3.7	–1.0	15.3	28	2.7	13.8	SE
	Aug	159	20	74	–	5.0	–3.0	21.3	16	2.8	13.3	SE
1998	Jun	270	172	51	–	0.9	–3.0	9.6	5	1.6	8.1	SE
	Jul	204	20	125	–	4.7	–2.6	13.8	33	2.3	12.1	SE
	Aug	114	12	64	–	4.6	–1.8	11.5	55	2.4	12.2	ESE
1999	Jun	294	206	33	–	1.5	–4.5	10.4	2	2.3	15.0	–
	Jul	212	32	123	–	6.2	–0.7	15.1	21	2.6	14.8	–
	Aug	143	16	73	–	2.9	–2.7	15.2	11	2.5	14.9	SE
2000	Jun	294	103	126	–	1.9	–6.2	11.7	10	2.1	15.1	SE
	Jul	228	27	141	–	5.3	–1.2	19.1	13	2.9	15.9	SE
	Aug	153	19	82	–	4.0	–3.5	11.6	0	2.3	13.4	SE
2001	Jun	293	168	67	–	2.1	–4.9	11.9	26	2.1	13.3	–
	Jul	231	27	146	–	4.9	–1.5	11.8	7	2.9	13.1	–
	Aug	180	20	84	–	5.8	–0.8	12.6	21	2.9	14.4	–
2002	Jun	344	151	113	–	2.6	–2.8	14.9	1	1.6	6.8	SE
	Jul	205	23	105	424	5.7	–0.9	13.8	11	2.6	9.9	SE
	Aug	129	16	51	272	4.9	–3.1	11.6	15	2.8	12.9	SE
2003	Jun	294	108	106	612	2.2	–4.8	14.7	7	1.6	5.4	SE
	Jul	210	26	96	431	7.7	1.8	16.7	6	2.8	14.2	SE
	Aug	151	20	56	313	6.6	–0.5	15.4	3	2.5	10.1	SE
2004	Jun	279	73	111	571	2.5	–3.4	19.1	3	2.3	13.6	SE
	Jul	225	30	95	464	7.2	–0.7	19.0	10	2.8	10.5	SE
	Aug	150	20	62	302	5.6	–1.4	17.2	4	2.4	12.6	SE
2005	Jun	261	53	–	519	2.7	–3.5	13.4	6	2.4	11.8	SE
	Jul	215	29	–	428	6.9	–0.6	21.8	28	2.9	13.3	SE
	Aug	154	21	51	321	4.6	–2.7	14.0	4	3.2	10.9	SE
2006	Jun	312	208	54	675	1.0	–4.4	9.5	0	1.7	6.9	SE
	Jul	256	28	131	550	6.6	–1.2	22.8	12	2.5	11.3	SE
	Aug	158	21	61	336	5.5	–4.5	16.3	2	2.6	12.0	SE
2007	Jun	287	86	116	609	3.3	–2.4	15.8	9	2.2	14.8	SE
	Jul	251	32	118	531	5.9	–1.8	16.4	8	2.2	6.5	SE
	Aug	149	20	56	320	6.6	–2.6	13.6	6	2.7	12.3	SE
2008	Jun	284	145	74	612	5.2	–1.5	12.8	3	1.9	11.7	ESE
	Jul	260	32	126	551	8.8	0.0	18.4	8	2.8	14.2	SE
	Aug	141	19	51	296	8.0	0.3	17.1	49	3.3	16.9	SE
2009	Jun	257	32	134	532	1.9	–2.4	9.3	3	2.6	11.0	SE
	Jul[2]	233	30	103	487	7.9	0.4	18.1	26	3.3	15.4	SE
	Aug[2]	145	18	48	292	4.4	–1.8	11.6	31	2.8	24.4	SE
2010	Jun[2]	272	95	98	548	1.9	–8.1	12.8	13	2.0	10.2	SE
	Jul[2]	264	40	123	529	5.3	–1.7	15.1	1	2.6	15.7	SE
	Aug[2]	164	27	58	325	5.3	–2.6	16.1	2	2.6	15.0	SE

Table 2.5 Mean wind statistics are based on wind velocity and direction measured 7.5 m above terrain in 1997, 1998, 2000 and 2002-2009. Due to re-evaluation of figures from 2003, differences can be seen if compared to earlier publications. Calm is defined as wind speed lower than 0.5 m s^{-1}. Max speed is maximum of 10 minutes mean values. Mean of maxes is the mean of the yearly maximums. The frequency for each direction is given as percent of the time for which data exist. Missing data amounts to less than 8 % of the entire year and less than 20 days within the same month.

Year	Mean[1)]				2007			2008			2009		
Direction	Frequency	Velocity (m s^{-1})			Frequency	Velocity (m s^{-1})		Frequency	Velocity (m s^{-1})		Frequency	Velocity (m s^{-1})	
	%	mean	mean of max	max	%	mean	max	%	mean	max	%	mean	max
N	15.8	4.5	24.2	29.6	17.2	4.5	29.6	18.7	5.0	21.5	15.5	4.2	24.4
NNE	3.6	2.7	18.8	28.9	3.8	2.2	17.6	4.0	3.1	28.9	3.5	2.6	17.0
NE	2.5	2.4	15.3	23.2	2.5	1.7	14.9	2.5	2.7	23.2	2.4	2.2	15.4
ENE	2.7	2.4	12.8	17.4	2.7	1.8	9.6	2.8	2.2	13.7	2.5	2.3	15.4
E	3.9	2.0	9.1	10.7	3.8	1.9	7.8	3.9	1.7	8.4	3.2	1.9	7.3
ESE	6.7	2.2	9.0	10.3	6.8	2.1	7.6	6.6	2.2	9.4	5.8	2.2	7.9
SE	8.7	2.4	9.5	18.1	10.5	2.4	7.6	7.7	2.4	8.1	9.7	2.4	10.1
SSE	5.8	2.4	9.4	16.2	6.7	2.4	7.8	5.3	2.4	9.6	6.4	2.6	8.5
S	4.1	2.5	8.1	9.9	4.2	2.3	7.7	3.6	2.5	8.3	5.1	2.7	8.1
SSW	3.0	2.3	8.7	13.4	3.0	2.1	8.6	3.0	2.3	8.4	3.7	2.4	6.7
SW	2.6	2.1	8.1	12.2	2.6	1.9	6.5	2.8	2.1	7.8	3.2	2.1	6.9
WSW	3.0	2.4	10.1	15.9	2.9	2.2	14.6	3.2	2.3	8.1	3.7	2.3	7.2
W	2.9	2.5	17.1	23.5	2.9	2.4	16.2	3.2	2.4	18.5	3.3	2.3	12.4
WNW	3.3	2.6	17.0	20.6	3.6	2.5	17.1	3.3	2.5	20.6	3.8	2.4	13.8
NW	6.5	3.6	19.4	25.1	6.3	3.1	16.8	6.5	3.7	16.9	6.9	3.2	15.3
NNW	21.9	5.0	23.2	26.2	18.9	4.8	26.2	21.1	5.2	22.1	19.9	4.7	18.0
Calm	3.1				1.6			1.9			1.5		

[1)]Data from 1997, 1998, 2000, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009

Winter hot spells (where the temperature suddenly rises above the freezing point) were registered at all stations. In mid-December one episode started at M6 13 December and reached the meteorological station 17 December 2009. Another hot spell was registered at all stations 1 January 2010.

Snow depth

The amount of snow measured at the meteorological station during the winter 2009/2010 was at an average level. A substantial amount of snow fell in the early fall 2009 during snow events 18 and 25 September. At this time, a snow cover of 20-30 cm developed in the valley with snowdrifts of up to 1-1.5 m in some areas. The build up of a continuous snow cover above 0.1 m was more than a month earlier than registered before (table 2.6). The maximum snow depth measured at the climate station was 70 cm and was reached 19 May, which is the latest registered (figure 2.2 and 2.5). Snowmelt started around 7 May and by 18 June, the ground was free of snow below the sensor at the

Table 2.6 Key figures describing the amount of snow at the meteorological station during the last 13 winters.

Winter	1997/ 1998	1998/ 1999	1999/ 2000	2000/ 2001	2001/ 2002	2002/ 2003	2003/ 2004	2004/ 2005	2005/ 2006	2006/ 2007	2007/ 2008	2008/ 2009	2009/ 2010
Max. snow depth, meter	0.88	1.30	0.49	0.68	1.33	0.60	0.69	0.73	1.10	0.48	1.30	0.17	0.68
Max. snow depth reached	29 Apr	11 Mar	19 May	25 Mar	15 Apr	13 Apr	13 Apr	12 Feb	26 Apr	4 May	4 Mar	17 Feb	19 May
Snow depth exceeds 0.1 m from	19 Nov	27 Oct	1 Jan	16 Nov	19 Nov	6 Dec	24 Nov	27 Dec	19 Dec	12 Jan	26 Oct	29 Jan	25 Sep
Snow depth is below 0.1 m from	25 Jun	3 Jul	14 Jun	24 Jun	20 Jun	14 Jun	13 Jun	7 Jun	1 Jul	8 Jun	24 Jun	16 May	16 Jun
Days with snow above 0.1 m	219	250	166	221	214	191	203	162	194	148	243	108	265

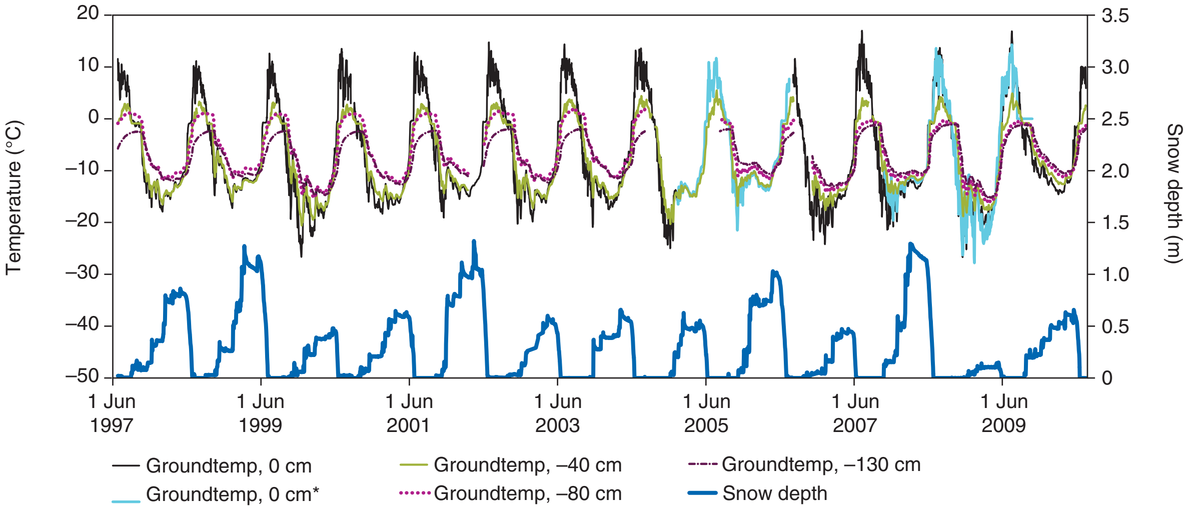


*Figure 2.5 Daily mean soil temperatures and snow depths from the meteorological station. In August 2006, soil temperature sensors were replaced. *Data from sensor at the snow depth station.*

meteorological station (table 2.6). This is close to the average date for snowmelt in the valley. All together it is the winter with the longest lying continuous snow cover above 0.1 m (265 days) whereas the winter before had the shortest period (108 days) registered since 1997 (table 2.6). The insulating effect from the early snow cover is clearly reflected in the soil temperatures, which were higher than during most winters (figure 2.5).

Snow depth is also being measured at the automatic weather stations M2, M3, M6 and M7 (figure 2.6). At M3 and M7, snow depth was highest in the early winter. By 26 June, snow had disappeared from all stations.

In order to achieve a better spatial resolution, snow depths are also being measured along two main transects, i.e. one transect (SNM) running from Lomsø into the valley and another (SNZ) running along the ZERO-line from the old delta up to 420 m a.s.l. The snow depths will be used as input for the Snow Model covering the central valley.

In the mid-October 2010, the valley was more or less totally covered by light new snow with a bulk density: 0.150 cm^{-3}. However, shortly after, the wind packed the snow and the density increased to 0.250 cm^{-3}. In general, the snow in Zackenberg tends to be very hard packed. At the end of the winter 2009/2010, the snow bulk density near the climate station was 0.350 cm^{-3}.

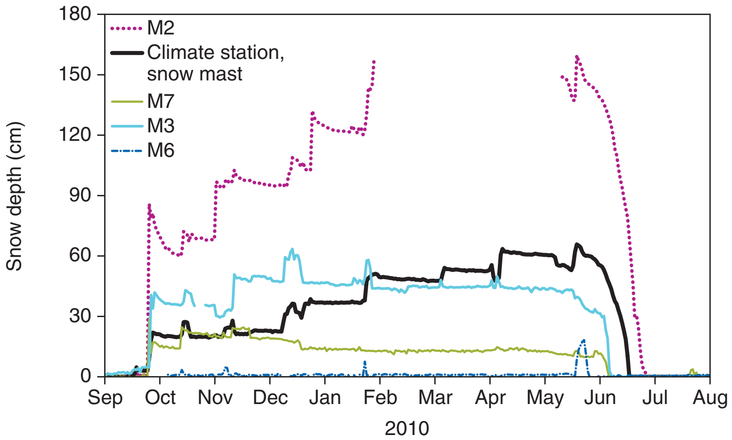


Figure 2.6 Snow depths at the automatic weather stations, M2 (17 m a.s.l.), M3 (420 m a.s.l.), M6 (1282 m a.s.l.) and M7 (145 m a.s.l.) and the Climate station.

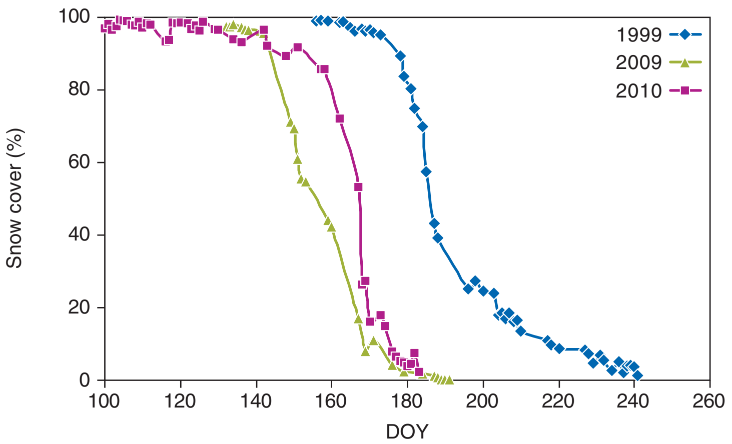


Figure 2.7 Snow cover depletion curves from the central part of Zackenbergdalen. For simplicity only the very early year, 1999 and the very late year 2009 are shown together with the depletion curve for 2010. Curves exist from 1998-2010.

Snow cover

All photos from the digital cameras has now been orthorectified and used as input for new and updated snow depletion curves (figure 2.7).

The snow cover for 2010 was relatively extensive during the spring but not very deep. The date for 50 percent snow cover was close to average. The rest of the snow melted at a very fast rate and 2010 ended up being one of the years where all snow within the area of the camera coverage disappeared earliest.

*Table 2.7 Area size and snow cover 10 June in 13 bird and mammal study sections in Zackenbergdalen and on the slopes of Aucellabjerget 2001-2010 and mean for the period 1995-2009 (see figure 4.1 in Caning and Rasch 2003 for map of sections). Photos were taken from a fixed point 480 m a.s.l. on the east facing slope of Zackenbergbjerget within ± 3 days of 10 June and extrapolated according to the methods described by Pedersen and Hinkler 2000. Furthermore, the proportions of the areas not visible from the photo point are given. *Based on satellite photos (9 June 1995 and 11 June 1996). Gray values are based on only part of the given section due to missing photo coverage.*

Section	Area (km²)	Area hidden (%)	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Mean (1995-2010)
1 (0-50 m)	3.52	3.5	73	77	68	48	31	74	38	62	13	53	54
2 (0-50 m)	7.97	1.2	87	87	92	49	25	81	43	77	5	61	61
3 (50-150 m)	3.52	0.0	89	82	83	51	35	77	40	74	11	48	59
4 (150-300 m)	2.62	0.0	79	56	73	39	28	65	36	54	19	32	48
5 (300-600 m)	2.17	0.0	56	36	49	16	25	62	25	46	17	12	34
6 (50-150 m)	2.15	75.3	84	78	74	56	50	80	50	59	18	49	60
7 (150-300 m)	3.36	69.3	84	74	90	56	46	82	58	69	34	44	64
8 (300-600 m)	4.56	27.5	45	52	66	30	29	67	26	45	16	25	40
9 (0-50 m)	5.01	6.2	96	96	100	58	23	73	49	80	18	56	65
10 (50-150 m)	3.84	2.9	97	93	100	56	47	92	57	85	43	55	73
11 (150-300 m)	3.18	0.2	97	88	100	66	61	88	54	73	77	51	75
12 (300-600 m)	3.82	0.0	73	65	98	53	70	85	38	53	64	43	64
13 (Lemmings)	2.05	1.0	83	83	89	46	25	79	41	73	4	64	59
Total area	**45.70**	**12.9**	**82**	**77**	**83**	**49**	**37**	**77**	**43**	**65**	**28**	**44**	**58**

Snow cover 10 June (which has been chosen as a good early season indicator for biological conditions) was given for different sub-sections of the study area in table 2.7. Values for 2010 are close to average or in some sections (especially above 50 m a.s.l.) very low compared to average for the period 1995-2010.

Active layer depth

Development of the active layer (the layer above the permafrost that experiences seasonal freeze and thaw) starts when the snow disappears from the ground and the air temperature becomes positive. The depth of soil thaw was measured throughout the field season at two grid-plots; ZEROCALM-1 (ZC-1) covering a 100×100 meter area with 121 grid nodes and ZEROCALM-2 (ZC-2) covering a 120×150 meter area with 208 grid nodes.

In ZC-1, the first grid node was free of snow 14 June and within 10 days, all snow in this relatively homogenous grid site had melted. The maximum thaw depth was reached at the end of August and was close to the maximum thaw depth measured at this plot (figure 2.8 and table 2.8).

In ZC-2, there were 2 grid nodes without snow cover 9 May and by 12 July; all grid nodes were free of snow. The maximum thaw depth was reached at the end

Figure 2.8 Thaw depth progressions in ZEROCALM-1 and ZEROCALM-2 2010 based on seven and eight re-measurements (red line).

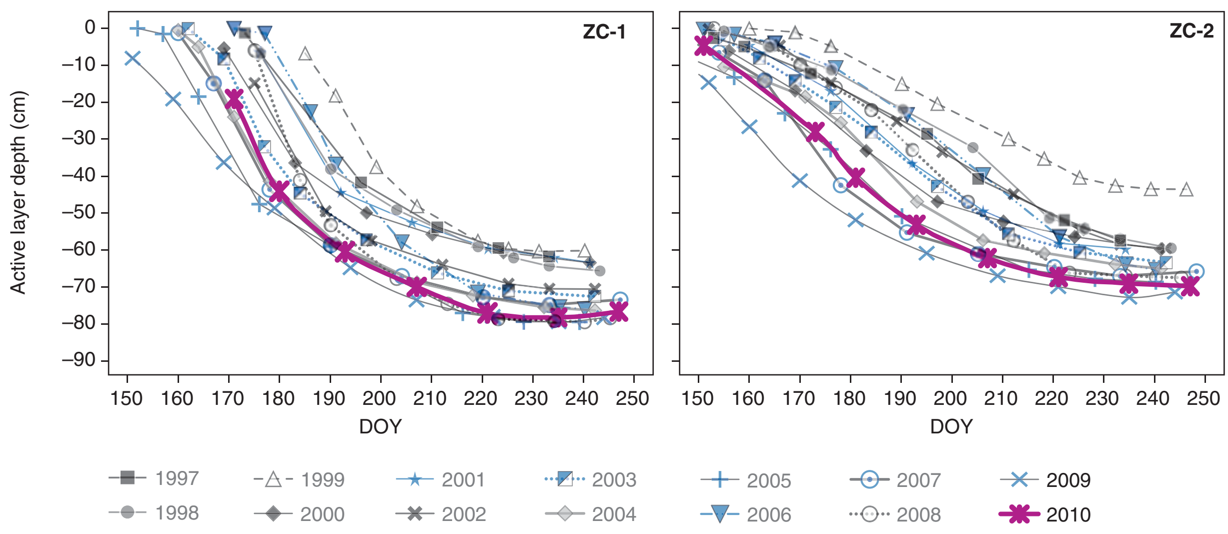


Table 2.8 Maximum thaw depth (in cm) in ZEROCALM-1 and ZEROCALM-2 measured late August 1997-2010.

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
ZEROCALM-1	61.7	65.6	60.3	63.4	63.3	70.5	72.5	76.3	79.4	76.0	74.8	79.4	79.4	78.2
ZEROCALM-2	57.4	59.5	43.6	59.8	59.7	59.6	63.4	65.0	68.6	67.6	67.1	67.5	72.9	69.5

of August/early September. The plot was close to the deepest thaw depth that has been measured since 1997, even though the timing of the snowmelt was average.

Data from the two ZEROCALM-sites is reported to the circumpolar monitoring programme CALM III (Circumpolar Active Layer Monitoring-Network 2009-2014) maintained by the Centre for International Studies, University of Delaware www.udel.edu/Geography/calm.

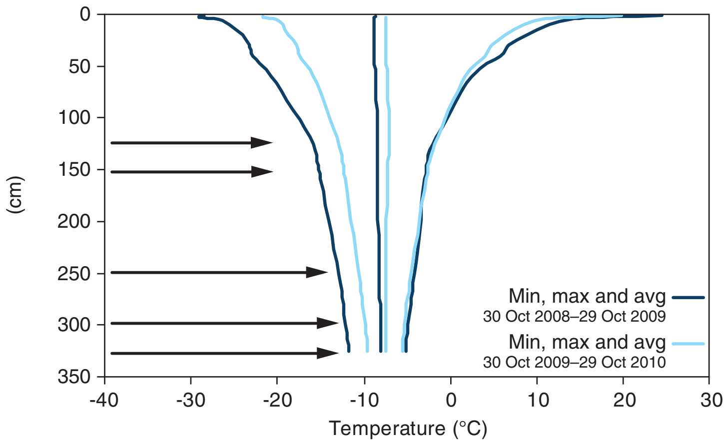
Temperature in different settings and altitudes

GeoBasis operates several mini data loggers for year-round temperature monitoring in different altitudes and different geomorphologic settings in the landscape. Positions and a short description of the sites are given in the GeoBasis manual.

In July 2010, new temperature loggers were installed at the methane station in the fen, three loggers near chamber one and three loggers near chamber six. At both sites the temperature are now being logged at 5, 10 and 30 cm soil depth in order to get more information on the freeze-in of the soil since this seems to have a crucial effect on the late season methane fluxes. Next to these temperature sites, a water permeable tube was installed in which a pressure transducer was mounted to obtain water table fluctuations in the fen (see section 2.4 on soil moisture).

Year-round soil temperatures in the active layer are also being logged at the meteorological station and at the automatic weather stations M2, M3, M4 and M5 (figure 2.1). At one of the stations (M4), a 325 cm deep borehole makes it possible to monitor temperatures from the upper part of the permafrost (Jensen and Rasch 2009). Now two years of data has been obtained from this borehole (figure 2.9). The warmer conditions in 2009/2010 compared to 2008/2009 probably reflects the insulating effect from the very different snow cover situations where 2008/2009 had the shortest duration of a continuous snow cover and 2009/2010 had the longest snow cover (table 2.6). In the near future, we hope to be able to establish a deeper borehole. During the International Polar Year, 2007-2009, many boreholes were made to establish more knowledge of the state of the permafrost all over the Arctic – but for Greenland there is a gap and it would be very valuable to include a 10-20 m deep borehole with temperature loggers as part of the Zackenberg long-term monitoring programme.

Figure 2.9 Minimum, mean and maximum temperatures from the borehole at M4, 30 October 2008-29 October 2009 (black) and 30 October 2009 to 29 October 2010 (blue).



Lake drainage

On 6 May 2010, we were able to download data from the digital camera that was installed at A.P. Olsen land in April 2008 in order to cover fluctuations in the glacier-dammed lake (figure 2.10). Daily photos had been obtained from 10 May 2008 to 21 October 2009 where the memory card was full. The photos showed how the lake built up from a minimum in spring 2008 to a maximum in late August (figure 2.10) and how new ice covered the lake from 24 September. Due to the limited light conditions, the photos from 4 November to 31 January turn out dark and therefore it is not possible to see the known lake drainage 26 November 2008. In spring 2009, the lake level was similar to the level in spring 2008 which suggest that there is a certain threshold for when the lake drains. In 2009, the lake reached a maximum 10 August. Then the level started to drop and between 11 and 12 August, the lake drained completely through the glacier and a major flood was observed in Zackenbergelven after this outburst. The distance from the lake to the hydrometric station is approximately 35 km. Depending on the

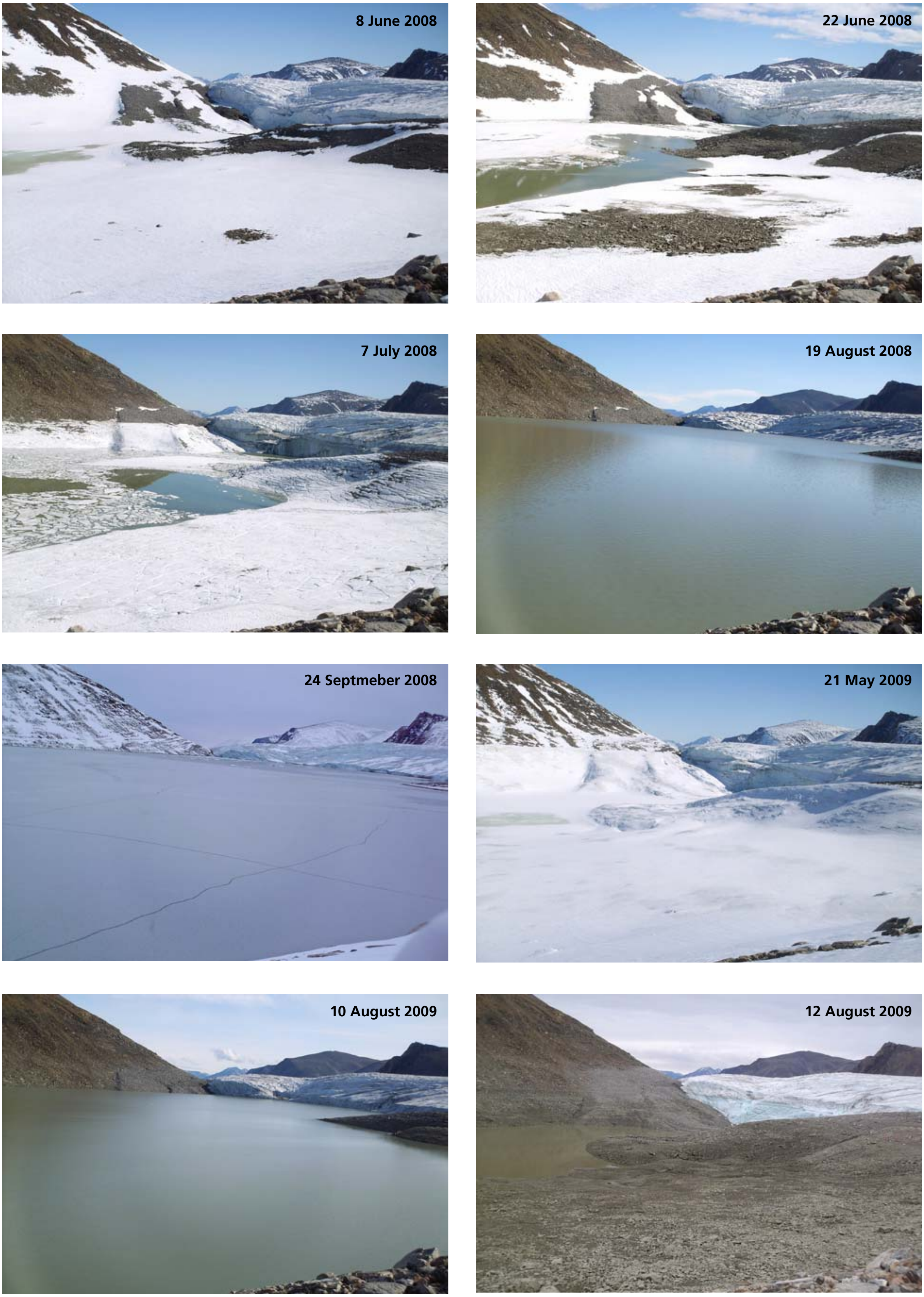


Figure 2.10 Glacier dammed lake at A. P. Olsen. The lake was built up during the summer and covered by ice in September before it drained 26 November 2008. In 2009, the lake built up again and drained 11-12 August 2009.

seasonal timing for the outburst, severe erosion can take place along the riverbanks. If it happens during winter (as in 2008) when the landscape is covered by ice and snow, the erosion is minimal whereas if it happens throughout summer (as in 2009) when the riverbanks are free of snow and the soil has thawed, the erosional impact may be very large.

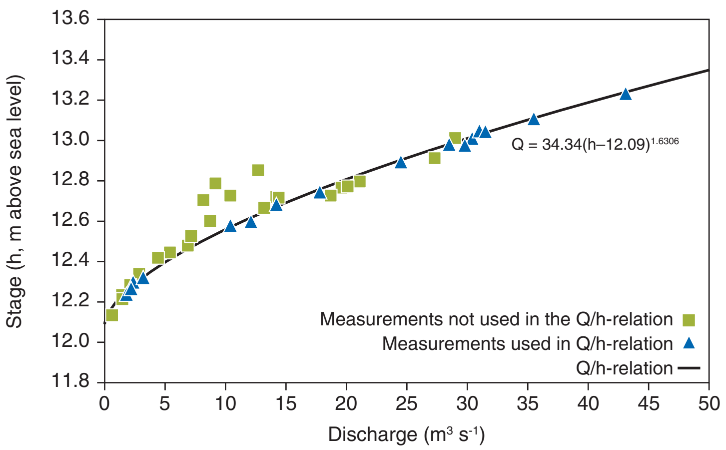
During the 2010 field season, no major flood situations were observed in Zackenbergelven. Studies of satellite images confirmed that in late October the lake area was larger than observed before (Mikkel Tamstorf, personnel comm.) and that an outburst during the coming winter or spring seems very likely.

2.3 River water discharge and sediment transport

Zackenbergelven

The drainage basin of Zackenbergelven includes Zackenbergdalen, Store Sødal, Lindemansdalen and Slettedalen. The basin covers an area of 514 km², of which 106 km² are covered by glaciers. The first hydrometric station was established in 1995 on the western riverbank near the river mouth (Meltofte & Thing 1996). In 1998, the hydrometric station was moved to the eastern riverbank, due to problems with the station being buried beneath a thick snowdrift each winter. During the years, the station has been flushed away by major floods a few times. The present position on the eastern riverbank near the river crossing site is not perfect since large boulders at the river bottom creates some rather big waves during high flow. However, by combining different methods to decide water level fluctuations reliable data are obtained.

Figure 2.11 Water level, discharge relation curve (Q/h-relation) for Zackenbergelven at the hydrometric station, valid 15 August 2009-18 September 2010. The coefficient of correlation (R^2) for the curve is 0.999.



At the station, water level, water temperature, air temperature and conductivity are logged automatically every 15 minutes. In 2010, the water level was measured with a sonic range sensor and different pressure transducers.

Q/h-relation

After a large flood in 2005, the river cross profile changed and a new Q/h-relation had to be established. The new relation was valid until the end of the 2006 season. Unfortunately, the changed river cross profile made manual discharge measurements at high water levels almost impossible and the lack of high flow measurements resulted in a Q/h-relation that was considered preliminary. Discharge measurements from 2008 were supposed to improve the relation but did not fit the measurements from 2007. This indicated that the river profile was still unstable and again the Q/h-relation was only preliminary.

The lack of measurements at high flows was the main reasons why the Environmental Protection Agency in 2009 donated an Acoustic Doppler Current Profiler (ADCP) of the type Q-liner. A Q-liner is a little boat with an ADCP-sensor that measures velocity in a number of depths in a given water column and provides an accurate bottom profile. One of the great advantages is that the Q-liner can be controlled from the shore through Bluetooth communication, which increases personnel safety during high flows.

In 2010, 33 discharge measurements were carried out. Of these, 19 measurements were carried out under snow and ice-free conditions where the Q/h-relation is valid. Unfortunately, there were uncertainties about the water level during three of these so the new Q/h-relation is based on 16 measurements and is valid from 15 August 2009 until 18 September 2010 (figure 2.11).

River water discharge

Zackenbergelven broke up 30 May, when water started to run from several of the streams in the eastern part of the drainage basin. Contribution from the main streams Lindeman and Store Sødal was not significant until 5 June.

A new method for calculating the discharge in the beginning of the season when the riverbed and -banks are covered with ice and/or snow has been used on data from the beginning of both 2009 and

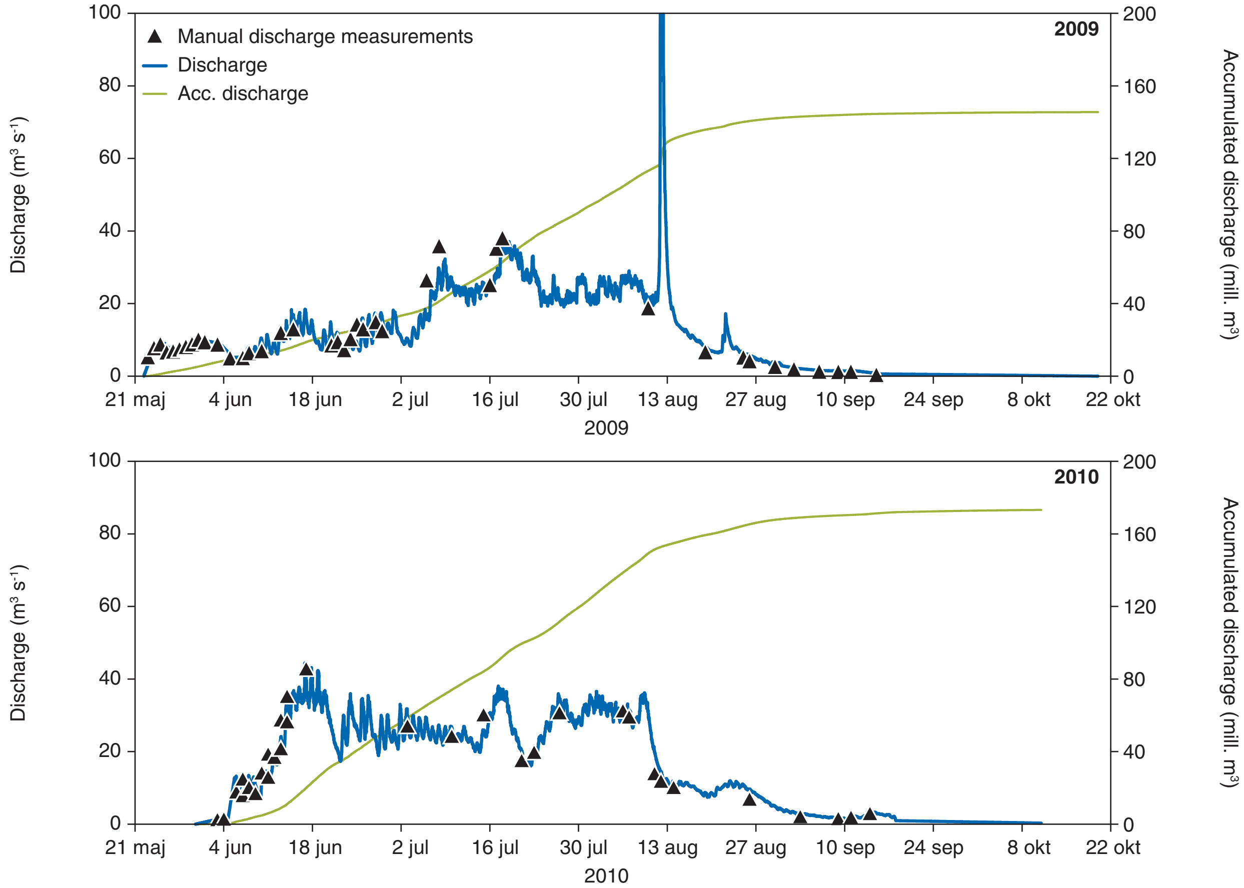


Figure 2.12 River water discharge in Zackenberg-elven during 2009 (upper) and 2010 (lower).

2010. The method is based on the water levels registered, for more details please see section 6.2.

The water discharge from 2010 is shown in figure 2.12. From the river started flowing and until 11 June the river bed and banks were covered with ice and/or snow to such a degree that the Q/h-relation was not valid. Instead, the discharge is approximated by interpolation between manual discharge measurements 3 June and 4 June. During the period 5 June to 11 June, the new method described in section 6.2 is used to calculate the discharge. From 11 June to 18 September, the discharge is calculated from the Q/h-relation (figure 2.11). After 18 September, the discharge is estimated to decrease linearly to an assumed zero discharge 21 October.

The total amount of water drained from the catchment in 2010 was 173 million m^3, which corresponds to an average discharge season (table 2.9). The peaks in discharge all seems to be correlated with higher temperatures in the more elevated areas of the drainage basin and likewise the significant drop in discharge observed 9 August correlates with a drop in temperature in these areas (figure 2.13a and b). The slight increase in mid-September was a response to the rainy period 9-14 September and was reflected as a peak in the conductivity. From mid-September, ice started to cover the river and by 26 September, it was possible to cross the river on the ice. However, some water was still running below the ice at least until 21 October.

Due to problems with the precipitation gauge during the period 22 January to 7 April it has not been possible to calculate the total amount of precipitation for the hydrological year 2010, which is set to 1 October 2009 to 30 September 2010. The measured precipitation during the period where the gauge was functioning was 125 mm (table 2.9).

The water discharge after the flood in 2009 is now final and the re-evaluated data for 2009 gives a total discharge of 145 million m^3 for 2009, which is close to a minimum of what, has been registered (table 2.9 and figure 2.12).

Suspended sediment and river water chemistry

Daily water samples were collected in the morning (8:00) and in the evening (20:00) in order to determine suspended sediment concentrations (SSC). As shown in figure 2.13c, SSC showed the highest concentra-

*Table 2.9 Total discharges in Zackenbergelven in the years 1996-2010, corresponding water loss for the drainage area (514 km^2), and precipitation measured at the meteorological station. 1) The hydrological year is set to 1 October previous year to 30 September present year. *) For 2005, no data was available during the flood from 25 July 05:00 until 28 July 00:00. After this date and until the new hydrometric station was set up 5 August, the discharge are estimated from manual readings of the water level from the gauge. **) No precipitation data available from 22 January to 7 April. The date for river break-up 1999 differs from earlier reports where 20 June was given. 20 June was the date for a very large spring flood, but water had been running since 9 June.*

Hydrological year[1)]	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Total discharge (mio. m^3)	132	188	232	181	150	137	338	189	212	200*	172	183	201	146	173
May														6	<1
June	43	45	50	41	41	53	143	71	46	66	31	47	56	26	54
July	67	80	98	123	61	47	150	71	100	100	98	96	77	62	68
August	21	61	78	17	47	34	46	43	64	34	40	34	51	47	46
September	1	2	4	0	0	3	0	4	2	??	??	7	14	5	4
October													3	<1	<1
Water loss (mm)	257	366	451	352	292	267	658	368	412	389	335	356	391	284	337
Precipitation (mm)	239	263	255	227	171	240	156	184	279	266	206	133	219	157	>125*
Total annual transport															
Suspended sediment (ton)		29444	130133	18716	16129	16883	60079	18229	21860	71319	27214	51118	39039	44716	23538
River break-up	late May	4 Jun	10 Jun	9 Jun	8 Jun	8 Jun	4 Jun	30 May	1 Jun	3 Jun	12 Jun	2 Jun	7 Jun	22 May	30 May

tions early in the season. At the same discharge rates, concentrations of suspended sediment are much lower in late July and in August than in the first part of the summer –probably due to depletion of easy erodible material along the riverbed and banks. A distinct diurnal variation is measured early in the season whereas no variation is measured late in the season. This correlates with diurnal discharge variations being more distinct early in the season (figure 2.13b). Usually, the SSC was highest and showed larger fluctuations in the evening than in the morning.

Highest concentration of SSC during the 2010 season was 1058 mg l^{-1} which was measured in the evening of 23 June as a single peak value. Since concentrations were low both before and after this peak it might be due to local erosion along the riverbank or a smaller landslide.

During the entire runoff period, the suspended sediment transport amounted to 23221 tonnes (table 2.9). In order to compare values between years, the total amount of sediment given was based solely on the SSC measured in the morning (not all years have measurements from the evening) but included any measurements carried out during flood events. If evening values were included, the total transport in 2010 would amount to 36413 tonnes. This indicates that all the calculated sediment yields given in the table were to some extent underestimated.

Daily variations of conductivity and water temperature are shown in figure 2.13d and e. The very first melt water early in the season show a high conductivity; a well-known phenomenon ascribed to solutes being washed out of the snow (Rasch et al. 2000). During the dry summer, the conductivity was very stable; the only increases were measured during rain events in September. The conductivity in the river peaks during rainy periods due to increase surface and sub-surface drainage from land and soil water that has higher conductivity than melt water.

Throughout the entire season, samples from the river were collected for mercury analysis. Results from 2010 were not ready at the deadline for this report but data from 2009 with total amounts of Hg in water and sediment from Zackenbergelven has been published in Riget et al. 2011.

Suspended sediment and water discharge in Lindemanselven

Fluctuations of water level is also measured in Lindemanselven approximately 300 m upstream from the junction between

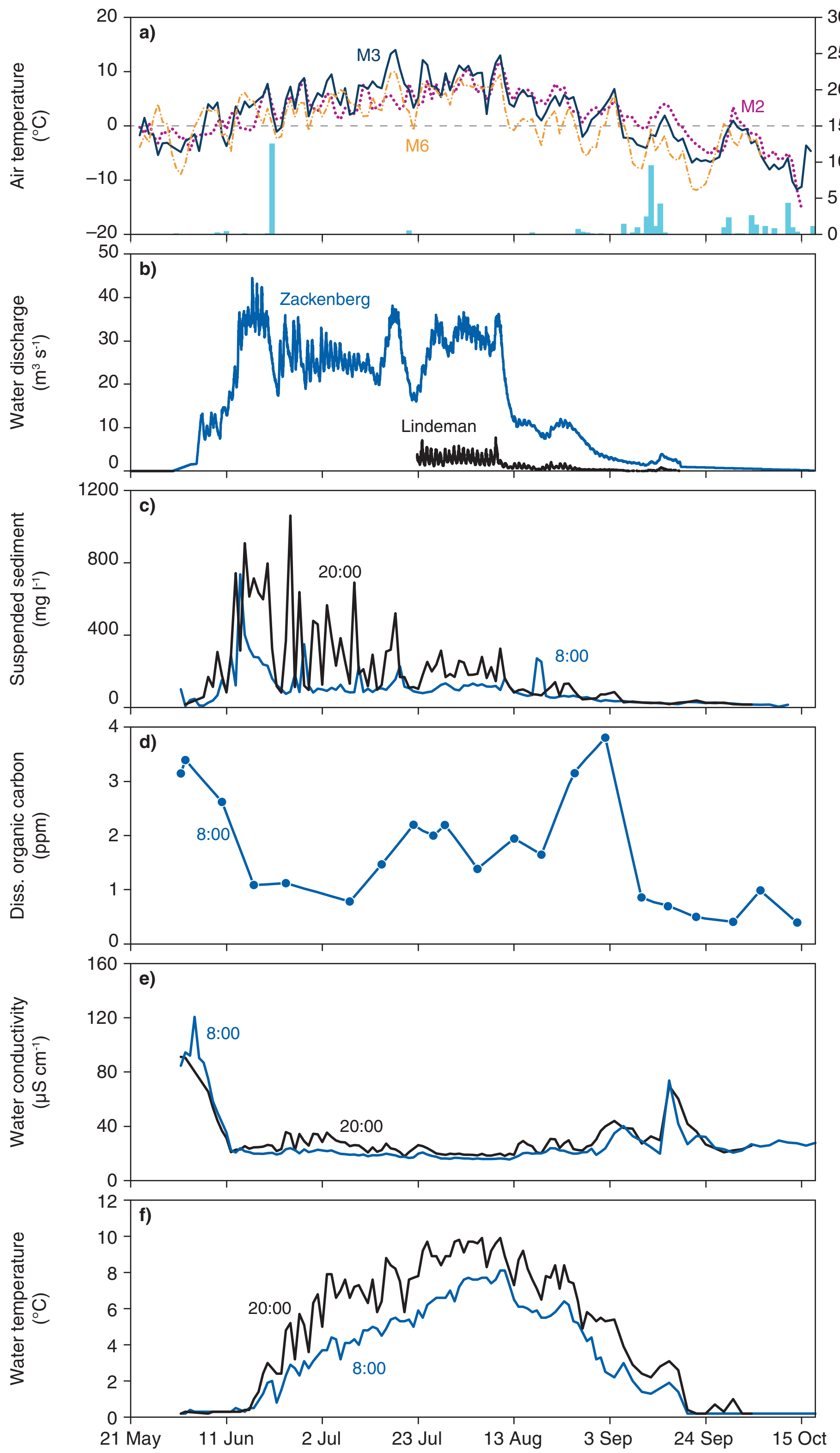


Figure 2.13 Diurnal mean air temperatures for 2010 at M2 (17 m a.s.l.), M3 (420 m a.s.l.) and M6 (1278 m a.s.l.) and rain registered at the meteorological station (a). Seasonal variations of selected parameters in Zackenbergelven (b-f).

the rivers from Lindeman and Store Sødal (UTM: 511662 E, 8269094 N, 82 m a.s.l.). A logger with a pressure transducer was installed 24 June when the riverbed was free of snow and data was logged continuously every 15 minutes. Unfortunately, the pressure sensor failed and had to be replaced, which means that there is only water level data from 24 July until 19 September where the logger was removed due to ice on the river. During the given period, runoff from Lindeman constituted 0-30 % of the total runoff in Zackenbergelven (figure 2.13b). As in Zackenbergelven the discharge in Lindemanselven, declined rapidly after 9 August.

2.4 Precipitation and soil water chemistry

Precipitation

Rain samples for chemical analysis were collected from an open bucket collector 20 July, 29 August, 12 and 13 September and 28 September (figure 2.13a). Furthermore, snow samples were collected from a snow pit 14 May, 9 and 10 October. All precipitation samples are being analysed for chemical composition.

