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Environmental Monitoring in the Kapp Linné-Grønfjorden Region (KLEO)

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1. Introduction

The ability to understand and predict environmental changes in Svalbard is highly dependent on the availability of detailed and long-term records of baseline environmental data from a regional network across the archipelago. The Kapp Linné region provides a strategic location for a dedicated long-term environmental observatory in the western coastal region of the Nordenskiöldland Peninsula. This region is greatly influenced by the Atlantic High Arctic maritime climate regime (Eckerstorfer and Christiansen 2011) with higher mean annual air temperature and greater precipitation than the more continental interior regime in central Spitsbergen (Humlum 2002). With the recent intensified Atlantification of the northern Barents Sea (Nilsen et al. 2016; Barton et al. 2018), environmental monitoring studies along the Nordenskiöldland coast may help to serve as an early warning system for climate change and accompanying environmental responses across the Svalbard archipelago.

The Kapp Linné Environmental Observatory (KLEO) was formulated as an international collaborative site within the Svalbard Integrated Arctic Earth Observing System (SIOS) to contribute the results of long-term and interdisciplinary environmental monitoring in the Kapp Linné region to the State of Environmental Science in Svalbard (SESS) report 2019 and to enhance future collaboration among researchers. In this report we will provide: (1) an introduction to the study area with an inventory of ongoing research programs, instrumental installations and archived data within the SIOS network, (2) highlight recent, significant developments in hydroclimate research and (3) provide an outline for future developments in collaborative interdisciplinary environmental research.

The KLEO research sites span an area extending from the west coast of Spitsbergen at the mouth of Isfjorden, to the eastern shore of Grønfjord (Figure 1). The regional physiography is strongly controlled by both the bedrock type and the structural architecture of the northwest-striking West Spitsbergen Fold Belt (Dallman 2015). In the west, the Isfjordflya terrain along the coast is the northern extension of the 40 km long Nordenskiöldkysten strandflat complex, a low-lying Precambrian bedrock platform that is mantled by prominent set of gravel raised beach deposits (Landvik et al. 1987). Isfjord Radio, the long-standing weather station at Kapp Linné is situated at the northern tip of the strandflat. A prominent ridgeline of sharp peaks, comprised of pre-Cambrian phyllite (Ohta et al. 1992) reaches up to 780 meters in elevation and separates the coastal strandflat from Linnédalen and defines the western margin of Linnédalen watershed. The sharp ridge is incised with numerous well-defined cirques (some with small glaciers) and flanked by steep, coarse alluvial fans and several rock glaciers. The broad central valley of Linnédalen is oriented NNW along bedrock strike, is approximately 14 km long and up to 2 km wide, and is floored by light-coloured Carboniferous quartzite (Ohta et al. 1992).

Linnébreen, at the southern head of the valley, is a small polythermal valley glacier (currently

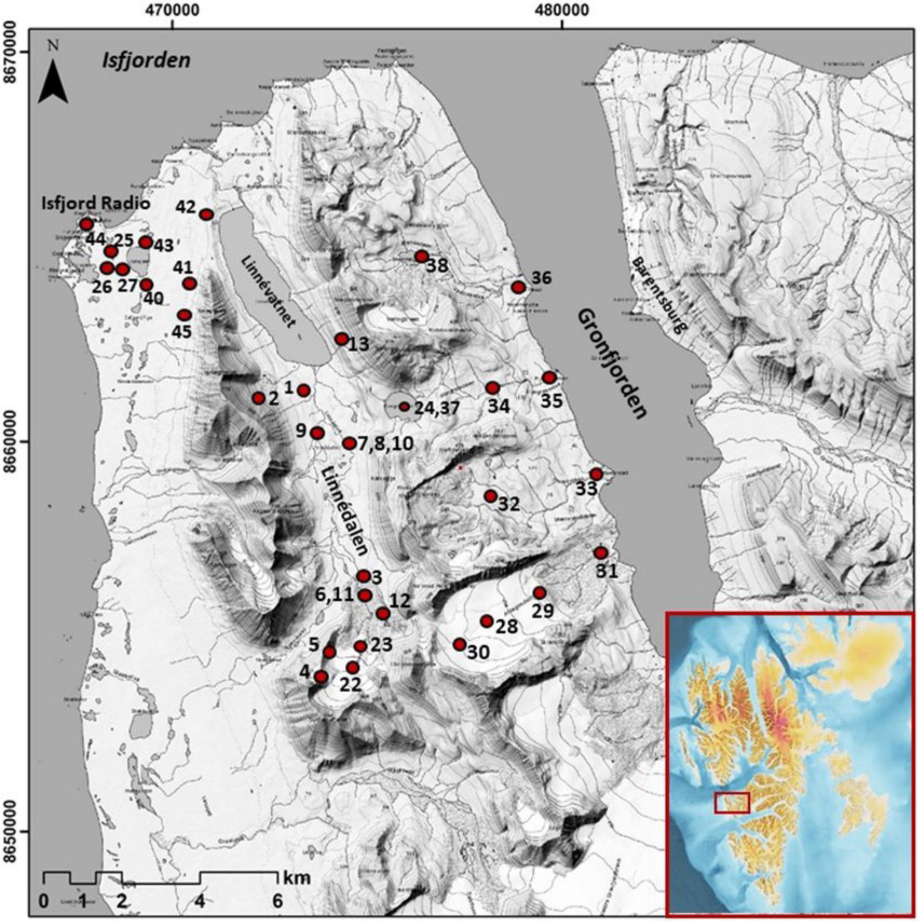


Figure 1: Location map of the Nordenskiöldkysten - Kapp Linné - Grønfjorden region. Inset map of Svalbard archipelago shows field area in red box. Numbers are monitoring instruments and installations. Refer to Appendix for descriptions.

approx. 2 km long) which resides in a steep bedrock amphitheatre and contributes meltwater to Linnéelva which flows almost 7 km to Linnévatnet (which will be described in more detail below). The eastern wall of Linnédalen is flanked by a ridge of Permian-age sedimentary rocks including dolomite, limestone, gypsum, and sandstone. This sedimentary sequence extends northeast of Linnévatnet to the Vardeborgsletta area where numerous karst features including dolines and sinkholes have been described by Salvigsen and Elgersma (1985). Kongressvatnet, a unique sulfate-rich 57-meter deep meromictic karst lake (Boyum and Kjensmo 1970; Guilizzoni et al. 2006; Holm et al. 2011), is situated in the saddle between Linnédalen and Grønfjorden in this same karst terrain. This unique lake yearly exhibits significant changes in lake level as a result of karst drainage. The eastern flank of the ridge is comprised of younger east-dipping sedimentary strata of Mesozoic age which are well exposed in the classic Festningen section along the Isfjorden shore at the western mouth of Grønfjorden (Mørk and Worsley 2006). Several east-facing cirque glaciers, Aldegondebreen and Vøringbreen, and the more extensive Grønfjordbreen valley glacier complex are located along this ridge. Grønfjorden and the terrain to the east occupies an incised plateau topography due to the flat-lying Cenozoic-age sedimentary rocks of the Van Mijenfjorden Group, which contains the coal-bearing Firkanten Formation mined in Barentsburg and around Longyearbyen (Ohta et al. 1992).

2. Overview of existing knowledge

Relatively easy logistical access to Kapp Linné and Barentsburg, coupled with existing research infrastructure at sites across Kapp Linné, in Linnédalen and in the Grønfjorden region provides a solid foundation on which to continue monitoring and observations and to develop new environmental monitoring studies. Current long-term monitoring studies highlighted in this report include hydroclimate monitoring and paleoclimate studies in Linnédalen (initiated in 2003), UNIS faculty and student research focused in permafrost and periglacial geomorphology (initiated in 2004) and studies in cryo-hydrology and paleoecology in the adjacent Grønfjord region by the University Centre in Svalbard (UNIS) and Barentsburg Science Center researchers. Figure 1 illustrates a location map of instruments and installments in the region. An array of instrumentation in the 31 km^2 catchment of Linnédalen documents changes in the glacial-fluvial-lake system including an automated weather station, snow and water temperature sensors, time-lapse cameras, and moorings deployed in Linnévatnet. Development of the instrumental network in the watershed was initially supported by grants from the U.S. National Science Foundation Polar Programs and monitoring efforts have been sustained in recent years by faculty-student research at UNIS. A detailed list of the installations and instruments and their respective data series is shown in Appendix 1.