Soil moisture and soil water

Variation in soil moisture content is measured at several sites. During the field season, soil moisture was measured once a week at all the soil water sites and in two transects in ZC-2 (the active layer grid site). Besides the manual measurements, soil moisture is monitored continuously at the three automatic stations M2, M3 and M4 (figure 2.14). M2 is located on a slope and affected by large snow accumulation but dries out quickly due to the primarily sandy material. M3 is located on a gentle slope 420 m a.s.l. and during the early summer this site is affected by a flow of melt water from snow patches further up Zackenbergfjeldet. Finally, M4 is located in the *Cassiope* heath near the meteorological station.

Except from an increase around 19 June due to a snow event a steady drying of the soil is observed until mid-September where a rainy period increased the soil moisture content just before soil freezing started. Soil freeze in the upper part of the active layer happened almost momentarily around 19

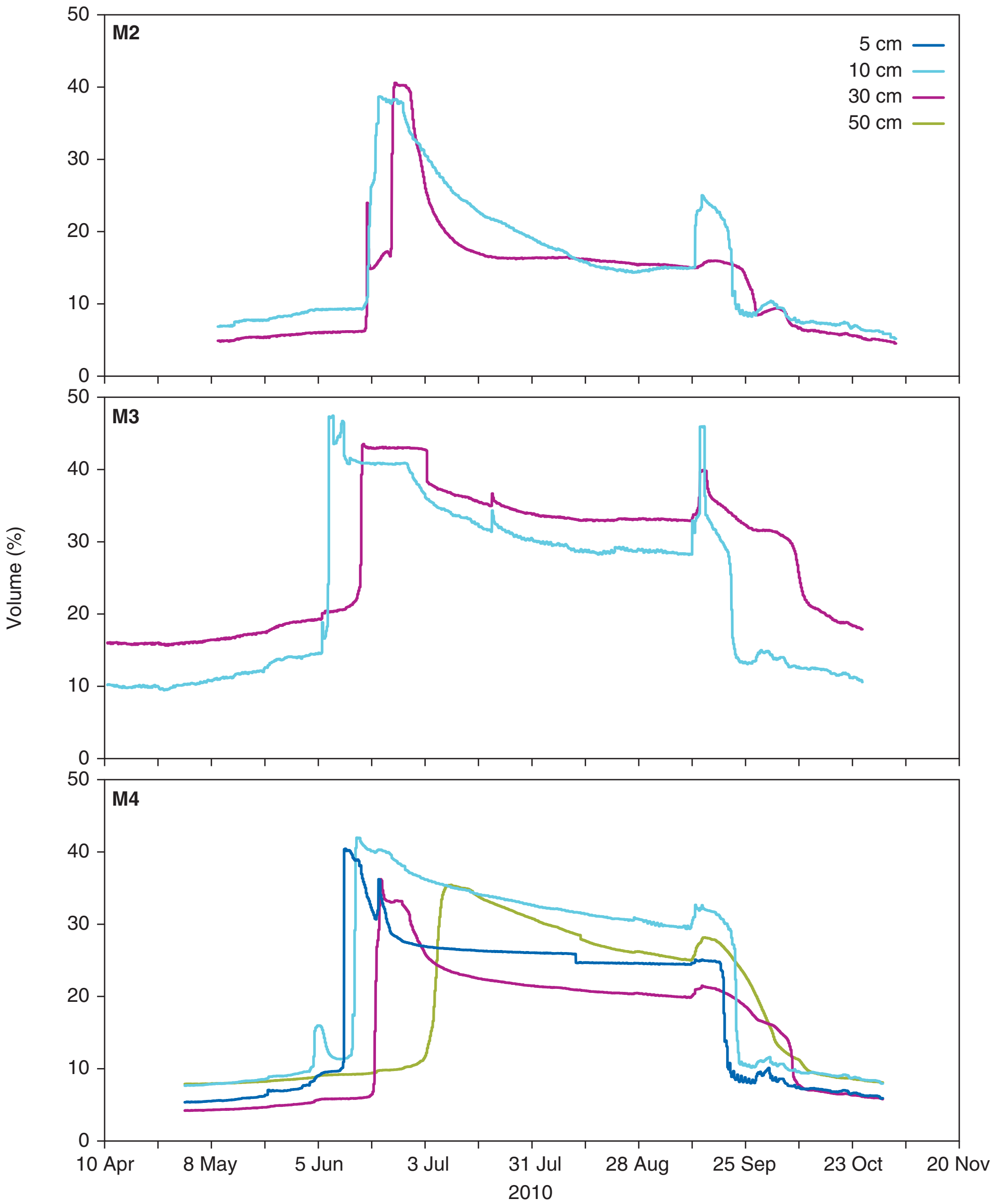


Figure 2.14 Soil moisture content throughout the field season 2010 at the three automatic weather stations M2, M3 and M4.

September at all three plots whereas it happens more gradually deeper in the soil as it is not directly exposed to the air temperatures. By mid-October most of the active layer was frozen at these sites.

At the methane station, in the fen, detailed variations in the water table was logged from mid-July to the end of September. Throughout the dry summer, the water table was lowered by 35 cm before the rain in September made the water table increase by 15-20 cm. A distinct diurnal variation was observed where the water table was lowest during midday and highest around midnight. In early September, the diurnal pattern ceased.

Four to five times during the season, soil water was collected from various depths in the active layer at three different sites covered by *Cassiope* heath, *Salix arctica*, and mixed heath vegetation, respectively. Unfortunately, soil water from the wet site has not been collected this year due to clocking of the lysimeters/suction probes. The collected water has been analysed for chemical composition.

2.5 Gas fluxes

Carbon gas fluxes are monitored on plot and landscape level in Zackenbergdalen using two measurement techniques:

- Automatic chamber measurements of the CH_4 and CO_2 exchange on plot scale in a fen site
- Eddy covariance measurements of the CO_2 and H_2O exchange on landscape scale in heath and fen sites.

Automatic chamber measurements

The CH_4 exchange has been monitored in six automatic chambers in a wet fen area since 2006 (Klitgaard et al. 2007). The temporal variation in CH_4 production is mainly associated with temperature, water table depth and substrate quality and availability. It has also been found from this site that frost action resulting in accumulated CH_4 gas squeezing out from the soil matrix can be of high importance for the annual CH_4 exchange (Mastepanov et al. 2008).

In 2010, measurements began 23 June and lasted until 2 November (figure 2.15). During this period, the system performed well and there were no major gaps in data. At the start of the measurement period CH_4 fluxes were low (<1 mg CH_4 m^{-2} h^{-1}), but increased rapidly and reached peak emissions around 7 July (ca. 2.4 mg CH_4 m^{-2} h^{-1}). The early summer and mid-summer peak emissions were similar to those measured in 2009, whereas earlier years have shown both higher (2006-2007) and lower (2008) peak values. The seasonal development of CH_4 exchange resembles previous years, with an early season peak followed by a smooth decrease in CH_4 emissions.

In mid-September 2010, CH_4 fluxes were close to zero. However, in October, both mean CH_4 fluxes and the variability between chambers increased. This coincides with the freeze-in period in the fen; in September soil temperatures in the top 15 cm were just above 0 °C, while in October, the soil profile began to freeze and soil temperatures decreased below zero. Thus, autumn frost action resulted in a remarkable increase in CH_4 emissions also in 2010, although the flux magnitude was not as high as has been detected in previous years, such as in 2007.

Eddy covariance measurements

The land-atmosphere exchange of CO_2 is measured using the eddy covariance

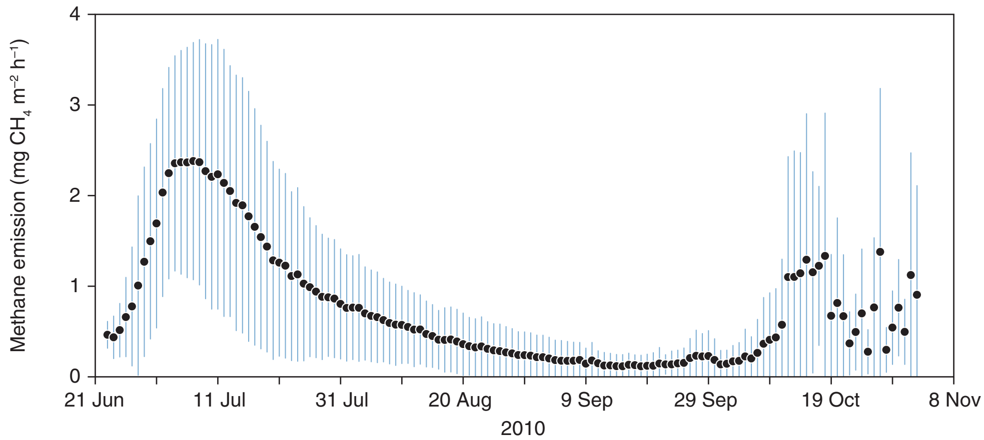
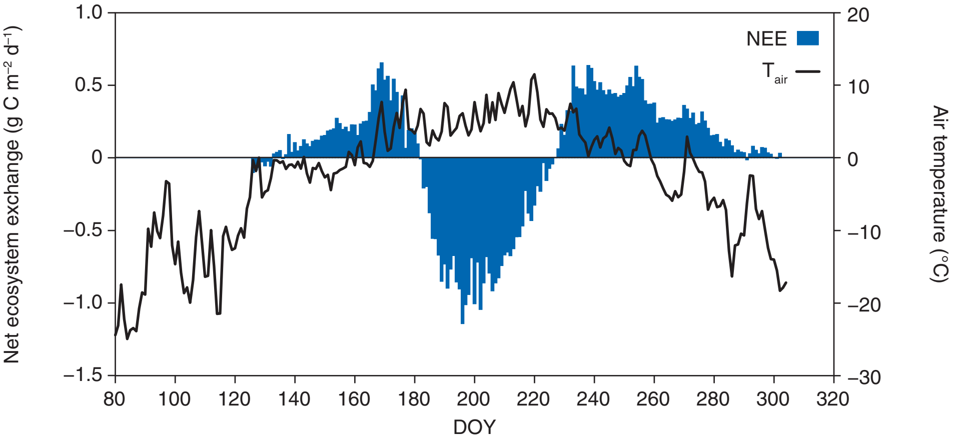


Figure 2.15 Diurnal methane (CH_4) emissions during 2010 measured at the fen site. Values are mean of six chambers (replicates) and error bars depict standard deviation.

Figure 2.16 Diurnal net ecosystem exchange (NEE) and air temperature (T_{air}) measured at the heath site in 2010.



technique in two sites in Zackenberg: one located in a well-drained *Cassiope* heath site where measurements have been conducted since 2000, and one located in a wet fen area where measurements have been conducted since 2007. Both eddy covariance systems consist of a 3D sonic anemometer and a closed-path infrared CO_2 and H_2O gas analyzer. For further details of the instrumentation see Klitgaard and Rasch 2008, and Rasch and Caning 2003. Raw data from the eddy covariance systems were calculated using the software package EdiRe (Robert Clement, University of Edinburgh). For more details on the flux calculation procedures see Jensen and Rasch 2010.

The temporal variation in the mean diurnal net ecosystem exchange of CO_2 (NEE) and air temperature during 2010 for the heath and fen sites is shown in figures 2.16 and 2.17, and tables 2.10 and 2.11. NEE refers to the sum of all CO_2 exchange processes; including photosynthetic CO_2 uptake by plants, plant respiration and microbial decomposition. The CO_2 uptake is controlled by climatic conditions, mainly temperature and photosynthetic active radiation (PAR), whereas respiratory processes are controlled mainly by temperature, soil moisture and the amount of biomass. The sign convention used in figures and tables is the standard for micrometeorological measurements; fluxes directed from the surface to the atmosphere are positive whereas fluxes directed from the atmosphere to the surface are negative.

Heath site 2010

Eddy covariance CO_2 flux measurements at the heath site, in 2010, were initiated 5 May and lasted until 31 October. During this period, less than 1 % of data were lost due to malfunction, maintenance and calibration. The eddy covariance mast was placed on top of approximately 60 cm of snow and the snow cover in the fetch was 100 % when measurements started. Early in the season measured CO_2 fluxes were fairly small; however, in the period between snow melt and start of net uptake, CO_2 emissions increased and a maximum spring diurnal emission of 0.66 g C m^{-2} d^{-1} was measured 18 June. As the vegetation developed, the photosynthetic uptake of CO_2 started, and

Figure 2.17 Diurnal net ecosystem exchange (NEE) and air temperature (T_{air}) measured at the fen site in 2010.

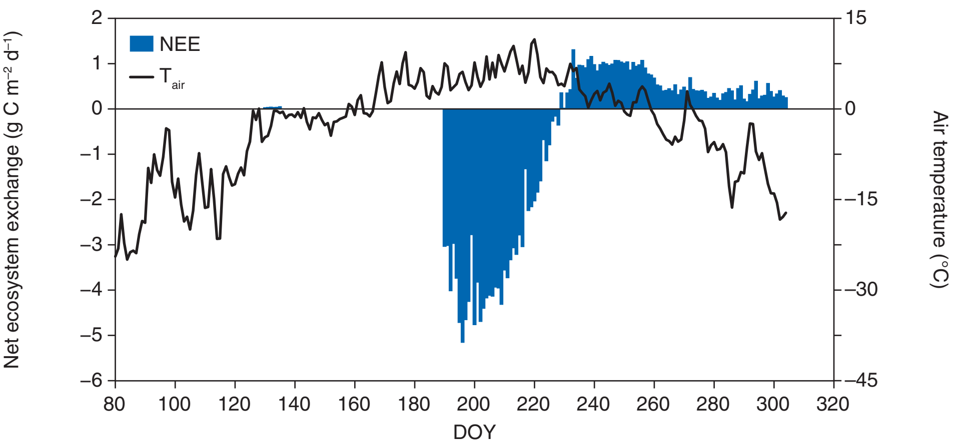


Table 2.10 Summary of the CO_2 exchange 2000-2010 at the heath site. Please note that the measuring period varies from year to year.

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008*	2009*	2010
Measurements start	6 Jun	8 Jun	3 Jun	5 Jun	3 Jun	21 May	27 May	27 May	30 Mar	16 May	5 May
Measurements end	25 Aug	27 Aug	27 Aug	30 Aug	28 Aug	25 Aug	27 Aug	28 Oct	28 Oct	22 Oct	31 Oct
Start of net uptake period	25 Jun	6 Jul	2 Jul	28 Jun	23 Jun	17 Jun	10 Jul	16 Jun	6 Jul	13 Jun	1 Jul
End of net uptake period	11 Aug	18 Aug	16 Aug	20 Aug	21 Aug	18 Aug	23 Aug	19 Aug	20 Aug	15 Aug	14 Aug
NEE for measuring period (g C m^{-2})	–19.1	–8.7	–9.5	–23.0	–22.4	–29.6	–21.6	–28.2	–11.2	–11.1	5.0
NEE for net uptake period (g C m^{-2})	–22.7	–19.1	–18.2	–30.4	–29.7	–33.4	–26.1	–37.8	–32.0	–23.1	–26.8
Max. daily accumulation (g C m^{-2} d^{-1})	–0.92	–0.94	–1.00	–1.40	–1.30	–1.15	–1.25	–1.32	–1.30	–0.97	–1.14

*Re-calculated compared with 15th Annual Report 2009 (see text)

1 July the heath ecosystem switched from being a source to a sink of atmospheric CO_2 on a daily basis.

The period with net CO_2 uptake lasted for 44 days, which is among the shortest net uptake periods measured so far. The onset of the uptake period varies from year to year due to timing of the snow-melt. The end of the uptake period is more stable as it is governed by fading solar radiation. The accumulated CO_2 uptake during the uptake period in 2010, –26.8 g C m^{-2}, was close to the mean of all measurement years (–27.2 g C m^{-2}). Also, the maximum diurnal CO_2 uptake (–1.14 g C m^{-2} d^{-1}, measured 15 July) was close to the mean of all years (–1.15 g C m^{-2} d^{-1}).

By 14 August, ecosystem respiration exceeded gross primary production and the heath ecosystem returned to being a net source of atmospheric CO_2. In the beginning of this period, soil temperatures remain comparably high, allowing decomposition processes to continue at a decent rate. Highest autumn diurnal emission was measured 26 August (0.64 g C m^{-2} d^{-1}). When soil started to freeze in mid-September diurnal NEE decreased, and at the end of the measuring period diurnal NEE was close to zero. During the entire measuring period (179 days), the net CO_2 balance amounted to 5.0 g C m^{-2}. This is the first year on record for which the heath ecosystem acts as a CO_2 source during the measuring period. As the measurements do not cover the whole year, the source strength of the heath is even higher.

Fen site 2010

Eddy covariance CO_2 flux measurements at the fen site in 2010 began 9 May. Unfortunately, the sonic anemometer broke down 16 May and had to be sent for service. Measurements were re-started 8 July and lasted until 1 November. In the first short period of measurements, 9-16 May, fluxes were close to zero. When measurements were re-started the net CO_2 uptake period had already begun, thus net uptake period NEE cannot be estimated. Maximum diurnal CO_2 uptake during the measurement period was estimated to –5.15 g C m^{-2} d^{-1} (measured 15 July). The fen ecosystem switched from being a sink for atmospheric CO_2 to a source 16 August, two days later than the heath site. Autumn CO_2 emissions were approximately 1 g C m^{-2} d^{-1} until soils started to freeze in mid-September. Highest autumn diurnal emission was measured 21 August (1.31 g C m^{-2} d^{-1}).

The growing season diurnal uptake as well as shoulder seasons diurnal emissions are generally higher in the fen site compared with the heath site. This is because of denser vegetation with higher leaf area index in the fen site, allowing for higher CO_2 uptake per area unit.

Table 2.11 Summary of the CO_2 exchange 2007-2010 at the fen site. Please note that the measuring period varies from year to year.

Year	2007	2008	2009	2010
Measurements start	20 Sep	10 Apr	31 Jul	9 May
Measurements end	19 Oct	30 Aug	13 Oct	1 Nov
Start of net uptake period	–	10 Jul	–	–
End of net uptake period	–	22 Aug	16 Aug	16 Aug
NEE for measuring period (g C m^{-2})	9.8	–65.8	3.5	–73.5
NEE for net uptake period (g C m^{-2})	–	–94.6	–	–
Max. daily accumulation (g C m^{-2} d^{-1})	–	–4.03	–	–5.15

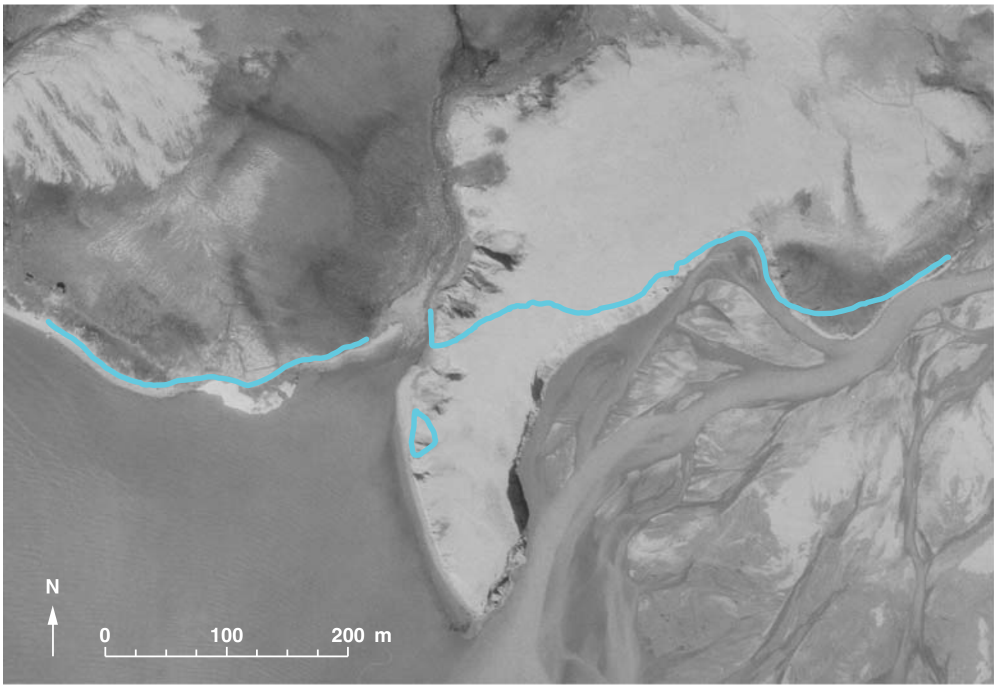


Figure 2.18 Delta and coastal cliff line measured by DGPS 17 October 2010 (red line) on an aerial photo from 8 August 2000.

2.6 Geomorphology

Coastal geomorphology

The delta cliff at the western side of Zackenbergelven's outlet has been subject to severe erosion and block slumping through the years of monitoring. Within the last ten years, the cliff has retreated landwards by more than 200 m (figure 2.18). In July 2010, the water from the river overwashed the lower part of the cliff and a small island was separated from the rest. This means that some of the water from Zackenbergelven now flows in a more western direction along the shoreline, which results in less transparent and more sediment rich water near the old trapping station.

3 Zackenberg Basic

The GlacioBasis programme

Michele Citterio, Horst Machguth, Trine Schmidt Jensen, Signe Hillerup Larsen and Andreas Ahlstrøm

The aim of the GlacioBasis monitoring programme at Zackenberg is to produce an uninterrupted record of high quality glaciological observations from the A.P. Olsen Ice Cap and its outlet glacier in the Zackenberg river basin (figure 3.1). The GlacioBasis programme was started in 2008 and is operated by GEUS on funding administrated by the Danish Energy Agency.

The A. P. Olsen Ice Cap is located at 74° 39′ N, 21° 42′ W. The summit of the Ice Cap reaches an elevation of 1425 m and the terminus of the outlet glacier contributing to the Zackenberg river basin is at 525 m. Zackenberg Research Station is located SE of the site, approximately 35 km downriver from the glacier terminus. The most direct access to the glacier terminus is through Store Sødal.

The severe scarceness of glacier mass balance measurements from the local glaciers and ice caps surrounding the Greenland Ice Sheet, the strong impact that such ice masses are expected to exert on sea level rise in the present century (Meier et al. 2007), and the particularly marked warming expected to take place in the Arctic (IPCC 2007) highlight the scientific relevance of GlacioBasis monitoring tasks. The monitoring data are suitable for calculating surface energy balance and glacier mass budget with physically based models that once calibrated and validated with *in situ* data, will allow exploring the sensitivity of glaciers to future climate scenarios.

The need to measure winter accumulation requires fieldwork to be carried out during springtime, immediately before

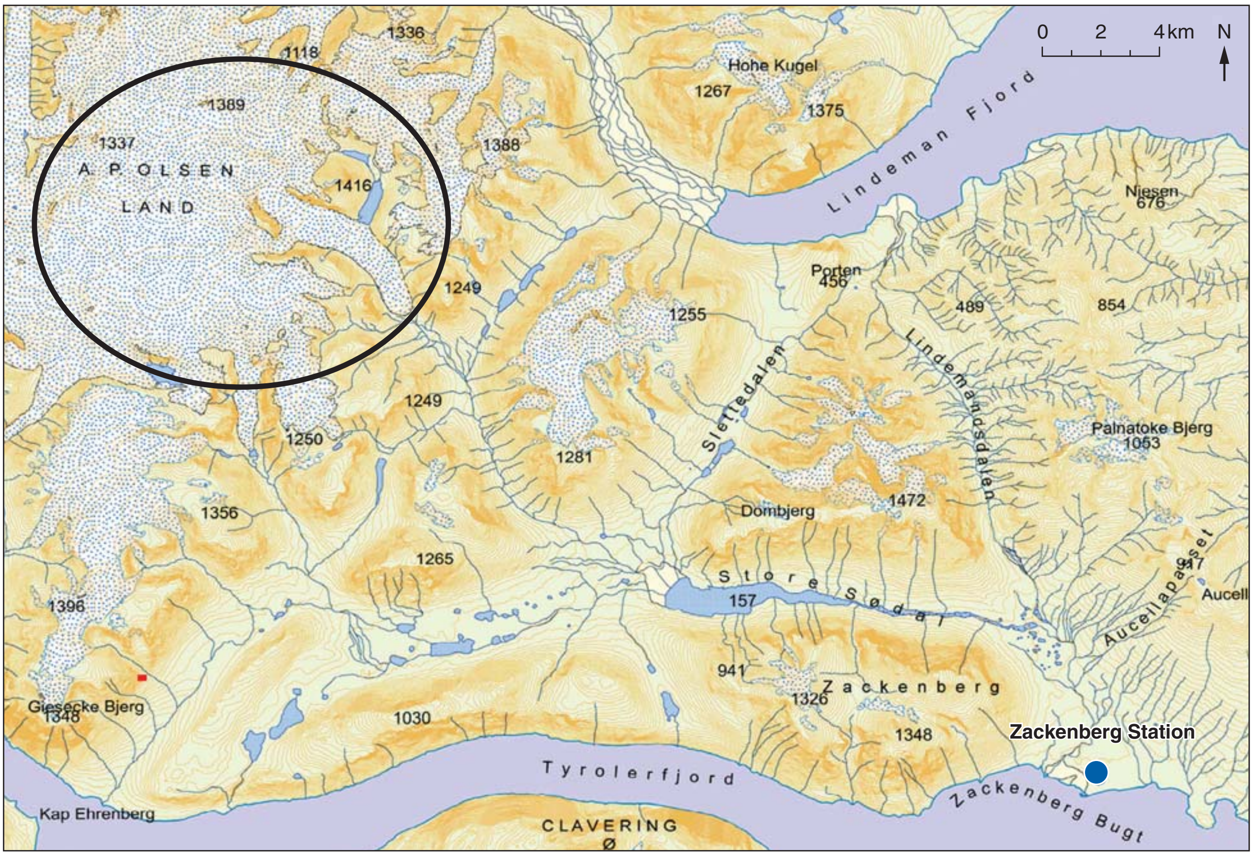


Figure 3.1 Map of the Zackenberg region, with A.P. Olsen Ice Cap in the northwestern corner of the map. The main investigation area is marked by a circle. Geological Survey of Denmark and Greenland (GEUS), Copenhagen.

the onset of snowmelt. This timing is also required for snowmobile use, which is the most effective means to reach the glacier and transport the required equipment and instrumentation. Fieldwork must be carried out every year in order to maintain the stakes network operational, to service the automatic weather stations (AWS) on the glacier, and to carry out the DGPS and snow radar surveys.

3.1 Overview of fieldwork in 2010

In 2010, the GlacioBasis programme was carried out successfully. All ablation stakes were revisited, measured and redrilled if needed, and the last missing ablation stake has been established close to the glacier terminus (stake 1). Snow pits have been dug and density measured at several locations over the altitudinal range of the Ice Cap.

The three AWS have been serviced, data retrieved and the sensor recalibration plan implemented. All stations were found in good conditions and left in full working order.

In 2010, the first Differential GPS (DGPS) work was carried out, providing a reference to calculate surface velocity at the sites of the ablation stakes as well as surface elevation changes along the central flow line and several transects. A test of Real Time Kinematic (RTK) GPS with two Trimble R7-GNSS receivers showed that radio coverage was poor from the master GPS in the forefront of the glacier, even when using a VHF repeater. Therefore, all DGPS work has been conducted by logging master and rover GPS receivers and later post-processed.

The snow depth survey using the 500 MHz radar from GeoBasis was carried out along the same tracks of the DGPS work.

The actual work on the glacier was carried out 10, 11, 12, 13, 14 and 15 May, before snow conditions deteriorated due to rising temperatures. Overall, snow cover on the ground was quite limited both in the valley and on the glacier, with extensive areas along the left side of the lower tongue being mainly devoid of snow up to the ice dammed lake and the flat glacier sector at the foot of the rock face of summit 1416 (figure 3.1). The 2008 snowmobile route on the glacier terminus was entirely snow-free, but the 2009 access from the right side of the tongue was again easy and safe in 2010. Due to the limited thickness of the snow cover, some crevasses were open and visible, particularly at, and just up-flow of the icefall where a moderately crevassed area had been recognized during the helicopter reconnaissance in 2009. A safe route was found, marked and always followed in this area. This was especially important because on two occasions it became necessary to drive the snowmobiles in very low visibility conditions due to persistent low altitude clouds.

Michele Citterio, GEUS, and Horst Machguth, GEUS and University of Zurich, took part in the fieldwork.

3.2 Automatic Weather Stations

The GlacioBasis programme uses one larger automatic weather station (AWS) and two smaller stations deployed on the glacier surface to obtain *in situ* time series of physical parameters describing the weather above the glacier surface. The main GlacioBasis AWS was deployed in March-April 2008 on A.P. Olsen Ice cap (AWS1 in this report). AWS1 has now completed the third year of uninterrupted operation and proved very reliable, having only required minor maintenance to the mechanical construction of the station in 2009 and 2010. AWS2 also required some maintenance in May 2010, to reestablish a weakened frame supporting the ice ablation sonic ranger. As to AWS3, a sonic ranger was added to monitor the changes of the surface now that the tripod is firmly anchored in the surface.

GlacioBasis uses the same recalibration plan developed for PROMICE (Ahlstrøm et al. 2009). Ideally, a stock of spares and replacement parts should be kept in storage at Zackenberg Research Station to increase the chances that unanticipated issues be resolved quickly, since GlacioBasis relies on a single trip per year.

During 2010, the three AWS worked normally, with AWS3 stopping transmitting 19 October at 05:00, during a time of moderately high and growing wind. It resumed, however, in March 2011 suggesting that damage may be limited to the mechanical construction of the tripod.

Data is calibrated based on the manufacturer's calibration report, and the calibration factors are traced to the corresponding units through the device serial number using the same Glaciobase database as used at GEUS to handle the sensors inventory for PROMICE. Details on Glaciobase are provided by Ahlstrøm et al. 2009 and are not repeated here. Validation of the data is carried out using the same procedures established for PROMICE; again, details on this are provided by Ahlstrøm et al. 2009 and are not repeated here.

Detailed information on each AWS and a selection of the observed data is shown below, where plots show the entire availability of data starting from the establishment of the first two AWS's in late March 2008. Measurements requiring extensive post-processing after instrument calibration to produce physically meaningful values are not shown. For instance, calibrated radiometer readings need extensive corrections to account for two-axes sensor tilt before global radiation, surface albedo and the radiative energy fluxes can be computed. For the same reason, relative humidity is shown below as calibrated sensor output referring to saturation above liquid water even for temperature below 0 °C.

The AWS1 station

Description: AWS1 – A.P. Olsen Main AWS (centreline, lower tongue).
Coordinates: 74° 37.5′ N, 21° 22.55′ W, elevation (WGS84): 660 m.
Measured parameters: barometric pressure, aspirated Tair, aspirated RHair, wind speed, wind direction, downwelling SW, upwelling SW, downwelling LW, upwelling LW radiation, sensor T of LW radiometers, ice ablation, ice level, snow level, eight-levels thermistor string, two-axes station tilt, GPS position, diagnostics. Experimental sensors (variable from year to year, currently a snow pillow, until 2010 a second identical radiation shield but with no forced aspiration).
Time series: uninterrupted from 29 March 2008 to today for all sensors except the sonic rangers, which had intermittent problems. The wind direction has a systematic correctable shift.
Current availability: all transmitted data (hourly summer/three-hourly winter); 10 minutes from flash card between 29 March 2008 and 12 May 2010.

AWS1 was established in March 2008, and in 2010 normal maintenance and scheduled calibration were carried out. The support frame for the ice ablation sonic ranger had failed and was reestablished (figure 3.2).

To compensate for displacement due to glacier flow, the tripod was in May 2010 entirely dug free of the snow and moved back up-glacier to the original 2008 position. This is required to counteract the displacement due to glacier flow. While two years are a relatively short interval, AWS1 is partly affected by shadowing from the surrounding mountain ridges and even a minor displacement would affect the usefulness of the measurements for surface energy balance modelling.

As a site and station especially well suited to technical experiments and testing of new devices, an experimental snow pillow has been installed in 2010. The previous 2008-2010 experiment of running two identical radiation shields for air temperature and relative humidity probes with and without forced air circulation was completed and the second shield dismantled.

Figure 3.2 The AWS1 station as found in May 2010. The failed frame supporting the sonic ranger can be seen on the left. To counteract glacier flow, the station was entirely dug free from the snow cover and moved back to its original position of 2008. Photo: Michele Citterio, GEUS.

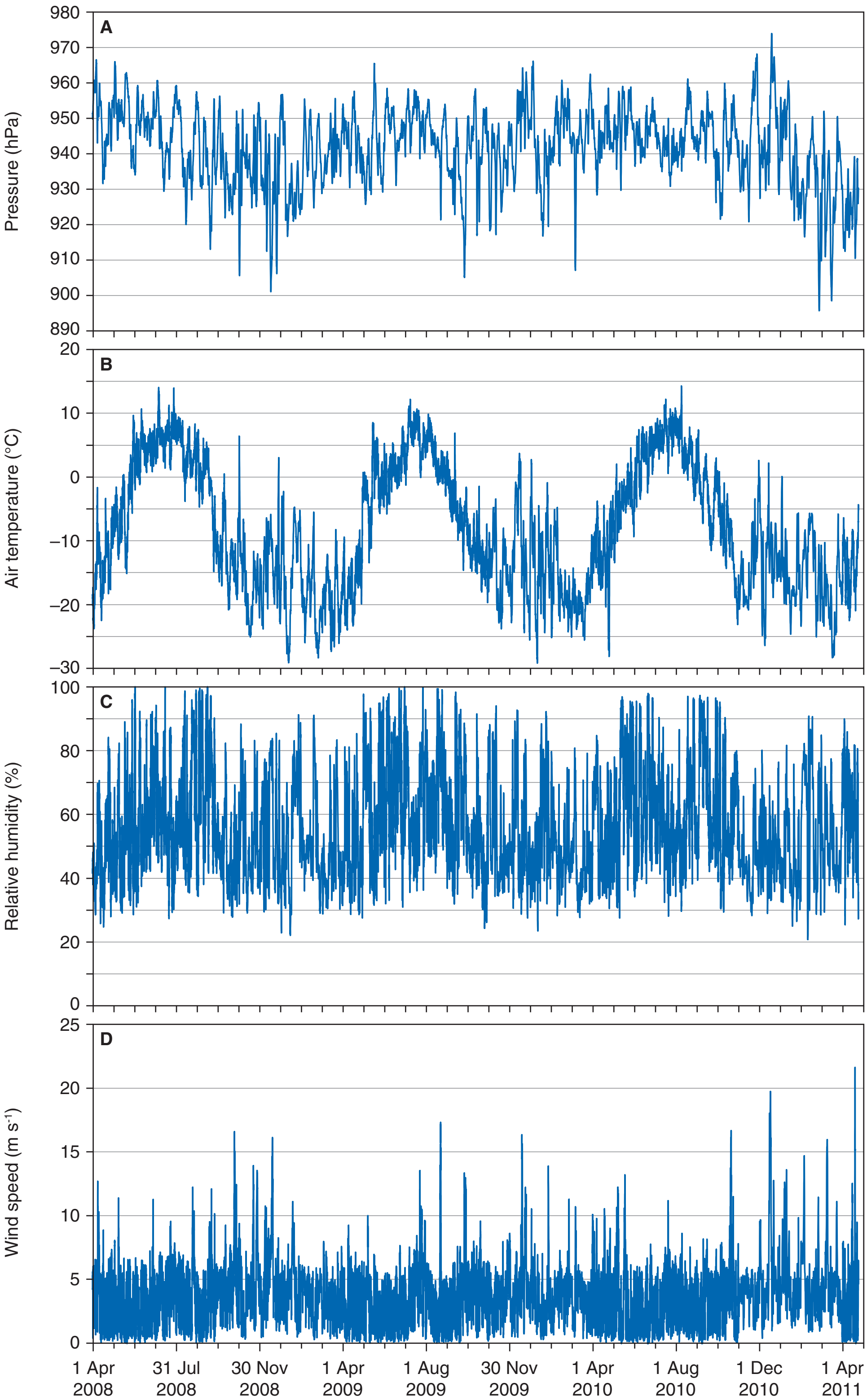


Figure 3.3 The complete available time series of selected parameters at AWS2. Barometric pressure (A), air temperature (B), relative humidity (C) and wind speed (D).

AWS1 has been working without interruption since the day it was set up 29 March 2008. The only sensor failure known to date affected one of the two sonic rangers, which became unstable during summer 2008 and was found tilted in May 2009, when it was reset to the proper position. As is normal in the ablation area, both sensors drilled into the ice (the ablation meter and the thermistors string) are gradually melting out, and need to be re-drilled every year. Complete time series of barometric pressure, air temperature, relative humidity and wind speed are shown in figure 3.3.

The AWS2 station

Description: AWS2 – A.P. Olsen small AWS (centreline, middle tongue, just up-

flow of lake and lateral glacier confluence).
Coordinates: 74° 38.6′ N, 21° 28.2′ W, elevation (WGS84): 880 m.
Measured parameters: aspirated T_{air}, aspirated RHair, wind speed, wind direction, ice level, snow level, GPS position, and diagnostics.
Time series: uninterrupted from 31 March 2008 to today for all sensors except the sonic rangers, which had intermittent problems.
Current availability: 10 minutes from flash card from 31 March 2008 to 13 May 2010. There is no satellite data telemetry; therefore, data is only retrieved once a year in the field.

This AWS is a smaller version of AWS1 and it is not equipped with satellite transmission. In 2010, the metal frame supporting the sonic ranger measuring ice ablation was found weakened but still standing (figure 3.4). The frame was reestablished, data downloaded and the scheduled recalibration plan was implemented.

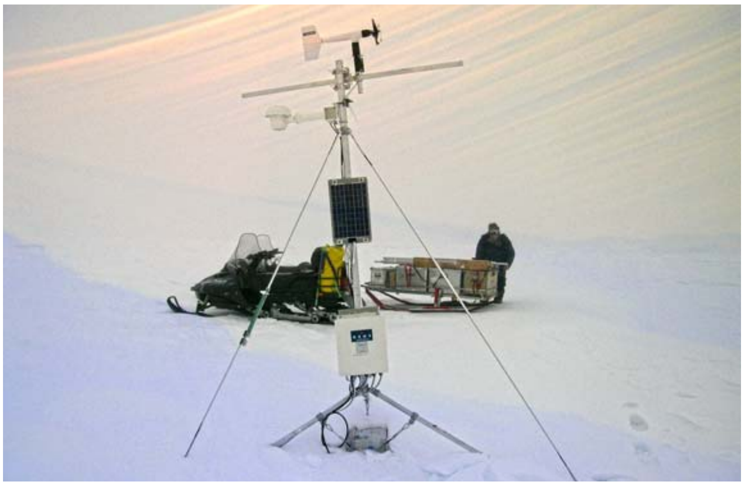


Figure 3.4 The AWS2 station as found in May 2010. Photo: Michele Citterio, GEUS.

Data retrieval in the field is required for this station; therefore, the plots in figure 3.5 stop in mid-May 2010. Further data will be retrieved upon the next revisit in May 2011. Air temperature, relative humidity and wind speed are shown in figure 3.5.

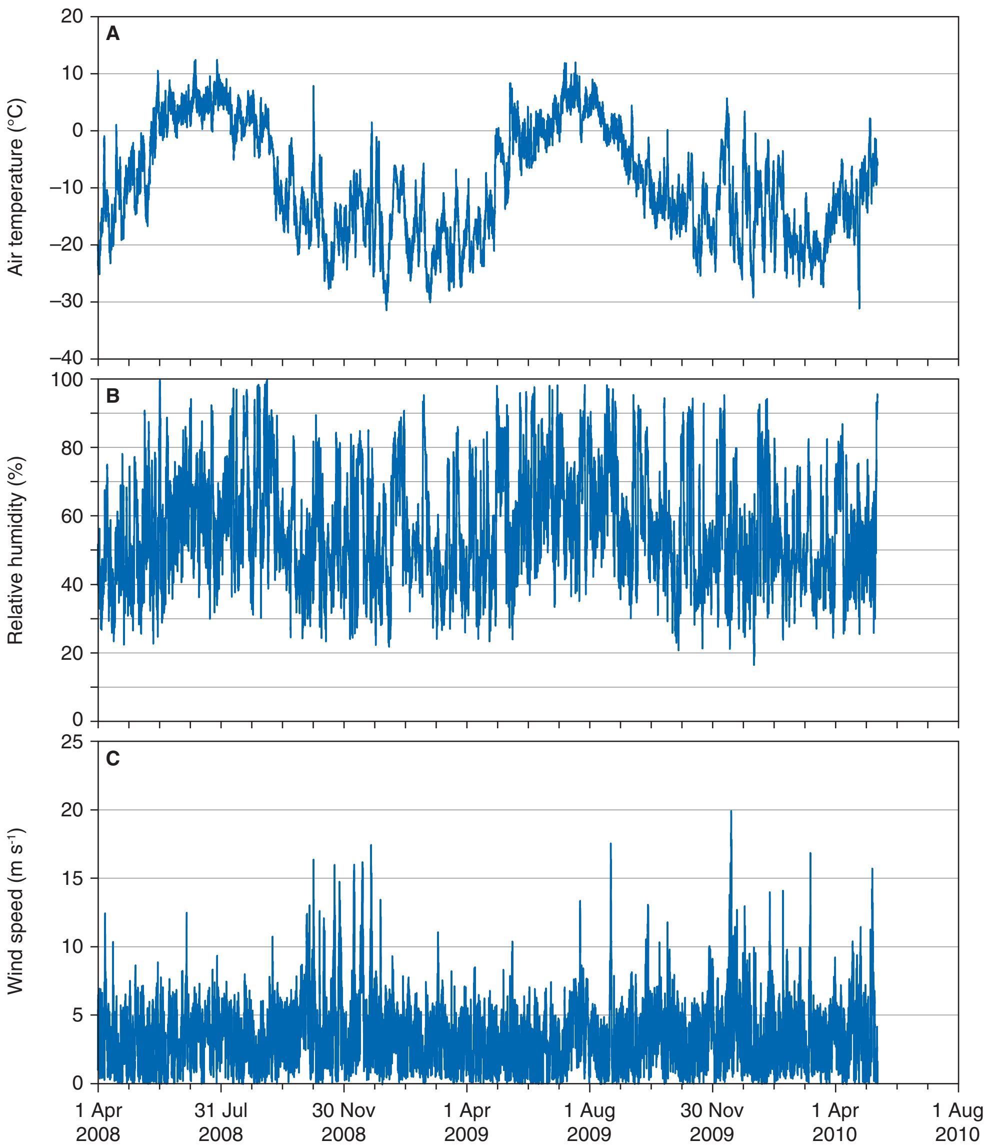


Figure 3.5 The complete available time series of selected parameters at AWS2. Air temperature (A), relative humidity (B) and wind speed (C).

The AWS3 station

Description: AWS3 – A.P. Olsen summit (at the wide-open flat just SSW of A.P. Olsen Summit)
Coordinates: 74° 38.9' N, 21° 39.1' W, elevation (WGS84): 1475 m.
Measured Parameters: aspirated Tair, aspirated RHair, wind speed, wind direction, downwelling SWi, upwelling SW, downwelling LW, upwelling LW, sensor T of the LW radiometer, ice & snow level, eight-levels thermistor string, two-axes station tilt, GPS fix, diagnostics.
Time series: from 6 August 2009 to 19 October 2010, for all sensors except the sonic rangers which had intermittent problems, with a four days gap just before the revisit 11 May 2010. On 19 October 2010 transmission stopped abruptly during moderately high wind conditions and resumed spontaneously 13 March 2011.
Current availability: 10 minutes from flash card from 6 August 2009 to 11 May 2010, then one- or three-hourly transmitted data until revisit in 2011 (see above for gaps).
Notes: fitted for extension with one additional thermistor string, one additional sonic ranger.

This AWS was setup by helicopter in August 2009. It is equipped with a subset of the sensors on AWS1 and it was found in good working order upon revisit in May 2010. No mechanical failure had occurred but the wind direction had been defective since installation, so the wind monitor instrument was replaced and an "alpine type" unit was selected which features a special surface colour and finish designed to better cope with riming (figure 3.6, note the black wind monitor with reduced surface propeller). Both here and at the lower stations riming has been observed to be severe at times.

Transmissions from ASW3 suddenly stopped 19 October 2010 during moderately high, worsening wind conditions. The mechanical structure of the tripod may have partly failed, most likely following failure of a guy-wire, however transmissions resumed spontaneously 13 March 2011, reporting reasonable values for most sensors. The tilt meters read in excess of 20 degrees from the vertical line in both directions, again suggesting that a guy-wire or an aluminium tube failed. Figure 3.7 shows air temperature, relative humidity and wind speed from AWS3, with the gap in winter 2010-2011.

3.3 Ablation stakes network

A network of 14 ablation and surface velocity stakes distributed along the central flow line was established in spring 2008 on the outlet glacier of the A.P. Olsen Ice Cap and along three transects at elevations of approximately 675, 900 and 1300 m a.s.l. (figure 3.8). In May 2010, one more stake was established very close to the terminus (stake 1, figure 3.8) for better covering of the area with the strongest ablation. The location of the stakes was provided in Jensen and Rasch 2010.

Surveying the network of ablation stakes is a core task of GlacioBasis, because it provides a direct measurement of the glacier mass balance, which is central to the entire programme. Ablation stakes are 6 m long metal rods drilled into the ice and measured periodically to quantify the amount of water lost to ablation. Stakes are distributed over the glacier surface with the primary aim to cover the entire elevation range of the glacier, because glacier mass balance shows the

Figure 3.6 The AWS3 station near the Summit in May 2010 after minimal maintenance. Being in the accumulation area, the tripod is firmly frozen in the firn. Photo: Michele Citterio, GEUS.