Regional Climatology: The Isfjord Radio meteorological station (78.0623°N 13.6157°E, 7 m a.s.l). is located on Kapp Linné at the southern edge of the mouth of Isfjorden. The first meteorological station was established on 1 September 1934 and was operating until 30 June 1941, then was destroyed by the actions of war. On 1 September 1946, the station was re-established at the same location. The measurements and observations have been conducted as one of the WMO indexed stations with the international numbering system 01013 until 30 June 1976. From this date onwards, the station was no longer used for climatological purposes; however an automatic weather station was re-established again for the periods 1 Jan 1997 – 5 Feb 2002, 20 Jun 2002 – 6 Dec 2004, and from 10 Sep 2014 to present. For the climatological description in this report, the data were homogenised

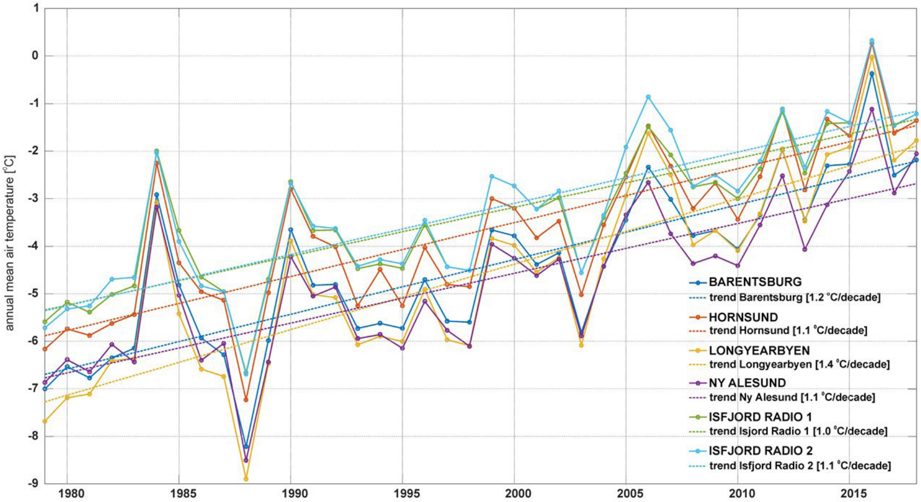
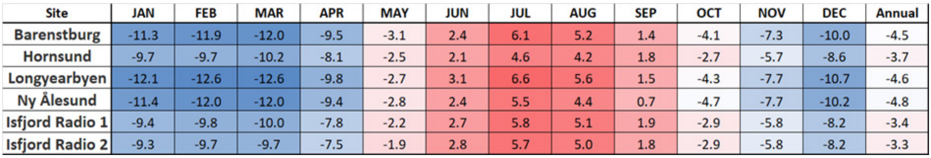


Figure 2: Variability of annual mean air temperatures in 1979-2018 at Barensburg, Hornsund, Longyearbyen, Ny-Ålesund, and two homogenised series for Isfjord Radio 1 and 2, where gaps were filled using data from Barentsburg and Longyearbyen respectively.

for the period 1979-2018 using the aforementioned original series together with the reconstructed daily series by linear regression from neighbouring stations in Barentsburg and Longyearbyen as predictors. Warm and humid air transported by extratropical cyclones from lower latitudes and warm West Spitsbergen current have a significant influence on the climate of Isfjord Radio, which is maritime and mild, concerning its high latitude. The long-term (1979-2018) mean annual air temperature (MAAT) is -3.4°C. The coldest month is March with the average temperature -10.0°C and the warmest July with 5.8°C.

A comparison of the mean annual air temperatures and their trends per decade at meteorological stations: Barentsburg (WMO Site 20107), Hornsund (WMO Site 01003), Svalbard Lufthavn (WMO Site 01008), Ny-Ålesund (01007) and Isfjord Radio is shown in Figure 2. In the case of Isfjord Radio, there are two homogenised series where gaps in the data series were filled using linear regression on data from Barentsburg (Isfjord Radio 1) and Longyearbyen (Isfjord Radio 2). The trends were estimated by the modified Mann-Kendall test (Mann 1945; Kendall 1975; Hamed and Rao 1998). The slope of the trend was estimated using the Sen's method (Sen 1968). A statistically significant increase in annual mean air temperatures at all stations shows that air temperature in the whole western and central part of Spitsbergen is shaped by the common sets of climatic processes that have broad impacts on the Atlantic Arctic (Osuch and Wawrzyniak 2017). The tendency is the same, and the range of these changes is from 1.0°C per decade at Isfjord Radio 1, to 1.4°C per decade in Longyearbyen.