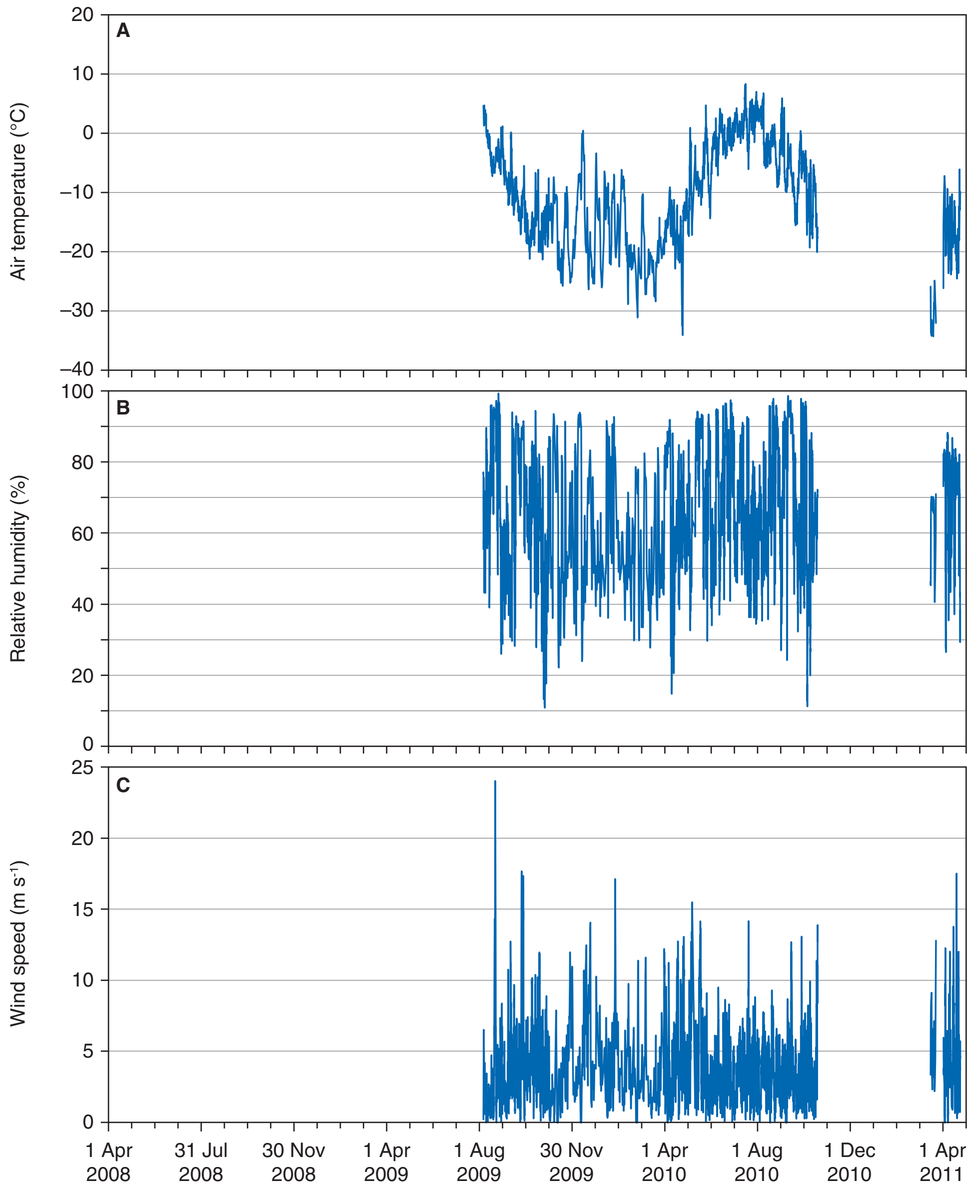


Figure 3.7 The complete available time series of selected parameters at AWS3. Air temperature (A), relative humidity (B) and wind speed (C).

strongest gradient with elevation. Stakes are also arranged in transects at roughly the same elevation in order to capture the lateral variability moving out from the centreline of the glacier, due e.g. to shading and long wave radiation from the surrounding rock walls. Figure 3.8 provides an overview and map of the investigated outlet glacier of the A.P. Olsen Ice Cap. Ablation is measured by subtracting the length of stake above the ice in 2009 from the length in 2010. The resulting number must be checked for evidence of any disturbance to the stake, like melting-in at the bottom of the stake that can be a typical source of inaccuracy. Even though all stakes were visited in 2010, only some of them had been accessible in 2009 and it is therefore advisable to wait for the 2011 measurements so that well-controlled values can be given.

3.4 Snow radar survey

Monitoring snow accumulation allows for obtaining the winter mass balance and it is most important in the higher reaches of the glacier, the accumulation area. The most effective method to map snow depth is to use snow radar towed by snowmobile and connected to a differential GPS system to precisely geolocate the radar traces. A 500 MHz GPR (ground penetrating radar) available through GeoBasis was again used with success for this purpose in 2010. Manual probing of snow depth with an avalanche probe was carried out at about 100 known points along the same track of the radar profiles over the entire length of the glacier to calibrate the radar velocity in the snow. The GPR data have been post-processed and

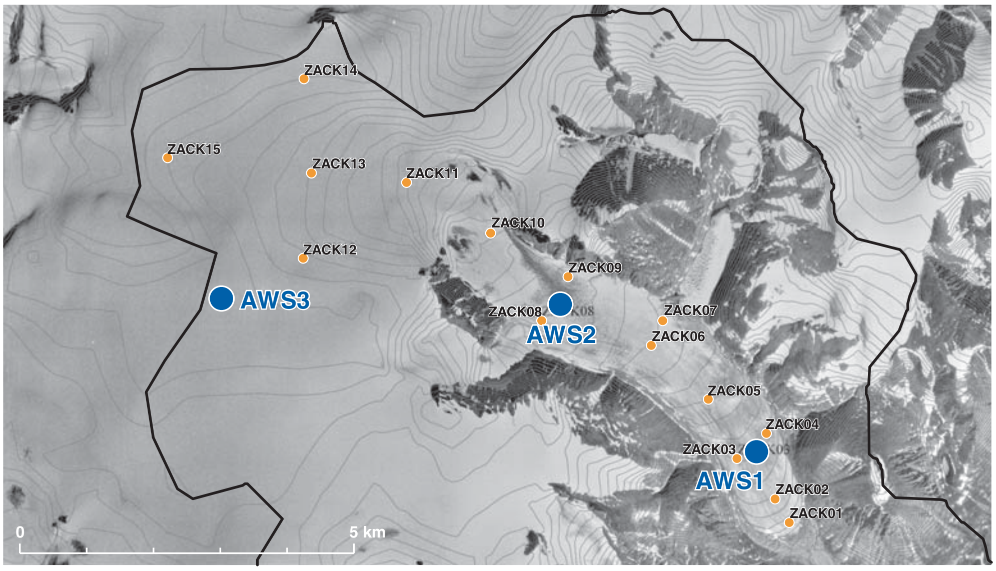


Figure 3.8 Orthophotograph of the investigated outlet glacier with the position of ablation stakes (orange dots) and AWSs (blue dots).

interpreted using the ReflexW software and then calibrated for radar velocity in the snowpack by least squares fitting of the radar and manual measurements (figure 3.9). The results show that velocities within the snowpack were rather consistent over the altitudinal range, while some values disagree between manual probing and radar interpretation, mainly close to the altitude of the equilibrium line. In such conditions the radar interpretation can typically be wrong when the operator, instead of the previous year summer surface, picks the deeper reflector of two years before, resulting into an erroneously high snow depth. Manual probing can also be wrong when stronger layers in the snowpack are mistaken by the operator for the actual ice surface, leading to underestimates of snow depth. These errors can be detected through the plot in figure 3.9. The plot shows a cluster of points clearly too deep in the radar interpretation, and possibly one point too shallow in the manual probing.

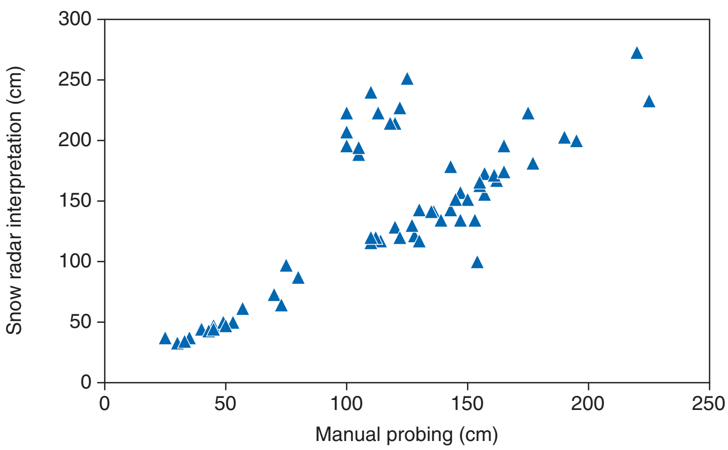


Figure 3.9 Results of snow depth from manual probing versus interpreted snow radar profiles after velocity calibration.

Knowledge of snow density is required to convert surveyed snow thickness into water equivalent. Snow densities have been measured in 2010 by digging a number of snow pits from the elevation of the lower weather station (AWS1) to the Summit weather station (AWS3) and by surveying the density profile along the snow stratigraphy.

3.5 Surface velocity and elevation survey

Ice flow transports mass from the accumulation to the ablation area, and over time a glacier typically tends to adjust its shape towards a steady state where surface mass balance is compensated by ice flow through any cross section normal to the flow vectors of the glacier. However, climate does not remain constant, and therefore glaciers are not in steady state. To set observed glacier change into perspective and correctly interpret it as an expression of climate change, an estimate is required of how close the glacier is to steady state in the present climate. This can be done, under certain assumptions, from the surface velocity field and know-ledge of the bedrock profile from ice radar.

Differential GPS also provides the required accuracy to monitor elevation changes of the glacier surface after repeated surveys are acquired and post-processed over the years.

In 2010, all ablation stakes have been measured by DGPS (figure 3.10) by setting up a base station in the forefront of the glacier and using a second Trimble

R7-GNSS receiver as the rover on the glacier. The settings of the system are critical; the rover in particular needs to provide real-time positions in a format suitable for the Malå X7R radar, log raw GPS observables for the static post-processing, minimize power and memory consumption and log raw GPS observables at a rate high enough for kinematic post-processing (figure 3.11). The settings that were used successfully in 2010 are documented below:

- **Receiver:** Trimble R7 GNSS s/n 4906K34295, hw 1.0, fw 4.12, boot 3.55, 256Mb flash card (FAT32).
- **GPS settings:** elev. mask 10d, PDOP mask 25, kinematic, track L2C, L5, GLONASS.
- **Antenna:** Zephir Model 2, bottom of mount, 0.000 m.
- **Logging:** measurement 10 Hz, position 10 Hz.
- **Serial output:** Port 3, NMEA-GGA, 10 Hz, 115200 bps, no parity, no flow control.
- **Rover:** CMR listen to any station, Network type none, RTK low latency.
- **Radio:** Rover, freq. <blank>, TrimTalk 450s at 9600 bps.

Figure 3.10 The position of ablation stakes in 2010 was measured by DGPS. The GPS receiver is shown configured with a VHF antenna for RTK-GPS, but post-processing had to be used because VHF signal coverage was poor. Photo: Michele Citterio, GEUS.

Remote sensing

Starting with 2009, GlacioBasis has an active role in increasing the amount and quality of new imagery acquisitions by the currently operational satellites, with the ability to submit request for scheduling dedicated image acquisitions of A.P. Olsen Ice Cap and the Zackenberg river catchment area by the ASTER instrument onboard the Terra satellite. This is possible through the affiliation to the GLIMS project (GEUS act as regional centre for

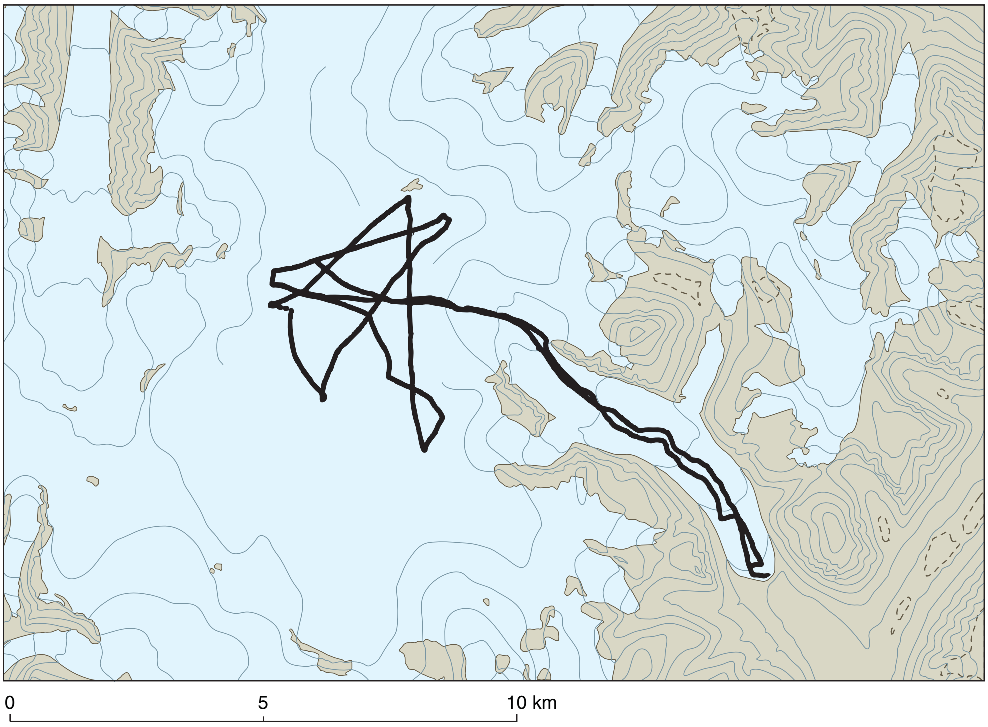


Figure 3.11 Profiles surveyed in kinematic DGPS mode to accurately measure the surface elevation of the glacier. Snow radar data have also been recorded along the same path. Post-processing of the raw GPS files was carried out either in static mode for the position of the ablation stakes, or in kinematic mode for the surface elevation profiles and transects. The accurate position of the base station was determined by the Precise Post Processing (PPP) technique, based on using refined GPS orbital and clock data more accurate than those broadcast in real time, using approximately 20 hours of logged observations. After the precise location of the master receiver was calculated, the same master raw data file was used again to differential post-processing the rover GPS data, resulting in the map of this figure.

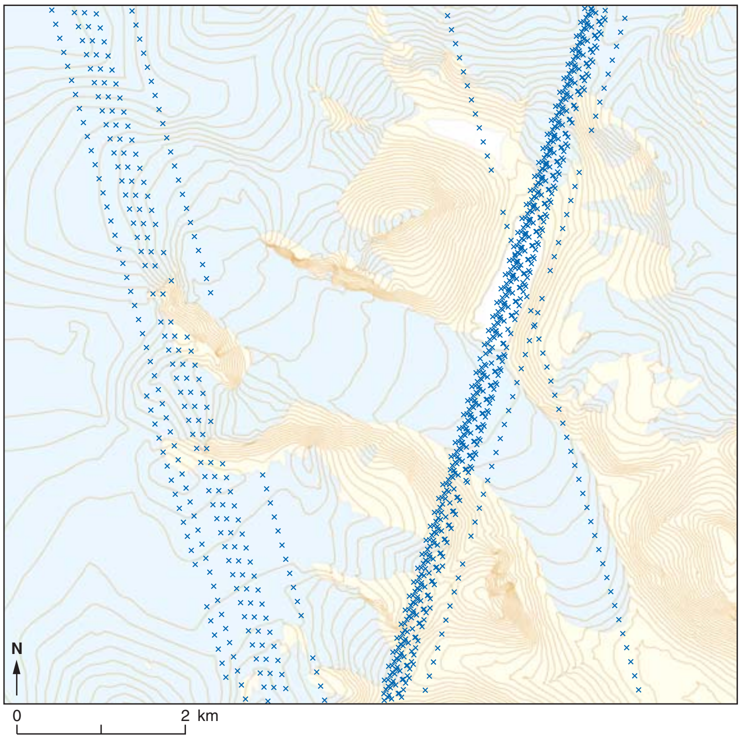


Figure 3.12 Paths on the ground of ICESat orbits between 2003 and 2009, showing the usable orbits passing along the axis of the lake.

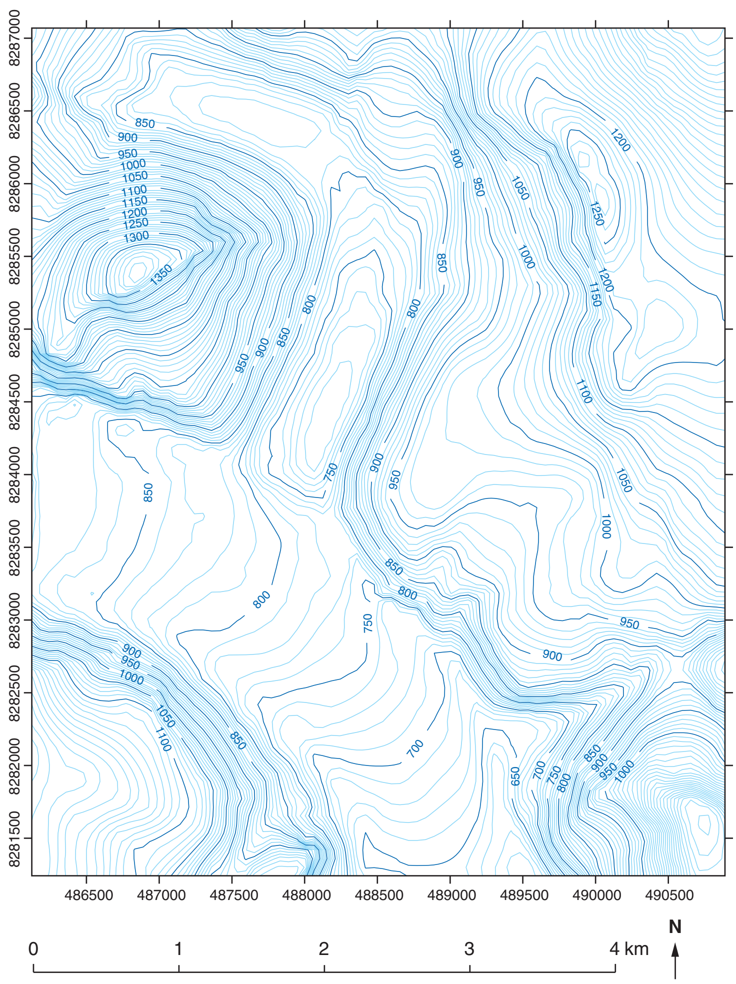


Figure 3.13 Preliminary elevation contours map produced from the DEM grid obtained after fusion of the previously available topography of the lake surroundings and the kriging interpolation of 2003-2009 ICESat altimetry.

Greenland within GLIMS), and through submission of a specific request every year. This offers the additional advantage of being able to tune the hardware settings of the Terra/ASTER instrument to best suit glaciological applications, e.g. to prevent saturation over snow covered areas due to hardware dynamic range constraints of the satellite instruments. On-demand acquisitions continued in 2010, resulting in several images completely or partly cloud-free and therefore usable to track the seasonal retreat of the transient snow line.

During 2010, the water volume and the bottom elevation of the ice-dammed lake have been determined from remote sensing by using ICESat laser altimetry data. It was noticed that 14 overpasses of ICESat between 2003 and 2009 happened to measure almost exactly parallel to the main elongation of the lake (figure 3.12).

Taking advantage of the positional inaccuracy of ICESat orbit repetitions, a complete coverage of the lake bottom was obtained. The paths on the ground of the ICESat orbits do not repeat exactly, which in this specific application is a favourable thing. Two digital elevation models (DEM) of the empty (figure 3.13) and filled lake have been produced by kriging, fused with the available DEM of the surrounding area, and differenced to produce a preliminary estimate of water volume in the ice dammed lake of 9-10 10^6 m^3. This is an important result because it provides the volume of water being released into Zackenbergelven during the recurring glacier outburst floods.

4 Zackenberg Basic

The BioBasis programme

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This chapter reports the 2010 field season of BioBasis. The BioBasis programme at Zackenberg is carried out by the Department of Arctic Environment, National Environmental Research Institute, Aarhus University. BioBasis is funded by the Environmental Protection Agency as part of the environmental support programme Danish Cooperation for Environment in the Arctic (DANCEA). The authors are solely responsible for all results and conclusions presented in this chapter, which do not necessarily reflect the position of the Environmental Protection Agency.

Please refer to previous Zackenberg Annual Reports for presentation of data covering the earliest years of the monitoring programme. Detailed information on the BioBasis methods and updated sampling protocols are available at the Zackenberg website (http://www.zackenberg.dk).

The 2010 BioBasis field team consisted of Martin Ulrich Christensen (day 138-156), Lars Holst Hansen (day 156-211 and 243-307), Jannik Hansen (day 156-229), Thomas B. Berg (day 194-218), Niels Martin Schmidt (day 194-215), Noémie Boulanger-Lapointe (day 222-243), Michelle

Table 4.1 Inter- and extrapolated date of 50 % snow-cover for white arctic bell-heather Cassiope tetragona, *mountain avens* Dryas integrifolia/octopetala, *arctic poppy* Papaver radicatum, *arctic willow* Salix arctica, *purple saxifrage* Saxifraga oppositifolia *and moss campion* Silene acaulis. **Denote extrapolated dates.*

Plot	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Cassiope 1	154	158	164	157	<155	143	164	155	164	138	150
Cassiope 2	<156	172	171	164	168	158	183	167	174	145	164
Cassiope 3	165	171	171	158	159	148	179	158	172	140	164
Cassiope 4	165	172	168	158	159	158	174	164	174	148	167
Dryas 1	<156	<151	<150	155*	<154	<140	150*	<145	147	<135	<142
Dryas 2/*Salix* 7	173	184	179	173	173	168	192	170	182	157	174
Dryas 3	<156	157	157	157	<155	<140	151	<145	147	136	<142
Dryas 4	<156	158	157	151*	<153	<140	164	152	162	135	<142
Dryas 5	<156	156	157	157	<153	<140	177	<145	152	<135	142
Dryas 6/*Papaver* 4	172	179	181	170	173	165	191	164	184	149	170
Papaver 1	153	171	169	163	166	152	179	162	169	139	162
Papaver 2/*Salix* 5	166	172	171	172	163	158	183	161	178	149	166
Papaver 3	165	172	170	165	160	158	174	163	174	148	167
Salix 1	<155	<151	<150	151*	<155	<140	145*	<145	137	<135	<142
Salix 2	165	172	165	165	161	156	178	160	169	148	162
Salix 3	<155	158	158	153*	<155	138*	160	151	163	<135	146
Salix 4	159	162	161	164	157	150	165	154	161	147	158
Salix 6					173	166	186	165	182	149	169
Saxifraga/*Silene* 1	<155	<151	<150	152*	<154	<140	<146	<145	<131	<135	<142
Saxifraga/*Silene* 2	<155	<151	<150	151*	<154	<140	<146	<145	<131	<135	<142
Saxifraga/*Silene* 3	<155	147*	<150	152*	<154	128*	158	152	145	<135	<142
Silene 4	173	179	176	170	170	163	186	164	176	150	167

Table 4.2 Inter- and extrapolated date of 50 % open flowers (50/50 ratio of buds/open flowers) for white arctic bell-heather Cassiope tetragona*, mountain avens* Dryas integrifolia/octopetala*, arctic poppy* Papaver radicatum*, arctic willow* Salix arctica*, purple saxifrage* Saxifraga oppositifolia *and moss campion* Silene acaulis*. *Denote interpolated dates based on less than 50 buds + flowers.*

Plot	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Cassiope 1	180*	185	184	178	175	167	185	178	186	173	176
Cassiope 2	–	193	188	184	187	173	201	186	193	180	186
Cassiope 3	–	192	190	183	182	173	200	185	194	178	184
Cassiope 4	–	200	188	186	185	183	200	186	195	183	190
Dryas 1	178	173	176	181	173	164	177	173	172	170	170
Dryas 2	206	213	210	200	200	198	215	192	204	188	200
Dryas 3	179	187	179	180	175	164	180	177	174	175*	174
Dryas 4	178	187	179	174	174	164	187	178	186	173	172
Dryas 5	174	186	179	179	172	164	172	171	175	172*	172
Dryas 6	203	210	213	198	199	194	214	191	206	185	200
Papaver 1	186	193	193	186	193	185	206	188*	195	184	190*
Papaver 2	197	195	194	189	190	190	208	188	204	185	194
Papaver 3	192	198	194	192	187	187	201	187*	199	186	193
Papaver 4	202*	208*	214	198	194	194	214	192*	204	186*	197*
Salix 1	163	159	160	168	156	155	165	161	161	155	162
Salix 2	180	180	179	179	173	165	196	177	187	167	177
Salix 3	163	175	167	166	159	157	174	165	174	152*	161
Salix 4	169	179	177	174	173	164	180	170	174	167	174
Salix 5	–	–	–	186	175	164	194	174	193	168	179
Salix 6	–	–	–	–	197	184	200	179	194	171	184
Salix 7	–	–	–	–	187	187	202	182	195	179	186
Saxifraga 1	158	159	154	165	157	144	151	160*	159*	149*	153
Saxifraga 2	161	159	157	165	157	152	157	158	158	150	157
Saxifraga 3	159	160	158	165	<154	146	172	165	159*	146*	161
Silene 1	178	179	174	182	173	165	170	173	172	174	174
Silene 2	184	181	178	185	181	166	182	179	173	184	179
Silene 3	180	185	179	185	172	166	194	179*	173	180	178
Silene 4	210	210	209	201	201	197	194	193	207	187	199

Table 4.3 Inter- and extrapolated date of 50 % open seed capsules for arctic poppy Papaver radicatum*, arctic willow* Salix arctica *and purple saxifrage* Saxifraga oppositifolia*. *Denote interpolated dates based on less than 50 flowers + open capsules.*

Plot	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Papaver 1	222	228	232	213	219	212	232	223	211*	203	223*
Papaver 2	230*	228	229	215	219	215	234	221	226	206	221
Papaver 3	227	230	232	218	216	212	223	220	215	212	225
Papaver 4	229*	236	238*	222	227	220	239*	222*	222*	214*	222*
Salix 1	225	214	210	214	208	201	219	218	211*	220	223
Salix 2	233	230	223	215	218	215	231	220	227	218	222
Salix 3	225	226	217	209	209	206	223	215	225	213*	218
Salix 4	226	225	224	215	219	210	223	219	225	220	222
Salix 5	–	–	–	216	220	219	>240	221	229	215	227
Salix 6	–	–	–	223	223	226	>240	222	234	217	228
Salix 7	–	–	–	225	223	226	>240	224	234	221	229
Saxifraga 1	222	220	216	219	205	203	217*	218	195	209*	212
Saxifraga 2	228	226	213	223	209	212	217	216	205	213	214
Saxifraga 3	220	225	224	221	205	212	225	221	188	215*	218

Table 4.4 Area size (m²) and pooled numbers of flower buds, flowers (or catkins) and senescent flowers (or catkins) of white arctic bell-heather Cassiope tetragona, *mountain avens* Dryas integrifolia/octopetala, *arctic poppy* Papaver radicatum, *arctic willow* Salix arctica, *purple saxifrage* Saxifraga oppositifolia, *and moss campion* Silene acaulis. **Numbers for arctic cotton-grass* Eriophorum scheuzerii *and 'dark cotton-grass'* Eriophorum triste *2010 will be published in the 2011 report. ***Saxifraga *1 had a second flowering peak at 77.*

Plot	Area	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Cassiope 1	2	28	1711	1510	851	2080	1392	973	435	1183	233	431
Cassiope 2	3	8	1353	952	1001	1745	1203	593	300	958	555	340
Cassiope 3	2	0	771	449	817	791	862	432	92	704	256	227
Cassiope 4	3	3	578	164	1189	1274	1857	520	223	1340	437	304
Dryas 1	4	607	1016	627	744	444	391	321	150	190	254	334
Dryas 2	60	46	172	290	552	1174	519	521	577	806	395	410
Dryas 3	2	266	577	235	294	273	198	134	92	92	32	129
Dryas 4	6	55	301	187	224	218	143	168	191	141	90	192
Dryas 5	6	312	506	268	589	351	233	123	125	103	51	318
Dryas 6	91	140	550	430	627	1854	878	1324	1144	1606	593	889
Papaver 1	105	197	237	277	278	286	207	153	108	80	68	53
Papaver 2	150	236	466	456	564	402	682	416	334	500	341	416
Papaver 3	90	240	259	301	351	221	316	234	236	190	188	138
Papaver 4	91	35	65	59	56	37	68	71	29	71	26	80
Salix 1 mm.	60	681	536	1454	1931	1127	375	303	184	0	243	858
Salix 1 ff.	60	900	1047	1498	2159	1606	386	223	241	0	234	1172
Salix 2 mm.	300	55	803	1206	967	1276	737	654	317	758	304	522
Salix 2 ff.	300	95	1304	1816	1638	1862	1089	1076	386	506	570	1512
Salix 3 mm.	36	330	1196	344	621	693	285	204	169	492	39	183
Salix 3 ff.	36	137	1009	315	333	476	188	129	154	332	51	311
Salix 4 mm.	150	965	680	1589	1751	1984	1317	1508	1108	1894	1414	1086
Salix 4 ff.	150	796	858	1308	1418	1755	1038	905	827	1768	1528	822
Salix 5 mm.	150	–	–	–	494	844	945	1052	414	831	513	287
Salix 5 ff.	150	–	–	–	371	1314	1333	1365	525	1209	681	526
Salix 6 mm.	150	–	–	–	-	2162	2445	591	525	1565	137	447
Salix 6 ff.	150	–	–	–	1145	2736	2010	947	1085	2401	406	1875
Salix 7 mm.	60	–	–	–	612	621	746	286	351	515	185	147
Salix 7 ff.	60	–	–	–	839	512	705	180	266	570	319	207
Saxifraga 1	7	1552	558	542	1213	463	159	36	190	124	23**	293
Saxifraga 2	6	387	515	617	561	584	522	167	313	99	123	171
Saxifraga 3	10	403	558	318	509	609	241	150	394	90	84	506
Silene 1	7	1327	674	766	1191	1187	312	430	94	171	159	1085
Silene 2	6	692	568	1094	917	1406	740	540	285	267	260	188
Silene 3	10	274	348	480	1000	719	503	739	379	170	168	493
Silene 4	1	358	462	470	794	509	483	312	423	373	499	424
E. scheuz. 1	10	229	111	582	843	780	201	302	533	310	98	*
E. scheuz. 2	6	201	358	581	339	956	597	540	142	193	61	*
E. scheuz. 3	10	38	367	260	237	359	67	44	31	37	17	*
E. scheuz. 4	8	117	121	590	445	176	57	23	55	74	14	*
E. triste 1	10	1	0	3	11	12	0	0	1	1	0	*
E. triste 2	6	43	56	67	39	117	44	49	13	14	25	*
E. triste 3	10	0	0	0	0	0	0	0	0	0	0	*
E. triste 4	8	0	0	0	0	0	0	0	0	0	0	*

Table 4.5 Area size (km²) and Normalised Difference Vegetation Index (NDVI) values for 13 sections of the bird and musk ox monitoring areas in Zackenbergdalen together with the lemming monitoring area based on an Landsat satellite image from 30 July 2010 (see Schmidt et al. 2011) for position of the snow sections). The image has been corrected for atmospheric (humidity, aerosols, and solar angle) and terrain effects. All negative NDVI values, i.e. from water and snow-covered areas, have been replaced by zeros.

Section	Area	Min.	Max.	Mean	Std. dev.
1 (0-50 m)	3.52	0.00	0.77	0.35	0.23
2 (0-50 m)	7.97	0.00	0.84	0.44	0.24
3 (50-150 m)	3.52	0.00	0.84	0.51	0.17
4 (150-300 m)	2.62	0.00	0.69	0.40	0.17
5 (300-600 m)	2.17	0.00	0.67	0.27	0.16
6 (50-150 m)	2.15	0.00	0.67	0.43	0.20
7 (150-300 m)	3.36	0.00	0.70	0.43	0.18
8 (300-600 m)	4.56	0.00	0.75	0.31	0.21
9 (0-50 m)	5.01	0.00	0.83	0.47	0.18
10 (50-150 m)	3.84	0.00	0.77	0.49	0.16
11 (150-300 m)	3.18	0.00	0.68	0.41	0.17
12 (300-600 m)	3.82	0.00	0.81	0.38	0.20
13 (Lemmings)	2.05	0.00	0.80	0.45	0.19
Total Area	**45.72**	**0.00**	**0.76**	**0.41**	**0.19**

Schollert Skovgaard (day 194-236), Christian Bay (day 187-215) and Ditte Katrine Kristensen (day 187- 215).

4.1 Vegetation

The weekly records of snow cover, plant flowering and reproduction were conducted by Martin Ulrich Christensen, Lars Holst Hansen, Thomas B. Berg, Noémie Boulanger-Lapointe and Jannik Hansen. Gas flux measurements were conducted by Lars Holst Hansen and Michelle Schollert Skovgaard. Pinpoint analyses were carried out by Michelle Schollert Skovgaard and Pernille Lærkedal Sørensen. Michelle Schollert Skovgaard did leaf fluorescence measurements. Christian Bay and Ditte Katrine Kristensen undertook the survey of the ZERO line and the northern range species examinations.

Reproductive phenology and amounts of flowering

The 2010 BioBasis field season began day 142 (22 May). Snowmelt was later than in 2009 but still relatively early with dates of 50 % snow cover; earlier than or equalling the median for previous seasons in all plant plots (table 4.1). The relatively early snowmelt resulted in earlier than average 50 % flowering in 26 of 28 plots when compared to previous seasons (table 4.2). Only in one *Salix* and one *Saxifraga* plot was the flowering later than average.

Despite the relatively early snowmelt and flowering, not all plant plots had earlier than average dates of 50% open seed capsules (table 4.3). Four of 14 plots had later than average dates.

In the 2010 season, 24 of 35 categories had fewer than or close to the average number of flowers hitherto recorded (table 4.4). There were new minima in two arctic poppy *Papaver radicatum*, two arctic willow *Salix arctica* (male catkins), and one moss campion *Silene acaulis* category.

Table 4.6 Mean NDVI values for 13 sections of the bird and musk ox monitoring areas in Zackenbergdalen together with the lemming monitoring area based on Landsat TM, ETM+ and SPOT 4 HRV and ASTER satellite images 1995-2010 (see Meltofte et. al 2008 for position of sections). The data have been corrected for differences in growth phenology between years to simulate the 31 July value, i.e. the approximate optimum date for the plant communities in most years. Data from 2003 are not available due to technical problems.

Section	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
1 (0-50 m)	0.37	0.43	0.44	0.44	0.30	0.41	0.34	0.34	–	0.42	0.41	0.39	0.37	0.37	0.28	0.35
2 (0-50 m)	0.43	0.5	0.5	0.51	0.41	0.48	0.43	0.44	–	0.50	0.49	0.47	0.44	0.49	0.35	0.44
3 (50-150 m)	0.54	0.53	0.54	0.53	0.41	0.51	0.47	0.49	–	0.54	0.53	0.48	0.46	0.53	0.41	0.51
4 (150-300 m)	0.46	0.45	0.46	0.44	0.31	0.43	0.36	0.38	–	0.41	0.40	0.38	0.35	0.46	0.32	0.40
5 (300-600 m)	0.36	0.35	0.38	0.38	0.22	0.37	0.26	0.26	–	0.31	0.30	0.28	0.24	0.38	0.20	0.27
6 (50-150 m)	0.48	0.48	0.47	0.46	0.33	0.44	0.39	0.41	–	0.46	0.45	0.43	0.40	0.47	0.32	0.43
7 (150-300 m)	0.48	0.46	0.48	0.45	0.32	0.43	0.38	0.39	–	0.45	0.44	0.40	0.37	0.47	0.33	0.43
8 (300-600 m)	0.42	0.38	0.41	0.42	0.25	0.35	0.28	0.29	–	0.33	0.32	0.32	0.28	0.38	0.21	0.31
9 (0-50 m)	0.42	0.5	0.52	0.51	0.39	0.50	0.44	0.45	–	0.52	0.51	0.47	0.44	0.53	0.37	0.47
10 (50-150 m)	0.52	0.53	0.54	0.52	0.40	0.52	0.48	0.48	–	0.55	0.54	0.49	0.46	0.55	0.42	0.49
11 (150-300 m)	0.47	0.45	0.46	0.42	0.26	0.41	0.35	0.36	–	0.45	0.44	0.39	0.38	0.51	0.36	0.41
12 (300-600 m)	0.42	0.42	0.44	0.45	0.28	0.32	0.34	0.33	–	0.41	0.40	0.39	0.33	0.45	0.27	0.38
13 (Lemmings)	0.42	0.49	0.5	0.49	0.40	0.47	0.41	0.43	–	0.48	0.47	0.45	0.42	0.48	0.34	0.45
Total	**0.45**	**0.46**	**0.48**	**0.47**	**0.32**	**0.43**	**0.38**	**0.38**	–	**0.45**	**0.44**	**0.42**	**0.39**	**0.47**	**0.32**	**0.41**

Table 4.7 Peak NDVI recorded in 26 plant plots 2000-2010 together with date of maximum values. NDVI values from 2000-2006 are based on data from hand held RVI measurements, and have been recalculated to account for varying incoming radiation that otherwise affects the measurements. Note that the greening measured accounts for the entire plant community, in which the taxon denoted may only make up a smaller part. Data from 2004 are not included due to instrumental error.

	2000		2001		2002		2003		2005		2006		2007		2008		2009		2010	
Plot	**NDVI**	**DOY**	**NDVI**	**DOY**	**NDVI**	**DOY**	**NDVI**	**DOY**	**NDVI**	**DOY**	**NDVI**	**DOY**	**NDVI**	**DOY**	**NDVI**	**DOY**	**NDVI**	**DOY**	**NDVI**	**DOY**
Cassiope 1	0.39	211	0.4	203	0.40	224	0.37	210	0.37	217	0.36	220	0.35	218	0.36	239	0.33	238	0.32	224
Cassiope 2	0.41	204	0.41	203	0.39	210	0.39	217	0.40	217	0.38	220	0.37	218	0.39	239	0.36	205	0.39	216
Cassiope 3	0.35	204	0.37	203	0.34	210	0.34	217	0.38	210	0.35	224	0.41	218	0.34	239	0.31	213	0.33	217
Cassiope 4	0.42	204	0.41	203	0.38	217	0.40	210	0.44	210	0.41	220	0.39	218	0.45	239	0.39	238	0.38	211
Dryas 1	0.42	204	0.44	203	0.43	210	0.43	189	0.39	190	0.37	220	0.35	218	0.41	239	0.37	205	0.38	203
Dryas 2/ *Salix* 7	0.47	211	0.47	203	0.51	217	0.47	203	0.48	217	0.46	220	0.49	218	0.49	239	0.48	213	0.47	210
Dryas 3	0.49	204	0.51	203	0.51	210	0.50	203	0.46	196	0.45	220	0.42	190	0.43	206	0.44	205	0.51	189
Dryas 4	0.38	204	0.42	203	0.40	210	0.38	203	0.41	210	0.38	212	0.36	211	0.40	239	0.36	205	0.36	183
Dryas 5	0.34	204	0.37	203	0.36	210	0.34	196	0.33	210	0.30	212	0.26	176	0.35	239	0.31	213	0.33	203
Dryas 6/ *Papaver* 4	0.46	204	0.46	203	0.47	217	0.45	203	0.47	210	0.44	220	0.43	218	0.47	250	0.46	238	0.44	203
Eriophorum 1	0.58	196	0.61	203	0.61	210	0.59	189	0.60	196	0.60	220	0.51	190	0.57	219	0.54	205	0.55	203
Eriophorum 2	0.54	204	0.56	203	0.54	210	0.53	203	0.52	196	0.52	220	0.47	218	0.51	206	0.49	213	0.51	203
Eriophorum 3	0.53	204	0.52	203	0.53	210	0.50	203	0.47	196	0.47	220	0.43	218	0.50	206	0.53	213	0.51	203
Eriophorum 4	0.69	204	0.69	203	0.70	217	0.71	189	0.72	210	0.72	220	0.68	197	0.64	206	0.67	196	0.69	203
Papaver 1	0.41	204	0.42	203	0.45	210	0.42	203	0.42	217	0.41	220	0.41	218	0.42	239	0.40	213	0.42	203
Papaver 2/ *Salix* 5	0.43	204	0.44	203	0.45	210	0.43	203	0.46	210	0.44	220	0.45	218	0.44	239	0.42	213	0.43	217
Papaver 3	0.42	204	0.43	203	0.42	210	0.42	203	0.45	210	0.41	212	0.40	218	0.46	239	0.38	238	0.39	211
Salix 1	0.54	204	0.56	203	0.56	210	0.57	189	0.52	196	0.51	220	0.51	197	0.53	206	0.50	213	0.56	183
Salix 2	0.52	204	0.54	203	0.55	210	0.53	189	0.52	196	0.53	220	0.48	197	0.50	211	0.47	205	0.53	203
Salix 3	0.44	204	0.46	203	0.46	210	0.43	189	0.41	210	0.41	220	0.38	197	0.41	206	0.37	213	0.39	189
Salix 4	0.49	204	0.51	203	0.52	210	0.50	189	0.49	196	0.49	220	0.47	218	0.48	206	0.44	213	0.47	196
Salix 6	–	–	–	–	–	–	0.48	212	0.48	210	0.46	220	0.47	218	0.44	239	0.42	213	0.46	211
Saxifraga/ Silene 1	0.27	204	0.29	203	0.26	210	0.27	196	0.24	210	0.24	212	0.20	218	0.22	250	0.24	245	0.24	203
Saxifraga/ Silene 2	0.38	204	0.4	203	0.37	210	0.39	189	0.37	190	0.34	212	0.35	218	0.37	206	0.37	238	0.29	183
Saxifraga/ Silene 3	0.29	204	0.32	182	0.29	210	0.29	203	0.27	210	0.27	212	0.25	218	0.27	239	0.27	231	0.26	175
Silene 4	0.38	196	0.37	203	0.37	217	0.35	196	0.39	210	0.35	224	0.39	218	0.38	239	0.38	213	0.34	217
Mean of all	**0.44**	**204**	**0.46**	**202**	**0.45**	**212**	**0.44**	**200**	**0.44**	**206**	**0.43**	**219**	**0.41**	**211**	**0.43**	**228**	**0.41**	**217**	**0.42**	**202**

Vegetation greening

The greening index data (NDVI) inferred from an ASTER satellite image from 30 July 2010 are presented in table 4.5. The mean landscape NDVI in the 2010 season was around the average of the previous season (table 4.6). Table 4.7 lists the peak dates (as day of year) of the NDVI in the permanent plots. NDVI in the plots peaked relatively early in 2010. In all but five of the 26 plant plots, peak NDVI was earlier than average of previous seasons.

Figure 4.1 summarises the NDVI transect data across the 2010 season in three altitude categories. Transect NDVI was measured from snowmelt and into the autumn until the ground was covered with snow. The main vegetation types peaked around day 206. The pattern of vegetation greening was similar in the

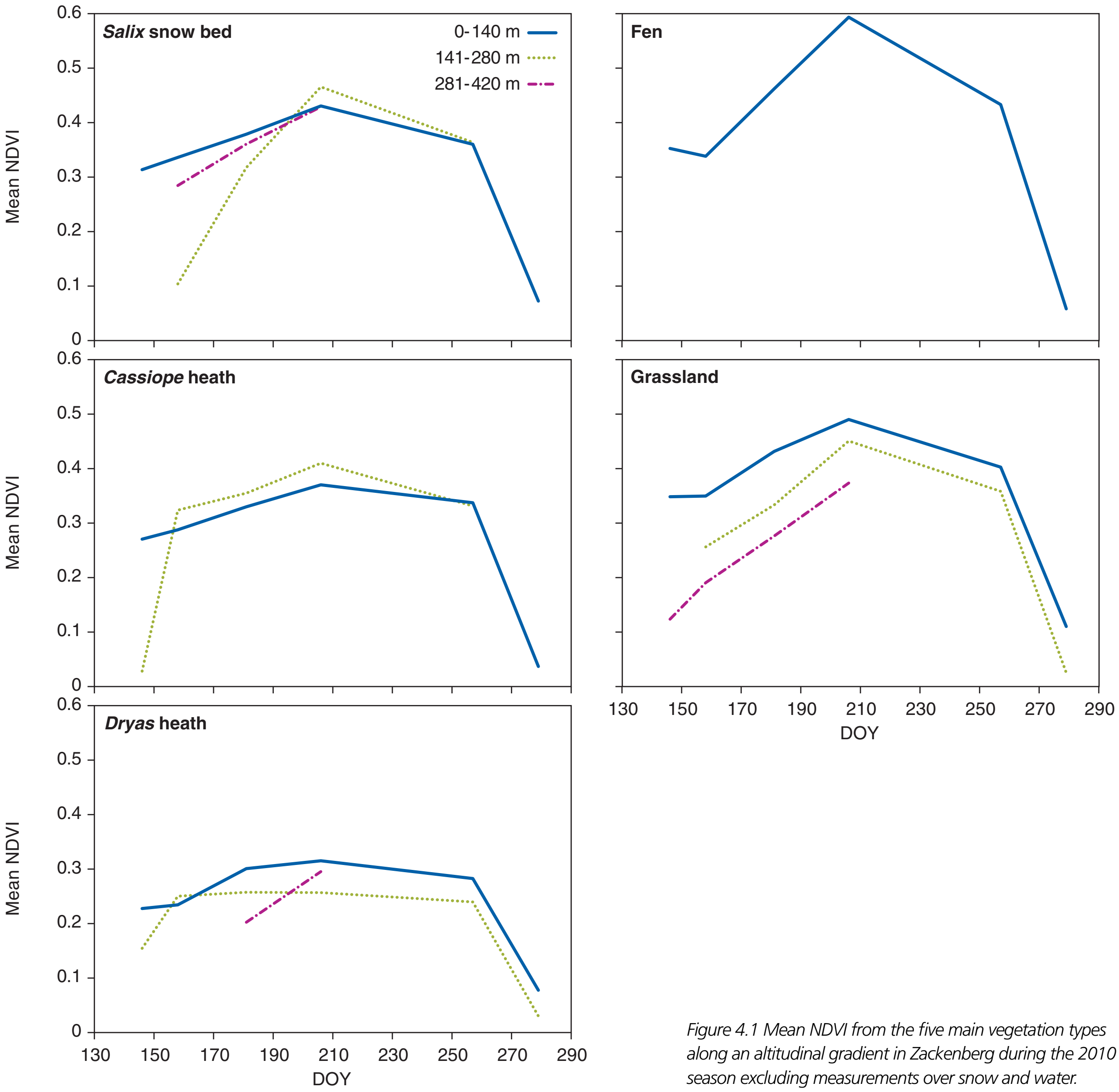


Figure 4.1 Mean NDVI from the five main vegetation types along an altitudinal gradient in Zackenberg during the 2010 season excluding measurements over snow and water.

three altitude categories, and the NDVI levels in each altitude category were similar within all vegetation types but the grassland, where higher NDVI values were observed with decreasing altitude.

Carbon flux in ITEX temperature chamber and UV-B exclusion plots

The ITEX experimental warming plots were established in late June and removed in late September at the two heath sites dominated by *Salix arctica* and *Cassiope tetragona*. The experimental UV-B exclusion plots, located close to the ITEX *Salix* site, were established in late June and taken down in late September. The experimental UV-B exclusion removed a large proportion of ambient UV-B irradiance and was compared with transparent filter control and an open control. During the period, treatment responses were monitored fortnightly by measurements of ecosystem CO_2 exchange using the closed chamber technique.

For the ITEX warming plots, the net ecosystem exchange (NEE), ecosystem respiration (R_{eco}) and gross primary production (GPP) are presented in figure 4.2. The *Salix* heath was more productive than the *Cassiope* heath, which is in line with results from previous years. Both sites functioned as sinks for atmospheric CO_2 in July-August, while in September-October they were small sources. Warming generally increased both R_{eco} and GPP at both sites; however, the difference between control plots and warmed plots was only significant for R_{eco} measurements from *Salix* heath in July and

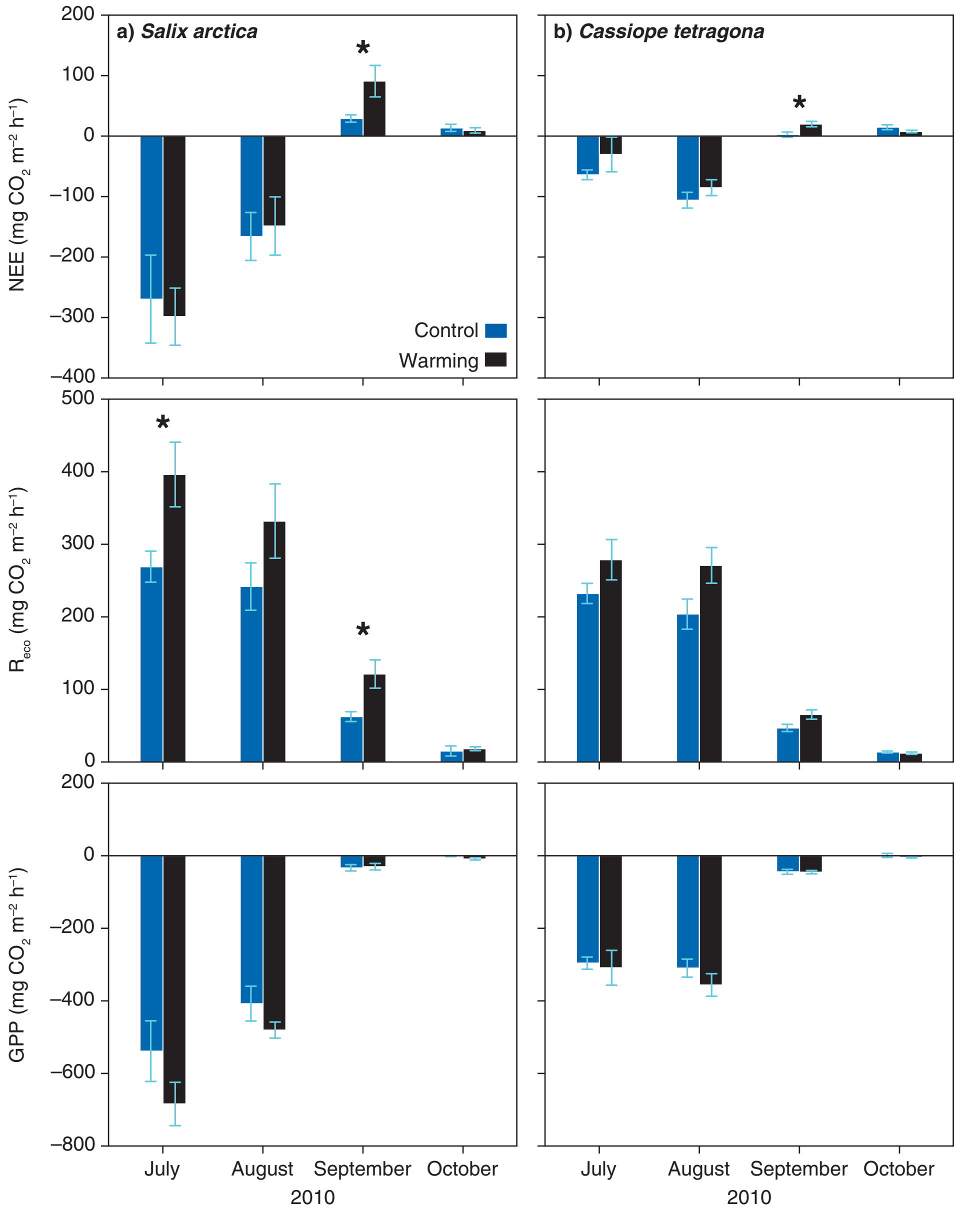


Figure 4.2 Ecosystem CO_2 exchange in ITEX and control plots during July-October 2010. Measurements were carried out fortnightly on (A) Cassiope tetragona *dominated heath and (B)* Salix arctica *dominated heath. Flux is positive when CO_2 is released from the ecosystem and negative when CO_2 is accumulated by the ecosystem. Depicted are means ± standard error of ecosystem respiration (R_{eco}), net ecosystem exchange (NEE) and gross primary production (GPP). Treatment effects were analysed using ANOVA. Stars indicate significant differences at α=0.05 level.*

September. For NEE, there was a significant difference at both the *Salix* heath and *Cassiope* heath in September; warmed plots were stronger sources of atmospheric CO_2 compared with controls. There were no significant differences in NEE or GPP in either site when comparing temporal averages throughout the measured period for each plot. For R_{eco}, there was a significant difference at the *Cassiope* heath (p=0.0288) and a close to significant difference at the *Salix* heath (p=0.0531).

The seasonal development and magnitudes of NEE, R_{eco} and GPP in the UV-B exclusion plots were similar to those recorded at the ITEX *Salix* site (figures 4.2 and 4.3). In July-August there was a tendency towards increased GPP and R_{eco} in UV-B exclusion plots compared with filter control (figure 4.3), and the CO_2 sink strength was also stronger as deduced from the NEE measurements; however, there were no significant differences between treatment effects for NEE, R_{eco} and GPP. Nor were there any significant differences when comparing temporal averages throughout the measuring period.

Leaf performance in UV-B exclusion plots

The total performance index (PI_{total}), integrating responses of antenna, reaction centre, electron transport and end acceptor dependent parameters, was the most sensitive parameter in both *Salix* and *Vaccinium*. The PI_{total} was reduced by around 15 % in *Vaccinium* and around 20 % in *Salix* when comparing the filter treatment to reduced UV-B (table 4.8). The PI_{total} was significantly decreased 21 July and 31 July

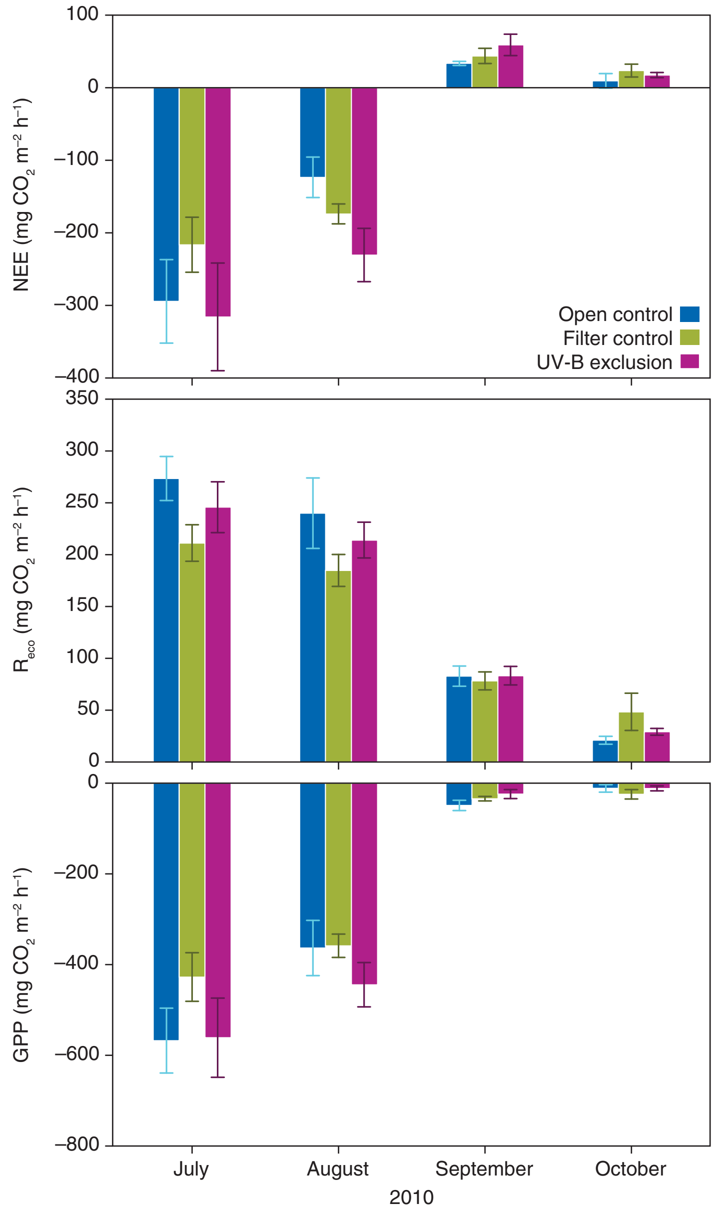


Figure 4.3 Ecosystem CO_2 exchange in UV-B exclusion plots, filters control and open control during fortnightly measurements in July-October 2010. Flux is positive when CO_2 is released from the ecosystem and negative when CO_2 is accumulated by the ecosystem. Depicted are means ± standard error of ecosystem respiration (R_{eco}), net ecosystem exchange (NEE) and gross primary production (GPP). Treatment effects were analysed using ANOVA. Stars indicate significant differences at α=0.05 level.

in *Salix*, but no significant differences were observed in single measurement days in *Vaccinium* when filter treatment was compared to reduced UV-B (figure 4.4).

Re-examination of the ZERO line

The botanical monitoring of the ZERO line took place during three weeks in July and for the third time since the establishment of the line in 2000. The ZERO line was established as a transect crossing the main part of the vegetation types known from the Zackenberg study area. The line goes from the coast with salt marsh and ends at the peak of Aucellabjerget at a distance of approximately 6 km from the coast. The purpose of the monitoring is to record long-term changes in the vascular plant species composition and the distribution of plant communities. Of the original 128 analyses, 105 have been analysed in 2005 and 2010 as the upland analyses (600 m a.s.l.) were abolished in 2005 because the markers were not in the original position and it was not possible to re-establish the plots. A comparison of data from the three years is in a process of being analysed.

Two species of vascular plants new to the flora of Zackenberg area were found outside the monitoring sites. *Honckenya peploides var. diffusa* was found near the shoreline east of the river and *Draba crassifolia* was found in a *Salix arctica* snow bed north of Kamelen. In 2005, *Mertensia maritima* was found at the research station, presumably introduced by a visitor from West Greenland. The total number of vascular plant species known from Zackenberg is 155 making the valley the most diverse middle arctic area in Greenland.

Monitoring of northern limit species

Selected vascular plant species which have their known northern distribution limit in the Zackenberg area are monitored every fifth year. Comparing with the results from 2005 there were marked differences. Many of the plots exhibit an increase in number of flowers and fruits, which contrast the conclusion of the comparison of the 2000 and 2005 data (Bay 2006). The low arctic species *Campanula gieseckiana*, which had a marked reduction in reproduction from 2000 to 2005, now has an increase in number of flowers and buds in nearly all plots. The plots, which had the largest decline in reproduction in 2005 (from 155 flowers to 0), now have 86 flowers. Contrary, *Carex lachenalii* a late snow bed species, is the only species monitored, which had a decline in the reproduction.

4.2 Arthropods

All five-pitfall trap stations and the one window trap station (four trap chambers) were open during the 2010 season. Sampling procedures were concurrent with previous seasons. Fieldwork was carried out by Lars Holst Hansen, Noémie Boulanger-Lapointe, Martin Ulrich Christensen and Jannik Hansen. Unfortunately, the transport box carrying the bulk of the arthropod samples did not arrive in Denmark after the field season. Consequently, samples have not been sorted. We hope to be able to present the arthropod data from the 2010 season in the 2011 Annual Report.

*Table 4.8 Seasonal response in the UV-B exclusion plots. Parameters are: The ratio of PSII reaction centre's (RC) and absorbance flux, [RC/ABS]. The maximum quantum yield, [ϕ_{Po} = FV/FM)] which corresponds to the efficiency an absorbed photon will be trapped by PSII RC leading to QA reduction. The fraction of electrons transported beyond QA- per exiton trapped by the open reaction PSII RC, [$\psi_{Eo} = ET_o/TR_o$]. The efficiency with which an electron can move from the reduced intersystem electron acceptors to the PSI end acceptors, [$\delta_{Ro} = RE_o/ET_o$]. The total performance index integrating the responses of antenna, reaction centre, electron transport and end acceptor dependent parameters [PI_{total} = (RC/ABS) x [$\phi_{Po}/(1-\phi_{Po})$] x [$\psi_{Eo}/(1-\psi_{Eo})$] x [$\delta_{Ro}/(1-\delta_{Ro})$]]. The presented values are the seasonal mean ± standard error for open control (no filter), filter control (transparent filter, Mylar) and UV-reduction (UV-B absorbing filter, Teflon). The relative effect of ambient UV-B is given as the difference in percent for filter minus UV reduction (Δ%F-UV = [(F-UV)/F*100)]). Statistical significant differences F vs. UV are in bold (p<0.05).*

Species	Parameter	Open Control (C)	Filter Control (F)	UV-B reduction (UV-B)	Δ% F-UV-B
	RC/ABS	0.602 ± 0.009	0.594 ± 0.012	0.615 ± 0.009	–3.5
	$\phi_{Po} = F_V/F_M$	0.739 ± 0.005	0.736 ± 0.009	0.761 ± 0.005	–3.5
Salix arctica	$\psi_{Eo} = ET_o/TR_o$	0.504 ± 0.009	0.488 ± 0.012	0.527 ± 0.009	–8.0
	$\delta_{Ro} = RE_o/ET_o$	0.616 ± 0.013	0.581 ± 0.013	0.577 ± 0.008	0.7
	PI_{total}	3.326 ± 0.222	2.821 ± 0.211	3.411 ± 0.196	–20.9
	RC/ABS	0.483 ± 0.018	0.477 ± 0.014	0.510 ± 0.011	–6.9
	$\phi_{Po} = F_V/F_M$	0.688 ± 0.016	0.696 ± 0.012	0.711 ± 0.009	–2.2
Vaccinium uliginosum	$\psi_{Eo} = ET_o/TR_o$	0.553 ± 0.017	0.541 ± 0.013	0.566 ± 0.009	–4.7
	$\delta_{Ro} = RE_o/ET_o$	0.510 ± 0.008	0.518 ± 0.008	0.539 ± 0.008	–3.9
	PI_{total}	2.642 ± 0.212	2.204 ± 0.199	2.545 ± 0.197	–15.5

The material from previous seasons is stored in 90 % ethanol (before 2008, in 70 % ethanol) at the Museum of Natural History, Aarhus. Please contact the BioBasis manager (nms@dmu.dk) regarding access to the collection. The total number of arthropods collected in 2010 is unknown at the deadline for the report, but 442 samples were collected during the season. Ice and snow at the arthropod trap stations melted relatively early in 2010. In five out of six plots for which median day of 50 % snow or ice cover can be calculated (Art1-6), snow or ice melt was earlier than those medians for all seasons (table 4.9).

Insect predation on Dryas flowers

The percentage of *Dryas* flowers marked by predation from "black moths" *Sympistis zetterstedtii* was about average compared to previous seasons (table 4.10).

4.3 Birds

Bird observations were made by Martin Ulrich Christensen, Jannik Hansen, Noémie Boulanger-Lapointe and Lars Holst Hansen. Other researchers and staff – not least Jeroen Reneerkens and his colleagues (see section 6.12) – provided much valued, additional information throughout the season. Local site names can be found in Schmidt et al. 2011.

Breeding populations

Between day 166 and 176 (15 June to 25 June), a complete, initial census was carried out. That is a normal start and a slightly delayed last day of census. The weather prevented census work on a few days during the period. The completion of the survey took 36 'man-hours', which is average. The entire census was carried out on days with good weather conditions.

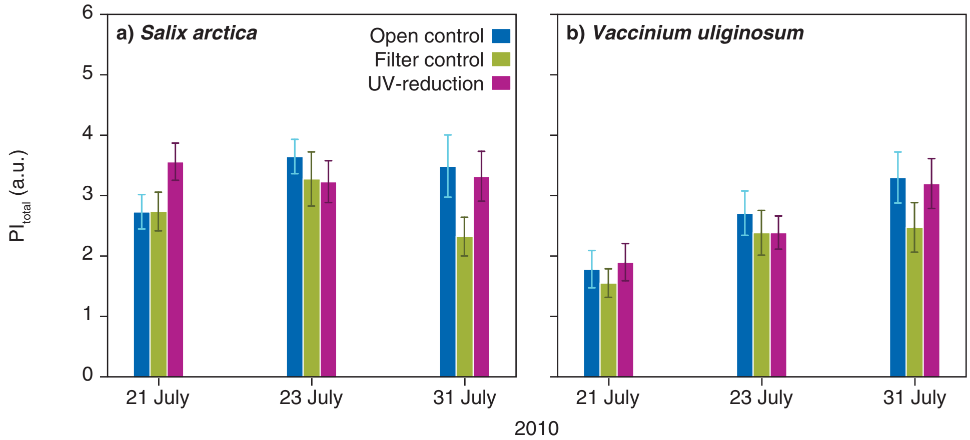


Figure 4.4 Seasonal variation in total performance index (PI_{total}). The PI_{total} integrates the responses of antenna, reaction centre, electron transport and end acceptor dependent parameters [PI_{total} = (RC/ABS) x [$\phi_{Po}/(1-\phi_{Po})$] x [$\psi_{Eo}/(1-\psi_{Eo})$] x [$\delta_{Ro}/(1-\delta_{Ro})$]]. The presented values are the seasonal mean ± standard error for open control (no filter), filter control (transparent filter, Mylar) and UV-reduction (UV-B absorbing filter, Teflon). Three campaigns were conducted on Salix arctica (A) and Vaccinium uliginosum (B).

Table 4.9 Date of 50 % snow-cover (ice-cover on pond at Station 1) in the arthropod plots 1996-2008. [a]0 % snow, [b]<1 % snow, [c]7 % ice cover, [d]3 % snow.

Station no.	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Art. 1	153	157	154	163	<153[c]	<140	156	148	154	144	151
Art. 2	<156[a]	<151[a]	<151[a]	152	<153[a]	<140[a]	<147	<146[a]	147	135	<142[a]
Art. 3	161	170	165	171	156	154	174	158	172	147	162
Art. 4	159	172	171	162	158	156	179	161	174	138	163
Art. 5	<156[a]	159	154	156	<153[a]	<140	154	<176[b]	150	138	145
Art. 7	<156[a]	<150	<151[a]	153	<153[a]	<140	<147	<176[b]	144	134	<142[d]

Table 4.10 Peak ratio (%) of mountain avens Dryas integrifolia/octopetala *flowers depredated by larvae of "black moth"* Sympistis zetterstedtii *in mountain avens plots in 1996-2010.*

Plots	*Dryas* 1	*Dryas* 2	*Dryas* 3	*Dryas* 4	*Dryas* 5	*Dryas* 6
1996	2	0	11	17	2	0
1997	6	5	18	1	8	0
1998	3	0	3	7	2	0
1999	0	0	0	0	0	0
2000	0	0	0	0	0	0
2001	0	0	0	0	0	0
2002	15	1	7	11	9	0
2003	2	0	1	5	2	0
2004	15	4	33	39	3	1
2005	1	1	10	3	0	0
2006	27	3	6	18	2	6
2007	0	2	8	4	0	5
2008	34	25	67	32	2	8
2009	8	5	27	14	33	5
2010	7	7	16	11	6	47

In addition, large parts of the census area were covered regularly during June, July and most of August, exceptions being the closed goose moulting area along the coast (table 6.1) and on the slopes of Aucellabjerget above 350 m a.s.l. The latter was covered on six occasions by the BioBasis staff and by the many visits by Jeroen Reneerkens and colleagues (section 6.12).

The total effort in 2010 was average in June but lower in July compared to previous years.

The results of the initial census, supplemented with records during the rest of the season (see Schmidt et al. 2010), are presented in tables 4.11 and 4.12. These are compared with the estimates of previous seasons.

The first red-throated diver *Gavia stellata* was observed day 150 (30 May). On day 156 (5 June), the first pair of red-throated divers settled in a fen near the research station. Three pairs attempted to breed within the census area and two nests were found. They both fell victim to predation. In adjacent areas, a red-throated diver pair was recorded in the lake, Vesterport Sø. The pair briefly nested at the nest site used in the last few seasons (2007-09). Like the last couple of years, this attempt was unsuccessful due to predation.

A female and two male pintail ducks *Anas acuta* were seen around the study area from day 158 (7 June) until day 173 (22 June), after which one male disappeared. The remaining pair stayed until day 198 (17 July). No nest or other signs of nesting were found. This is the first time pin-tailed ducks have been present in the study area during the breeding season (table 4.12).

Sanderling *Calidris alba* territories were recorded at comparatively high numbers, which has been the trend in recent years (table 4.12). Dunlin *Calidris alpina* territories were found in higher than average numbers (cf. Hansen et al., in preparation – a). It should be noted that numbers from earlier years might have been underestimated (Meltofte 2006). The number of common ringed plover *Charadrius hiaticula* territories was near average.

Ruddy turnstone *Arenaria interpres* territories were almost back to the average numbers, as were red knot *Calidris canutus* territories (tables 4.11 and 4.12).

No red-necked phalarope *Phalaropus lobatus* nests were found in 2010. A female was seen in ponds around the research station from day 159 (8 June), and with a male from day 162 (11 June). The pair was last seen on day 168 (17 June). One red phalarope *Phalaropus fulicarius* nest was found in the census area in 2010. In the census area, a female was seen in fens near the research station during days 166-171 (15-20 June), being with a male on day 168 (17 June). The nest was found fully laid on day 181 (30 June), and by day 185 (4 July) all four eggs were starred. However, day 187 (6 July) the nest was found to have suffered predation. The nest cup smelled of arctic fox urine.

Table 4.11 Estimated numbers of pairs/territories in four sectors of the 15.8 km² census area in Zackenbergdalen, 2010.

Species	<50 m a.s.l. 7.77 km²	50-150 m a.s.l. 3.33 km²	150-300 m a.s.l. 2.51 km²	300-600 m a.s.l. 2.24 km²	Total
Red-throated diver	3	0	0	0	3
Pintail duck	1	0	0	0	1
King eider	1-3	0	0	0	1-3
Long-tailed duck	5	0	0	0	5
Rock ptarmigan	1	0	0-1	0	1-2
Common ringed plover	12-14	3	4-5	8-9	27-31
Red knot	4	10	7	3	24
Sanderling	31-38	2-3	9-12	12-13	55-67
Dunlin	64-70	21-23	2	0	87-95
Ruddy turnstone	16	18-20	3	0	37-39
Red-necked phalarope	1	0	0	0	1
Red phalarope	1	0	0	0	1
Long-tailed skua	7	6	0	0	13-19
Glaucous gull	1	0	0	0	1
Arctic redpoll	1	0	0	0	1
Snow bunting	16-19	23	6-7	3	48-52
Lapland bunting	1	0	0	0	1

Table 4.12 Estimated numbers of pairs/territories in the 15.8 km² census area in Zackenbergdalen. 2010 compared to the 1996-2009 averages.

Species	No. of territories	Average min. and max no. territories 1996-2009	No. of nests found[1]	Comments
Regular breeders				
Red-throated diver	3	2.4-2.8	1	Chicks seen in adjacent areas
Pintail duck	1	0	0	
Common eider	0	0.4	0	
King eider	1-3	1.2-1.9	0	
Long-tailed duck	5	5.4-6.4	0	
Rock ptarmigan	1-2	2.6-3.6	0	
Common ringed plover	27-31	28.7-35	1	
Red knot	24	24.7-32	3	
Sanderling	55-67	50.3-58	17	
Dunlin	87-95	74-84.2	8	
Ruddy turnstone	37-39	41.4-46.5	10	
Red-necked phalarope	1	0.8-1.7	0	
Long-tailed skua	13-19	18.1-22.1	1	
Glaucous gull	1	0.4	1	
Common raven	2	-	0	Nests outside the census area
Arctic redpoll	1	6.4-10.4	0	
Snow bunting	48-51	42-47	1	Nests of passerines are only found opportunistically
Irregular breeders				
Pink-footed goose	0	0.1	0	
Eurasian golden plover	0	0.1	0	
Red phalarope	1	0.6-0.8	1	
Snowy owl	0	0.1	0	
Northern wheatear	0	0.1-0.2	0	Territory recorded outside census area
Lapland bunting	1	0	1	

[1]Within the census area

Table 4.13 Median first egg dates for waders at Zackenberg 2010 as estimated from incomplete clutches, egg floating and hatching dates, as well as weights and observed sizes of pulli.

Species	Median date	Range	N	Average 1996-2009
Common ringed plover	162	162	1	166.8
Red knot	163	161-166	3	166.8
Sanderling	163	152-178	23	168.7
Dunlin	165.5	152-177	8	166.7
Ruddy turnstone	165	157-172	12	164.5

Long-tailed skua *Stercorarius longicaudus* territories were found in lower numbers than usual (table 4.12). Only one pair nested in the census area (see below).

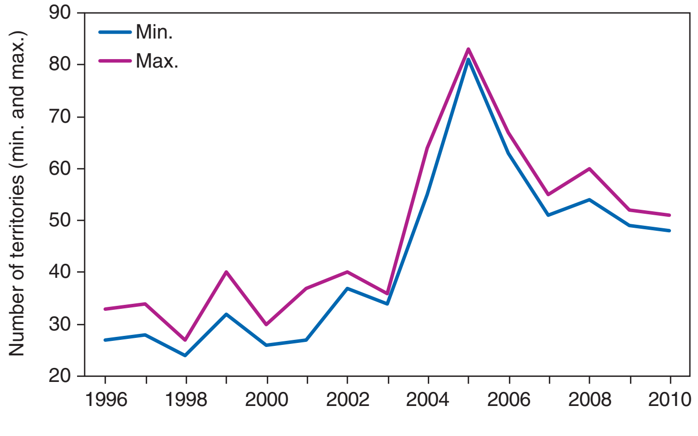
A glaucous gull *Larus hyperboreus* pair had a nest on an islet in the same stretch of Zackenbergelven, as it has had since at least 2004. No chicks were seen, and the nest is thought to have fallen victim to predation. This species is seen daily throughout the season.

The number of territories for rock ptarmigan *Lagopus muta* was low. During the census, only one territory and a single possible territory was found. The brood of the certain pair was encountered on day 216 (4 August). In adjacent areas, a female with a brood of 10 was found on the southern slopes of Zackenbergbjerget, at 50 m a.s.l. day 209 (28 July).

Numbers of snow bunting *Plectrophenax nivalis* territories were below the average of the last few years, yet higher than the period 1996-2003 (table 4.13 and figure 4.5). Juveniles of snow bunting were seen both within the census area and in adjacent areas – in fair numbers. No systematic counts of juveniles were made, but the impression is that snow buntings had a breeding season with a rate of successful fledging higher than average.

Only one Arctic redpoll *Carduelis hornemanni* territory was recorded this year (table 4.12).

Figure 4.5 Numbers (minimum and maximum) of snow bunting territories in the census area at Zackenberg, 1996-2010.



For the first time since the start of BioBasis, a pair of Lapland bunting *Calcarius lapponicus* bred in the study area. One pair nested on the lower slopes of Aucellabjerget. Fledglings were observed day 199 (18 July). Unfortunately, we do not have the number of fledglings. This is the northernmost breeding record of the species (cf. Boertmann 1994).

Reproductive phenology in waders (Charadriiformes)

Nest initiation was early in all species (table 4.13). 28.3% of all wader nests were initiated before 10 June, 86.6% before 20 June and just 10% after 20 June.

The snow cover 10 June was 72% and nest initiation was early compared to previous seasons (table 4.14).

Reproductive success in waders (Charadriiformes)

The all wader nest success was extremely low in 2010 – lower than ever before during the BioBasis programme. After the modified Mayfield method (Johnson 1979), 91% of the wader nests were subjected to predation.

Dunlin nests were hit less hard than other wader species, with 61.5% nest success, which is a high success rate. It was another rough season for sanderling nests (table 4.15). Three red knot nests were found in 2010, all suffered predation. Just over a third of the ruddy turnstone nests were successful, the rest falling victim to predation. As described above, a single red phalarope nest was unsuccessful.

The number of fox encounters was relatively low. However, in these numbers we have excluded fox visits to the research station, which were pronounced this year. An adult fox brought surprisingly young pups to the research station as early as day 187 (6 July). The apparent "getting used to" the research station is an increasing problem – primarily linked to problem around the research stations waste dispo-

Table 4.14 Snow cover 10 June together with median first egg dates for waders at Zackenberg 1995-2010. Data based on less than 10 nests/broods are in brackets, less than five are omitted. The snow cover is pooled (weighted means) from section 1, 2, 3 and 4 (see section 2.2), from where the vast majority of the egg laying phenology data originate.

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Snow cover on 10 June	84	82	76	80	91	53	84	79	83	48	28	85	48	71	4	72
Sanderling		(168)	169	169	174.5	168	173.5	168	164	160	(166)	181	166	169	167	163
Dunlin	(169)	163.5	164	167.5	173	163.5	176	159	163	164	163	178	166	169	162	165.5
Ruddy turnstone	(163)	170.5	164	163.5	175	163	174	160	159	160	162	(172)	158	170	154	165

Table 4.15 Mean nest success (%) 1996-2010 according to the modified Mayfield method (Johnson 1979). Poor data (below 125 nest days or five predations) are given in brackets. Data from species with below 50 nest days have been omitted (-: no nests at all). Nests with at least one pipped egg or one-hatched young are considered successful. Also given are total numbers of adult foxes observed by the bird observer in the bird census area during June-July (away from the research station proper), along with the number of fox dens holding pups.

Species	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	1996-2010
Common ringed plover				(60)		(38)				–	(0)	–	(2)	–		45-48
Red knot	–	–			–		–			–	–	(100)				18.5
Sanderling	(72)	(33-100)	(88)	40	(46)	19	(33)	45	71-85		(7)	3	5	7.5	3	15.5-16.5
Dunlin			28-47	65	68	(75)		63	93	(43)	47	48	17	(80)	(61.5)	57-62
Ruddy turnstone	21-68	67-100	16	23-28	29	(60)	52	21-27	83			67	(32)	(7)	(33.7)	35-40
Red-necked phalarope	–	–	–		–	–	–	–	–		–	–	–		–	0.8
Red phalarope	–	–	–	–	–	–	–	–	–	–		–	–	–		42.2
All waders	33-63	52-100	32-37	42-44	44	43	43	42-44	87-90	22	37	18	16	14	9	31.4
N nests	17	31	44	44	47	32	21	51	55	15	28	60	58	66	46	42.3
N nest days	163	228	334	520.8	375	328.4	178.9	552	700	104	332.2	532.7	423.5	508.5	306.5	373.3
Fox encounters	14	5	7	13	11	14	21	11	16	18	22	23	20	11	9	
Fox dens with pups	2	0	1	0	2	2	0-1	2	3	0	2	3	5	3	3	

Table 4.16 Mean clutch sizes for waders at Zackenberg 1995-2010. Samples of fewer than five clutches are given in brackets.

Species	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Weighted mean (species)
Common ringed plover	4.00*	4.00*	3.50*	4.00*	3.50*	4.00*	3.50*	4.00*	4.00*	4.00*		3.75*		3.75*		4.00*	3.88
Red knot				4.00*	4.00*		4.00*		4.00*	4.00*			4.00*	4.00*	4.00*	4.00*	4.00
Sanderling	4.00*	4.00	3.86	4.00	3.67	4.00	3.43	3.83	4.00	4.00	3.75	3.63	3.73	3.77	3.91	3.92	4.28
Dunlin		4.00*	3.75*	3.90	3.70	3.93	3.63	4.00*	4.00	3.92	4.00	3.13	3.79	3.67	4.00	4.00	4.01
Ruddy turnstone		3.71	3.79	3.82	3.58	3.80	3.75	4.00	3.77	3.92	3.86	3.00*	4.00*	3.71	3.78	3.92	4.10
Weighted mean	4.00	4.00	3.76	3.90	3.65	3.89	3.63	3.95	3.94	3.94	3.89	3.33	3.76	3.74	3.91	3.80	4.13

sal procedures (see chapter 7). Pups were recorded in three dens this season (table 4.15). A probable, partial explanation of the high predation on wader eggs.

The mean wader clutch size was 3.80 in 2010, which is below average (table 4.16). Nests containing fewer than four eggs were sanderling; two nests of three eggs. Ruddy turnstone; two nests of three eggs. A ruddy turnstone nest, unusually, contained five eggs. The three ruddy turnstone nests suffered predation.

In July and early August, alarming parents, and later juveniles, were found in the

Table 4.17 Egg-laying phenology, breeding effort and success in long-tailed skuas at Zackenberg 1996-2010. Median egg laying date is the date, when half the supposed first clutches were laid. Number of clutches found includes replacement clutches. Mean hatching success according to the modified Mayfield method (Johnson 1979). Nests with at least one pipped egg or one-hatched young are considered successful. Also given, are numbers of lemming winter nests within the 2 km^2 lemming census area (see section 3.4). Please note that in 2006 only one of two eggs hatched (other never hatched).

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Median 1st egg date		158	163	168	170	166	160	166	160	159	170	163	164	168	172
No. of clutches found	8	17	23	8	5	21	14	7	21	8	2	15	9	2	1
No. of young hatched	1	25	16	2	2	18	14	5	36	6	1	11	3	1	0
Nest success % (Mayfield)		80.6*	26.7	18.1*	17.5*	39.5	44.1	76.2*	94*	51.8*	100*	23	33	25.9	0
Estimated no. of young fledged	0	5	6	1	0	5	4	2	22	1	0	1	2	1	0
Lemming winter nests pr. km^2	224.5	247.2	467	227.4	136.8	208.5	178.3	66	238.7	170.8	189.6	236.8	75.5	49.1	25.4

Table 4.18 Average brood sizes of barnacle geese in Zackenbergdalen during July and early August, 1995-2010, together with the total number of broods brought to Zackenbergdalen. Average brood size data from autumn on the Isle of Islay in Scotland are given for comparison, including the percentage of juveniles in the population (Ogilvie 2011, pers. comm.).

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Primo July		3.0*	3.1	2.9*	1.9	3.2*	1.8*	2.4	1.8*	2.6	1.7*	2.0*	1.3	4*	1.0*	1.5*
Medio July		2.3*	2.7	2.3	1.8	3.1*	1.7*	2.4	1.2*	2.3	2.7	1.5*	1.5	1.6	1.4*	1.8*
Ultimo July	2.0*	3.0*	2.6	2.2	1.7	3.1		2.3	1.1*	2.3	2.2*	1.1*	3.3*	1.5*	1.0*	1.4*
Primo August	2.3*	2.3*	2.4		1.8		2.0*	2.2	1.2*	1.9*		1.5*	–	1.0*	1.5*	1.6*
No. of broods	≥7	6-7	19-21	≥18	29	11	4	32	8	26	14	9	28	15	9	18
Scotland	2.00	2.30	1.95	2.28	1.92	2.20	1.94	2.23	1.59	2.35	1.67	1.15	2.14	1.86	1.90	2.26
% juv.	7.2	10.3	6.1	10.5	8.1	10.8	7.1	12.5	6.4	15.9	6.3	3.23	9.8	8.2	3.8	11.2

fens and marshes (dunlins), on the slopes of Aucellabjerget and in the dry lowlands (common ringed plovers, red knots, sanderlings, dunlins, turnstones).

Data on chick survival is scarce, and as early as day 168 (17 June), flocks of long-tailed skuas roamed the lower slopes of Aucellabjerget and the lowlands. The largest flock held 32 individuals.

Reproductive phenology and success in long-tailed skuas *Stercorarius longicaudus*

Only one nest was found, initiated after the census period (later than the average of any preceding year). The nest suffered predation. No collared lemming *Dicrostonyx groenlandicus* was observed by the bird observer, reflecting a season with record low lemming winter nests found (table 4.17). On day 223 (11 August), a large juvenile (able to fly) appeared in the area, seemingly coming from Store Sødal or Lindemansdalen.

One observation of a three calendar year bird, in a flock of four birds, is the only observation of immature this season.

Barnacle geese *Branta leucopsis*

No activity was seen at the barnacle goose colony on the southern face of the Zackenbergfjeldet. However, the colony was probably active, since birds were frequently seen flying towards that part of the mountain, and families with pulli were seen at the foot of the mountain later in the season. For further details about the colony, see Hansen et al. 2010.

In Zackenbergdalen, the first families with goslings were seen day 180 (29 June). Eighteen broods were seen this year (table 4.18), and the maximum number of goslings seen at one time, was six.

The mean brood size was low early in the season, but numbers were close to, and even above, the average later in the season (table 4.18).

Southward migrating barnacle geese were seen from day 220 (8 August), when four flew over the present delta. 144 barnacle geese were seen migrating southwards in 2010. The last four flying over the research station day 258 (15 September).

On Isle of Islay, Western Scotland, the percentage of young in the flocks arriving

Table 4.19 The number of immature pink-footed geese and barnacle geese moulting in the study area at Zackenberg 1995-2010. The closed area is zone 1c (see www.zackenberg.dk/maps).

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Pink-footed Goose																
Closed moulting area and further east	310	246	247	5	127	35	0	30	41	11	17	27	0	0	1	10
Coast west of closed area	230	40	~60	0	29	0	0	0	0	10	0	3	2	0	0	0
Upper Zackenbergdalen	0	0	15	0	0	0	0	0	0	0	0	1	0	2	1	0
Pink-footed Goose total	540	286	322	5	156	35	0	30	41	21	17	31	2	2	2	10
Barnacle Goose																
Closed area at Lomsø and Kystkærene	21	0	29	21	60	84	137	86	120	81	87	148	66	106	70	80
Coast east of closed area	>120	~150	96	55	66	0	109	80	45	0	2	218	46	125	77	13
Coast west of closed area	0	0	0	0	0	30	0	0	0	0	29	29	106	65	34	0
Upper Zackenbergdalen	41	85	2	75	<57	27	60	0	14	0	25	30	6	41	51	0
Barnacle Goose total	>182	~235	127	151	<183	141	306	166	179	81	143	425	224	337	232	93

to their wintering quarters was relatively high (table 4.18; Ogilvie 2011).

Immature barnacle geese moulted in numbers below average (1995-2009 average: 209) in 2010 (table 4.19).

Common birds, not breeding in the census area

Between day 156 (5 June) and day 182 (1 July), 2066 individual immature pink-footed geese *Anser brachyrhynchus* (recorded unsystematically) on northbound moult migration flew over Zackenbergdalen. Only ten immature pink-footed geese were found moulting in the Zackenberg area in 2010 (table 4.19). Immature pink-footed geese on southward migration were recorded from late July to day 226 (14 August), 100 were seen in the former delta. No more records were made in 2010.

On day 170 (19 June), the first pair of common eiders *Somateria mollissima* was seen in Kystkærene. No ducklings were seen at or near Zackenberg in 2010. A male and three female king eiders *Somateria spectabilis* were seen day 161 (10 June). No nesting attempts were recorded, and no ducklings were seen in 2010. For both eider species, small flocks were seen from June to ultimo July (king eider)/mid-August (common eider).

Long-tailed ducks *Clangula hyemalis* were seen from day 154 (3 June), after which pairs were seen almost daily until mid-July. In late July and August, only a few pairs were seen. No nest or ducklings were seen in 2010.

We estimate that two pairs of common raven *Corvus corax* nested in areas beyond the borders of the census area, with home ranges well within our study area. The first three juvenile birds were seen day 217 (3 August) at Sydkærene.

Visitors and vagrants

In table 4.20, we present data on avian visitors and vagrants. A single pectoral sandpiper (likely female) was seen from day 159 (8 June) to day 163 (12 June). The first ever greylag goose *Anser anser* in Zackenberg, was seen in a flock of 14 pink-footed geese migrating north 28 June. These were the only notable rarities in 2010. Further details will be published in Hansen et al. in preparation (b).

Sandøen

BioBasis did not visit Sandøen during the breeding season in 2010. Researchers from the National Environmental Research Institute, Aarhus University in collaboration with the Greenland Institute of Natural Resources, conducted investigations primarily on walruses. For details, please consult section 6.13 and chapter 7.

Daneborg

At Daneborg, the common eider colony between the sledge dog pens had above average numbers of nests: 2889 nests (Sirius Patrol, pers. comm.; 2002-2009 average nest numbers: 2259). This is the highest numbers in five years.

Table 4.20 Numbers of individuals and observations of avian visitors and vagrants at Zackenberg 2010, compared with the numbers of individuals observed in the preceding seasons, 1995-2009. Multiple observations reasonably believed to have been of the same individual have been reported as one individual.

Visitors and vagrants																	
	Previous records															2010	
Species	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**No. individuals**	**No. of observations**
Great northern diver	0	0	0	0	0	0	1	0	0	0	0	0	2	2	0	1	1
Wooper swan	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0
Greylag goose	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Snow goose	0	0	0	0	0	2	11	0	23	0	0	0	1	0	0	0[a]	0
Canada goose	0	0	0	0	0	0	0	0	0	0	0	4[a]	3[a]	0	1	0	0
Merlin	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Gyr falcon	1	1	1	3	0	4	5	1	3	4	2	0	3[b]	2[c]	4	3	4
Pintail duck	0	0	0	1[c]	0	0	0	0	0	0	0	0	3[d]	0	0	3	11
Common teal	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Eurasian golden plover	0	3	1	3	1	0	3[e]	1	0	1	1	1	1	1	2	2	2
White-rumped sandpiper	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0
Pectoral sandpiper	0	0	0	1	0	0	0	2	0	0	0	1	1	0	1	1	3
Purple sandpiper	0	0	0	0	0	0	0	1[f]	0	0	0	0	0	0	0	0	0
Red phalarope	0	0	0	4-5[d]	0	0	4[d]	0	1	0	2[d]	11[d]	0	2	0	2	3
Common snipe	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Whimbrel	0	0	0	0	0	1	1	0	0	2	1	0	1	2	0	0	0
Eurasian curlew	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Redshank	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Pomarine skua	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
Arctic skua	0	0	11	6	0	2	7	4	3	2	0	1	0	0[g]	0	0	0
Great skua	0	0	0	4	0	0	0	1	0	0	0	0	0	0	0	0	0
Lesser black-backed gull	0	0	0	0	0	0	1	0	1	2	1	4	0	0	0	0	0
Iceland gull	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0
Great black-backed gull	0	0	0	0	0	1	3	0	0	0	0	0	0	0	0	0	0
Black-legged kittiwake	0	0	0	0	0	0	0	0	14[b]	0	0	0	0	0	0	0	0
Arctic tern	≈200	2	1	2	0	14	0	0	32	0	0	0	0	57	0	0	0
Snowy owl	0	0	2	1	1	1-2	≥4[d]	0	0	0	0	0	1b	0	0	0	0
Meadow pipit	0	0	0	1	0	0	0	0	0	0	1[c]	1[c]	0	0	0	0	0
White wagtail	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Northern wheatear	4	8[d]	4	3[d]	1-2[d]	0[h]	0	0	0	0	2	1	4[b]	2	2[i]	5[j]	7
Lapland longspur	0	0	0	0	1-2	0	1	0	0	0	1	0	0	0	0	2[e]	7

[a]Two outside census area
[b]See Hansen et al. 2008
[c]After regular season, four observations of one to three birds
[d]Northernmost records in East Greenland (cf. Bortmann 1994)
[e]At least one territory, possible territory or breeding found, see table 4.14
[f]Juvenile
[g]Before the regular season, one in adjacent areas
[h]One dead individual found
[i]Furthermore, another two pairs plus two juveniles in adjacent areas.
[j]Three juveniles, all from pair(s) outside the census area

Notes on rarities

The Rarities Committee for Denmark, Faroe Islands and Greenland (under BirdLife Denmark) had an observation of a pectoral sandpiper from 2009 under review. Similarly, a report has been submitted to the committee on the observation of the same species in the 2010 season.

4.4 Mammals

The mammal monitoring programme was conducted by Martin Ulrich Christensen, Lars Holst Hansen, Jannik Hansen, Thomas B. Berg, Noémie Boulanger-Lapointe and Niels Martin Schmidt. The station personnel and visiting researchers supplied supplemental observations during the entire field season.

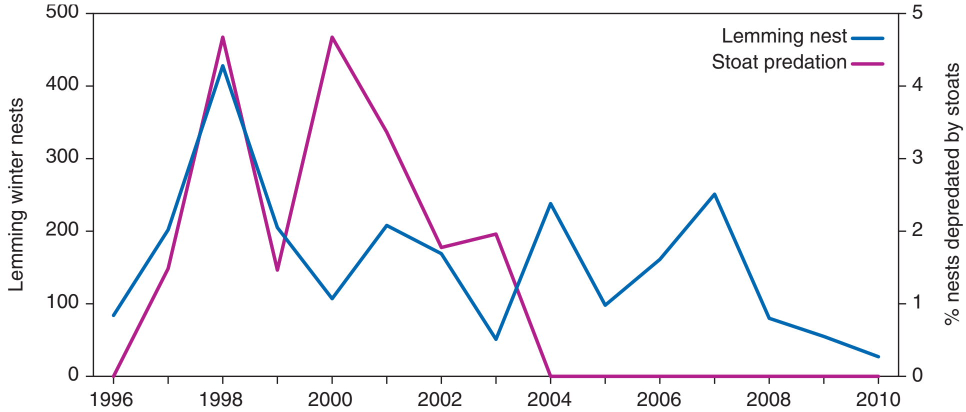


Figure 4.6 The number of collared lemming winter nests registered within the 1.06 km² designated lemming census area (blue line), along with the percentage of winter nests taken over by stoats (red line) 1996-2010.

The collared lemming *Dicrostonyx groenlandicus* census area was surveyed for winter nests during July and August. Throughout the entire season, when weather permitted a sufficient coverage, musk oxen *Ovibos moschatus* were counted every third day from a fixed elevated point at the research station. Counting took place between 19:00 and 23:00, and covered the 47 km² designated census area including the coastal areas and the slopes of Aucellabjerget. At the same time, numbers of seals on the ice in Young Sund and arctic hares *Lepus arcticus* in the designated monitoring area on the south-east and east facing slopes of Zackenbergfjeldet were censused day 142 (22 May) – day 185 (4 July) and day 182 (1 July) – day 266 (23 September), respectively.

The total numbers of musk oxen, including sex and age from as many individuals as possible, were censused weekly within the 47 km² census area from July to October with an additional census in May. The 15 known arctic fox *Vulpes lagopus* dens (nos. 1-10 and 12-16) plus an additional den found this season (no. 17) within the central part of Zackenbergdalen were checked approximately once a week for occupancy and breeding. The 29 fixed sampling sites for predator scats and casts were checked in early September. Observations of other mammals than collared lemming, arctic fox, musk ox, arctic hare and seal sp. are presented in the section "Other observations" below.

For the fifth year in a row, BioBasis collected arctic fox scats for analysis of the parasitic load.

Table 4.21 Annual numbers of collared lemming winter nests recorded within the 1.06 km² census area in Zackenbergdalen 1996-2010 together with the numbers of animals encountered by one person with comparable effort each year within the 15.8 km² bird census area during June-July.