Table 1: Comparison of mean monthly air temperature between Barentsburg, Hornsund, Longyearbyen, Ny-Ålesund and two reconstructed time series from Isfjord Radio. Measurements cover the period from 1979 to 2018.



Site	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Annual
Barenstburg	-11.3	-11.9	-12.0	-9.5	-3.1	2.4	6.1	5.2	1.4	-4.1	-7.3	-10.0	-4.5
Hornsund	-9.7	-9.7	-10.2	-8.1	-2.5	2.1	4.6	4.2	1.8	-2.7	-5.7	-8.6	-3.7
Longyearbyen	-12.1	-12.6	-12.6	-9.8	-2.7	3.1	6.6	5.6	1.5	-4.3	-7.7	-10.7	-4.6
Ny Ålesund	-11.4	-12.0	-12.0	-9.4	-2.8	2.4	5.5	4.4	0.7	-4.7	-7.7	-10.2	-4.8
Isfjord Radio 1	-9.4	-9.8	-10.0	-7.8	-2.2	2.7	5.8	5.1	1.9	-2.9	-5.8	-8.2	-3.4
Isfjord Radio 2	-9.3	-9.7	-9.7	-7.5	-1.9	2.8	5.7	5.0	1.8	-2.9	-5.8	-8.2	-3.3

A comparison of mean monthly conditions at the investigated stations during the period 1979-2018 is presented in Table 1. The span of observed mean monthly air temperatures during the year is varying between stations. The smaller difference is observed at Isfjord Radio and Hornsund while higher for Longyearbyen and Barentsburg due to the smaller influence of the ocean.

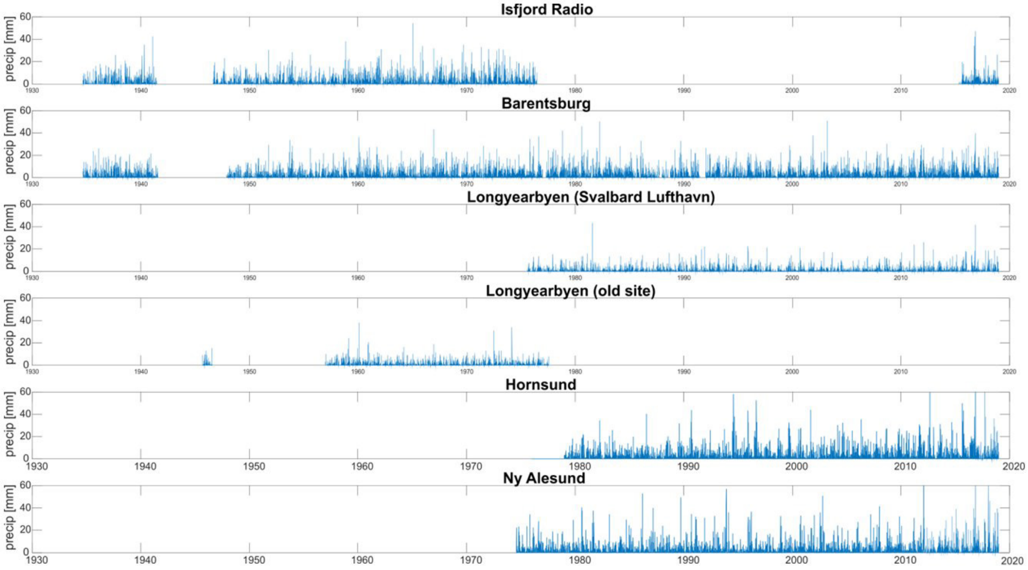


Figure 3: Diurnal sum of precipitation time series at meteorological sites in Spitsbergen in the period 1934-2018.