Year	New winter nests	Old winter nests	Animals seen
1996	84	154	0
1997	202	60	1
1998	428	67	43
1999	205	36	9
2000	107	38	1
2001	208	13	11
2002	169	20	4
2003	51	19	1
2004	238	15	23
2005	98	83	1
2006	161	40	3
2007	251	21	1
2008	80	20	4
2009	55	9	0
2010	27	23	0

Collared lemming *Dicrostonyx groenlandicus*

In 2010, only 27 collared lemming nests from the previous winter were recorded within the 1.06 km² census area (table 4.21). This is the lowest number ever registered.

During the years 1996-2009, between 0% and 4.7% of the lemming winter nests have been depredated by stoats, but as in the six previous seasons, not a single nest was found depredated by stoat in 2010 figure 4.6). No lemmings were seen by the bird observer and only one lemming was observed by others researchers. In a project trying to catch live lemmings, only one individual was caught. On one occasion, a long-tailed skua was observed with a freshly caught lemming.

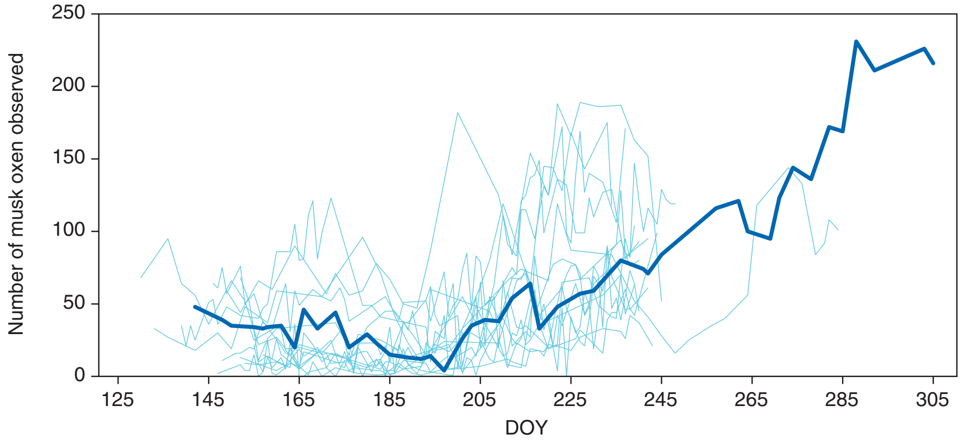


Figure 4.7 Number of musk oxen recorded from a fixed elevated point at the research station from mid-May to mid-October for 2010. Thin lines are musk ox numbers from previous seasons.

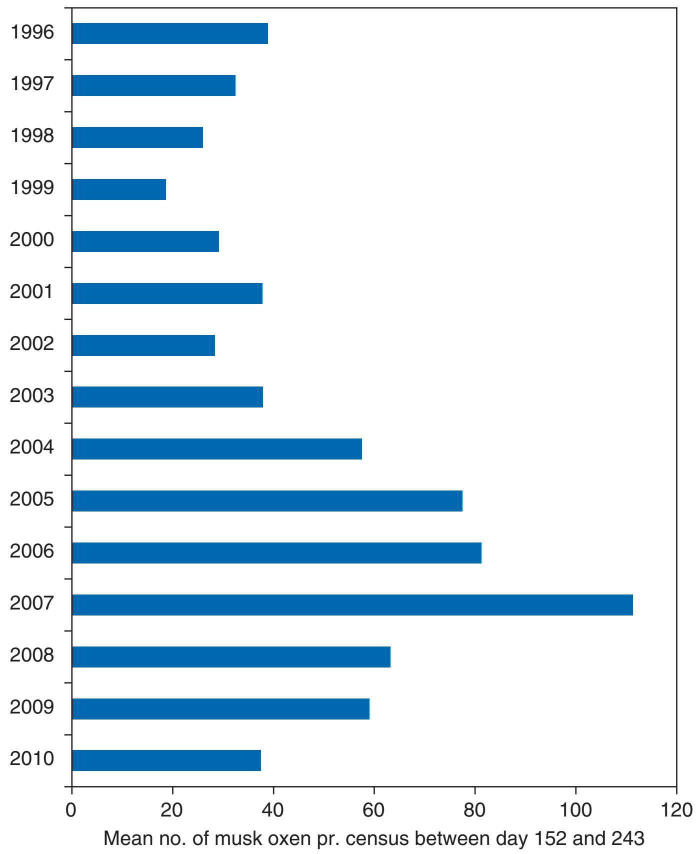
Musk ox *Ovibos moschatus*

The musk ox occurrence in 2010 within the census area in Zackenbergdalen exhibited marked variation in numbers, ranging from four to 231 towards the end of the field season (figure 4.7). This record high number was counted in the extended season. Hence, we have few data from previous seasons for comparison but the increase in number seemed later than in most previous seasons. Figure 4.8 summarises the censuses from a fixed point within the main field season (June, July and August) from 1996 to 2009. The downward trend, which started in 2008, seems to continue with an average number (37.5) now below the mean of the years 1996-2009 (49.9).

Based on the weekly field censuses, table 4.22 lists the sex and age composition of the seasons during July-August. In 2010, males of four years or older constituted the highest proportion ever recorded. On the other hand, calves and yearlings represented low proportions relative to previous seasons. Figure 4.9 illustrates the temporal development in the proportions of the different sex and age classes during the 2010 season. The proportion of males of four years of age or older showed a decrease over the course of the season and females of the same age class showed an increase.

Six fresh musk ox carcasses (two calves, two males and two females) were found during the 2010 season (table 4.23).

Figure 4.8 Mean number of musk oxen recorded from a fixed elevated point at the research station between days 152-243 (including both days), 1996-2010.



Arctic fox *Vulpes lagopus*

In 2010, breeding was verified in two dens and a minimum of 11 arctic fox pups (all white colour phase) was observed at the known dens (table 4.24). One additional breeding den high on Aucellabjerget was discovered. The den seemed to have been overlooked in previous seasons, as there were indications of use in several years. Late in the season, one immature dark colour phase fox was observed at the research station on a few occasions.

Arctic hare *Lepus arcticus*

In 2010, 18 counts under good visibility were made during July and August with a mean of 3.1 hares per census (Table 4.25). This is very close to average of previous seasons (3.2). An additional five counts were carried out in September with a mean of 4.4.

Seals *Phoca* sp.

Different seal species were observed on the ice of Young Sund but the specific species can only rarely be identified from the research station. Seals were recorded from

Table 4.22 Sex and age composition of musk oxen based on weekly counts, within the 47 km² census area, in Zackenbergdalen from July-August 1996-2010.

	M4+		F4+		M3		F3		M2		F2		1M+1F		Calf		Unsp. adult		No. of
Year	Total	%	Total	%	Total	%	Total	%	Total	%	Total	%	Total	%	Total	%	Total	%	weekly counts
1996	98	14	184	27	7	1	31	5	54	8	17	3	146	22	124	18	15	2	9
1997	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
1998	97	29	97	29	22	7	19	6	30	9	27	8	14	4	22	7	1	0	8
1999	144	38	106	28	21	6	21	6	9	2	12	3	5	1	30	8	32	8	8
2000	109	30	118	32	11	3	15	4	2	1	7	2	31	8	73	20	3	1	8
2001	127	30	120	29	8	2	19	5	26	6	19	5	43	10	55	13	4	1	7
2002	114	20	205	36	20	3	24	4	38	7	43	8	51	9	77	13	0	0	8
2003	123	23	208	39	24	5	23	4	16	3	19	4	44	8	72	14	0	0	8
2004	122	22	98	18	13	2	28	5	5	1	8	1	32	6	124	23	119	22	7
2005	212	23	260	28	11	1	46	5	43	5	21	2	116	13	200	22	6	1	9
2006	205	29	123	17	29	4	55	8	62	9	34	5	102	14	94	13	0	0	7
2007	391	25	341	22	73	5	152	10	80	5	83	5	202	13	246	16	8	1	9
2008	267	34	189	24	38	5	57	7	44	6	58	7	58	7	63	8	18	2	8
2009	269	42	176	28	32	5	38	6	32	5	23	4	30	5	18	3	21	3	8
2010	246	49	101	20	40	8	26	5	29	6	21	4	8	2	18	4	15	3	9

day 152 (1 June) until day 185 (4 July) after which the ice was too fragmented. Fourteen counts were made with an average of 7.2 seals per census (table 4.26). An additional four counts were carried out in May with a mean of 5.8 (SD=0.96).

Other observations

One polar bear (*Ursus maritimus*) was observed in the research area. On 3 October, a single young individual, probably two years old, was observed inside the research station area.

Outside the research area, an adult polar bear was observed and scared off on Sandøen and a young individual was shot and killed after attacking researchers by Kap Breusing on Clavering Island.

In 2010, no stoats *Mustela erminea* were observed, and none of the new lemming winter nests found in the census area was

Table 4.23 Fresh musk oxen carcasses found during the field seasons of 1995-2010. F=female, M=male.

Year	Total carcasses	4+ yrs F/M	3 yrs F/M	2 yrs F/M	1 yr F/M	Calf
1995	2	0/1				1
1996	13	7/1	0/1	0/2	1/1	
1997	5	0/2		1/0	1/0	1
1998	2	0/2				
1999	1	0/1				
2000	8	0/6	1/0			1
2001	4	0/4				
2002	5	1/2	1/0			1
2003	3	0/2				1
2004	2	1/1				
2005	6	2/3				1
2006	5	0/2			0/1	2
2007	12	3/4	1/0		1/0	3
2008	11	3/1	2/0			5
2009	15	4/5				8
2010	6	2/1	0/1			2

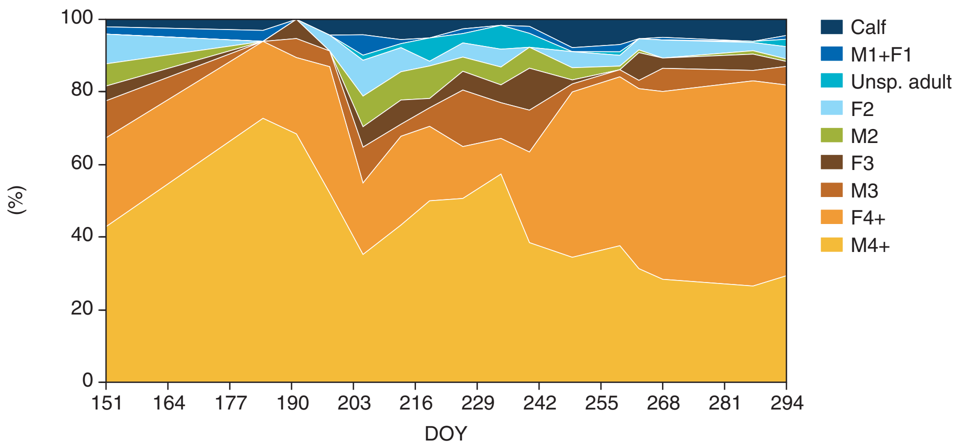


Figure 4.9 Sex and age composition of musk oxen registered during the weekly field censuses within the census area during the 2010 season.

Table 4.24 Numbers of known fox dens in use, numbers with pups and the total number of pups recorded at their maternal dens within and outside the central part of Zackenbergdalen 1995-2010. W=white phase, D=dark phase.

Year	No. of known dens inside/outside	No. of dens in use inside/outside	No. of breeding dens inside/outside	Total no. of pups recorded
1995	2/0	0/0	0/0	0
1996	5/0	4/0	2/0	5W+4D
1997	5/0	1/0	0/0	0
1998	5/0	2/0	1/0	8W
1999	7/0	3/0	0/0	0
2000	8/0	4/0	3/0	7W
2001	10/2	6/1	3/1	12W+1D
2002	10/2	5/1	0-1/0	0
2003	11/2	8/1	3/0	17W
2004	12/2	12/2	4/1	18+W
2005	14/2	6/0	0/0	0
2006	15/1	6/1	3/0	17W
2007	14/1	12/1	3/1	23W
2008	15/1	14/1	4/1	24W
2009	15/1	13/1	3/0	10W
2010	16/1	14/1	2/0	11W

Table 4.25 Numbers of arctic hares within the designated census area per observation day counted during July and August.

Year	Counts	Average	SD	Range
2001	22	1.2	1.3	0-5
2002	16	0.4	0.6	0-2
2003	20	2.4	1.8	0-6
2004	23	0.9	1.1	0-3
2005	48	5.5	5.1	0-26
2006	39	5.9	3.7	1-19
2007	18	4.8	3.0	0-11
2008	17	2.5	2.3	0-7
2009	16	4.8	2.8	1-12
2010	18	3.1	1.9	0-7

Table 4.26 The number of seals counted per observation day during the period from 1 June until the fjord ice became too fragmented in early/mid July 1997-2010. Only counts conducted under good visibility are included.

Year	Counts	Average	SD	Range
1997	23	8.5	5.0	3-21
1998	18	7.4	4.5	0-18
1999	22	25.1	12.3	2-61
2000	16	14.4	7.0	2-28
2001	16	22.1	14.2	3-57
2002	13	28.7	3.8	9-48
2003	12	63.6	32.1	14-126
2004	13	19.0	6.4	9-30
2005	15	13.4	12.8	2-48
2006	21	14.1	4.5	6-22
2007	13	6.2	4.6	0-16
2008	11	14.0	5.6	6-27
2009	6	3.2	1.5	1-5
2010	14	7.2	4.0	2-15

depredated by stoats. During the standardised collection of scats and casts, one stoat scat was found.

One walrus (*Odobenus rosmarus*) was observed in the shallow water southeast of Halvøen, and one was observed from Pashuset on a single occasion (this individual was also included in a seal count undertaken at the same time). As there was research activity on Sandøen again this season, BioBasis did not count the walrus hauling out there.

Collection of wildlife samples

Tissue samples from dead vertebrate species encountered in the field were collected (table 4.27). Samples were taken from six musk ox carcasses, six arctic char *Salvelinus alpinus*, one gyr falcon and one bearded seal *Erignathus barbatus* (table 4.27). In addition, scats and casts were collected at 29 permanently marked sites in the valley (table 4.28).

4.5 Lakes

Sommerfuglesø and Langemandssø are situated in Morænebakkerne and have been sampled annually since 1997. The lakes were sampled six times from 28 June to 17 September as part of the BioBasis monitoring programme. The sampling frequency has been extended with a sampling date early in the season while the lakes are still partly ice covered as well as late in the season, where the ice is re-appearing.

Overall, it appears from the results (tables 4.29 and 4.30) that the 2010 season covering July and August (i.e., the period

Table 4.27 Wildlife tissue samples collected in 2010 and all seasons collectively.

Species	2010	1997-2010
Arctic fox	0	10
Arctic hare	0	1
Collared lemming	0	6
Dunlin	0	4
Glaucous gull	0	1
Musk oxen	6	63
Northern wheatear	0	1
Rock ptarmigan	0	2
Seal (sp.)	1	1
Gyr falcon	1	1
Arctic char	6	6
Three-spined stickleback	6	6

Table 4.28 Numbers of casts and scats from predators collected from 29 permanent sites in Zackenbergdalen. The samples represent the period from mid/late August the previous year to mid/late August in the year denoted.

Year	Fox scats	Stoat scats	Skua casts	Owl casts
1997	10	1	44	0
1998	46	3	69	9
1999	22	6	31	3
2000	31	0	33	2
2001	38	3	39	2
2002	67	16	32	6
2003	20	1	16	0
2004	16	3	27	0
2005	24	0	7	6
2006	29	0	15	4
2007	54	4	13	3
2008	30	1	16	0
2009	22	2	11	1
2010	22	1	3	0

sampled in previous years) has been characterized by a fairly early ice-off and a warm summer. The results were only slightly different when including the extended season (i.e., from ultimo May to mid-September) except for the average temperatures that for obvious reasons are lower when periods with partly ice coverage are included.

Table 4.29 Physico-chemical variables and chlorophyll a concentrations in Sommerfuglesø (SS) and Langemandssø (LS) during July and August 2010.

Lake	SS	SS	SS	SS	LS	LS	LS	LS
Day	193	213	226	234	193	213	226	234
Ice cover (%)	1	0	0	0	1	0	0	0
Temperature (°C)	12	14	8.5	7.2	7.4	13	9	7.2
pH	6.5	6.9	6.7	6.5	6.3	6.5	6.6	6.8
Conductivity (µS cm^{-1})	15	18	20	20	7	19	21	15
Chlorophyll *a* (µg l^{-1})	0.84	1.09	1.38	1.71	1.03	1.26	1.27	1.24
Total nitrogen (µg l^{-1})	170	380	180	260	130	240	240	220
Total phosphorous (µg l^{-1})	3	4	8	4	8	10	11	9

Physical and chemical conditions

Observations 24 May and 28 June revealed that the ice cover went from 100 % to 40 % and 10 % of the lake surfaces at Sommerfuglesø and Langemandssø, respectively. The 50 % ice cover dates were estimated to be 13 and 26 June, respectively. These dates are early ice-off but still within the range found for previous years (tables 4.29-4.31).

The early ice melt and a warm July caused the water temperatures to reach 12-14 °C by the end of July (table 4.29). The

Table 4.30 Average physico-chemical variables in Sommerfuglesø (SS) in 1999-2010 (July-August) compared to single values from mid-August 1997 and 1998. ND = no data.

Lake	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS
Year	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Date of 50% ice cover	ND	192	199	177	183	184	175	176	169	186	166	181	179	165
Temperature (°C)	6.3	6.5	6.1	10.1	8.4	8.3	11	8.7	9.8	10.1	10	10.6	9.5	10.4
pH	6.5	7.4	6.7	5.8	6.6	6	6.5	6.3	6	6.2	6.6	5.9	6.7	6.7
Conductivity (µS cm^{-1})	15	13	10	18	18	8	12	15	22	11	10	16	22	18
Chlorophyll *a* (µg l^{-1})	0.84	0.24	0.41	0.76	0.67	1.27	1.84	1.62	1.59	0.65	1.49	0.57	0.89	1.26
Total nitrogen (µg l^{-1})	ND	130	210	510	350	338	277	267	263	293	323	238	298	248
Total phosphorous (µg l^{-1})	4	9	11	10	19	11	11	7	9	8	10	6	7	5

Table 4.31 Average physico-chemical variables in Langemandssø (LS) in 1999-2010 (July-August) compared to single values from mid-August 1997 and 1998. ND = no data.

Lake	LS	LS	LS	LS	LS	LS	LS	LS	LS	LS	LS	LS	LS	LS
Year	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Date of 50% ice cover	ND	204	202	182	189	187	183	178	173	191	167	182	172	174
Temperature (°C)	6.8	6.4	4	9.5	8.4	8.1	11.1	9.1	10.5	9.8	10.6	8.8	9.1	9.2
pH	6.5	7	6.3	5.5	6.4	5.5	6.1	6.1	6	6.3	6	5.7	6.5	6.6
Conductivity (µS cm^{-1})	8	9	7	9	8	6	6	8	14	5	7	7.8	18	15
Chlorophyll a (µg l^{-1})	1.04	0.32	0.38	0.9	1.46	2.72	3.14	0.98	1.62	0.56	1.54	0.92	1.06	1.2
Total nitrogen (µg l^{-1})	ND	80	120	290	340	387	237	230	247	203	268	138	172	208
Total phosphorous (µg l^{-1})	8	7	7	11	20	13	10	11	11	6	8	6	9	10

Table 4.32 Biovolume (mm³ l⁻¹) of phytoplankton species in Sommerfuglesø and Langemandssø during July-August 2010.

Lake	SS	SS	SS	SS	LS	LS	LS	LS
Day	**193**	**213**	**226**	**234**	**193**	**213**	**226**	**234**
Nostocophyceae	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Dinophyceae	0.044	0.117	0.451	0.379	0.122	0.086	0.118	0.146
Chrysophyceae	0.363	0.316	0.423	0.110	0.381	0.523	0.499	0.516
Diatomophyceae	0.009	0.003	0.003	0.003	0.003	0.006	0.002	0.007
Chlorophyceae	0.018	0.002	0.012	0.015	0.007	0.024	0.110	0.255
Others	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total	**0.434**	**0.438**	**0.889**	**0.507**	**0.513**	**0.639**	**0.729**	**0.925**

mean temperatures for the entire period were 8 °C and 7.3 °C, and 10.4 °C and 9.2 °C for the July-August period in Sommerfuglesø and Langemandssø, respectively (table 4.29). This implies that the season on average followed the general trend of warming that has been observed for several years (tables 4.30 and 4.31).

The water chemistry measurement included concentration of total nitrogen and total phosphorus as well as conductivity and pH. All parameters were within the levels that have been recorded during previous years (tables 4.29-4.31). It should be noted that the nutrient concentrations are lower than the average in the beginning of the season (late may) and higher in the autumn (mid-September).

Phytoplankton

The mean chlorophyll *a* concentration (indicator of the phytoplankton biomass) was around 1.2 µg l⁻¹ in both lakes with little variation over the entire season (0.59-1.71 µg l⁻¹; tables 4.30 and 4.31). The phytoplankton communities were dominated by chrysophytes (table 4.32) during most of the season in both lakes, with averages of 55 % and 68 % of the total biovolume in Sommerfuglesø and Langemandssø, respectively. Dinophytes were equally important in Sommerfuglesø and constituted 39 % of the biovolume as an average for the season. In Langemandssø, it constituted only 2 %.The remaining biomass in both lakes were mainly Chlorophytes. Typical genera were *Gymnodium* spp., *Uroglena* spp. and *Ochromonas* spp. The results are comparable to findings from previous years (tables 4.33 and 4.34). The

Table 4.33 Average biovolume (mm³ l⁻¹) of phytoplankton species in Sommerfuglesø from 1997 to 2010 (note that some years are missing).

Lake	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS
Year	**1998**	**1999**	**2001**	**2002**	**2003**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Nostocophyceae	0	0.005	0	0	0	0	0	0	0	0	0
Dinophyceae	0.034	0.044	0.015	0.006	0.027	0.185	0.068	0.113	0.184	0.053	0.248
Chrysophyceae	0.022	0.096	0.358	0.066	0.237	0.554	0.145	0.386	0.092	0.261	0.303
Diatomophyceae	0.002	0	0.001	0	0	0	0.007	0	0	0.003	0.005
Chlorophyceae	0.005	0.002	0	0	0.002	0.009	0.004	0.001	0	0	0
Others	0	0	0.004	0	0	0	0	0	0	0.002	0
Total	**0.063**	**0.147**	**0.377**	**0.073**	**0.266**	**0.749**	**0.223**	**0.499**	**0.276**	**0.319**	**0.555**

Table 4.34 Average biovolume (mm³ l⁻¹) of phytoplankton species in Langemandssø from 1997 to 2010 (note that some years are missing).

Lake	LS	LS	LS	LS	LS	LS	LS	LS	LS	LS	LS	LS
Year	**1997**	**1998**	**1999**	**2001**	**2002**	**2003**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Nostocophyceae	0	0	0	0	0	0	0	0	0	0	0	0
Dinophyceae	0.291	0.185	0.305	0.04	0.156	0.123	0.03	0.068	0.05	0.222	0.095	0.118
Chrysophyceae	0.066	0.187	0.048	0.592	0.377	0.358	0.296	0.318	0.192	0.262	0.424	0.48
Diatomophyceae	0.002	0	0	0.002	0	0	0	0.009	0	0	0	0
Chlorophyceae	0.016	0	0.002	0.002	0	0.003	0.019	0.008	0.017	0.004	0.013	0.099
Others	0	0	0	0	0	0	0	0	0	0	0	0
Total	**0.375**	**0.372**	**0.354**	**0.637**	**0.533**	**0.484**	**0.345**	**0.404**	**0.259**	**0.487**	**0.532**	**0.70**

Table 4.35 Density (no l^{-1}) of zooplankton in Sommerfuglesø (SS) and Langemandssø (LS) during July-August 2010.

Lake	SS	SS	SS	SS	LS	LS	LS	LS
Day	**193**	**213**	**226**	**234**	**193**	**213**	**226**	**234**
Cladocera	0.2	12.2	12.9	6.1	0.0	0.0	0.0	0.0
Copepods	8.4	2.7	5.7	4.9	4.0	34.7	25.2	16.6
Rotifers	58.9	32.0	0.1	0.0	87.9	71.0	22.3	10.0
Others	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.0
Total	**67.5**	**46.9**	**18.6**	**10.9**	**92.0**	**105.7**	**47.6**	**26.7**

phytoplankton diversity and biomass was lowest in the start of the season (late May) and increased towards August.

Zooplankton

The composition of the zooplankton communities revealed that *Daphnia pulex* was recorded in high numbers (up to 13 individuals l^{-1}) in Sommerfuglesø, which has no fish population, and was absent in Langemandssø, that holds a population of dwarf-sized Arctic char. Both lakes had populations of cyclopoide copepods (*Cyclops abyssorum alpininus*) and rotifers (*Keratella* sp. and *Polyarthra* sp.). The densities of these populations were highest in Langemandssø (table 4.35). The recorded species composition as well as densities were within the range found in previous years (tables 4.36 and 4.37). The zooplankton abundances were high already in late May, decreased over the summer, and were lowest at the last sampling date in mid-September.

Daphnia pulex *from Sommerfuglesø 2010. Photo: Liselotte Sander Johansson.*

Keratella hiemalis *from Langemandssø 2010. Photo: Liselotte Sander Johansson.*

Table 4.36 Average density (no l^{-1}) of zooplankton species in Sommerfuglesø from 1997 to 2010.

Lake	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS
Year	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Cladocera														
Daphnia pulex	0.3	10.5	0.3	6.7	8.2	6.8	7.7	0.7	6.4	7.07	3.8	6.33	2.87	7.8
Macrothrix hirsuiticornis	0.1	0	0	0	0	0	0	0	0.07	0	0	0	0	0
Chydorus sphaericus	0.05	0	0	0	0.06	0	0	0	0.13	0	0	0	0	0.1
Copepoda														
Cyclops abyssorum alpinus (adult+copepodites)	0.8	0.5	0.5	0.3	0.5	0.2	0.9	0.3	0.07	0.27	2	1.27	0.47	2
Nauplii	5.7	1.3	6.5	1.1	1.4	2.3	0.3	0.3	0.2	1.67	0.13	1.93	0.07	3.7
Rotifera														
Polyarthra dolicopthera	171	90	185	97	74	11	0.5	1.87	7.67	42.2	108	49.8	150.18	45
Keratella quadrata group	4.5	3	17	0	0	0.4	0.1	0	0	0.33	0	0	0	0
Conochilus sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Euchlanis sp.	0	0	0	0	0	0	0	0	0.33	0.07	0	0	1.78	0

Table 4.37 Average density (no l^{-1}) of zooplankton species in Langemandssø from 1997 to 2010.

Lake	LS	LS	LS	LS	LS	LS	LS	LS	LS	LS	LS	LS	LS	LS
Year	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Cladocera														
Daphnia pulex	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0
Macrothrix hirsuiticornis	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0
Chydorus sphaericus	0	0.1	0	0.5	0.1	0.07	0	0	0.13	0.07	0.07	0	0	0
Copepoda														
Cyclops abyssorum alpinus (adult+copepodites)	3.3	2.9	4.1	22	13.4	6.8	8.6	4.9	5.8	11.74	8.93	2.27	14.11	15
Nauplii	5.2	3.8	6.4	3.1	4.5	4.5	4.2	0	2.2	5.13	1.07	3.07	2.27	5.3
Rotifera														
Polyarthra dolicopthera	316	330	274	168	248	22	78	71	99	181.33	40	185.3	32.67	46.3
Keratella quadrata group	4.5	28	34	0	0	0.3	0	1.3	0	41.33	0	2.6	0	1.3
Conochilus sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Euchlanis sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Arctic char in Langemandssø

A single fish was caught in Langemandssø based on a two hour fishing trip using a standard gill net (figure 4.10). The fish was a 11.2 cm mature female (weight=14.5 g) with an estimated age of approximately eight years from counting annual rings in the ear stones. The stomach content was analysed and it was found constituting multiple food items including remains of chironomids, copepods and daphnids, as well as remains from biota that could not be identified due to degradation, and zooplankton.

Stickleback *Gasterosteus aculeatus*

Nine dead three-pined sticklebacks *Gasterosteus aculeatus* were discovered in the old delta (pers. comm. Jannik Hansen). The sticklebacks have been preserved for further analyses as this species has not previously been recorded in the area. The results will be presented in the 2011 Annual Report.

*Figure 4.10 An 11 cm female dwarf Arctic char (*Salvenius alpinus*) caught in Langemandssø in August 2010. A Leatherman knife is used for scaling. Photo: Kirsten S. Christoffersen.*

5 Zackenberg Basic

The MarineBasis programme

Mikael K. Sejr, Thomas Juul-Pedersen, Søren Rysgaard, Morten Hjort, Kunuk Lennert, Egon Frandsen, Peter Schmidt Mikkelsen and Winnie Martinsen

The marine component of the ZERO monitoring programmes was started in 2003 and the data collected in 2010 represent the eighth season of the programme. The programme was designed with the aim to 1) produce long-term data series of core physical, chemical and biological parameters and 2) to increase knowledge of Arctic marine ecosystem structure and function in a changing climate. This is accomplished by combining continuous sampling by moored instruments with intensive sampling during a three week field campaign in August. The work is focused on the outer part of Young Sund but supplemented with oceanographic measurements in Tyrolerfjord and in the Greenland Sea. The sampling strategy during the summer field campaign is to describe the geographic variation in the entire study area including Tyrolerfjord and the Greenland Sea by visiting a number of stations once (figure 5.1). Furthermore, to describe the short-term temporal variability by sampling a single station on daily basis when the weather allows ("water column station", figure 5.2). The parameters selected for the programme were selected based on broad scale ecological research efforts during the 1990s of most of the compartments of the ecosystem. The findings of the research projects were synthesized by Rysgaard and Glud 2007.

During the summer field campaign, the water is repeatedly sampled at a hydrographic station (the "standard" station) to monitor the vertical, daily and inter-annual variation in salinity, temperature, oxygen concentration, fluorescence and turbidity using a CTD. Additionally water samples are collected for determination of nutrients ($NO_3^- + NO_2^-$, PO_4^{3-}, SiO_4), dissolved inorganic carbon, total alkalinity and surface pCO_2 and light (PAR) attenuation coefficients. In the water column, samples are also collected to determine the species composition of phyto- and zooplankton. On the sea bed, we measure sediment-water fluxes of oxygen, dissolved inorganic carbon and nutrients together with rates of sulphate reduc-

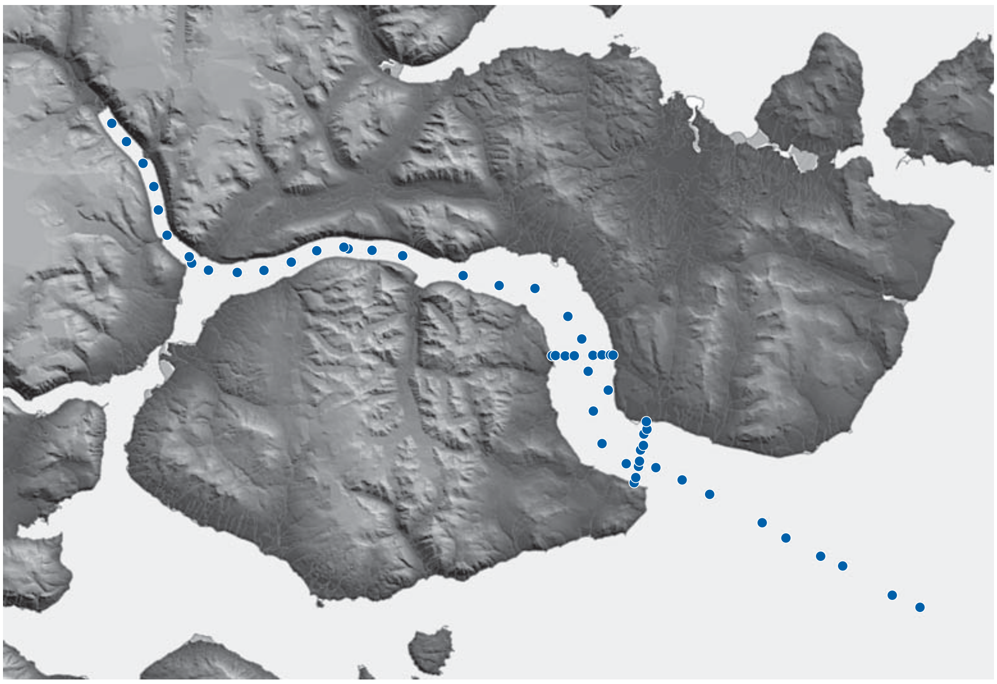


Figure 5.1 Map of the sampling area. The dots represent the hydrographic sampling stations from the innermost Tyrolerfjord on the left to the East Greenland Shelf on the right.

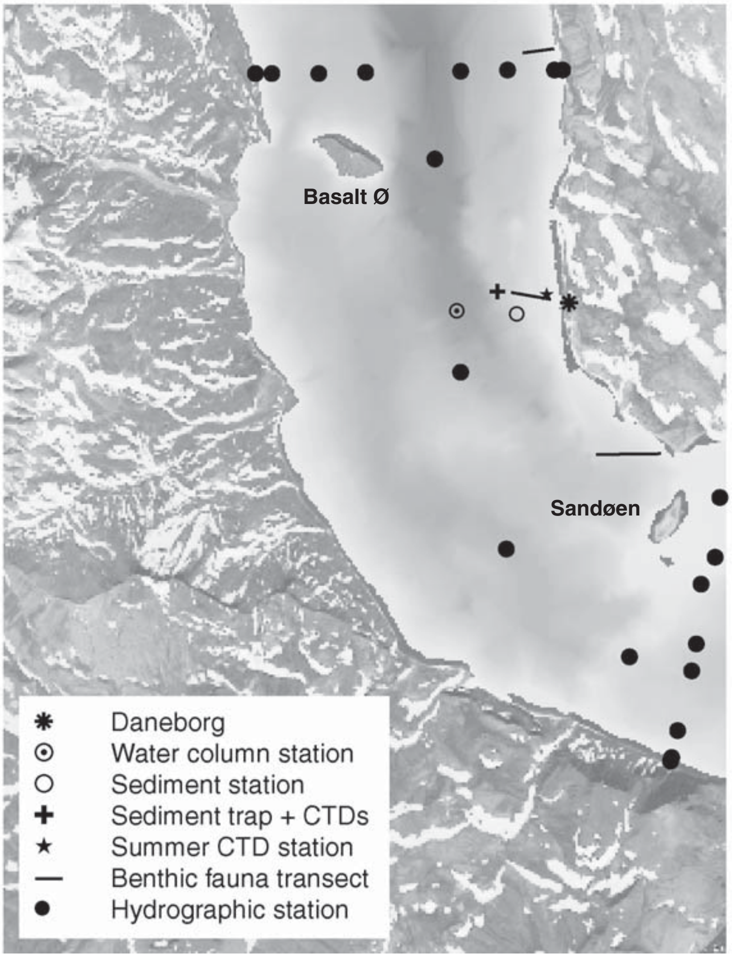


Figure 5.2 Map showing the sampling stations in the outer part of Young Sund in more details.

tion and sediment profiles of oxygen. The abundance and composition of the benthic macrofauna are quantified using sea bed photography and the annual growth of the macroalgae *Saccharina latissima* is estimated.

Data collected in the summer are supplemented to the largest extend possible with continuous measurements from autonomous equipment. Automated cameras provide photos of changes in daily sea ice cover in the fjord. In the water, continuous measurement of salinity, pressure and temperature are conducted every 10 minutes at approximately 40 and 55 m depth. The flux of vertically sinking particles is also estimated throughout the year using a sediment trap at approximately 60 m.

Table 5.1 Summary of sea ice and snow conditions in Young Sund.

	2003	2004	2005	2006	2007	2008	2009	2010
Ice thickness (cm)	120	150	125	132	180	176	155	148
Snow thickness (cm)	20	32	85	95	30	138	45	45
Days with open water	128	116	98	75	76	132	90	99

5.1 Sea ice

Sea ice is a defining component of the Arctic marine ecosystem and plays an important role for ocean circulation, ecosystem productivity and the exchange of energy and greenhouse gases between ocean and atmosphere. In Young Sund the sea ice conditions are monitored by remote sensing and photography combined with observations and measurements conducted by the Danish Military. Photographs of the fjord taken by local autonomous systems are combined with satellite images (figure 5.3, bottom right). In 2009, two new autonomous camera systems were installed at the top of Brisbane Bjerget (figure 5.4) to provide a view of the outer part of Young Sund and to document the timing and extend of the polynya outside the fjord. Based on the observation by the military and photos, the period of open water in the fjord was documented to last from 10 July to 17 September a total of 99 days (table 5.1). The sea ice reached a maximum thickness of 148 cm and a maximum snow thickness of 45 cm (figure 5.5). Based on observation by the military, sea ice conditions have been reconstructed in Young Sund and show a relatively stable open water period of approximately 90 days per year from 1963 to 1999 after which the variability increase to 131 days of open water in 2003. Since 2003 when local camera systems were installed in Young Sund it has been frequently observed that during ice melt extensive melt ponds are formed on the ice and then usually from one day to the next the outer part of the fjord changes from ice covered to ice free. This suggests that factors such as ice conditions outside the fjord combined with wind speed and direction could be important factors influencing export of ice out of the fjord and thus contributing to the inter-annual variation in duration of the ice free period. However, the available satellite images for July 2010 reveal that the ice disappeared in Young Sund during a period with complete ice cover outside the fjord. Therefore, in 2010, most of the ice formed in Young Sund also melted within the fjord and the export of ice out of the fjord appeared to be minimal. There are several potential heat sources in the fjord that can cause sea ice to melt. Obviously, atmospheric temperature is the primary driver of formation and melting of sea ice. However, snow is an excellent insulator and thick snow cover early in winter could

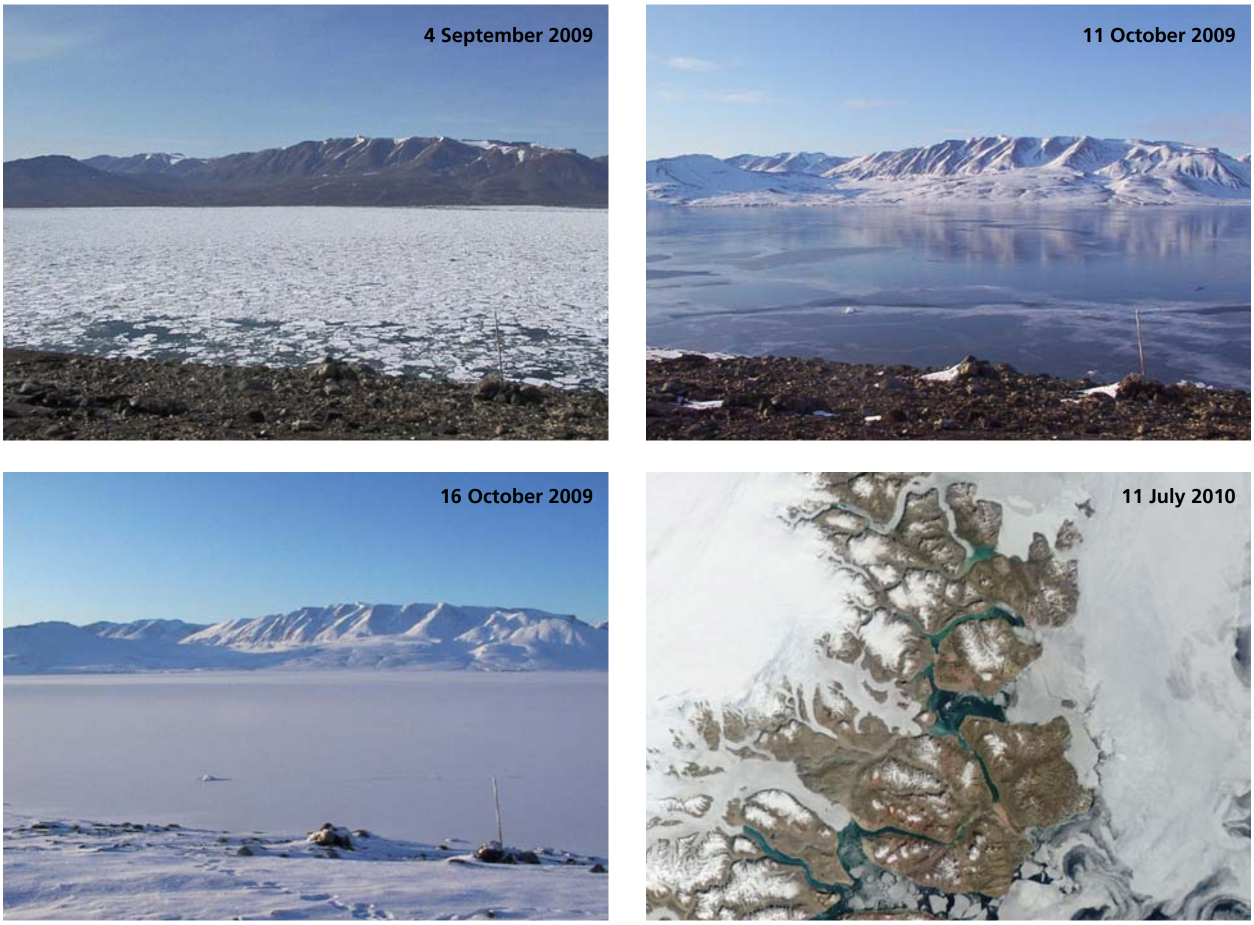


Figure 5.3 Examples of images used to monitor ice conditions 2009-2010 in Young Sund.

decrease ice thickness. The cumulative number of positive degree days for May and June were significantly correlated ($p<0.05$, $R^2=0.26$) to the day when ice disappeared in the fjord i.e. in a warm year the fjord becomes ice free earlier. However, only 26 % of the inter-annual variation can be explained by air temperature alone. In addition to atmospheric temperature, two other sources of heat could potentially contribute to melting of the sea ice during summer 1) inflow of melt water from land and 2) circulation of water within the fjord. Zackenbergelven usually starts to flow in early June but most of the discharge takes place in July where the water temperature is 2-3 °C (Jensen and Rasch 2010). Total discharge in June of Zackenbergelven from 1996 to 2009 explains 11 % of the inter-annual variation in the day of open water during summer ($p<0.05$, $R^2=0.11$). In addition to the input of heat to the system, the freshwater can enhance circulation below the ice. As seen in figure 5.6 the temperature in May and June in the water column is –1.7 °C. A CTD profile from March 2009 confirms that majority of the water column is at –1.7 °C (figure 5.6). However, the profile also shows a thin layer of warmer water just below the sea ice. Therefore, the water column in Young Sund has only a limited potential for melting ice compared to the water column in Nuuk where higher temperatures combined with tidal mixing could mediate glacial melting (Mortensen et al. 2011). Analysis of the dates of ice melt and ice formation in Young Sund reveals that the variability in the open water period is primarily related to the date of ice formation. For 1996 to 2010, the average day of permanent ice cover was day 290 but with a range of observations of 48 days. The data

Figure 5.4 The two new camera systems mounted at the top of Brisbane Bjerget.

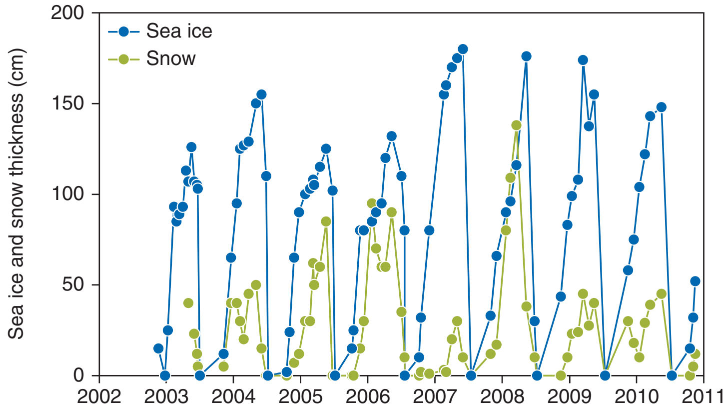


Figure 5.5 Snow and sea ice thickness in the outer part of Young Sund.

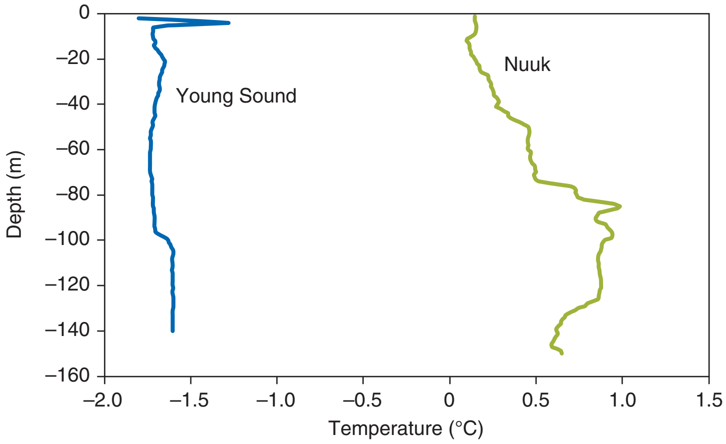


Figure 5.6 Vertical profiles of temperature (March 2009) in Young Sund and at the main sampling station of the MarineBasis programme in Nuuk.

of spring melt was on average day 193 but with a range of only 20 days. Air temperature expressed as the cumulative positive degree days in September and October can explain 41 % of the inter-annual variations in the date of formation of permanent ice cover in the fjord.

Sea ice is important for several aspects of the fjord. For instance, sea ice blocks the exchange of CO_2 between air and sea and the variation in open water period will influence both the processes that determine carbon balance of the surface water and the amount of CO_2 absorbed by the fjord (Sejr et al. 2011). Sea ice also influence the amount of the light available for production by macroalgae which thus influence large scale differences in marine productivity along the Greenlandic coast and the inter-annual variation within Young Sund (Sejr et al. 2009 and Krause-Jensen et al. unpublished).

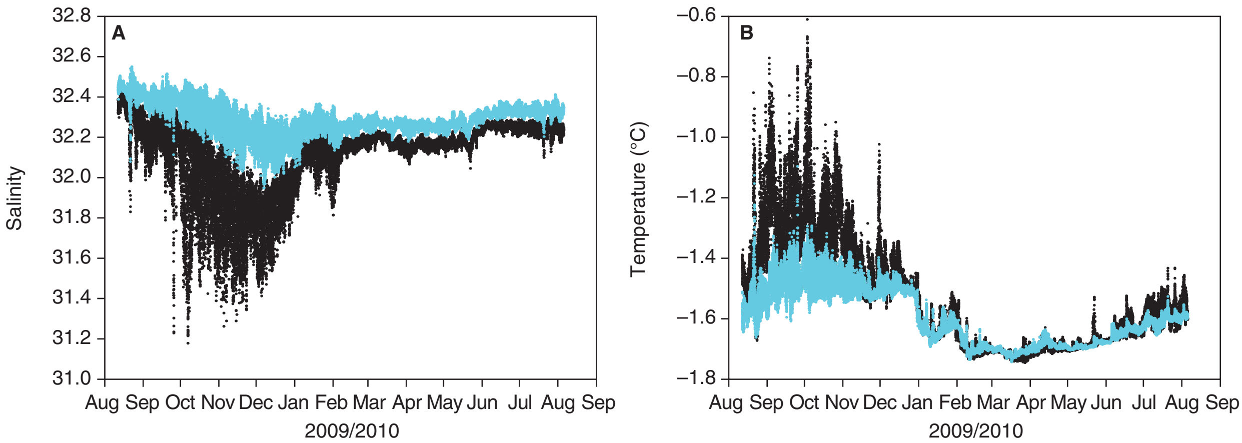
5.2 Water column

Seasonal data from mooring

A mooring consisting of two CTDs and a sediment trap was deployed 11 August 2009 and retrieved 5 August 2010. The seasonal temperature at two depths (figure 5.7) show the same pattern as observed in previous years with high variability in autumn through November and December. In January to March variability is low but temperature show a decreasing trend from –1.5 °C to –1.7 °C. and salinity increase from approximately 31.8 to 32.1 (at 48 m).

The automated long-term sediment trap effectively collected sinking material during 352 days (figure 5.8). The sediment trap is comprised of 12 separate sampling bottles, each bottle sampling during a preprogrammed period. High sinking fluxes of total matter and total particulate carbon (TPC) was observed until mid-October, when values decreased and remained at lower levels until summer the following year (July 2010). $\delta^{13}C$ values and C:N ratios suggest that sinking carbon was comprised of degraded algal material. Annual vertical sinking fluxes of total matter and TPC (920 and 13.9 g m^{-2} y^{-1}, respectively) where

Figure 5.7 Time series of temperature and salinity at two depths during the 2009-2010 seasons in Young Sund.



considerably higher than in 2006/07 and 2007/08 (285 and 207 g m^{-2} y^{-1} for total matter and 3.5 and 3.2 g m^{-2} y^{-1} for TPC, respectively). These values remain below sinking fluxes reported during 2002/03 (1420 and 17 g m^{-2} y^{-1} for total matter and TPC, respectively (Rysgaard and Glud 2007)). The exceptionally high sinking flux in 2002/2003 corresponds to very high discharge of water, carbon and sediments from Zackenbergelven in 2003 (Jensen and Rasch 2010). Accumulated sinking fluxes confirm that the majority of annual sinking fluxes occurred during the initial months of sampling (i.e. August-October). The relatively high flux of carbon in September and October is of interest as it indicates that primary production could still be significant during this period despite the decreasing day light. Measurements of pelagic production are very limited in Young Sund and no measurements have been conducted in September and October. Although hours of daylight decrease rapidly during this period and the angle of the sun is low, episodes of high wind and decreasing temperatures of the surface water can be expected to break down the stratified surface layer and provide nutrients to the photic zone. In Nuuk, a considerable proportion of the primary production takes place in late summer (Jensen and Rasch 2010).

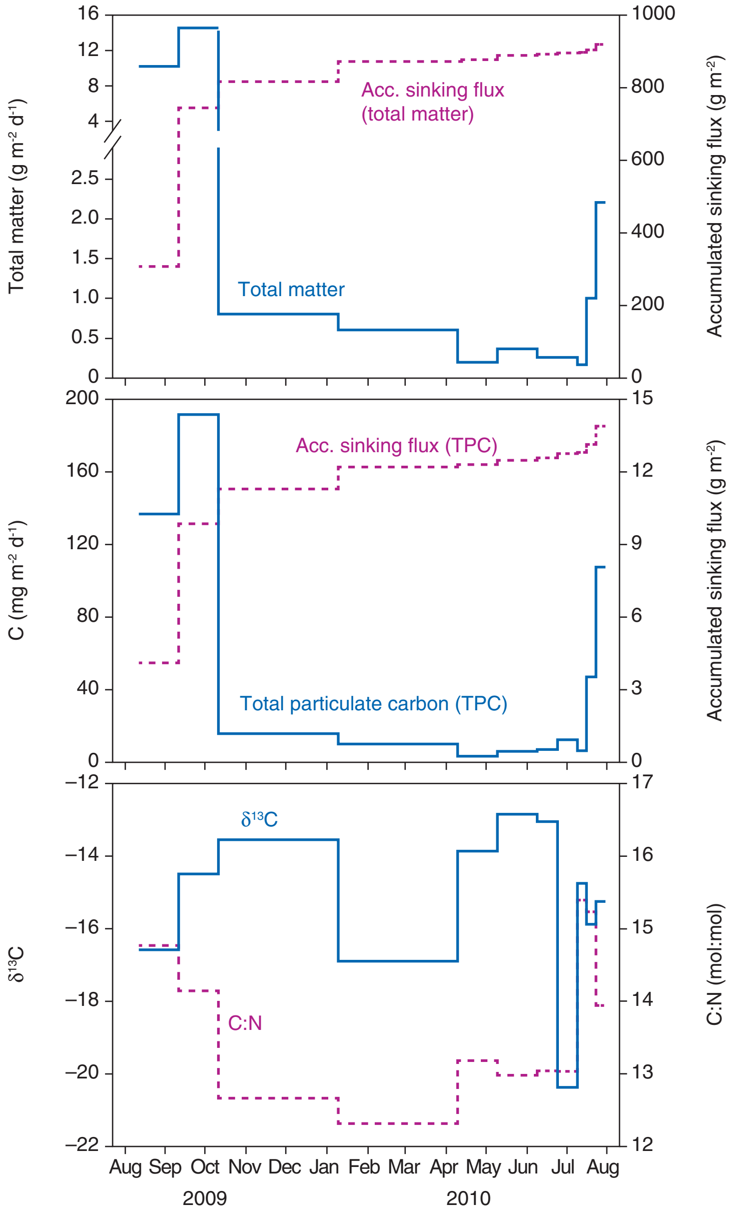
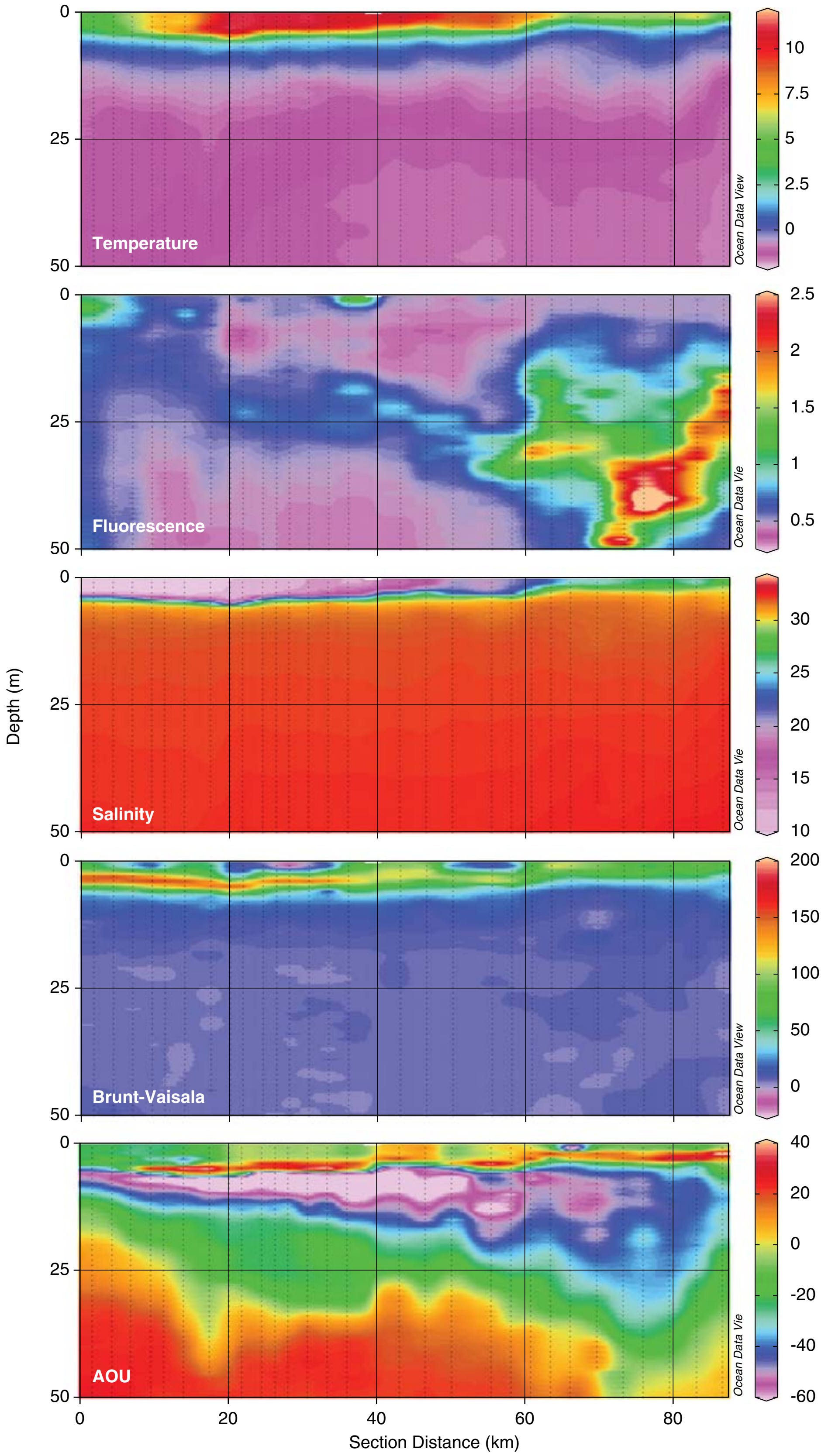


Figure 5.8 Data on the vertical particle flux measured by an automatic sediment trap in outer Young Sund 2009-2010.

Summer distribution of temperature, salinity, nutrients, and chlorophyll

The physical and chemical characteristics of Young Sund and surroundings are measured in order to estimate the spatial and temporal variability: 1) Short-term variability is estimated by daily measurements at the main hydrographic station. 2) The spatial variability is covered by measuring vertical profiles in the water column along three transects in the area, one transect extending from Tyrolerfjord to the Greenland Sea, and two transects across the outer part of Young Sund (see figure 5.2). CTD casts along the entire fjord and into the Greenland Sea show the influence of freshwater run-off from land into the fjord (figure 5.9). This creates a thin surface layer of 5 m thickness in the fjord with salinities below 20 psu. This layer is present in the inner fjord and approximately to Daneborg. Temperature in this surface layer is also well above the rest of the fjord. Maximum temperatures of up to 10 °C are found in the central part of Tyrolerfjord. Although direct measurements of pelagic primary production are not included in the monitoring programme indication of the distribution and controlling factors can be inferred from the data of water chemistry. The oxygen concentration in the water column can be used to estimate the balance between production of carbon (produces O_2) and it subsequent degradation (consumes O_2). By expressing the oxygen concentration in the water column as apparent oxygen uptake (AOU, µmol kg^{-1}), the deviation from 100 % saturation is apparent (figure 5.9). The presence of water over-saturated in O_2 (negative AOU) indicates net production of carbon by phytoplankton. Peak production is found at approximately 10 m depth in an area extending from Kap Ehrenberg to Daneborg. Below 30 m, the oxygen content is generally under-saturated indica-

Figure 5.9 Spatial variations in oceanographic conditions along the fjord transect 3 August 2010. Data on temperature (°C), fluorescence, salinity, the Brunt-Vaisala frequency (cycl. h^{-1}, a measure of water column stability) and apparent oxygen uptake (AOU, µmol kg^{-1}). Measurements were conducted to the bottom but only the top 50 m are shown.



ting a net degradation of carbon. The area with the highest phytoplankton production does not correspond to the area with highest fluorescence, which is a tracer of phytoplankton biomass. Fluorescence is highest in the Greenland Sea at depths around 35 m.

At the main hydrographical station, nine CTD casts were made between 28 July and 13 August, which show the short-

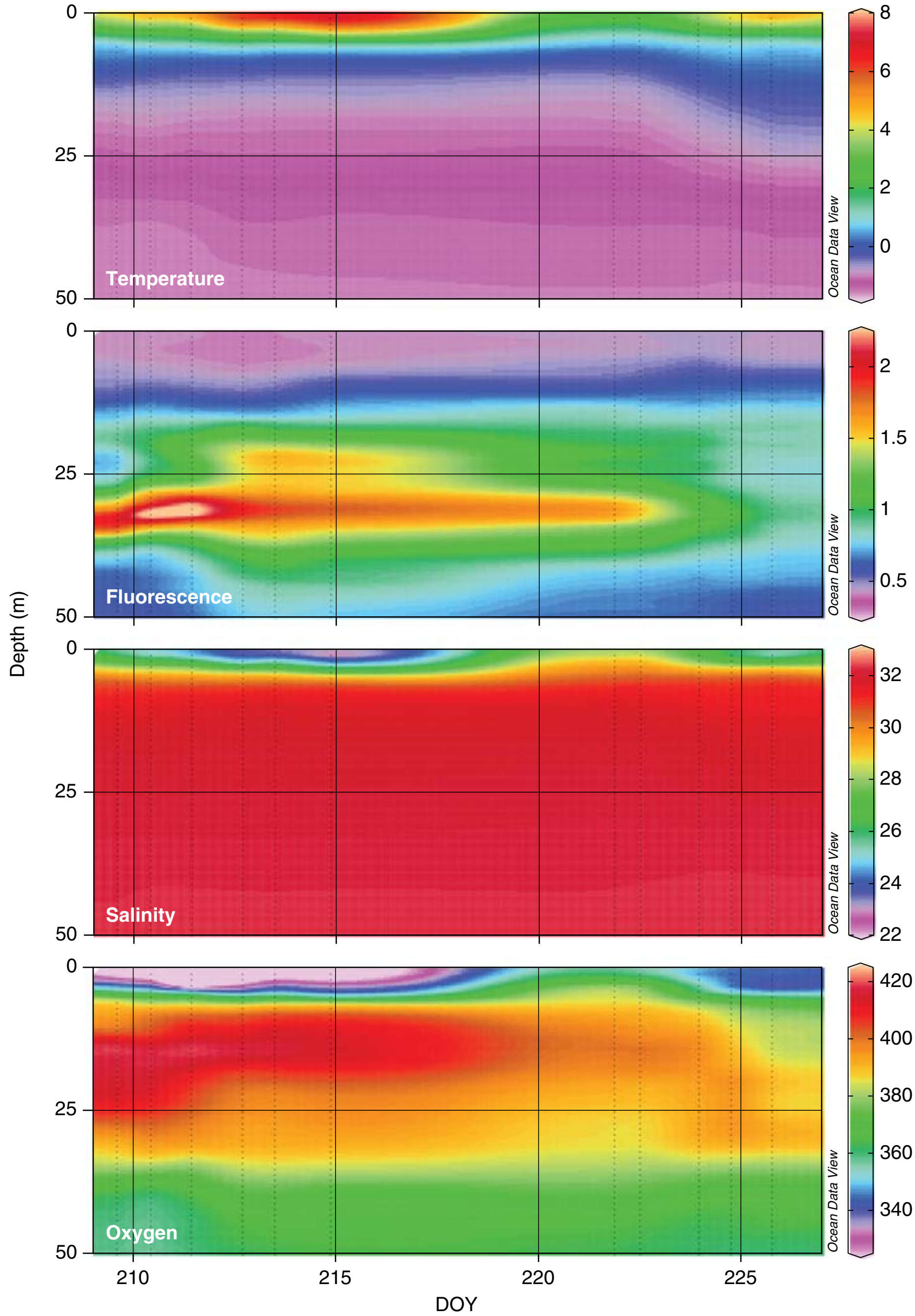


Figure 5.10 Temporal variation in oceanographic conditions at the main station sampled nine times from 28 July to 13 August 2010. Measurements were conducted to the bottom at 160 m but only the top 50 m are shown.

term variability in the fjord. At this station, the influence of freshwater is visible in the surface water. Maximum phytoplankton production as indicated by AOU takes place at 15 to 20 m depth whereas the peak fluorescence is found at 30 to 35 m, which corresponds to the depth of maximum chlorophyll *a* value (figure 5.10). The first part of the study period (until day 218), shows what happens during periods of calm weather: a shallow surface layer is established with low salinity and high temperature. Primary production creates a layer with water supersaturated with O_2 and concentrations of chlorophyll *a* and fluorescence build up below at approximately 30 m depth. After a period of storm (9 August), wind induced mixing had removed the developed peaks in O_2, fluorescence and chlorophyll *a* and had also caused increased values in phosphorous and silicate in the top 30 m of the water column (figure 5.11).

In figure 5.12 the vertical distribution of the parameters influencing phytoplankton production and distribution are plotted for 5 August.

Compared to previous years, the average conditions at the main hydrographic station in 2010 were characterized by relatively low temperature and high salinity (figure 5.13). The calm conditions through

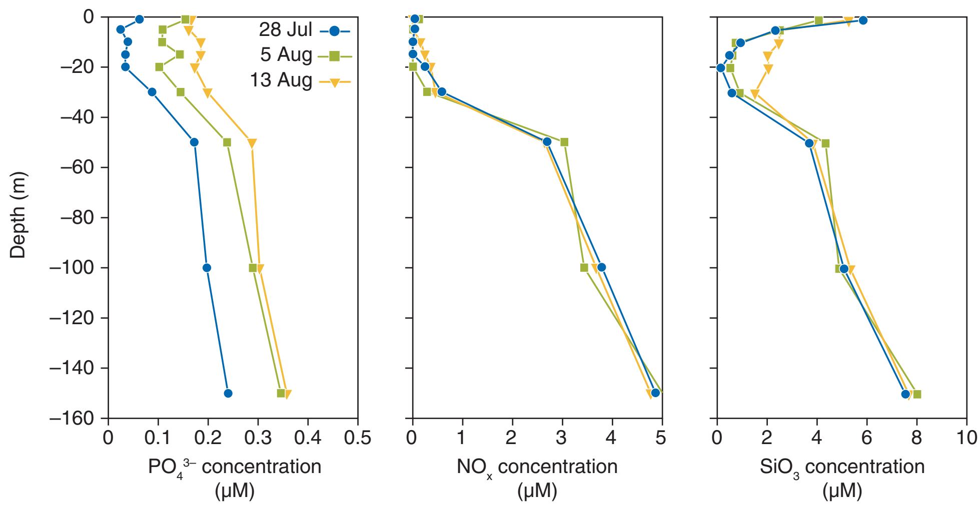


Figure 5.11 Vertical nutrient profiles at the main station in outer Young Sund 2010.

most of the study period resulted in high chlorophyll *a* content and consequently low values of NOx and phosphorous.

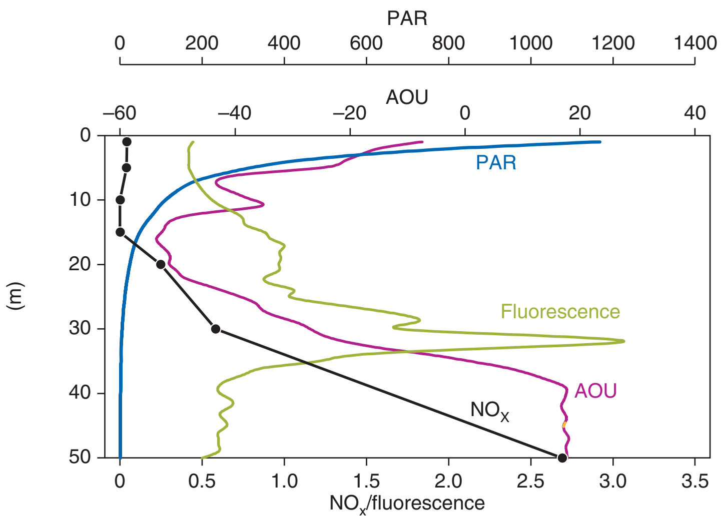
Attenuation of PAR

The availability of photosynthetical active radiation for phytoplankton plays a crucial role for where in the water column phytoplankton production takes place and the annual productivity of the system. The average PAR attenuation coefficient (figure 5.14) was relatively high in 2010 at the main station. A contributing factor was the calm condition and subsequent formation of high chlorophyll *a* concentrations. Inorganic particles also contribute to the attenuation of PAR especially in the top 5 m.

Surface *p*CO_2

Since 2006 measurements of surface content of CO_2 has been conducted in Young Sund. Measurements are used to estimate the air-sea flux of CO_2 during the ice free period.

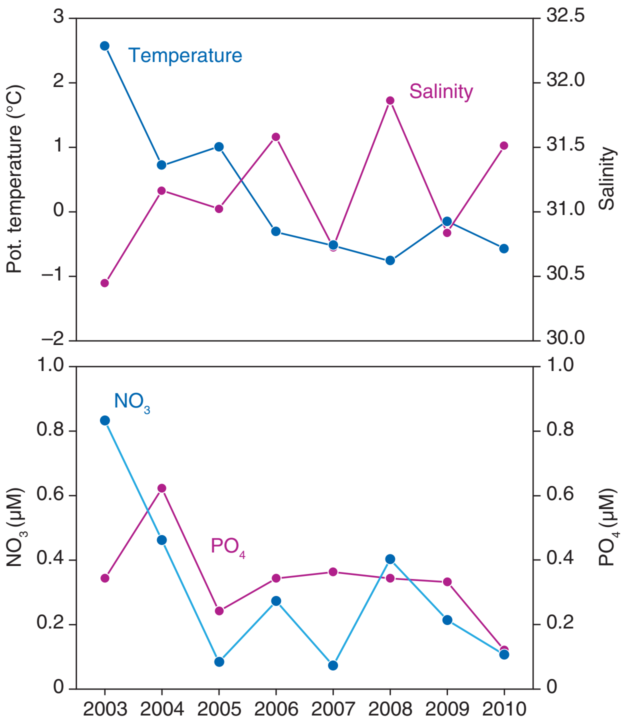
Figure 5.12 Vertical profiles of parameters estimated to control the distribution of phytoplankton and primary production in August in Young Sund. Photosynthetically available radiation (PAR), Inorganic nitrogen (NOx), fluorescence and apparent oxygen uptake (AOU, µmol kg⁻¹).



The difference between the partial pressure of CO_2 in air and atmosphere (ΔpCO_2) is always negative during summer in Young Sund indicating that the fjord is a sink of atmospheric carbon. Measurements along the fjord transect showed most negative values in the inner part of Tyrolerfjord (figure 5.15). In general, the surface water along the fjord transect displayed ΔpCO_2 values that were less negative that the average of 2006-2009. Repeated sampling of the main station during the study period resulted in an average ΔpCO_2 value, which was similar to previous years.

Zoo- and phytoplankton

Three times during the study period, vertical net hauls were taken at the main station for determination of the species composition of zoo- and phytoplankton. The zooplankton is sampled in vertical net hauls from 150 to 0 m. The composition of the copepod fauna (table 5.2) shows the dominance of calanoid copepods but also smaller species such as *Oithona* spp. and *Onacea* spp. are abundant. In fact, *Oithona* spp. and *Onacea* spp. are this year found in their highest abundance and constitute 65 % of the total copepod abundance. When including *Microcalanus spp*. the three small species constitute 84 %. The high abundance of the three species is apparent in figure 5.16 where the proportion of the four large species is small in 2010 compared to previous years (figure 5.15a). The temperate species *Calanus finmarchicus*, which has increased in abundance since the beginning of the programme in 2003, was found in low numbers in 2009. So was the Arctic species *Calanus hyperboreus*, which was found in the lowest number so



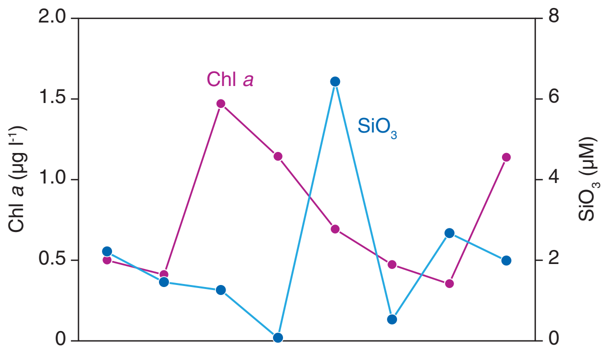


Figure 5.13 Summary of average hydrographic conditions in the surface layer (0-45 m) in August at the standard station in Young Sund.

far. This means that the ratio of adult and copepodite abundance of *C. hyperboreus* to *C. finmarchicus* was 0.4 in 2010. In 2003, it was 56:1 (figure 5.16). This shift in relative abundance between the two species could be an indication of increased influence of water of Atlantic origin in the area or an expansion of the northern range of the temperate *C. finmarchicus*.

Phytoplankton samples were also collected three times during the study period in the 0-50 m depth interval (table 5.3). Compared to previous years the number of species (approximately 20 different taxa) found in the samples was similar. The diversity, measured as the Shannon-Wiener diversity index was slightly higher in 2010 than in 2009, mainly because the abundance was more evenly distributed among taxa. The dominant species were very similar to 2009 with the dominance of the genus *Fragilariopsis*, *Chaetoceros*, *Thalassiosira* and *Chaetoceros*.

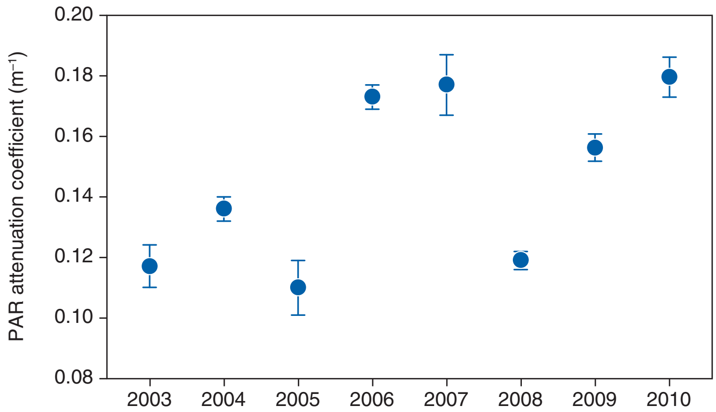


Figure 5.14 Attenuation coefficients (average ± se) in the water column of photosynthetical available radiation (PAR) during summers 2003-2010.

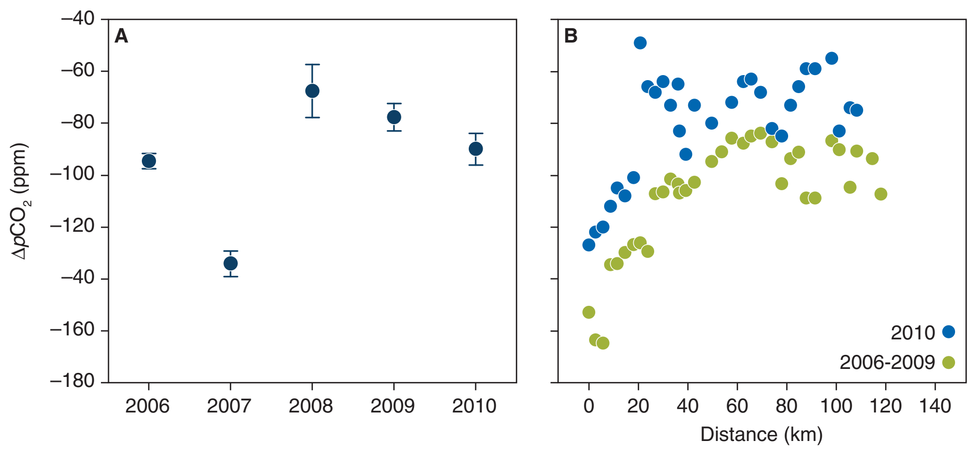


Figure 5.15 Difference in partial pressure of CO_2 (ΔpCO_2) in the atmosphere and surface water (1 m) in Young Sund. Left panel show average summer values (± se) for the standard station and right panel shows values along a transect starting in the Tyrolerfjord and ending in the Greenland Sea. Negative ΔpCO_2 values indicate uptake of atmospheric CO_2 by the fjord.

Table 5.2 Summary of the copepod species composition at the main sampling station in 2010.

Species	Stadium	28 July mean no m^{-2}	28 July se n=3	5 August mean no m^{-2}	5 August se n=3	13 August mean no m^{-2}	13 August se n=3
Calanus hyperboreus	female	21.33	21.33	42.67	21.33	85.33	21.33
	male	0.00	0.00	0.00	0.00	0.00	0.00
	C V	96.00	18.48	106.67	42.67	170.67	28.22
	C IV	106.67	28.22	106.67	21.33	362.67	28.22
	C III	80.00	33.31	106.67	10.67	32.00	18.48
	C II	32.00	32.00	330.67	21.33	170.67	28.22
	C I	0.00	0.00	0.00	0.00	0.00	0.00
Calanus glacialis	female	138.67	76.92	128.00	64.00	128.00	48.88
	male	0.00	0.00	0.00	0.00	0.00	0.00
	C V	501.33	171.66	352.00	0.00	426.67	59.39
	C IV	64.00	48.88	0.00	0.00	0.00	0.00
	C III	10.67	10.67	0.00	0.00	0.00	0.00
	C II	0.00	0.00	0.00	0.00	0.00	0.00
	C I	0.00	0.00	0.00	0.00	0.00	0.00
Calanus finmarchicus	female	224.00	18.48	298.67	42.67	298.67	21.33
	male	16.00	9.24	0.00	0.00	0.00	0.00
	C V	1077.33	28.22	1077.33	129.77	1632.00	342.17
	C IV	0.00	0.00	53.33	21.33	10.67	10.67
	C III	0.00	0.00	0.00	0.00	0.00	0.00
	C II	0.00	0.00	0.00	0.00	0.00	0.00
	C I	0.00	0.00	0.00	0.00	0.00	0.00
Metridia spp.	female	64.00	36.95	42.67	28.22	74.67	28.22
	male	10.67	10.67	21.33	10.67	0.00	0.00
	C V	85.33	10.67	224.00	32.00	149.33	69.95
	C IV	5.33	5.33	0.00	0.00	10.67	10.67
	C III	10.67	10.67	10.67	10.67	10.67	10.67
	C II	58.67	5.33	64.00	18.48	138.67	56.44
	C I	101.33	26.67	138.67	46.49	149.33	38.46
Pseudocalanus spp.	female	378.67	129.49	565.33	202.67	778.67	113.11
	male	0.00	0.00	10.67	10.67	0.00	0.00
	C V	69.33	14.11	288.00	80.53	565.33	101.75
	C IV	16.00	9.24	85.33	69.95	181.33	46.49
	C III	32.00	18.48	53.33	21.33	138.67	38.46
	C II	133.33	32.44	266.67	46.49	640.00	55.43
	C I	282.67	107.07	533.33	85.33	608.00	66.61
Pareuchaeta spp.	female	0.00	0.00	0.00	0.00	0.00	0.00
	male	0.00	0.00	0.00	0.00	0.00	0.00
	C V	0.00	0.00	10.67	10.67	10.67	10.67
	C IV	0.00	0.00	0.00	0.00	0.00	0.00
	C III	0.00	0.00	0.00	0.00	21.33	21.33
	C II	0.00	0.00	0.00	0.00	0.00	0.00
	C I	0.00	0.00	0.00	0.00	0.00	0.00
Calanoida n.det.	female	0.00	0.00	0.00	0.00	0.00	0.00
	male	0.00	0.00	0.00	0.00	0.00	0.00
	C	597.33	150.15	426.67	85.58	405.33	77.86
Microcalanus spp.	female	448.00	120.21	565.33	70.89	874.67	397.78
	male	96.00	43.71	202.67	60.22	149.33	39.81
	C	3413.33	1257.43	4544.00	391.91	6506.67	1111.37
Oithona spp.	female	6101.33	1096.96	7509.33	153.84	9130.67	1006.07
	male	672.00	102.87	618.67	111.36	800.00	97.76
	C	3824.00	693.83	4810.67	768.23	6506.67	1166.11
Onacea spp.	female	357.33	43.66	917.33	28.22	1098.67	74.67
	male	165.33	62.88	245.33	64.88	650.67	228.03
	C	4800.00	1053.57	7765.33	2108.87	4757.33	1497.44

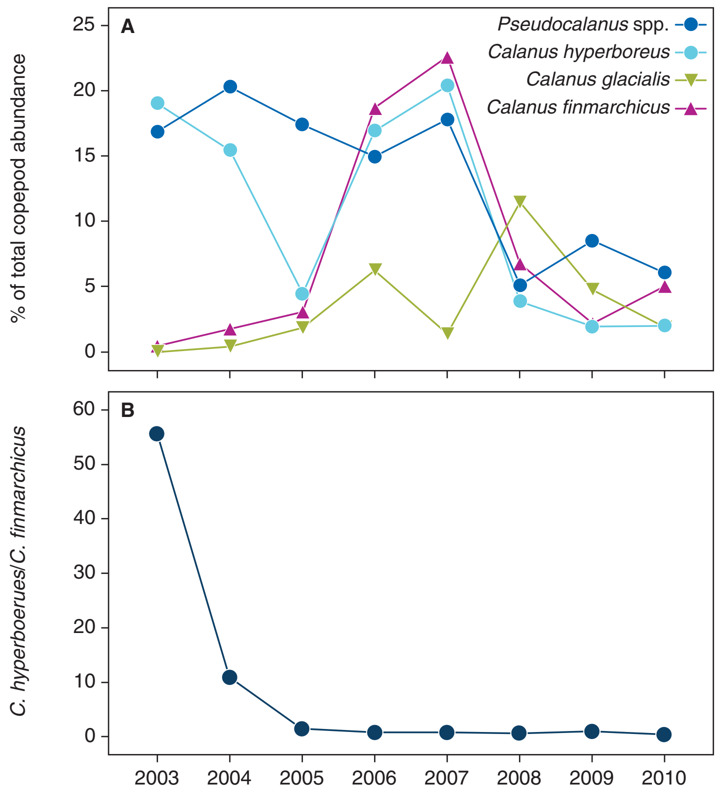


Figure 5.16 A) The relative abundance (%) of total copepods found in vertical net hauls at the main sampling station in 2010. B) The ratio between the abundance of the arctic copepod Calanus hyperboreus (adults and copepodits) and the temperature Calanus finmarchicus in Young Sund.

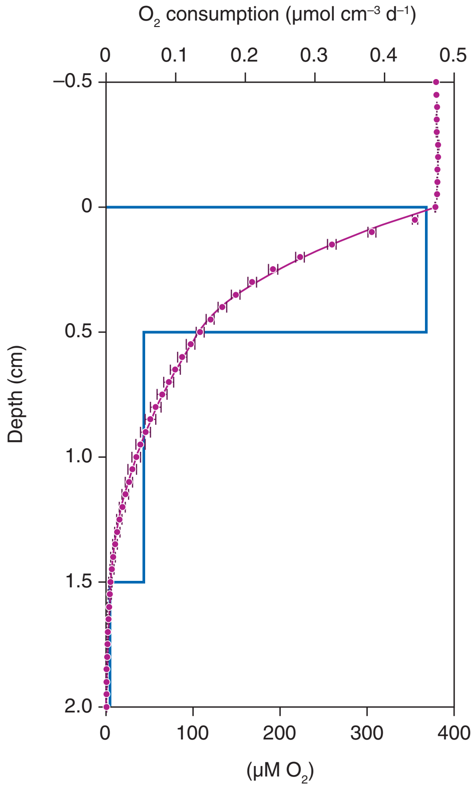


Figure 5.17 Vertical concentration profiles of oxygen (dots) and modelled consumption rates (line) in the sediment at 60 m depth in Young Sund during August 2010.

5.3 Sediment

Sediment-water exchange rates of oxygen and nutrients, oxygen conditions and sulphate reduction

A fraction of the pelagic production settles on the sea bed where it is mineralized or buried in the sediment. The extent to which a portion is mineralised and released into the overlying water column as inorganic carbon and nutrients is dependent upon a number of processes. In the surface sediment layers organic matter is oxidised through oxygen electron acceptors and below the oxidised zone, sulphate (SO_4^{2-}) reduction becomes the dominant process. Sediment processes were measured in recovered intact sediment cores (n=10). The oxygen consumption rate in the sediment (4.710 mmol m^{-2} d^{-1}; table 5.4 and figure 5.17) were within values recorded in previous year (between 2.834 and 6.624 mmol m^{-2} d^{-1} from 2003-09). During 2003-09 we found that the oxygen consumption rate was well correlated to the open water period ($p<0.03$, $R^2=0.62$) suggesting that there was a link between open water period, light avai-lability, primary production, and vertical sinking flux to sediment mineralization. The aerobic zone extended down to approximately 1.5 cm (figure 5.17) which is comparable to most previous years. DIC effluxes from the sediment are generally

Table 5.3 Phytoplankton diversity in Young Sund at 0-50 m depth during 2010. The ten most abundant species are listed together with the relative proportion (%) of total cell count.

	28 July	5 August	13 August
No. Species	**18**	**22**	**21**
Shannon Wiener index	2.0	2.3	2.0
Pilous evenness	0.7	0.7	0.6
Fragilariopsis cylindrus	27.4	3.5	14.6
Fragilariopsis oceanica	12.5	9.1	41.0
Pauliella taeniata	17.4	3.3	0.3
Chaetoceros sp.	9.5	10.0	0.5
Thalassiosira sp.	7.0	9.7	4.6
Fragilariopsis sp.	3.7	18.0	0.0
Chaetoceros decipiens	4.8	3.0	5.9
Thalassiosira anguste-lineata	2.3	7.7	1.5
Navicula sp.	0.2	10.0	1.8
Chaetoceros wighamii	0.8	7.1	1.3

Table 5.4 Sediment-water exchange rates of O_2 (TOU), DIC (dissolved inorganic carbon), NO_3^- + NO_2^-, NH_4^+, SiO_4 and PO_4^{3-} measured in intact sediment cores. Sulphate reduction rates (SRR) in the sediment integrated to a depth of 10 cm, diffusive oxygen uptake by the sediment (DOU) and the ratios of DOU to TOU and SRR to DIC flux. SRR/DIC flux is calculated in carbon-equivalents. n denotes the number of sediment cores. Positive values indicate a release from the sediment to the water column. All rates are in mmol m^{-2} d^{-1}. SE denotes the standard error of the mean.

Parameter	Average	± SE	n
TOU	4.710	0.468	10
DIC	–	–	–
NO_3^- + NO_2^-	0.030	0.061	10
NH_4^+	-0.098	0.012	10
PO_4^{3-}	0.010	0.005	10
SiO_4	0.261	0.056	10
SRR	1.317	0.248	3
DOU	2.897	–	9
TOU/DOU	1.626	–	–
SRR/DIC	–	–	–

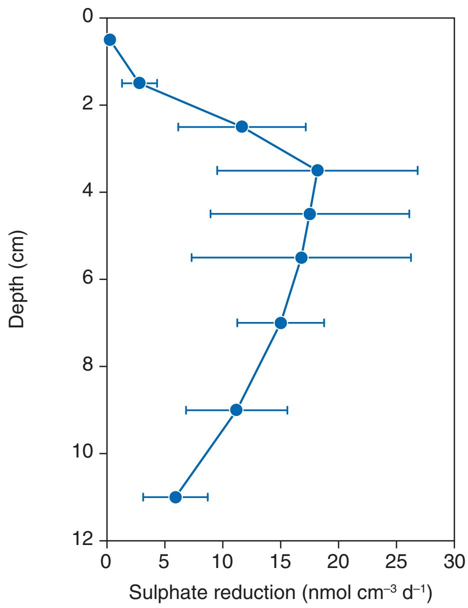


Figure 5.18 Sulphate reduction rates in the sediment at 60 m depth in Young Sund during August 2010.

in the same range as oxygen consumption, although difference does occur in some years. However, dissolved inorganic carbon (DIC) samples from sediment-water exchange experiments were unfortunately lost. The ratio between total (TOU) and diffusive (DOU) oxygen uptake is an indicator for the bioturbation activity, and the ratio corresponded to values recorded in 2003-04 and 2007-09, while lower values were recorded in 2005-06. The anaerobic nature of sulphate reduction processes meant

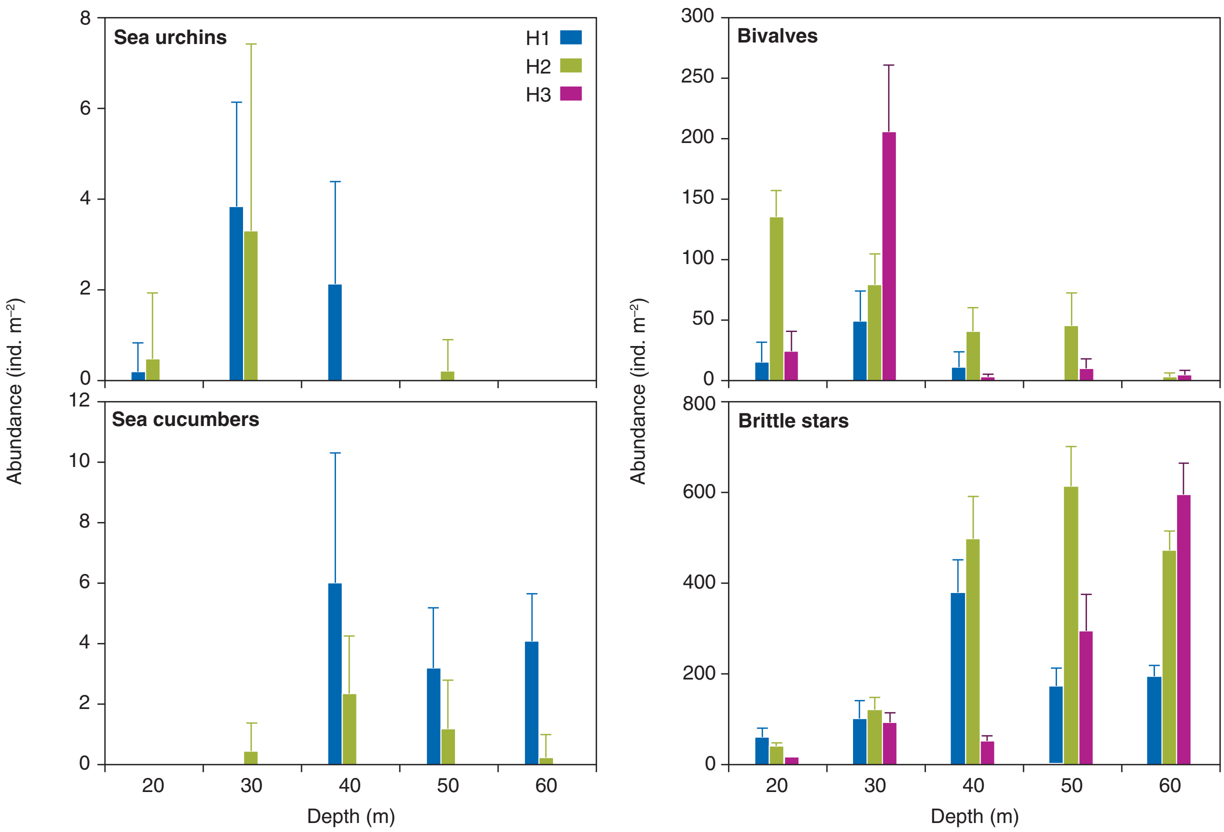


Figure 5.19 Abundance of dominant benthic fauna identified from sea floor photographs along three transects (H1, H2, and H3) in the outer part of Young Sund.

that low rates were recorded in the upper sediment layers and increased with depth where it was the dominant process (figure 5.18).

Macrofauna

The composition and abundance of dominant benthic fauna is monitored each year using an underwater-camera system that covers approximately 0.3 m^2 of the sea bed. The photos are taken along three transects (H1, H2, H3) in the fjord (see figure 5.2) covering 10 m depth intervals from 20 to 60 m. In total, an area of about 50 m^2 is covered each year. As in previous years brittle stars are the most abundant taxa (figure 5.19). Three species are found in Young Sund and on the shelf outside the fjord where they contribute significantly to the benthic carbon cycling (Blicher and Sejr 2011).

Bivalves are another important group of benthic species. Their abundance peak at 20-50 m depth, which coincide with optimal food conditions. The difference in abundance between the sites surveyed is relatively consistent among years and the highest abundance is found at 30 m depth at H3.

Macroalgae

Large specimens of the brown algae *Saccharina latissima* are sampled in early August every year. The annual production of new blades was identified and the length, biomass and production in terms of carbon were estimated (figure 5.20).

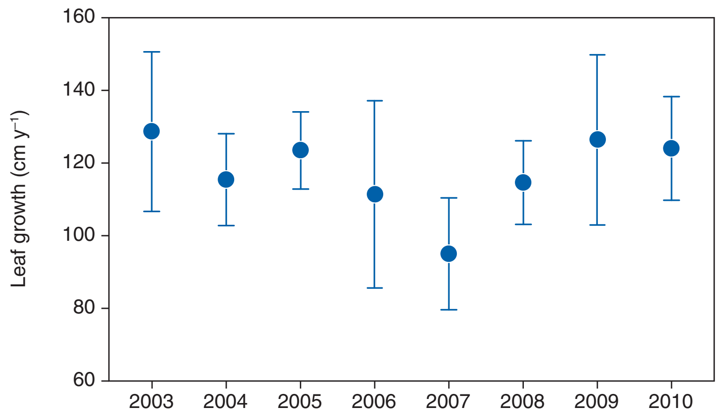


Figure 5.20 Average leaf growths (±SE) of the macroalgae Saccharina latissima *at 10 m depth in Young Sund.*

In 2010, the length of the new leaves was relatively long compared to previous years. The average was 124 cm and was only exceeded in 2003 and 2009. Light availability is most likely the primary driver of annual growth. Ice conditions are thus an important factor determining growth. Because the species is perennial, the length of the leaf blade most likely integrates light condition during the year of collection and the previous years. The time series from Young Sund are currently being used in a study of how sea ice influences the spatial and temporal variation in macroalgae growth and depth distribution in Greenlandic waters (Krause-Jensen et al. unpublished).

6 Research projects

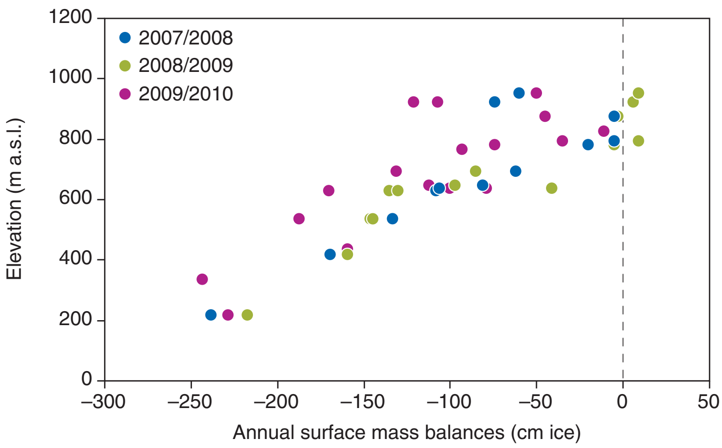
6.1 Climate change and glacier reaction in the Zackenberg region

Bernhard Hynek, Daniel Binder, Gernot Weyss, Thomas Marke, Ulrich Strasser and Wolfgang Schöner

Glaciological field work at Freya Glacier on Clavering Island was carried out around the end of the melt season in late August. To determine the surface mass balance 2009/2010 ablation was measured at approximately 15 stakes and accumulation was measured with ground penetrating radar (GPR) and in snow pits. Additionally, albedo was measured on the glacier and air temperature sensors have been installed in different elevations to provide input data for mass balance modelling. Ablation during summer 2010 was higher than in the previous two years, as shown in figure 6.1, which lead to a mean glacier wide surface mass balance of –750 mm w.e. in 2009/2010 (compared to –510 and –466 mm w.e. in 07/08 and 08/09, respectively.)