Measurements of daily sum precipitation at Isfjord Radio started on 1 September 1934 and were conducted in the same periods as air temperature described in the previous section. Precipitation time series at the six meteorological sites in Spitsbergen: Isfjord Radio, Barentsburg, Longyearbyen (old site), Longyearbyen (Svalbard Lufthavn), Hornsund, and

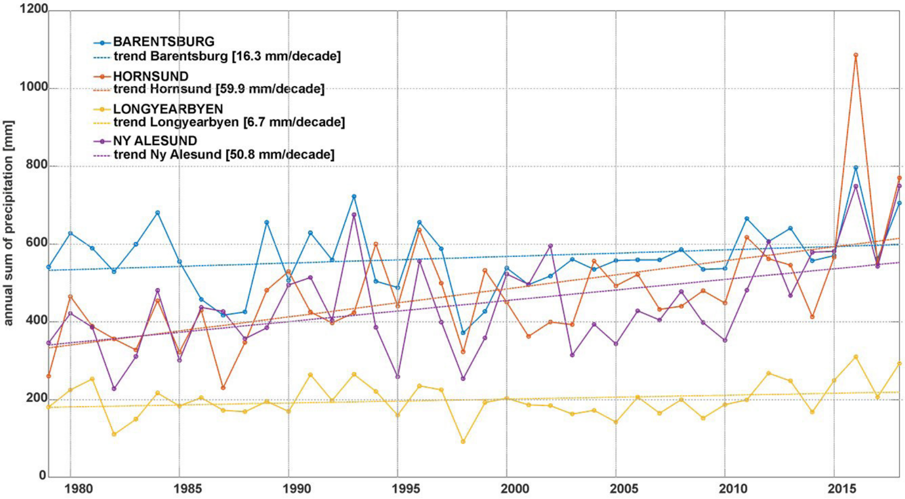


Figure 4: Variability of an annual sum of precipitation in 1979-2018 at Barentsburg, Hornsund, Longyearbyen, and Ny-Ålesund.

Ny-Ålesund are presented in Figure 3. Precipitation was not observed continuously at these sites before 1979. There are gaps and breaks in data that make current precipitation trend analyses difficult or impossible. As no data are available for Isfjord Radio for period 1 Jan 1979 - 2 May 2015 and in some shorter periods, the analyses were performed for other stations (Figure 4). The more detailed description is provided in this section for the Barentsburg data, located 14.5 km to the East from Isfjord Radio.

A comparison of the mean monthly sum of precipitation at the investigated stations during the period 1979-2018 is presented in Table 2. The highest annual precipitation is observed at Barentsburg (565 mm) and the lowest at Longyearbyen (200 mm). Hornsund and Ny-Ålesund have similar sums of precipitation. Although there are differences in the amount of precipitation between stations, their seasonal runs are generally similar. The driest months at all stations are May and June. The highest precipitation occurs in September at Hornsund and Ny-Ålesund, in November at Barentsburg, and in August at Longyearbyen. The span of the observed mean monthly sum of precipitation during the year

Table 2: Mean monthly sum of precipitation over period 1979-2018 at Barentsburg, Hornsund, Longyearbyen, and Ny-Ålesund.

Site	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Annual
Barentsburg	60	51	56	41	30	21	28	40	55	61	63	59	565
Hornsund	35	29	29	22	24	29	46	55	76	54	40	35	474
Longyearbyen	18	18	18	10	7	9	18	24	23	16	19	19	200
Ny Ålesund	51	41	45	26	18	16	29	39	57	41	44	39	446