As in previous years, re-freezing of melt water was observed all over the glacier, partly as superimposed ice and partly as internal accumulation in the firn area. The re-freezing of melt water is supposed to have a significant influence on the total mass balance and the runoff of Freya Glacier but it is only partly accounted for by traditional mass balance measurements. First results of mass balance modelling using data of the Zackenberg climate stations showed the importance of *in situ* meteorological and glaciological measurements on the glacier for data input and model validation.

Figure 6.1 Measured annual surface mass balance at the ablation stakes in the last three years.



The plans for 2011 are therefore to install an automatic weather station on Freya Glacier and to measure the vertical temperature distribution in the upper ice and snow layers in order to quantify the subsurface heat flux and hence the potential of superimposed ice formation and melt water retention throughout the year. Additionally, the retreat of the snowline, firn- and ice-stratigraphy and runoff will be monitored in an extended field campaign to provide a good validation dataset for physically based mass balance and runoff models.

The analysis of GPR data, from a survey in May 2008 suggests that Freya Glacier is a polythermal glacier with temperate ice layer near the bed of the glacier around the mean equilibrium line altitude (ELA). Figure 6.2 shows GPR data gathered with three different centre frequencies (20, 50, 90 MHz). The location of the cross profile was right at a bottleneck orthographically below the confluence area of the two accumulation branches. Caused by the high GPR sensitivity for liquid water, mapped high backscatter zones hint at ice at its pressure melting point (temperate ice). The frequency-dependent spatial extent of the high backscatter zones is a function of the predominant ‘water pocket’ size and geometry. The mean high backscatter pattern is most likely driven by climatic as well as dynamic causes. High backscatter zones located below the glacier bed reflection are interpreted as side reflections. The thickest ice found during the GPR survey is 200 m, located in an overdeepening at the confluence area of the two accumulation branches. Follow-up surveys would be valuable in terms of a potential spatial extending of high backscatter zones in a warming climate, underlining the polythermal character of Freya glacier as well as yielding an obvious documentation for climate change impacts.

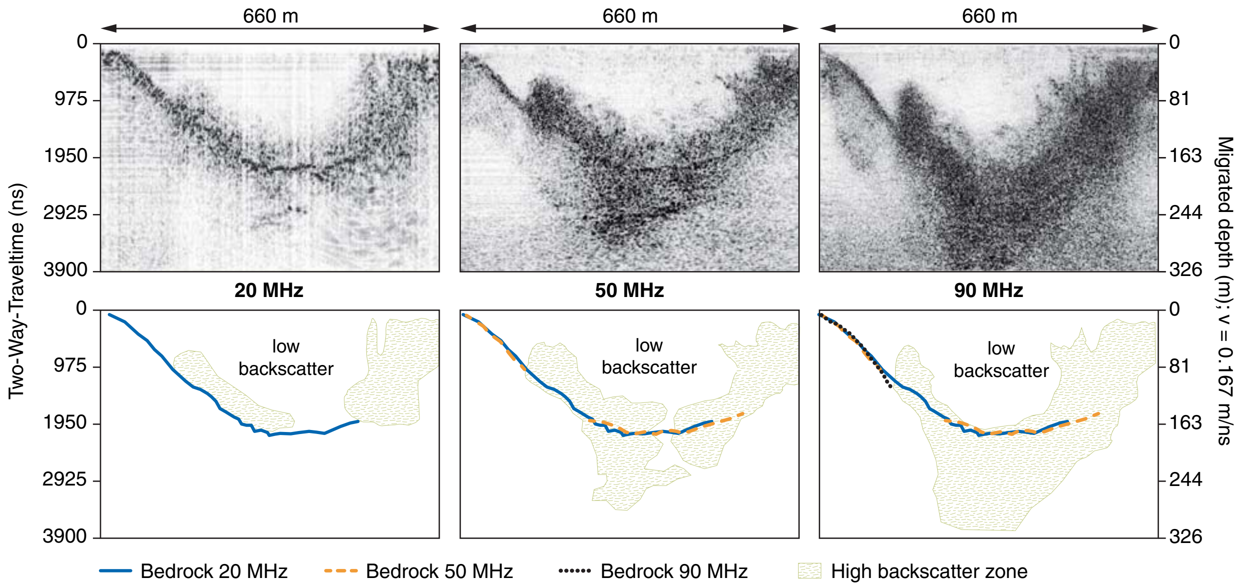


Figure 6.2 Cross section at a bottleneck, orthographically below the confluence area of the two accumulation branches. Three different GPR centre frequencies were used (20, 50, 90 MHz). Below each cross profile, interpreted glacier bed reflection and spatial extent of high backscatter zones are illustrated.

6.2 Discharge in Zackenbergelven at high flows and in ice affected periods

Kisser Thorsøe, Morten Larsen and Dorthe Petersen

During 2009 and 2010, the Environmental Protection Agency funded a project with three main aims:

- to train personnel from GeoBasis in the use of a Q-liner (for description of the Q-liner see section 2.3)
- to measure discharge at high flows and thereby being able to establish a better Q/h-relation for Zackenbergelven
- to develop a method to estimate the discharge in the beginning of the season when the river is affected by ice and the Q/h-relation therefore not are valid.

In 2009, one person from Asiaq was conducting two weeks of field work when high flows was expected, and in 2010 field work was conducted in the beginning of the season, when the river bed was still affected by ice and snow. In each season a system were established, which enabled the Q-liner to be pulled across the river. Measurements of the velocity could then be made in a number of verticals without compromising personnel safety. As Asiaq has great experience in using the Q-liner, measurements with the Q-liner was in both years carried out together with GeoBasis, which were trained to use the device. Furthermore, a manual for the Q-liner was made.

In 2009, eighteen discharge measurements were carried out with the Q-liner. Half of these were carried out during Asiaq's fieldwork. As there were very little snow in the winter 2008/2009, there were no high flows during the fieldwork, but the Q-liner was used later in the season and discharge measurements at high flows were carried out by GeoBasis. In 2008 the highest measured discharge was 23.4 $m^3 s^{-1}$ (measured with propeller), whereas it in 2009 was 38.3 $m^3 s^{-1}$ measured 18 July (measured with Q-liner). Because of the measurements at high discharges, the established Q/h-relation for the 2009 season was more reliable than the one established for the 2008 season. For the established Q/h-relations, see Jensen and Rasch 2010.

In 2010, twenty-five discharge measurements were carried out by the use of the Q-liner. Twelve of these were carried out during Asiaq's field work. The aim for the 2010 field work was to measure the discharge during river breakup. The 12 measurements were carried out when the river bed was affected by ice. Measurements at high flows were carried out, by Asiaq, during river breakup. The highest measured discharge was measured 14 June and was 35.5 $m^3 s^{-1}$. For the established Q/h-relation, see section 2.3.

In 2009 and 2010, 18 and 16 discharge measurements respectively, were carried out when the river bed was affected by ice. The established Q/h-relations are only valid under ice free conditions. If the Q/h-relation is used to calculate the discharge when the river is affected by ice, the discharge will be overestimated. Until now, the discharge in this period has been estimated by linear interpolation between manually discharge measurements. Therefore, it has been a wish to develop a method, where automatic registration of the water level could be used in the calculation of the discharge.

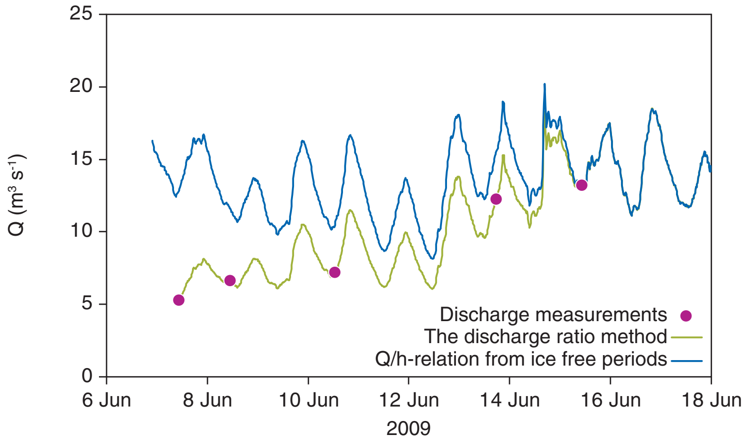
Based on a literature study two methods were chosen and tested on the data collected during the breakup periods in 2009 and 2010. We found both methods applicable but ended up using a Discharge Ratio method to calculate the discharge during the breakup. The discharge ratio is calculated as the ratio between the manually measured discharge and the discharge calculated from the Q/h-relation valid under ice free conditions for the mean water level during the measurement. During periods between manual discharge measurements, the discharge ratio is interpolated. The discharge time series is then calculated from the water level time series, the Q/h-relation and the discharge ratio. For the measurements in 2009 and 2010, the discharge ratio was found to decrease linearly with time through the breakup periods. A thorough description of both methods can be found in Larsen et al. 2011.

Figure 6.3 shows the measured and the calculated discharge during the breakup period in 2009. The time series is calculated by the Discharge Ratio method and the Q/h-relation valid under ice free condition.

Based on the analysis for the breakup period, recommendations for a future measuring programme were given. When the water level is not continuously registered, the discharge cannot be derived from a rating curve. It is therefore recommended to carry out two daily discharge measurements, one around noon, when the lowest daily discharge is expected and one around 22:00, when the highest daily discharge is expected. The final discharge time series is then interpolated between the manually measured discharges.

When the water level is continuously recorded, and a discharge can be calculated from the Q/h-relation and the Discharge Ratio method, it is recommended that a manual discharge measurement is carried out every third day.

Figure 6.3 Measured and calculated discharge during the break-up period in 2009. The discharge time series is calculated by the Discharge Ratio method and the Q/h-relation valid under ice free conditions.



6.3 Plant-soil-herbivore interactions in the Arctic – feedbacks to the carbon cycle

Julie Maria Falk and Lena Ström

Since the 1960s and 1970s the Arctic region (60 °N-90 °N) has on average become 1-2 °C warmer and climate change is proceeding faster here than elsewhere on the Earth (ACIA 2005, IPCC 2007). Changes in climate will most likely alter the carbon balance and the vegetation composition and density (ACIA 2005, IPCC 2007). The Arctic plant communities and their carbon balance are not only driven by the climate and the environment but can be affected by grazing (van der Wal 2006, Post and Pedersen 2008, and Rinnan et al. 2009). Grazing has previously been shown to influence the carbon allocation and root exudation (Holland et al. 1996 and van der Wal et al. 2007), greenhouse gas production and emission (Holst et al. 2008 and Sjögersten et al. 2008) and plant species composition and diversity (Post et al. 2008 and Olofsson et al. 2009). The current understanding of these processes is, however, limited. Increased knowledge of the controls of the Arctic carbon cycle will be of vital importance when discussing ecosystem carbon balance in a changing climate. To enlighten that topic a PhD project 'Plant-soil-herbivore interactions in the Arctic – Feedbacks to the carbon cycle' from Lund University (in collaboration with Department of Arctic Environment, Aarhus University) began in summer 2010. The field work for the project is to be carried out in the Zackenberg Valley over the next couple of years as part of the exclosure project carried out by Niels Martin Schmidt and Mads C. Forchhammer from Department of Arctic Environment, Aarhus University. During summer 2010, five blocks were established, each block consisting of three 100 m^2 squares, i.e. a

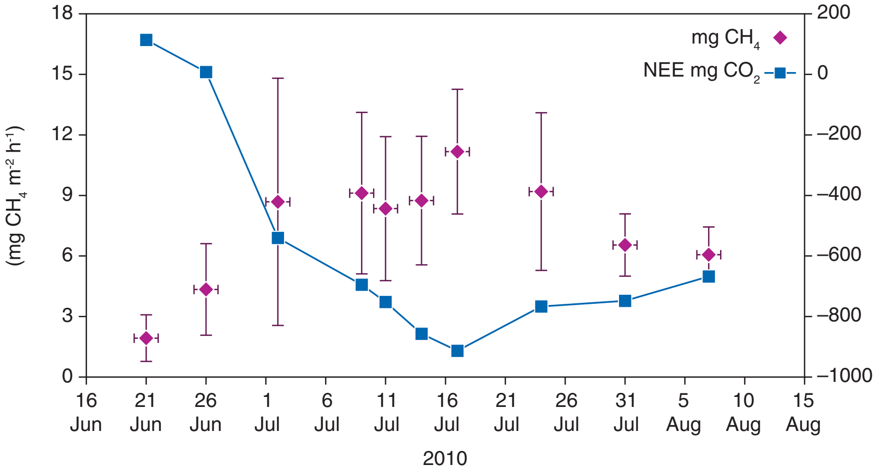


Figure 6.4 The average CH_4 emission (± SD.) and NEE from the 10 plots at the Rylekærene site.

control, a snow-fence and an exclosure that prevents muskoxen from grazing inside.

We established two 40×40 cm measuring plots within each of the squares to determine greenhouse gas fluxes, pore-water concentrations of labile carbon compounds (e.g. organic acids) and monitor physical parameters. A few manual CH_4 and CO_2 measurements were carried out from mid-July to beginning of August 2010 in these plots, using standard closed chamber techniques. In mid-July, the average CH_4 emission for the five blocks was 3.8 mg CH_4 $m^{-2}h^{-1}$, while it had dropped to 3.0 mg CH_4 $m^{-2}h^{-1}$ in the beginning of August. In addition to the measurements in the exclosure blocks, identical measurements were carried out in Rylekærene on 10 plots (40×40 cm) previously established in connection with TorbernTagesson's PhD project ('Land-atmosphere exchange of carbon in a high-Arctic wet tundra ecosystem'). Five of these plots were untreated controls and in five, we simulated grazing by cutting the vegetation approximately 5 cm above ground three times during the field season. During summer 2010, weekly CH_4 and CO_2 measurements were made from 21 June to 7 August. The mean CH_4 emission from the 10 plots is showed in figure 6.4. The CH_4 emissions increases as the snow melts, the temperature increases and the vegetation develops (as shown in figure 6.4 by the increased negativity of the Net Ecosystem Exchange of CO_2, NEE, which indicates increased plant uptake of CO_2) and starts to decline towards the end of the growing season. The largest standard deviation between the plots was seen in the beginning of the field season, where the fluxes may vary significantly within a few meters. We could not see any effect of the stimulated grazing on the CH_4 flux in any of these plots. We, however, hypothesize that the effects will increase with additional years of simulated herbivory.

In the end of the field season, 12 monoliths from the Zackenberg valley fen area were taken and transported back to the laboratory at Lund University. In the laboratory, the monoliths are grown under controlled environmental conditions and subjected to detailed studies. The aim of this project, combining *in situ* field measurements with detailed laboratory experiments, is to elucidate how interactions between plants, soil processes and herbivores affects the carbon cycle in an Arctic wet ecosystem, in a both short and long term perspective.

Figure 6.5 Measurements in an exclosure 2010. Photo: Julie Maria Falk.

6.4 Nitrogen fixation rates in high arctic dry heath and the influence of climate change and water additions

Pernille Lærkedal Sørensen, Michelle Schollert Skovgaard and Anders Michelsen

Biological nitrogen fixation is the main source of nitrogen input to nutrient limited ecosystems in the Arctic. Indeed, availability of nitrogen is a main control on other key ecosystem processes such as the cycling of carbon. Hence, nitrogen fixations can indirectly feedback on the climate, through control on the N-limited primary productivity in the Arctic. In spite of this, there have been no published records of nitrogen fixation rates from Greenland, up until now.

Rates of nitrogen fixation are controlled by different biological and physical factors, i.e. presence of nitrogen fixing organisms, availability of water, and temperature and incoming light. In order to investigate nitrogen input rates through nitrogen fixation, we measured nitrogen fixation in different ecosystem types at Zackenberg, NE Greenland. With the aim of evaluating the influence of climatic factors, we furthermore measured nitrogen fixation in a field experiment with warming, shading and water addition. We used the acetylene reduction assay to estimate rates of nitrogen fixation. In this assay, nitrogen fixing organisms reduces added acetylene to ethylene, instead of reducing atmospheric N_2 into ammonium, and hence, the production of ethylene corresponds to rates of nitrogen fixation.

Over the season, the average rates were 1.1(0.2) (seasonal average with S.E. in brackets) in the crusted heath, 20.4(3.8) in a dry *Salix*-heath, 6.8(1.7) in an *Eriopherum*-fen and 61.5(13.6) mmol ethylene m^{-2} h^{-1} in a moss-dominated snow bed. The rates are highest early in the season and decrease as the soil dries out. Using a theoretical conversion factor of 3:1 between ethylene production and amount of fixed nitrogen, and an active season of two months, we calculated the amount of nitrogen fixed in the different ecosystems to between 7 and 400 mg N m^{-2} $season^{-1}$.

The field experiment was on a dry heath dominated by *Salix arctica* and *Vaccinium uliginosum*, and the treatments were (a) control with no treatment, (b) warming with plastic tents and (c) shading with sack cloth. We established two cores with a diameter of 5 cm and a depth of 7 cm in each plot. One core in each plot was with no further treatment, and one core was watered with 10 ml deionised water the day before each measurement campaign, and again immediately before measurements.

We found that the nitrogen fixation rates in the climate change experiment were highest in the beginning of the measurement period, and that the rates were significantly lower in the non-watered cores compared to the ones with added water (figure 6.6). Warming and shading had however, no significant effect on nitrogen fixation rates.

In conclusion, the nitrogen fixation yields a large input of N to the ecosystem. Climate change does not seem to influence the rates of nitrogen fixation significantly. However, changes in precipitation patterns in form of more rain in the summer season, as predicted for the region, could lead to increased input of N via nitrogen fixation.

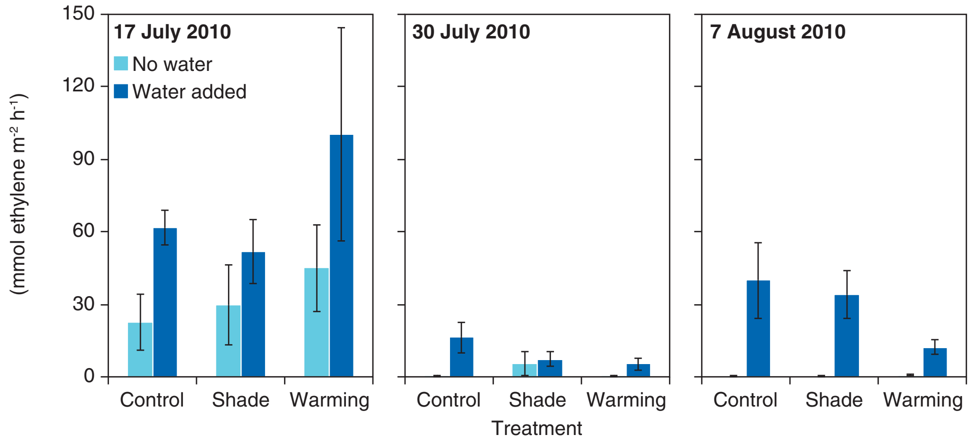


Figure 6.6 Mean ethylene production (n=6, ± S.E.) on 17 July, 30 July and 7 August in the control, shade and warming plots at the dry heath. Light blue bars: No water added to the plots prior to measurements. Blue bars: Water (10 ml deionised water) was added to the cores both 24 hours and immediately before measurements.

6.5 Arctic willow and Arctic bell-heather growth and populations' dynamic in four community types

Noémie Boulanger-Lapointe and Claudia Baittinger

Shrub cover increase is expected to be one of the major impact of climate change on Arctic terrestrial ecosystems (Sturm et al. 2001). Studies have documented this phenomenon in Low Arctic and alpine regions (see among others Forbes et al. 2010, Hallinger et al. 2010), but limited information is presently available from the High Arctic where woody species are restricted to prostrate growth forms. Although it has been shown, that dendrochronological analysis can be performed on dwarf shrubs, methodological difficulties have restricted their use in the past (Woodcock and Bradley 1994, Rayback and Henry 2006). During July 2010, we carried out a study to improve our knowledge of the growth patterns and wood anatomy of the arctic willow *Salix arctica* (figure 6.7) and the arctic bell-heather *Cassiope tetragona*. In conjunction with this, we evaluated arctic willow population dynamics in four community types.

Earlier tree-ring studies, conducted in three habitats in the valley bottom (15-40 m a.s.l.; *Salix* snow bed, *Cassiope* heath and ablation plateau) have demonstrated a negative correlation between *S. arctica* annual growth and spring snow cover (Schmidt et al. 2010, Schmidt et al. 2006). To build on these results, we revisited the area and paid special attention to sample individuals located close to each other in order to enhance cross-dating possibilities. Before willow removal, we pursued vegetation surveys and collected information on fertility, recruitment and mortality. In addition to the low elevation sites, we investigated a population on the slope of Aucellabjerget, in the Fell-field vegetation type (410-440 m a.s.l.). Preliminary results indicate that growth is much more restricted by competition than by any environmental variables. Thus, rich and dense populations (*Cassiope heath* and *Salix* snow bed) present a much smaller annual growth than low cover communities do (ablation plateau and Fell-field) (figure 6.8). Individuals from dense populations might thus be rejected for dendroclimatological studies since they present too many narrow and incomplete rings. On the other hand, population dynamic analysis point out that seedling establishment is frequent and strongly correlated with water availability. Mortality rate in the first years is also high and prevents populations from rapid expansion.

Figure 6.7 Arctic willow collected on the Ablation plateau. Photo: Noémie Boulanger-Lapointe.

S. arctica and the evergreen shrub *C. tetragona* are growing side by side in the *Cassiope* heath, which makes it possible to compare growth patterns between the two species. *C. tetragona* chronologies are built on stem length increment as derived from the distances between 'wintermarksepta' (formed at the end of the summer growth period when the pith is narrowing (Rozema et al.2009). 12 individuals of the species have been collected and are currently being processed.

Results from this project will be analysed and compared to data collected in the Canadian high-Arctic (Noémie Boulanger-Lapointe in prep.) and should provide interesting insights on shrubs response to climate change in the high-Arctic.

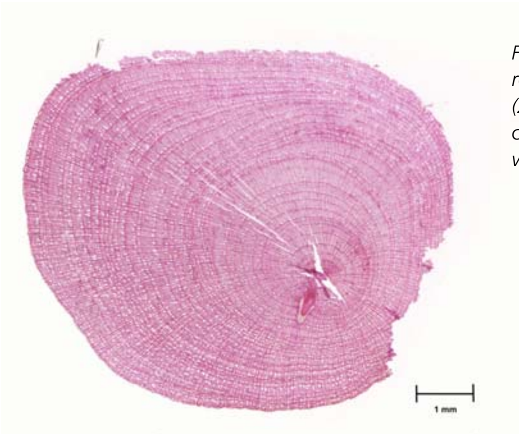


Figure 6.8 Arctic willow's root collar microsection (20 am) from a sample collected in the Fell-Field vegetation type.

6.6 Environmental drivers and expected impacts of climate change on the secondary growth of woody shrubs in Arctic ecosystems

Matteo Campioli

Net primary production (NPP) is a crucial process for plant subsistence and development. Furthermore, NPP represents the amount of atmospheric carbon (C) that is taken up by terrestrial ecosystems, thus a negative feedback to the greenhouse effect and climate change.

The stem secondary growth (i.e. increase in stem diameter) of woody shrubs is one of the least investigated component of NPP in arctic terrestrial ecosystems. The aim of this project was (1) to assess the secondary growth for dominant shrubs and plant communities in Zackenberg and (2) to elucidate the impact of manipulative experiments simulating climate change (warming and shading) on secondary growth.

We assessed secondary growth (expressed as grams woody biomass produced per 100 grams standing woody biomass) for: (i) *Cassiope tetragona*, in an exposed heath and a more sheltered location, both at low altitude (~40 m a.s.l.) (ii) for *Salix arctica*, at a low altitude heath (~40 m a.s.l.) and a high altitude fell-field (~470 m a.s.l.) and for (iii) *Empetrum hermaphrodite*, on a lowland sheltered location (the only location where *Empetrum* is abundant at Zackenberg). Values of secondary growth were 6-7% for *Cassiope*, 14-15% for *Salix* and 18% for *Empetrum*. These values are substantial and, in the case of *Empetrum*, even larger than equivalent values in the Sub and Low Arctic. On the other hand, because of the scarce vegetation cover, values of secondary growth per unit ground surface were low (4 and 15 g m^{-2} y^{-1}, at the exposed *Cassiope* heath and low altitude *Salix* site, respectively).

The impact of the differences in microtopography, wind exposure (exposed vs. sheltered) and altitude (low- vs. upland) on secondary growth was minor and not significant. On the other hand, the impact of 7 years of warming (open top small greenhouses) and shading (clothing) was large on the secondary growth of *Cassiope* (increased from 6% to 9-10%) but minor and non-significant for *Salix*.

Detailed analysis of these data and comparison with data from other arctic locations will be presented in a Master thesis in biology at the University of Antwerp and in two peer-reviewed publications (currently in preparation). Together with secondary growth, ancillary data on apical stem NPP and leaf NPP have also been collected. They will also be published in the above mentioned documents.

6.7 Herbivore influences on ecosystem functioning

Niels Martin Schmidt, Paul Henning Krogh and Mads C. Forchhammer

Biodiversity and its development over time is a corner stone in understanding ecosystem functioning, and biodiversity is therefore a central issue in management and conservation across biomes. Biodiversity in a given area is the product of the area and the history of the area. For instance, the biodiversity of vascular plants in Greenland is the product of local geology, local weather, regional climate, human disturbance, and not the least, the product of the interactions between local organisms on the various trophic levels, such as the consumer-resource interaction between vascular plants and herbivore animals. Herbivores can potentially enhance or buffer changes in biodiversity induced by external forcing by e.g. climate. This project aims at quantifying the long-term effects of the largest herbivore in high-Arctic Greenland, the musk ox *Ovibos moschatus*, and to assess biodiversity changes on two trophic levels, i.e. vascular plants and soil fauna, in Zackenbergdalen.

In July 2010, we established permanent musk ox exclosures in the large fen area Rylekærene at Zackenberg (figure 6.9). The set-up consists of two treatments, exclosure (EX) and snow-control (SC), and one control (C). The EX plots inhibit musk ox grazing, while the SC plots serve as controls for the potential effects of the fence itself, whilst still allowing musk oxen to graze the plot. The C plots are not manipulated controls. A randomized complete blocks design was established with three plots per each of 5 blocks, including the treatments EX, SC and C. Each plot measures 10x10m, and are positioned facing NNW, which is the dominating wind direction during winter. The EX plots are fenced on all four sides, while SC only has a fence towards NNW only, thereby making the potential snow fence

Figure 6.9 Musk oxen outside the exclosures. Photo: Julie Maria Falk.

effect in SC and EX plots comparable. The C plots are marked by iron bars only.

Fences were established by means of 5 mm V-shaped iron bars in the corners, supported by 25 mm iron poles for every 2 meters. All bars and poles were forced into the permafrost. The fence used is ordinary 100 cm sheep fence with 6 strings. Stiles were placed in all EX plots to reduce the wear on the fence. To minimize the potential trampling effects on the vegetation, board walks were placed in the wet parts of the plots. Additional board walks will be laid out in 2011.

In connection with the establishment of the exclosures, a suite of base line data were collected. These include data on plant diversity and species composition (frequency analysis), estimates of plant biomass, leaf area index and NDVI. Soil fauna species' biodiversity and species composition, as well as their food web structure derived from natural abundances of 13C and 15N, were examined treatment-wise across plot replicates. In all plots, we placed soil temperature loggers to allow for detection of changes sin soil temperature. Moreover, in all plots we placed nutrient sticks to examine the level of nutrients, and litter-bags to examine decomposition rates in the various treatments. Additional data collected were soil characteristics and depth of the active layer. The visual appearance of all plots was documented by detailed digital photography.

6.8 Effects of climate change on structure and dynamics of an ecological network

Claus Rasmussen and Jens Mogens Olesen

Climate change drives global environmental changes, which further alter, for example, population sizes and geographic range of species. This is well documented (e.g., Hegland et al. 2009). Yet, the greatest challenge is still pending to predict effects of global environmental changes on higher organizational levels in nature, e.g., at the level of entire ecological networks, encompassing hundreds of species and their interactions. Such interaction networks between plants and their pollinators can be highly susceptible to global environmental changes, e.g., climate change causes pronounced phenology shifts in some species, which affects other interacting species in a net-

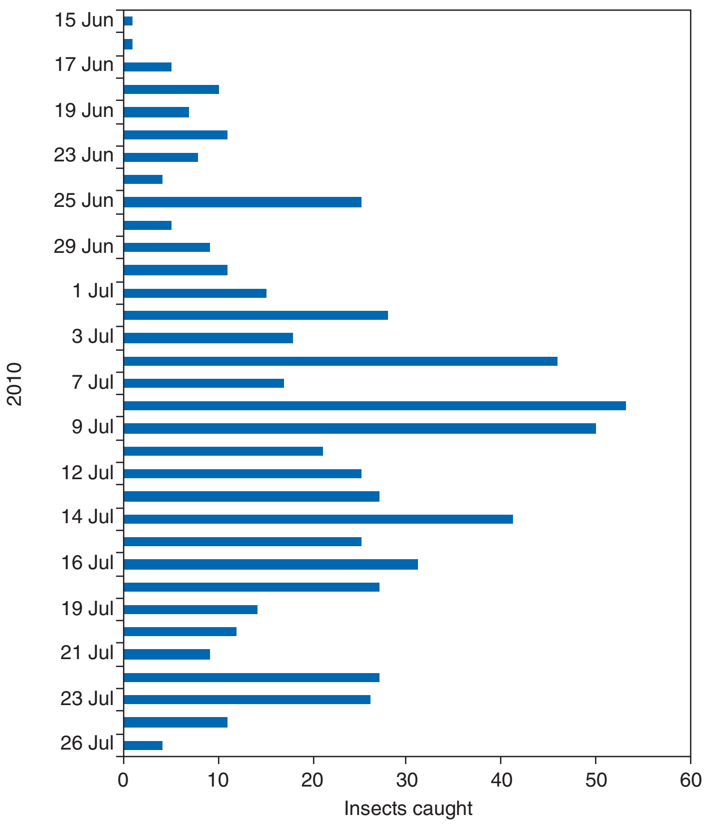


Figure 6.10 Insects caught at Zackenberg in 2010.

work (Høye et al. 2007). This may further affect network resistance to disturbance. Since 1995, Zackenberg Research Station in NE Greenland at 74 °N latitude has monitored many biotic and abiotic variables. In two consecutive seasons (1996-1997), Olesen et al. did a study at Zackenberg of the structure and seasonal dynamics of a network of plants and their pollinators, encompassing all flowering plants and observed flower-visiting animals (Olesen et al. 2008). They studied the day-to-day dynamics of this network and found that both species abundance and phenophase were important determinants of the network structure. These two factors are strongly affected by climate change (Høye et al. 2007, Olesen et al. 2008). Since climate has become warmer at Zackenberg since 1996-1997, we anticipate that our study system has undergone major changes. An exact replicate follow-up to the 1996-1997 study was therefore planned for two seasons (2010-2011) with the 2010 already completed. These studies will offer us a unique opportunity to analyze the influence of climate change on the structure, dynamics and stability of complex natural structures like ecological networks. The purpose is (i) to describe the structure and seasonal dynamics of the network in 2010-2011; and then (ii) to analyze how the network has changed during the intervening 13 years; and finally, (iii) to model the robustness and fragility of important network parameters.

942 insects were caught during the 2010 field period (6 June until 23 August) with the highest number in July (figure 6.10). Previous field seasons in 1996 and 1997 gave a total of 536 and 562 insects, respectively. The 1996-1997 insects represented 76 different species with the majority being flies. The higher number of insects in 2010 was due to a more intensive field period than previous years. The final identification of the insect captured in 2010 is still pending, but is expected to be similar to the diversity from 1996-1997. During the 2010 season, 41 different plant species were included in the study as opposed to 31 species in 1996-1997. Only dandelion (*Taraxacum phymatocarpum*) from the 1996-1997 study were not encountered during the 2010 season, although *Taraxacum arcticum* was locally common but not included in the 1996-1997 study. It is too early to conclude more about differences between the 1996-1997 season and 2010-2011 seasons, but there have been shifts in the composition of fauna and flora. With data from 2011, we will be able to discuss differences in detail, compare flight period for the species and eventually analyze, which ecological changes we can attribute to climate change and thus determine how complex systems respond to global climate change now and in future.

6.9 A high-Arctic food web

Tomas Roslin, Gergely Várkonyi and Bess Hardwick

Quantitative food webs (see Morris et al. 2005, van Veen et al. 2006) offer powerful tools for illustrating not only the trophic connections between different species in a community, but also the relative strengths of these connections. In this project, we construct a quantitative food web of the plants, the herbivorous moths and butterflies and their parasitoids of Northeast Greenland. When monitored over time, the baseline web constructed now will allow us to discriminate the effects of environmental change in the High Arctic.

Table 6.1 Summary statistics on larval material collected in 2010. For each species, we show the number of larvae collected per each of five different methods, the total number of larvae collected (N_i), the number of detectably parasitized larvae (P_i) and the resulting gross parasitism rate ($100*P_i/N_i$).

	Larvae collected per method							
Species	**Visual search**	**Stone turning**	**Pitfall**	**Sweep netting**	**With food**	**Total collected**	**Parasitized**	**Gross parasitism (%)**
Apamea zeta	1	4	5	0	0	10	2	20.0
Boloria spp.	8	1	43	3	1	56	17	30.4
Entephria cf. *byssata*	1	0	0	0	0	1	0	0.0
Entephria polata	28	0	3	0	4	35	1	2.9
Euxoa drewseni	3	0	2	0	0	5	1	20.0
Gynaephora groenlandica	124	1	0	2	0	127	19	15.0
Microlepidoptera sp.	0	1	0	0	0	1	0	0.0
Noctuidae sp.	0	1	0	0	0	1	1	100.0
Polia richardsoni	10	4	16	2	0	32	1	3.1
Pyla fusca	2	0	1	0	0	3	0	0.0
Sympistis nigrita	113	0	7	0	27	147	29	19.7
Syngrapha parilis	3	0	1	7	0	11	3	27.3
Total	**293**	**12**	**78**	**14**	**32**	**429**	**74**	

Work at Zackenberg was initiated in 2009. As a key initiative for 2010, we described the phenology of the target species during the early summer. Thus, we started our sampling at snow melt (5 June, when snow cover in the plateau area was still >90 %) and continued to 5 July (for the timing of sampling in 2009, see Roslin & Várkonyi 2010). A second initiative implemented for the first time in 2010 was live trapping of lepidopteran larvae by pitfalls. As in 2009, we also collected samples by sweep netting, visual searching and turning of stones. Adult insects were sampled by operating six Malaise traps for the duration of our stay.

The pitfall traps proved highly efficient in collecting additional larvae for rearing. Altogether, we collected 429 lepidopteran larvae of eleven species, one-fifth of which was obtained by pitfalls (table 6.1). All the larvae collected are subsequently reared in the laboratory until the adult lepidopteran or parasitoid emerges or the larva dies. Importantly, many species of Arctic Lepidoptera spend multiple years as larvae before emerging, and consequently, a large fraction of the larvae collected in 2010 are still being reared at the time of writing (March 2011). The results presented here are therefore only preliminary. So far, 74 (17 %) of the 429 larvae have turned out to have been parasitized, a figure comparable to 2009 (see Roslin & Várkonyi 2010).

Our sampling yielded a comprehensive description of the early-season phenology of the lepidopteran community. With progressing snow melt, increasing temperatures and developing vegetation, different species of lepidopteran larvae began appearing in a clear-cut sequence (figure 6.11). Leaf-feeding species including *Gynaephora groenlandica* and *Polia richardsoni* were the first to appear (compare figures 6.11 and 6.12). In contrast, *Sympistis nigrita* emerged relatively late, since the availability of food for this species is determined by the flowering of *Dryas*. The latest macrolepidopteran larvae to appear were those of *Syngrapha parilis*. Interestingly, the incidence of parasitism within species did not vary detectably with time (figure 6.11). This suggests that the parasitic wasps of the region initiate their activity at the same time as their hosts and/or that many caterpillars become parasitized prior to winter diapause. These results will be instrumental both in understanding the temporal dynamics of the local insect community and in defining the optimal sampling period for field seasons to come.

Our sampling methods so far have been strictly focused on specific sources of host mortality, i.e. parasitism by wasps and flies. To compare mortality attributable to these factors to mortality incurred by bird predation and by abiotic conditions, we will next conduct specific experiments. As another methodological invention, we will also examine the potential for bypassing laborious rearings by recent molecular techniques specifically tailored to dissecting trophic interactions.

Figure 6.11General phenology and parasitism status of the most commonly collected lepidopteran larvae. Each data point represents an individual larva of a species. Larvae highlighted in blue were found to be parasitized whereas larvae highlighted in light blue were not detectably parasitized. Data points are jittered vertically to lessen overlap. "Boloria spp." encompasses two species, B. chariclea *and* B. polaris, *which we so far are unable to separate as larvae.*

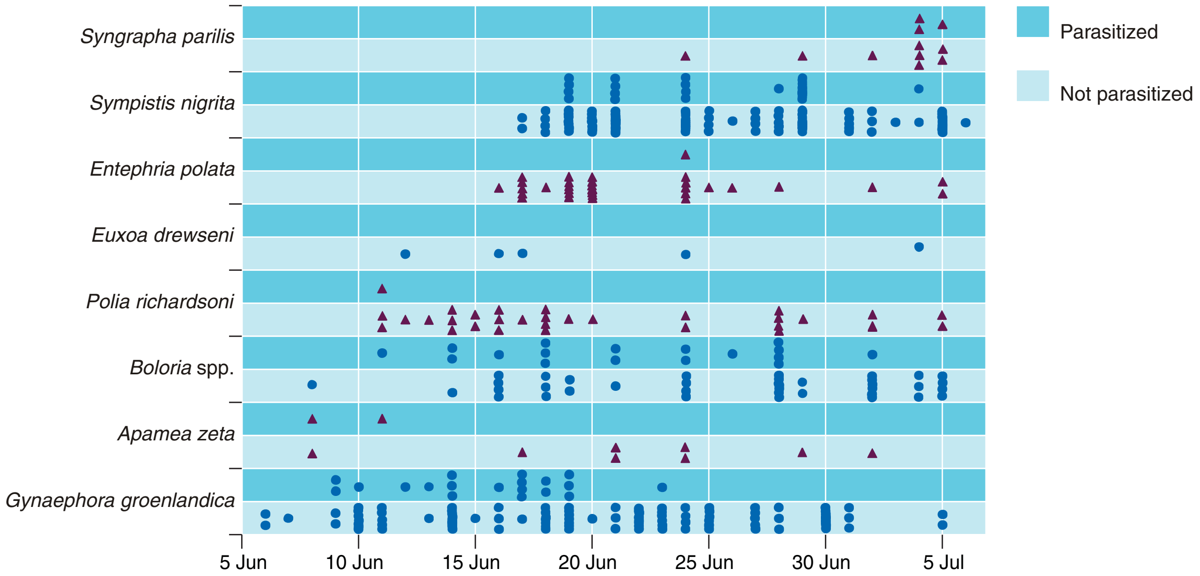


Figure 6.12 Larvae and diet of some macrolepidopteran species occurring in the Zackenberg Valley. A) Full-grown Entephria polata *larvae feed exclusively on* Dryas *flowers. B) Mid-instar* Sympistis nigrita *larvae confine their diet on the carpels and stamina of* Dryas*. C) Full-grown* Polia richardsoni *larvae are highly polyphagous but* Dryas *flowers represent an important food source. D) A single larva of* Entephria cf. byssata *was observed to feed on* Salix arctica *leaves. E) Larvae of* Gynaephora groenlandica *also feed on* Salix arctica*. F) Larvae of two species of* Boloria *fritillary have a mixed diet. Photos: Gergely Várkonyi.*

6.10 Arctic char in Zackenberg – growth and climate response

Anders Birk Nielsen and Kirsten S. Christoffersen

Arctic char (*Salvelinus alpinus* L.) is one of the few freshwater fish species in the high-Arctic regions. It has a circumpolar distribution and occurs frequently in several co-existing forms (Klemetsen et al. 2006). This is also the case in the Zackenberg area (Riget et al. 2000). Arctic char are found in lakes with water depths of more than approximately 5 m, which prevent the lake from freezing solid and the water column to become oxygen depleted during winter. Deeper lakes i.e., depths of more than 20 m, is most optimal for char because of better food sources, lower temperature and better oxygen conditions.

Arctic char are typically anadromous, i.e., migrate from freshwater to the sea to exploit more rich food sources during summer and then migrate back to the lake through rivers to spawn. Some populations are landlocked and remain in freshwater throughout their entire life. In landlocked populations, dwarf forms of 10-20 cm as adults are common especially in small lakes where competition is high and resources are few. As a result, these individuals mature at just 12 cm in length. The degree of parasitism is highly dependent on the migrational pattern with anadromous fish having much less parasites than the landlocked populations. Arctic char are opportunistic feeders, capable of consuming many different food sources of both vertebrate and invertebrate origin including amphipoda, sculpins, crustaceans, sea stars and even smaller Arctic char.

Generally, however, little is known about char population dynamics in Greenland lakes. In the Zackenberg area, the process of adaptation has been going on since the last period of deglaciation (some 6000 years ago). Thus, Arctic char is present in the area in a variety of different morphs, spanning from landlocked dwarf forms in some of the shallow lakes in Morænebakkerne to resident and migratory populations in the larger water bodies, such as Store Sø, in the adjacent Store Sødal. The Arctic char population in Store Sødal has generally received little attention, but investigations by Riget et al. 2000 clearly identified functional morphological groups consisting of littoral, pelagic, cannibalistic and seagoing forms. Any profoundly morphs remains to be discovered.

Figure 6.13 The centre of the otolith originates from the larval stage, while the black and white bands originate from winter and summer growth seasons, respectively. Photo: Anders B. Nielsen.

The anadromous Arctic char originating from Store Sø perform their migratory behaviour by passing through Zackenbergelven as soon as possible following ice break up in late May or early June. By undertaking this journey, the Arctic char benefit from the valuable foraging options in Zackenbergelven delta and the marine area of Tyrolerfjord for a period of approximately 60 days.

The fish perform the upstream migration from mid to late August, before low water levels and subsequent freezing closes the migratory window to Store Sø. Successful migratory Arctic char will spend their obtained energetic reserves on fall spawning and winter survival, until the next ice break up event in spring (Klemetsen et al. 2003).

To obtain more knowledge about the migratory fish population from Store Sø we performed a field campaign during late August. The specific purposes of the project were to investigate the present condition and retrospective somatic growth rate, through sagital otolith digital photo analysis (figure 6.13) and subsequent back calculated fork lengths of the sampled fish (figure 6.14). Relationships between otolith seasonal growth increments and the experienced environmental conditions by Arctic char populations are well-established (Kristensen et al. 2006). Based on data from the Zackenberg Bio- and GeoBasis programmes it was possible to evaluate the role of climate parameters on somatic growth rates of Arctic char.

Figure 6.14 Immature anadromous Arctic char with distinct black markings on the back. The characteristic slim form and interiorly placed mouth implies pelagic adaptation. Photo: Anders B. Nielsen.

Fieldwork

The fieldwork was conducted in Zackenbergelven from 26-30 August, approximately 100-400 m downstream from the Zackenberg station. Standard Nordic gill nets with multiple mesh sizes were used for sampling. The nets were placed across the river and were supervised frequently over the sampling periods. Approximately 20 fish was caught and 11 of these fish were further analyzed for fork length, weight and colour as well as sampled for tissue, otoliths, fin rays, scales and whole stomachs with contents. Collected tissue samples were used in studies of mercury levels, stabile isotopes and mtDNA for clarifications on genetic origin of the Arctic char population in Zackenbergelven.

Results and preliminary conclusions

All fish caught was aged using sagital otoliths, with resulting ages of the fish ranging from 4-8 years. None of the sampled fish had yet reached gonadal maturity and close to 75% where female. This corresponds well to proposed theories, that Arctic char females receive greater benefits in undergoing migration than males. Parasitation was moderate to low as expected, as most parasites are lost during the marine occupation. Some of the fish had limited fat reserves, which indicated that they had not had excessive food recourses available (contrary to what was expected).

The stomach contents were mainly consisting of chironomid larvae, pupae and imago's, with a species composition in favour of cold stenothermal habitats. A single fish had ingested fish fry. This showed that the recent feeding activity was performed in the river, probably as the fish were on their way back to the lake. Despite the sampling site was near the organic wastewater runoff from the station, no remnants of human food or activity were found in the stomachs of the Arctic char.

Initial analysis of the calculated fork lengths showed an accelerated growth rate for the youngest fish (figure 6.15). The estimated growth rates have all been subtracted ontogenetic age and fork length related growth effects (Kristensen et al. 2006).

We seem to be able to detect responses of the fish to climate variations as the obtained growth rates of the Arctic char subpopulation are correlated to precipitation. It appears that the fish better growth performance during years with increased snow and rain. By adding several other climatic parameters and using multiple linear regressions we find positive effects of early ice break-up date and cooler water temperatures.

Further analyses of samples and data are ongoing and no overall conclusions can be made at this stage. However, it is clear from the results of the project that incorporation of data from otoliths as ecological biomarkers has a great potential and operational use in a high-Arctic monitoring locality such as Zackenberg. With some specimens of Arctic char being up to 30 years of age, it is obvious that sampling for relatively few individuals can create retrospective data series to be correlated with the entire Zackenberg Basic monitoring programmes.

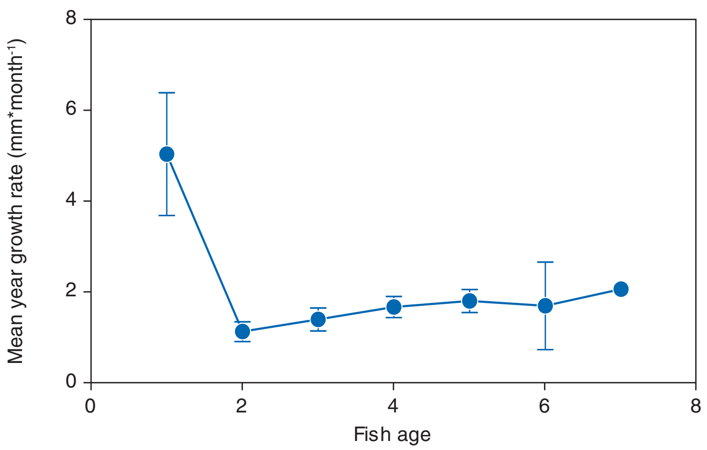


*Figure 6.15 Age specific growth rate of sampled anadromous Arctic char (*Salvelinus alpinus*), August 2010. The error bars represent the standard deviation of the mean (N = 11).*

6.11 MANA project

Philippe Bonnet, Kirsten Christoffersen and Marcus Chang

The MANA project is a collaboration of the IT University of Copenhagen, the Biology departments at University of Copenhagen, the School of Computing at Reykjavik University, Arch Rock Corporation, a company based in San Francisco that provides wireless sensor networks systems, and Dan-System a Small Danish Enterprise, specializing in technical solutions for niche markets.

The overall goal of the MANA project is to improve scientific data acquisition in remote, harsh environments, e.g., polar regions, deep-sea locations, or other planets.

Such environments are all hard to access by humans, and provide limited communication bandwidth. As a result, manual measurements are costly, manually tapped data loggers are unreliable, and remote supervised control is impractical. We aim at enhancing sensors and data loggers with computation and communication capabilities so that we can programme them to be reliable and autonomous. We plan to develop sensor network-based data loggers that check the data they collect and correlate measurements in time and space, and autonomously adapt their sampling strategy in order to optimize data quality as well as resource utilization.

We focus on the monitoring of limnic parameters in the Zackenberg region, North-East Greenland. The goal is to document the effects of climate change on lake environments, in particular in the winter season that has been neglected so far because of logistics constraints. Our data loggers promise to introduce a remarkable progress in terms of temporal resolution with respect to the manual measurements that have been carried out a couple of times a year since 1996.

The MANA project started on February 1st 2008. We installed the Capoh system composed of a buoy and a base station in August and October 2008, maintained it in August 2009. The status as of August 2010 is the following:

- The base station has been operating for the complete year, despite some hardware problems. This is a major improvement compared to the previous year.
- The Water Quality Monitor (WQM) sensor embedded in the buoy only operated for a month and then stopped taking measurements because of too low battery level. In addition, the connection between the WQM and the buoy electronics components seems to cause a problem. Both problems (too rapid energy depletion and flawed connection) are most likely linked. We will use a WQM in our lab and reproduce the Capoh system to isolate the problem. We reprogrammed the electronics on the buoy, changed the battery and we expect a better energy efficiency.
- The measurements obtained from the WQM show, as expected, a diurnal pattern for chlorophyll production.
- We installed a wireless link between the base station at the lake and House 6 in Zackenberg. From May to October, the base station should be accessible from a laptop connecting to the "MANA" wireless network at Zackenberg.

6.12 The occurrence of uni- and biparental incubation by sanderlings *Calidris alba*

Jeroen Reneerkens

The reproductive investment of both sexes in sandpipers (Scolopacidae) can vary substantially between and within species.

Sanderling incubate their clutches either uni- or biparental as suggested by frequent nest visits during which only one or two attending parents were observed (Tomkovich and Soloviev 2001, Reneerkens et al. 2011). The existence of both strategies has now been confirmed with data loggers by Reneerkens et al. 2011 who also showed that uniparentals invest more in incubation than biparentals. To understand why uniparental sanderlings invest more than biparentals, we should understand the potential benefits of uniparental incubation that outweigh these costs. If uniparental incubation is the result of a double-clutching breeding system (as suggested by Parmelee and Payne 1973), the advantage could be twice as large (chance of) reproductive success in a given breeding season. This benefit might, however, not be equally large for uniparental males and females, if extra-pair fertilizations occur and/or females produce the second clutch, which is being fertilised and maybe even incubated by a second male than her first clutch. Clearly, we still need more

Table 6.2 The occurrence of uni- and biparental clutches and the total number of sanderling clutches found in four successive summers (2007-2010) in Zackenberg.

Year	Uni	Bi	% uni-parental	Total number of clutches
2007	5	22	27	51
2008	9	15	43	39
2009	11	21	34	63
2010	6	6	50	33

insight into the breeding system of sanderlings, which can now be gained through the recent development of variable microsatellite primer sets that allow reliable parentage analysis (Luttikhuizen et al. in press).

Here, we report the occurrence of uni- and biparental incubation in Zackenberg in the breeding seasons of 2007-2010. Whether clutches were incubated by one ('uniparental') or two ('biparental') sanderlings was deduced by careful study of temperature profiles between the eggs. Because uniparentals exhibit a significantly higher recess frequency compared to biparentals such temperature profiles reliably reveal the number of attending adult birds on a nest (see Reneerkens et al. 2011 for a careful description of the method). This method was sometimes backed-up with observations of both a male and a female incubating at a given clutch. The frequency of observed uni- and biparental incubation in sanderlings in the different breeding seasons is depicted in table 6.2.

If double clutching would occur equally often as pairs in which incubation duties are shared between both male and female, two-third (66 %) of the nests would be uniparental. This percentage was never reached in neither year (table 6.2) suggesting that double clutching may not be the cause of uniparental incubation. Interestingly, the only three clutches of which it was known with certainty that they were replacement clutches (second clutch within a season after the first had been preyed upon), were all incubated by a single male only. Indeed, the average (expected) hatching date of uniparentals was significantly later than the biparentals in all those years (two-tailed t-test, t=2.01, P=0.039). It could be that a female is more tempted to desert the second clutch after being forced to invest in a second complete clutch, which undoubtedly costs quite some energy. Desertion of females at replacement clutches can, however, not solely explain the existence of uniparental clutches, because 11 of the 31 (35 %) uniparental clutches were being incubated by females. Confirming the theory of double-clutching (Parmelee and Payne 1973), in which females start incubating their second laid clutch, uniparental clutches incubated by females had on average a six day later (expected) hatching date (two-tailed t-test assuming unequal variances, d.f.=20, t=2.33, p=0.03).

Figure 6.16 Sanderlings at Zackenberg 2010. Photo: Jeroen Reneerkens.

6.13 Walrus studies with a note on birds on Sandøen

Erik W. Born, Steen Bo Andersen, Sigga Joensen, Lars Øivind Knutsen, Maria Coryell-Martin and Liselotte W. Andersen

In late July and early August 2010, the Greenland Institute of Natural Resources, conducted walrus studies at Sandøen at the entrance to Young Sund (North-east Greenland). The purpose was to collect skin biopsies and deploy satellite transmitters on unrestrained walruses hauling out at Sandøen. The fieldwork was a part of a long-term study that aims to determine site fidelity and numbers of walruses in the Young Sund study area, as well as the range of walruses in North-east Greenland during the open water season. Staff from the National Environmental Research Institute at Aarhus University participated for part of the period in order to retrieve data loggers deployed in previous years on common eiders *Somateria mollissima* at Daneborg, and on Arctic terns *Sterna paradisaea* and Sabine´s gulls *Larus sabini* at Sandøen.

Walrus studies

A few days before the beginning of the walrus study on Sandøen there had been strong winds with rain and snow in the Young Sund area. Therefore, the Sandøen walrus haul-out was deserted 20 and 21 July. During the period (22 July-7 August) when studies were conducted on Sandøen it was generally fair weather (mainly 1-2 m/sec easterly wind, sky clear and plus centigrade temperatures; however, a few days had 5-8 m/sec easterly wind and fog). The daily maximum count of walruses at the haul-out on the north-western beach of Sandøen (haul-out position: 74° 16′ 00.3 N, 20° 09′ 17.0 W) averaged 23.2 individuals (sd= 10.7, range: 1-41 walruses, n=14 days with observations) with no significant trend in daily maximum counts during the period between 22 July and 7 August (r^2=0.071, z = -0.902, p=0.367, n=14). The highest number was seen 31 July. Based on the shape and size of body and head, tusk dimensions, and the presence or absence of skin tubercles the majority of walruses at Sandøen were determined to be males. However, on several days, a group of two adult females with young occurred in the herd. During two systematic sampling sessions, 103 skin biopsies were collected from the group of walruses that hauled out on the island (figure 6.17). In each case, a ca. 0.5 g skin sample was taken by use of a sharp ca. 4 cm long and 4 mm wide hollow stainless steel tip (Ceta-Dart, Aarhus, Denmark) mounted on a dart shot from a Barnett Commando II Recur crossbow. The dart with the biopsy was retrieved via a thin fishing line attached to the crossbow. Distances at which samples were taken varied between approximately 10 and 25 m and the archer always lay down or sat downwind of the hauled out walruses. Biopsying caused minimal disturbance to the walruses and usually the walruses did not react to the impact of the dart. If they did, they raised their head shortly; in no cases did they move into the water. The skin biopsies are being analyzed at the Department of Wildlife Ecology and Biodiversity, Aarhus University, using 17 microsatellite markers for determination of individual identity. Site fidelity and trends in local population size will be determined by comparing genetic information from the 2010-samples with similar data obtained from samples taken on Sandøen in 2002, 2003 and 2004.

On 6 August, a helicopter reconnaissance was made along the beach of southern Shannon Island (ca. 75 °N). In 2009, walruses had been detected on the beach of SW Shannon. The purpose was to find walruses in order to obtain biopsies and deploy satellite transmitters in this area. However, no walruses or signs of walrus activity (i.e. drag marks

Figure 6.17 Skin biopsies were taken by use of a crossbow. Photo: Erik W. Born.

Figure 6.18 Minute (60 g) satellite transmitters (arrows) on two male walruses on Sandøen. Five SPOT-5 satellite tags were deployed on male walruses on 7 August 2010. Photo: Erik W. Born.

on the beach) were observed indicating that walruses had not used this stretch of the coast for hauling out 2010. Hence, five SPOT-5 matchbox satellite transmitters (Wildlife Computers, Remond, WA, USA) were deployed on the skin of five adult male walruses that hauled out on Sandøen 7 August. The transmitters that were deployed by use of a CO_2-gun were all attached mid-dorsally (figure 6.18). The transmitters lasted between 4 and 68 days (mean 36 d, sd=23.1, n=5). Relocations indicated that the instrumented walruses used Young Sund, Sabine Island, Shannon, Hochstetter Forland and Dove Bay areas during August-October (figure 6.19).

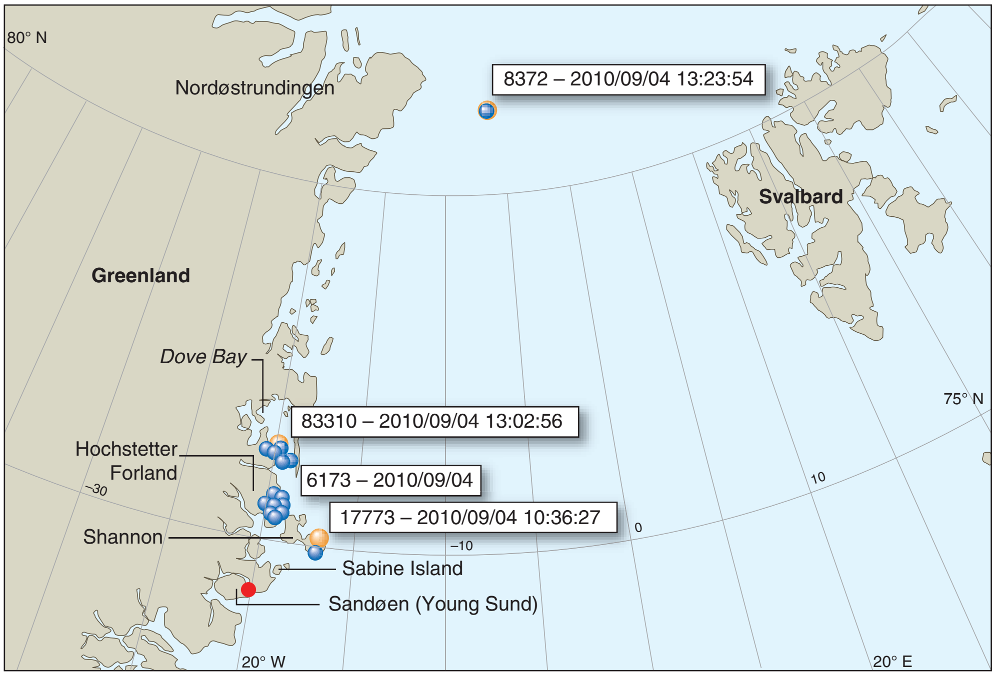


Figure 6.19 Locations received 4 September 2010 from four walruses instrumented with satellite transmitters at Sandøen 7 August 2010 (a fifth transmitters stopped 10 August).

However, one walrus moved in a directed manner as far north as the Northeast Water Polynya area at Nordøst-rundingen (ca. 81 °N) where transmissions stopped 12 September (figure 6.19). The last transmission was received 20 October from a walrus that had returned to the Young Sund area. Hence, the 2010 tracking study confirmed previous studies that walruses that use the Sandøen haul-out have a wide geographi-cal range in NE Greenland during the open water season.

Bird studies

Despite intensive observations during 20-21 July data loggers were not detected on any of the common eiders that nested at Daneborg. During 22 July-7 August regular observations were made of Sabine's gulls, Arctic tern and common eider on Sandøen in order to detect any individual that potentially still had an attached data logger deployed in 2007 and 2008. One Arctic tern was detected with a data logger. However, although Arctic tern courtship display was observed neither this species nor Sabine's gulls was nesting while we were on Sandøen. Therefore, it was not possible to retrieve the data logger. Apparently, relatively late break-up of the fjord ice in Young Sund delayed and prevented Arctic terns and Sabine's gull from breeding at Sandøen in 2010.

6.14 The German operation Bassgeiger on Shannon Island 1943/44: The "Battle of Weather" 2010

Jens Fog Jensen, Tilo Krause, Bjarne Grønnow and Morten Hjorth

Soon after the outbreak of World War II, the axis powers were denied access to data from international weather stations under allied control. Germany thus had to establish her own network of manned and automatic weather stations throughout the north Atlantic. These operations were primarily run by the Kriegsmarine and the Luftwaffe. In Greenland, several manned weather stations were established by the former. The two most successful of those were Holzauge and Bassgeiger in northeast Greenland, each in operation for almost an entire year in 1942-1943 and 1943-1944 respectively. The allied forces, in return, had established the North-East Greenland Sledge Patrol in 1941, in order to defend the northeast Greenland coast against German activities. In 2007 and 2008, archaeologists and historians from the National Museum of Denmark investigated the remains of the allied station at Eskimonæs on Clavering Island and the German station Holzauge at Hansa Bugt on Sabine Island (Jensen and Rasch 2009; Jensen and Krause 2009a, 2009b, 2011).

Fieldwork on Kap Sussi 2010

Our three men expedition visited the former German station on Cape Sussi in August 2010 with the following three purposes: a) The location of all facilities on site, b) Precision measurement of the natural topography and all localized installations c) Description and photo documentation of all sites and selected objects. During 10 intensive days in the field, all three tasks where honoured with the following result: In addition to the three distinctive structures of 1) Lieutenant Zachers grave, 2) the radio hut, and the snow drift with the "cave city" – we localized 21 features on site, including defence structures, several hidden depots and waste heaps. The total number of registered objects is well above 900. The site offer good conditions for preservation of organic material, since many objects have been buried in the collapsed snowdrift, where the German expedition dug out and hided their over wintering station after their ship had become stuck and grinded in the off shore drift ice.

The snowdrift where most of the German weather station was hidden has melted considerably (figure 6.20). The front parts of the "cave city" where many well-preserved objects are seen have thus become exposed to archaeological inquiry as well as looting and degradation by wind and light. The well-preserved books and clothing, which was registered in 2010 after 60 years of "waiting" below the snow will probably soon decompose and vanish. The conservation aspect is also relevant when considering the increased accessibility because of the depleting drift ice, which already has resulted in increased traffic in the area by cruise ships. Souvenir hunters and trampling can soon deplete the "untouched" character of historical monuments in Northeast Greenland. Historical photographs thus clearly indicate that for example lieutenant Zachers grave at Kap Sussy already show

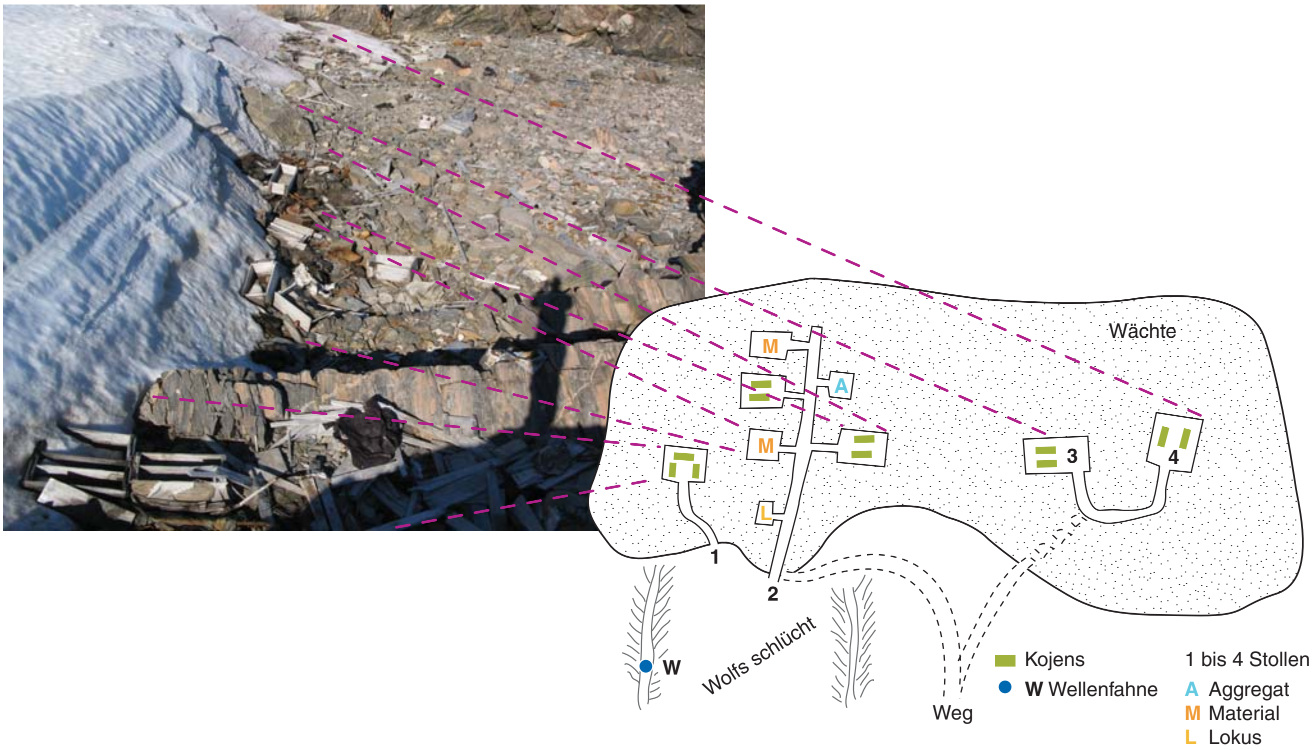


Figure 6.20 Snowdrift at Cape Sussi, where the German 'Unternehmen Bassgeiger' dug their makeshift headquarters of 1943/44. The remnants of the front part of the 'cave city' are visible along the edge of the snowdrift. To the right is the expedition leader's hand-drawn map of the dug quarters from January 1944. The drawing corresponds well with the remains seen today. Photo: Morten Hjorth. Archive: Arctic Institute.

signs of having been disturbed. Finally, it should be mentioned that not all objects are harmless to the interested visitor: At least 15 unexploded hand grenades and an even greater number of rifle grenades where thus registered adjacent to the structures.

In the course of climate changes, the formerly remote and generally inaccessible arctic regions are currently becoming more and more accessible. Simultaneously, the natural conditions, which hitherto secured the objects' preservation, such as the annual coverage by snow and ice, are in obvious retreat. The detailed mapping of the Eskimonæs and Hansa Bugt in 2008 and the mapping of Kap Sussi in 2010 has recorded the objects' status in this process, thus providing a professional basis for future efforts in the preservation of those exceptional relics from the weather war in the Arctic. We therefore hope that this initial historical-archaeological project will be helpful in future assessments of Greenland's historical remnants and their speed of deterioration, thus enabling specific measurements to be taken for their protection and for the heritage interpretation, similar to some of the measurements already taken on historical monuments in Svalbard (Bjerck and Johannesen 1999) and Antarctica (Roura 2009).

6.15 Shooting underwater images of a walrus in Young Sund for National Geographic

Magnus Elander

Up until last summer (2010), Swedish photographer Göran Ehlmé was alone in the world to have captured images of walruses feeding on the ocean floor. One particularly stunning picture called "Beast of the sediments" became the overall winner in BBC's "Wildlife Photographer of the Year" prestigious competition in 2006. This image left the editors at National Geographic Magazine in Washington with no peace.

Then they decided to give an assignment to Paul Nicklen, one of National Geographic's top photographers. Paul im-

Figure 6.21 In shallow water, photographer Paul Nicklen uses a 'pole-cam' to get close to his target and still keep a safety distance. Photo: Magnus Elander.

mediately contracted Göran Ehlmé to join as a supervisor and dive support. Göran in turn asked Magnus Elander, another Swedish photographer, to support the expedition to gather as much expertise as possible into the Zodiac. And then Washington decided to send Nathan Williamson, an experienced videographer, to make a 30 minutes behind-the-scene film for National Geographic Channel covering this major effort to shoot (at least) one single picture for the magazine.

When our four-member expedition arrived by Twin Otter to Daneborg 20 July, three weeks of hard work lay ahead. Thanks to the generous support from the MarineBasis team based in the boathouse in Daneborg, a Nanok team at Sandodden, and Erik W. Born and his team of walrus scientists on Sandøen, we were able to pitch our tent camp, get our Zodiac on the water, fill the dive tanks and get going in very short time.

Wildlife photography in general requires a lot of patience. Underwater wildlife photography is even more demanding. In addition, add extremely unpredictable animals like walruses, plus often-poor visibility in the seawater, and ocean temperatures around freezing to understand that the whole operation was a big gamble.

Although we were out on the fjord long hours every day, the efforts initially gave very poor results. However, perseverance does it. Twenty days in the Zodiac, more than 100 dives at depths between 10 and 30 meters plus a few days working in shallow water near Sandøen afforded a nice collection of unique walrus shots on Paul's memory cards in the camera (figure 6.21).

7 Disturbances in the study area

Jannik Hansen

This account covers the period from 4 May to 3 November 2010. For more details about the opening of the station and the operations see chapter 8.

Surface activities in the study area

May–August: The number of "person-days" (one person in the field one day) spent within the main research area, zone 1 was 70 (table 7.1), which is more than usual. This area is open to research, and more activity in this area is expected. The "low impact area" 1b was visited at a usual level. The "goose protection area", zone 1c, was visited only on very few occasions, during the closed period (20 June–10 August).

This season, the use of the all terrain vehicle (ATV) was mainly along the designated roads to the climate station and the beach at the delta of Zackenbergelven. Three trips in May and four in August were the only ones off the designated road system. However, the use of the ATV at and near the station has become higher since 2007, remaining at this higher level.

During the early part of the season, snowmobiles were used for longer transportation. This year, snowmobiles were used six times in May.

Table 7.1 'Person-days' and trips in the terrain with an All Terrain Vehicle (ATV) allocated to the research zones in the Zackenberg study area May –August 2009. 1c, the 'Goose Protection Area' is closed for human traffic from 20 June to 10 August (DOY: 171-222). Trips on roads to the climate station and the delta of Zackenbergelven are not included.

Research zone	May	June	July	Aug	Total
1	18	12	32	8	70
1b	1	5	11	15	32
1c (20 Jun-10 Aug)	0	2	1	0	3
2	15	2	2	3	22
ATV-trips	3	0	0	4	7

Aircraft activities in the study area

In 2010, the station had 50 fixed-wing aircraft visits and five helicopter visits. See chapter 8 for details. Building material was flown in, accounting for the high number of flights

Only once did the arrival of aircrafts make the waterfowl fly up from the lakes, ponds and fens nearby.

Discharges

Water closets were in use from late May onwards, facilitated by frost preventing equipment in the house of residence. From here, all toilet waste was ground in an electrical mill and led into the river.

Likewise, solid, biodegradable kitchen waste was run through a grinder mill, and into the river. The mill was in use until the end of the season.

Fly maggot killing agents are no longer used for the waste.

The total amount of untreated wastewater (from kitchen, showers, sinks and laundry machine) equalled approximately 1852 "person-days", which is more than average. The gradual phase-out of perfumed and non-biodegradable detergent, soap, dishwashing liquid etc. is continuing. More environmentally friendly products are substituting the former.

Combustible waste (paper, cardboard, wood etc.) was burned at the station. For management of other waste see chapter 8.

Manipulative research projects

From mid-June to the end of August, manipulation with UV-filters were continued at the site established in 2007 for BioBasis monitoring, and chlorophyll fluorescence measurements were conducted medio to ultimo July (see chapter 4).

For the seventh season, shade, snow melt and temperature was manipulated at two sites, each with 25 plots, - UTM zone 27: 8264733 N, 513460 E and 8264984 N, 513717 E. For a nitrogen fixation study, these plots (within a central frame) under-went acetylene reduction assays. Fifteen circular plots with a diameter of 10 cm with vegetation and the underlying soil to a depth of approximately 5 cm were subjected to $^{15}N_2$ air and harvested (including 2 cm top soil) after two days and three weeks, respectively (see below and see section 6.4).

Take of organisms and other samples

For GeoBasis, five soil samples were taken for mercury content studies (chapter 2). Sites are registered with BioBasis Zackenberg.

Tens of thousands of land arthropods were collected during the season, as part of the BioBasis programme (see section 4.4). Unfortunately, the box has been delayed in the transport, which means that the total number is yet unknown. The total trapping effort amounted to 3048 trap days and approximately 440 samples were collected. The total number of arthropods will be published in the 2011 ZERO Annual Report.

Twenty-four blood samples of approximately 80 µl were collected from adult and 40 of 10 µl of chicks of sanderlings *Calidris alba* for a parentage and breeding strategy study. The same project also collected approximately 2500 arthropods in pitfall traps at stations at different altitudes. The locations of these pitfalls were the same as in 2007-2009 (section 6.12). Sites are registered with BioBasis Zackenberg.

Tissue samples were collected from six musk oxen *Ovibos moschatus* (from carcasses), one gyr falcon *Falco rusticolus*, one seal Pinnipedia sp., six Arctic char *Salvelinus alpinus* and six three-spined stickleback *Gasterosteus aculeatus* (from carcasses) for a BioBasis DNA bank.

Approximately 70 faecal samples from Arctic fox were collected for a parasite survey (section 4.5).

For an arctic char *Salvelinus alpinus* project, 11 presmolt arctic chars were caught in Zackenbergelven and one dwarf form of arctic char was caught in Langemandssø (section 6.10).

For the "High Arctic food web", approximately 10,500 arthropods (mainly midges) insects were caught in six malaise traps. The traps were placed at Malaise 1: 0512682 E, 8264293 N; Malaise 2: 0512642 E, 8264315 N; Malaise 3: 0513735 E, 8265412 N; Malaise 5: 0513786 E, 8265758 N; Malaise 7: 0512062 E, 8264014 N; Malaise 8: 0512420 E, 8263480 N (see section 6.9). The project also caught 79 lepidopteran larvae in five live-trapping pitfall traps at four locations: PF-1/PF-2: 0512755, 8264260; PF-3: 0512417, 8263482; PF-4: 0512573, 8264107; PF-5: 0512423, 8264089. All other caught arthropods were released unharmed.

The Ecological Network project collected 942 arthropods (Diptera, Hymenoptera, Lepidoptera and Heteroptera) in a 500 m × 500 m area south of the research station (section 6.8). The precise extend of the area is registered with BioBasis Zackenberg.

For an arctic willow study and arctic bell-heather project, root collars and stems of 30 arctic willows *Salix arctica* were harvested. Roots of each individual plant were left at the collection site. Furthermore, 30 female catkins and 56 individuals of arctic willow *Salix arctica* were collected at four sites. At one site, two individuals of *Melandrium trifolium*, one Potentilla sp., one arctic poppy *Papaver radicatum*, and one arctic mouse-ear *Cerastium arcticum* were collected. At one site, five arctic blueberry *Vaccinium uliginosum* were collected. At three sites, six *Dryas* sp. was collected. In addition, at one site, 12 arctic bell-heather *Cassiope tetragona* were collected (section 6.5). Sites are registered with BioBasis Zackenberg.

For the CryoCARB project, between 15-21 soil cores (Ø 42mm, ~70 cm deep (~30 cm into the permafrost)) were taken at three sites (2-3 at each site): ZKA: 0513986, 8265870; ZKB: 0513974, 8265865; ZKC: 0513996, 8265872; ZKD: 0513881, 8265682; ZKE: 0513241, 8265674; ZKF: 0513243, 8265687; ZKG: 0513578, 8263694; ZKH: 0513563, 8263706; ZKI: 0513587, 8263702.

For a nitrogen fixation study, 20 plants in circular samples of Ø = 5 cm of the top 2 cm of soil and 15 plants in circular samples of Ø = 10 cm of top 2 cm of soil were collected (see section 6.4). Sites are registered with BioBasis Zackenberg.

8 Logistics

Henrik Spanggård Munch and Lillian Magelund Jensen

8.1 Use of the station

In 2010, the field season at Zackenberg Research Station was from 4 May to 2 November, in total 185 days. During this period, 73 scientists visited station. Of the 73 visiting scientists, 16 stayed at Daneborg. They were serviced by 10 logisticians employed by the National Research Institute at Aarhus University and stationed at Zackenberg during different parts of the field season. Besides that, Zackenberg Research Station received visits from

- The Danish Ministry of Climate and Energy, Aarhus University and Greenland Climate Research Centre.
- Four construction workers, while building the new storage.

The total number of bed nights during 2010 was 1869. 406 of the bed nights were spend at Daneborg. Of the 1869 bed nights, 301 were related to logistics during the field season, 18 were related to VIP delegation, and 12 were related to the construction workers.

During the season, the station was visited by person's from 12 different countries: Finland, Austria, Greenland, Sweden, Canada, Chile, Italy, Switzerland, Russia, USA, Netherland and Denmark.

8.2 Transportation

During the field season, fixed winged aircrafts (DeHaviland DHC-6 Twin Otter) landed 50 times at Zackenberg. Of the 50 landings, 26 landings were related to transport of cargo, and building material for the new storage at Zackenberg.

Five helicopter (AS 350) landings took place at Zackenberg. Of the five landings, two were related to the VIP visit and three were related to building of the new storage.

8.3 Maintenance

During 2010, the following construction and maintenance was carried out at the station:

- A new storage was built. The storage will be used by the monitoring programmes and by the logistics.
- Set up of a special drum press to minimize empty fuel drums and garbage from the station.

The maintenance condition of the station is very good. Besides the normal painting of the houses, we do not expect larger maintenance costs during the next years to come.

8.4 Handling of garbage

The non-burnable waste was packed in empty fuel drums and removed from the station by aircraft to Daneborg on the empty return flights during the fuel lifts from Daneborg to Zackenberg and from there by ship to Denmark. Fifty drums of waste were removed from the station.

8.5 Polar bear

The station was visited by one young polar bear in October 2010. The station has a contingency plan for polar bear situations. This plan was evaluated and updated in 2010.

A researcher, working at Clavering Island, was attacked by a polar bear in August 2010. The researcher sustained several bites and was treated by the Sirius Patrol before being evacuated to a hospital in Iceland. The researcher did not suffer permanent injuries from the polar bear attack.

The polar bear (a two-year old male) was shot and killed by a colleague of the researcher.

8.6 Weapon

The station has replaced the old rifles with Ruger Hark Eye 30-06.

8.7 Zackenberg at Daneborg

The new research house in Daneborg was ready for use 24 August. Contruction workers from Venslev Enterprises built the house during a four-week period, subsequently the interior of the house was finished by two logisticians from National Environmental Research Institute, Aarhus University.

The research house has been established with means generously funded by Aage V. Jensen Charity Foundation.

The research house can accommodate 10 scientists (in five double rooms) and has modern laboratory and storage facilities. The house contains a fully equipped kitchen, a living room with TV and stereo, toilet, shower and laundry facilities.

For information concerning booking and/or renting the research house for a specific period please contact the Zackenberg Secretariat (zackenberg@dmu.dk) at the Department of Bioscience, Aarhus University.

9 Personnel and visitors

Research Zackenberg

Claudia Baittinger, Research scientist, National Museum of Denmark, Denmark (Plant Ecology, 13 July-3 August)

Christian Bay, Research scientist, National Environmental Research Institute, Aarhus University, Denmark (BioBasis, 6 July-3 August)

Thomas Bjørneboe Gomes Berg, Research scientists, Naturama, Denmark (BioBasis, 13 July-6 August)

Jørgen Blytmann, Technician, Asiaq – Greenland Survey, Greenland (ClimateBasis, 10-17 August)

Noémie Boulanger-Lapointe, Research assistant, L'Université du Québec à Trois-Rivières, Québec, Canada (Plant Ecology, 13 July-3 August and BioBasis, 3-31 August)

Matteo Campioli, Research scientist, Research Group of Plant and Vegetation Ecology, University of Antwerp, Belgium (Plant Ecology, 27 July-10 August)

Marcus Chang, Research assistant, IT University, Copenhagen, Denmark (MANA, 17-31 August)

Martin Ulrich Christensen, Research assistant, National Environmental Research Institute, Aarhus University, Denmark (BioBasis, 18 May-5 June)

Torben R. Christensen, Research scientist, Department of Physical Geography and Ecosystems Analysis, Lund University, Sweden (Methane, 10-19 August)

Kirsten S. Christoffersen, Research scientist, Freshwater Biological Laboratory & Polar Science Centre, University of Copenhagen, Denmark (MANA and Limnology, 24-31 August)

Michele Citterio, GlacioBasis manager, Department of Marine Geology and Glaciology, Geological Survey of Denmark and Greenland, Denmark (GlacioBasis, 8-18 May)

Rasmus Egede, Technician, Asiaq – Greenland Survey, Greenland (ClimateBasis, 10-17 August)

Julie Maria Falk, Research assistant, National Environmental Research Institute, Aarhus University, Denmark (GeoBasis, 5 June-5 July and Plant-herbivore-soil, 6 July-10 August)

Mads C. Forchhammer, Research scientist, National Environmental Research Institute, Aarhus University, Denmark (Exclosures Zackenberg, 13 July-3 August)

Guisella Gacitua, Research assistant, National Environmental Research Institute, Aarhus University, Denmark (BioBasis, 10-31 August)

Jannik Hansen, Research assistant, National Environmental Research Institute, Aarhus University, Denmark (BioBasis, 5 June-17 August)

Lars Holst Hansen, Research assistant, National Environmental Research Institute, Aarhus University, Denmark (BioBasis 5 June-30 July and 31 August-3 November)

Christina Kaiser, Research scientist, Department of Chemical Ecology and Ecosystem Research, University of Vienna, Austria (Climate, 24-31 August)

Jan van der Kamp, Research assistant, Animal Ecology Group, University of Groningen, Netherland (Ornithology; 15 June-13 July)

Ditte Katrine Kristensen, Research assistant, National Environmental Research Institute, Aarhus University, Denmark (BioBasis, 6 July-3 August)

Magnus Lund, Research scientist, National Environmental Research Institute, Aarhus University, Denmark (GeoBasis, 4-21 May)

Horst Machguth, Research assistant, Department of Marine Geology and Glaciology, Geological Survey of Denmark and Greenland, Denmark (GlacioBasis, 8-18 May)

Thomas Marke, Research scientist, Institute of Geography and Regional Science, Karl-Franzens-University, Austria (Glaciology, 18-30 August)

Mikhail Mastepanov, Research scientist, Department of Physical Geography and Ecosystems Analysis, Lund University, Sweden (Methane, 10-18 August)

Jesper Bruun Mosbacher, Research assistant, Institute of Biology, Copenhagen University, Denmark (Flower observations and insect collecting, 6 July-24 August)

Anders Birk Nielsen, Research assistant, Freshwater Biological Laboratory & Polar Science Centre, University of Copenhagen, Denmark (Limnology, 24-31 August)

Claus Rasmussen, Research Scientist, Department of Biological Sciences, Aarhus University, Denmark (Flower observations and insect collecting, 1 June-27 July)
Jeroen Reneerkens, Research scientist, Animal Ecology Group, University of Groningen, Netherland (Ornithology, 15 June-13 July)
Andreas Richter, Research scientist, Department of Chemical Ecology and Ecosystem Research, University of Vienna, Austria (Climate, 24-31 August)
Tomas Roslin, Research scientist, Department of Agricultural Sciences, University of Helsinki, Finland (Insect community ecology, 5-15 June)
Niels Martin Schmidt, BioBasis manager, National Environmental Research Institute, Aarhus University, Denmark (BioBasis and Exclosures Zackenberg, 13 July-3 August)
Michelle Schollert Skovgaard, Research assistant, Department of Biology, University of Copenhagen, Denmark (BioBasis, 13 July-24 August)
Charlotte Sigsgaard, Research scientist, Department of Geography and Geology, University of Copenhagen, Denmark (GeoBasis, 4 May-5 June, 6-20 July and 30 August-3 November)
Kirstine Skov, Research assistant, Department of Geography and Geology, University of Copenhagen Denmark (GeoBasis, 5 July-30 August)
Ulrich Strasser, Research scientist, Institute of Geography and Regional Science, Karl-Franzens-University, Austria (Glaciology, 18-30 August)
Lena Ström, Research scientist, Department of Physical Geography and Ecosystems Analysis, Lund University, Sweden (Plant-herbivore-soil, 6-20 July)
Pernille Lærkedal Sørensen, Research scientist, Institute of Biology, University of Copenhagen, Denmark (Nitrogen fixation, 13 July-10 August)
Mikkel P. Tamstorf, GeoBasis manager, National Environmental Research Institute, Aarhus University, Denmark (GeoBasis, 4-21 May and 21 October-3 November)
Kisser Thorsøe, ClimateBasis manager, Asiaq – Greenland Survey, Greenland (ClimateBasis, 1-15 June)
Gergely Várkonyi, Research scientist, Finnish Environment Institute, Friendship Park Research Centre, Finland (Insect community ecology, 15 June-6 July)
Gernot Weyss, Research scientist, Department of Climatology, Central Institute for Meteorology and Geodynamics, Austria (Glaciology, 18-30 August)

Research Daneborg

Steen Bo Andersen, Research scientist, Greenland Institute of Natural Resources, Greenland (Walrus, 20 July-10 August)
Erik W. Born, Research scientist, Greenland Institute of Natural Resources, Greenland (Walrus, 20 July-10 August)
Maria Coryell-Martin, Research assistant, Greenland Institute of Natural Resources, Greenland (Walrus, 20 July-10 August)
Göran Ehlmé, Waterproof Diving International AB, Sweden (Underwater photography of walrus, 20 July-10 August)
Magnus Elander, Waterproof Diving International AB, Sweden (Underwater photography of walrus, 20 July-10 August)
Egon Frandsen, Technician, National Environmental Research Institute, Aarhus University, Denmark (MarineBasis, 27 July-17 August)
Bjarne Grønnow, Research scientist, National Museum of Denmark, Copenhagen, Denmark (Archaeology, 27 July-17 August)
Morten Hjort, Research scientist, National Environmental Research Institute, Aarhus University, Denmark (MarineBasis, 27 July-17 August)
Jens Fog Jensen, Research scientist, National Museum of Denmark, Copenhagen, Denmark (Archaeology, 27 July-31 August)
Sigga Joensen, Technician, National Environmental Research Institute, Aarhus University, Denmark (Walrus, 20 July-3 August)
Lars Øivind Knutsen, Research scientist, Greenland Institute of Natural Resources, Nuuk, Greenland (Walrus, 20 July-3 August)
Tilo Krause, Research assistant, National Museum of Denmark, Copenhagen, Denmark (Archaeology, 27 July-17 August)
Kunuk Lennert, Technician, Greenland Climate Research Centre, c/o Greenland Institute of Natural Resources, Greenland (MarineBasis, 27 July-17 August)
Winnie Martinsen, Technician, Greenland Climate Research Centre, c/o Greenland Institute of Natural Resources, Greenland (MarineBasis, 27 July-17 August)
Peter Schmidt Mikkelsen, Research assistant, Greenland Climate Research Centre, c/o Greenland Institute of Natural Resources, Greenland (MarineBasis, 27 July-17 August)
Paul Nicklen, National Geographic, USA (Underwater photography of walrus, 20 July-10 August)

Nathan Williamson, National Geographic, USA (Underwater photography of walrus, 20 July-10 August)

Logistics

Jòn Birgisson, Logistics assistant, National Environmental Research Institute, Aarhus University, Denmark (1 June-13 July)
Michael Jacobsen, Logistics assistant, National Environmental Research Institute, Aarhus University, Denmark (6 July-24 August)
Jan Thaudahl Jakobson, Logistics assistant, National Environmental Research Institute, Aarhus University, Denmark (13 July-31 August)
Søren Kyed, Logistics assistant, National Environmental Research Institute, Aarhus University, Denmark (27 July-17 August)
Dina Laursen, Cook, National Environmental Research Institute, Aarhus University, Denmark (1 June-20 July)
Henrik Spanggård Munch, Logistics leader, National Environmental Research Institute, Aarhus University, Denmark (1 June-6 July and 27 July-31 August)
Henrik Philipsen, Logistics assistant, National Environmental Research Institute, Aarhus University, Denmark (3-24 August)
Morten Rasch, Scientific leader, National Environmental Research Institute, Aarhus University, Denmark (17-31 August)
Lone Riis, Cook, National Environmental Research Institute, Aarhus University, Denmark (20 July-31 August)
Jørgen Skafte, Logistic leader, National Environmental Research Institute, Aarhus University, Denmark (4 May-1 June and 24 August - 2 November)

VIP (17-19 August)

Andreas Ahlstrøm, Geological Survey of Denmark and Greenland, Denmark
Thomas Egebo, Danish Ministry of Climate and Energy, Denmark
Lykke Friis, Danish Ministry of Climate and Energy, Denmark
Louise Grøndahl, Danish Ministry of Climate and Energy, Denmark
Lauritz Holm-Nielsen, Aarhus University
Sofus Rex, Danish Ministry of Climate and Energy, Denmark
Søren Rysgaard, Greenland Climate Research Centre, c/o Greenland Institute of Natural Resources, Greenland
Henrik Sandbech, National Environmental Research Institut, Aarhus University
Erik Meiniche Schmidt, Aarhus University

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Mikael K. Sejr, National Environmental Research Institute, Aarhus University

10 Publications

Scientific papers

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Olesen, J.M., Dupont, Y.L., O'Gorman, E.J., Ings, T.C., Layer, K., Melian, C.J., Trojelsgaard, K., Pichler, D.E., Rasmussen, C. and Woodward, G. 2010. From Broadstone to Zackenberg: Space, Time and Hierarchies in Ecological Networks. Advances in Ecological Research 40:1-69.

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General information

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Appendix

Julian Days

Regular years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	1	32	60	91	121	152	182	213	244	274	305	335
2	2	33	61	92	122	153	183	214	245	275	306	336
3	3	34	62	93	123	154	184	215	246	276	307	337
4	4	35	63	94	124	155	185	216	247	277	308	338
5	5	36	64	95	125	156	186	217	248	278	309	339
6	6	37	65	96	126	157	187	218	249	279	310	340
7	7	38	66	97	127	158	188	219	250	280	311	341
8	8	39	67	98	128	159	189	220	251	281	312	342
9	9	40	68	99	129	160	190	221	252	282	313	343
10	10	41	69	100	130	161	191	222	253	283	314	344
11	11	42	70	101	131	162	192	223	254	284	315	345
12	12	43	71	102	132	163	193	224	255	285	316	346
13	13	44	72	103	133	164	194	225	256	286	317	347
14	14	45	73	104	134	165	195	226	257	287	318	348
15	15	46	74	105	135	166	196	227	258	288	319	349
16	16	47	75	106	136	167	197	228	259	289	320	350
17	17	48	76	107	137	168	198	229	260	290	321	351
18	18	49	77	108	138	169	199	230	261	291	322	352
19	19	50	78	109	139	170	200	231	262	292	323	353
20	20	51	79	110	140	171	201	232	263	293	324	354
21	21	52	80	111	141	172	202	233	264	294	325	355
22	22	53	81	112	142	173	203	234	265	295	326	356
23	23	54	82	113	143	174	204	235	266	296	327	357
24	24	55	83	114	144	175	205	236	267	297	328	358
25	25	56	84	115	145	176	206	237	268	298	329	359
26	26	57	85	116	146	177	207	238	269	299	330	360
27	27	58	86	117	147	178	208	239	270	300	331	361
28	28	59	87	118	148	179	209	240	271	301	332	362
29	29		88	119	149	180	210	241	272	302	333	363
30	30		89	120	150	181	211	242	273	303	334	364
31	31		90		151		212	243		304		365

Leap years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	1	32	61	92	122	153	183	214	245	275	306	336
2	2	33	62	93	123	154	184	215	246	276	307	337
3	3	34	63	94	124	155	185	216	247	277	308	338
4	4	35	64	95	125	156	186	217	248	278	309	339
5	5	36	65	96	126	157	187	218	249	279	310	340
6	6	37	66	97	127	158	188	219	250	280	311	341
7	7	38	67	98	128	159	189	220	251	281	312	342
8	8	39	68	99	129	160	190	221	252	282	313	343
9	9	40	69	100	130	161	191	222	253	283	314	344
10	10	41	70	101	131	162	192	223	254	284	315	345
11	11	42	71	102	132	163	193	224	255	285	316	346
12	12	43	72	103	133	164	194	225	256	286	317	347
13	13	44	73	104	134	165	195	226	257	287	318	348
14	14	45	74	105	135	166	196	227	258	288	319	349
15	15	46	75	106	136	167	197	228	259	289	320	350
16	16	47	76	107	137	168	198	229	260	290	321	351
17	17	48	77	108	138	169	199	230	261	291	322	352
18	18	49	78	109	139	170	200	231	262	292	323	353
19	19	50	79	110	140	171	201	232	263	293	324	354
20	20	51	80	111	141	172	202	233	264	294	325	355
21	21	52	81	112	142	173	203	234	265	295	326	356
22	22	53	82	113	143	174	204	235	266	296	327	357
23	23	54	83	114	144	175	205	236	267	297	328	358
24	24	55	84	115	145	176	206	237	268	298	329	359
25	25	56	85	116	146	177	207	238	269	299	330	360
26	26	57	86	117	147	178	208	239	270	300	331	361
27	27	58	87	118	148	179	209	240	271	301	332	362
28	28	59	88	119	149	180	210	241	272	302	333	363
29	29	60	89	120	150	181	211	242	273	303	334	364
30	30		90	121	151	182	212	243	274	304	335	365
31	31		91		152		213	244		305		366