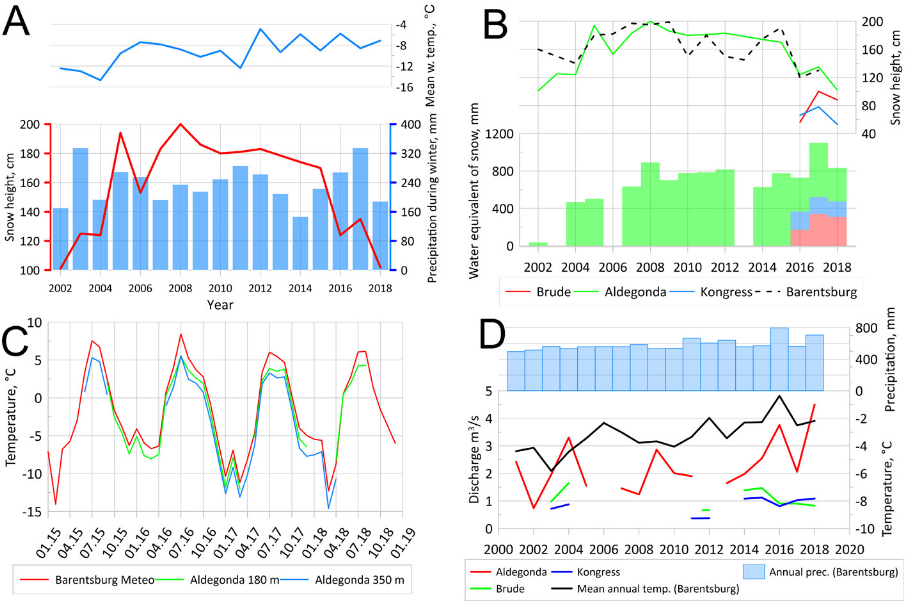


Figure 5: **A:** Variability of average snow cover height on Aldegonda glacier compared to average temperature and precipitation amount during the winter period (December-March); **B:** Variability of average snow cover height in Brude and Kongress river catchments, Aldegonda glacier and weather station in Barentsburg. **C:** Variability of average monthly temperature on weather stations in Barenstburg and Aldegonda glacier from 2015 to 2019; **D:** Variability of average water discharges of Aldegonda, Brude and Kongress rivers compared to annual precipitation and mean annual temperature in Barentsburg.

is varying between stations. The smallest difference is observed at Longyearbyen located in the inner part of the Spitsbergen island, with a more continental climate compared to the other stations.

Groundwater and Surface Water Hydrology in the Grønfjorden Region: Since 2001, the Arctic and Antarctic Research Institute (AARI) has been providing hydrological observations on the west shore of Grønfjorden in the Aldegonda, Bryde and Kongress watersheds. Snow cover observations (height, density, stratification) are carried out during the period of maximum snow accumulation (Figure 5A,B), and during the summer, continuous records of water and sediment discharge are collected. Complete observations on the rivers have been conducted since 2016. In addition to these observations on Aldegondabreen, two autonomous meteorological stations provide measurements at different altitudes (Figure 5C).The available data indicate a weak relationship between the average annual temperature, total annual precipitation and average river discharge (Figure 5D). The seasonal hydrographs of the rivers Aldegonda, Bryde, and Kongress correlate well with each other, despite the

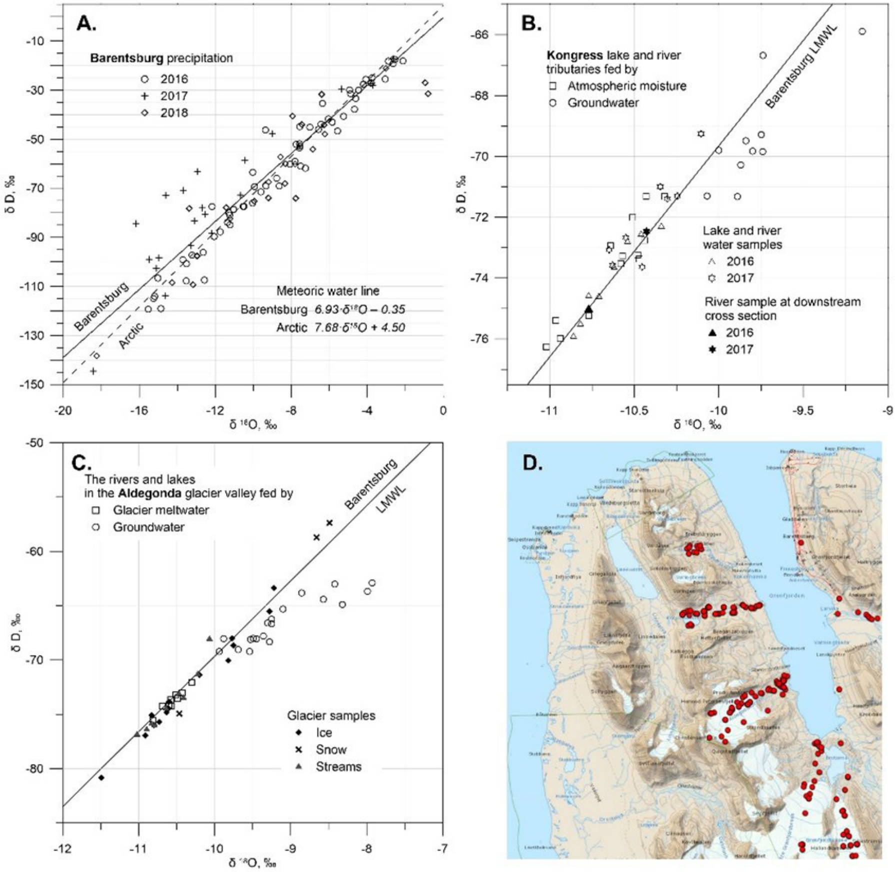


Figure 6: Isotopic composition of precipitation at Barentsburg meteorological station, surface and groundwater in Grønfjorden region. **A:** Meteoric water line (concentration of deuterium (δD) as a function of the concentration of oxygen-18 (δ18O): Barentsburg water line is calculated in 2016-2017, Arctic water line is drawn after Wetzel 1990; **B:** Isotopic signature of Kongressvatnet and adjacent rivers; **C:** Isotopic signature of Aldegondabreen snow, ice, meltwater and groundwater; **D:** Map of sampling sites for water isotopic composition, 2016-2018.

different types of river sources (Bryde and Aldegonda are glacier-fed rivers, Kongress lake- and snow-fed river). This is because the melting of the snow cover and liquid precipitation make a significant contribution to the annual river flow in all watersheds.

In 2016 at the Barentsburg research station AARI renewed the collecting of atmospheric precipitation samples for stable isotopic composition (δ18Oand δD) conducted in 1975-1981 by the Institute of Geography, Russian Academy of Sciences. Terrestrial waters, glacier snow, and ice have been sampled as well in the region of Grønfjorden in 2016-2018, enabling the water isotopes to provide a record of water source changes for the future. The local meteoric water line (Figure 6A) has been drawn from the isotopic composition of samples taken in 2016-2017 and is defined as $\delta D=6,93\delta18O-0,35$ (Skakun et al. 2019). The data of 2018 agree closely with the local Meteoric Water Line (LMWL), but show a slightly lower slope coefficient, indicating potential changes in moisture and water sources. Data from Barentsburg (1975-1981, 2016-2017) and Isfjord Radio 1960-1976 (Dansgaard 1964, IAE/WMO 2006) show that monthly mean isotopic composition of precipitation correlates well with monthly mean air temperature values, but the correlation varies between the winter and summer seasons. Isotopic composition in Ny-Ålesund and Hornsund poorly correlate with air temperature and depends on wind direction, ice formation in the fjords and other factors (Skakun et al. 2019).

The isotopic composition in Kongressvatnet showed that in spite of the dominance of meteoric water sources in the lake, there is strong inter-annual variability that indicates variations in groundwater recharge (Figure. 6B). The tributaries of Kongresselva also have different sources of water – thirteen of them have meteoric water (snowmelt and rain), and 8 have a groundwater source. At Aldegondabreen River, ice, snow and stream water (Figure 6C) collected on the glacier surface had isotopic composition close to LMWL, but the small lakes in the forefield are isotopically heavier due to evaporation and groundwater input. Lakes and streams further down the valley increasingly exhibit a deuterium excess (d-excess), demonstrating the sensitivity of stable isotopes to changing groundwater inputs, which are detectable in many of the watersheds on the west side of Grønfjorden.

Hydroclimate Research in the Glaciated Linnédalen Watershed: At the upper reaches of the watershed, the small valley glacier Linnébreen has been in steady retreat; earlier studies (2003-2013) detailed a sustained negative mass balance. Analysis of available imagery and annual mapping of the terminus since 2004 has shown that the glacier front has retreated approximately 1.8 km since 1936 and 1 km between 1995 and 2019 (Figure 7).

Downvalley from Linnébreen, a major research emphasis in Linnédalen since 2003 has been to monitor seasonal and interannual environmental processes in the glacier-river-lake system. Since lakes are situated in the lowest part of watersheds and they record inputs from physical, chemical and biological processes over short to long temporal scales, they can be acknowledged as sentinels of climate and environmental change (Williamson et al. 2009). In the Linnédalen watershed, integration of meteorological data, time-lapse photography, and temperature and sediment trap analysis provides a detailed archive of snow cover and melt, seasonal lake ice duration on Linnévatnet and timing and duration of fluvial activity including extreme events.

Linnévatnet (12 m a.s.l.) is a cold monomictic lake (Boyum and Kjensmo 1978) with the long axis oriented in an NNW-SSE direction along bedrock strike (Figure 1). The Linnévatnet

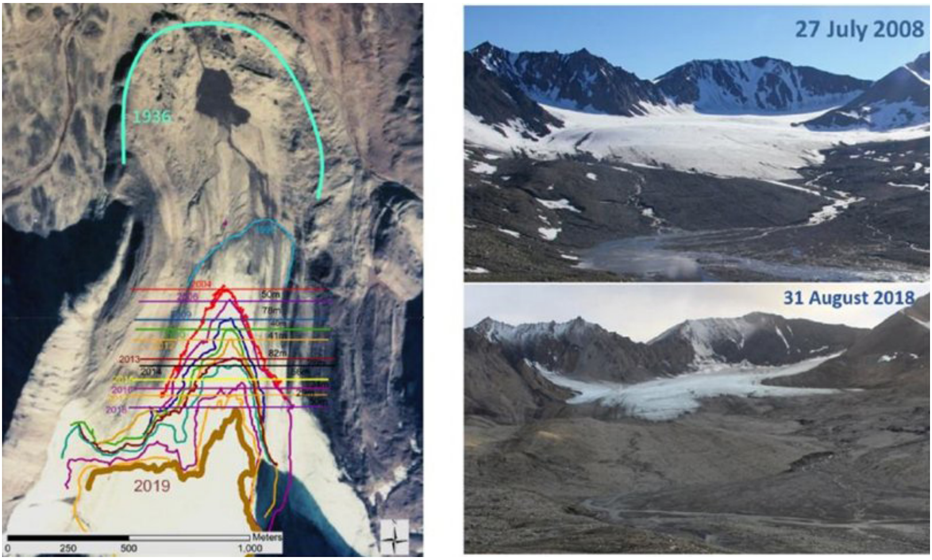


Figure 7: **Left:** A Map of Linnébreen showing ice margin positions from 1936 to present. The positions in 1936 and 1995 were obtained from air photographs and superimposed on georeferenced image from 1995. Positions from 2004 to 2019 are GPS tracks on georeferenced image. **Right:** Images of Linnébreen terminus from the time-lapse camera on Linnébreen Little Ice Age lateral moraine (view to the south).

watershed has an area of 27 km^2, of which 1.7 km^2 (6.3%) is glaciated (Snyder et al. 2000). There are three main basins: the SW and SE basins (11 and 16 meters depth, respectively) are located near the main inflow from Linnéelva in the south and separated by a bedrock ridge. The deeper main basin to the north has a maximum depth of 35 meters. The main inflow from Linnéelva enters the lake in the SE corner and a smaller braided stream in the SW corner originating in a cirque on Griegfjellet. Smaller inflows enter the lake from the numerous alluvial fans that drain snow and icy patches in gullies above the lake.

Temperature profiles in the lake, time-lapse imagery, and satellite remote sensing show that the ice-free season on Linnévatnet has been increasing over the last decade. Increases in ice-free duration have been documented throughout the Arctic (Lehnherr et al. 2018; Šmejkalová et al. 2016; Prowse et al. 2011; Magnuson et al. 2000). In-situ water temperature data collected at multiple depths at six locations since 2003 in Linnévatnet provide a unique opportunity to study the processes of lake ice formation and demise, and understand the climatic factors that are driving the decrease in ice cover duration. The work combines in-situ measurements with visible and near-infrared surface reflectance data from the Moderate Resolution Imaging Spectroradiometer (MODIS) to observe changes in reflectance of Lake Linné from 2000 – 2017 to determine the timing of summer ice-off (Cao et al. 2018). Sentinel-1 microwave backscatter data from Fall 2014 - Spring 2018 are

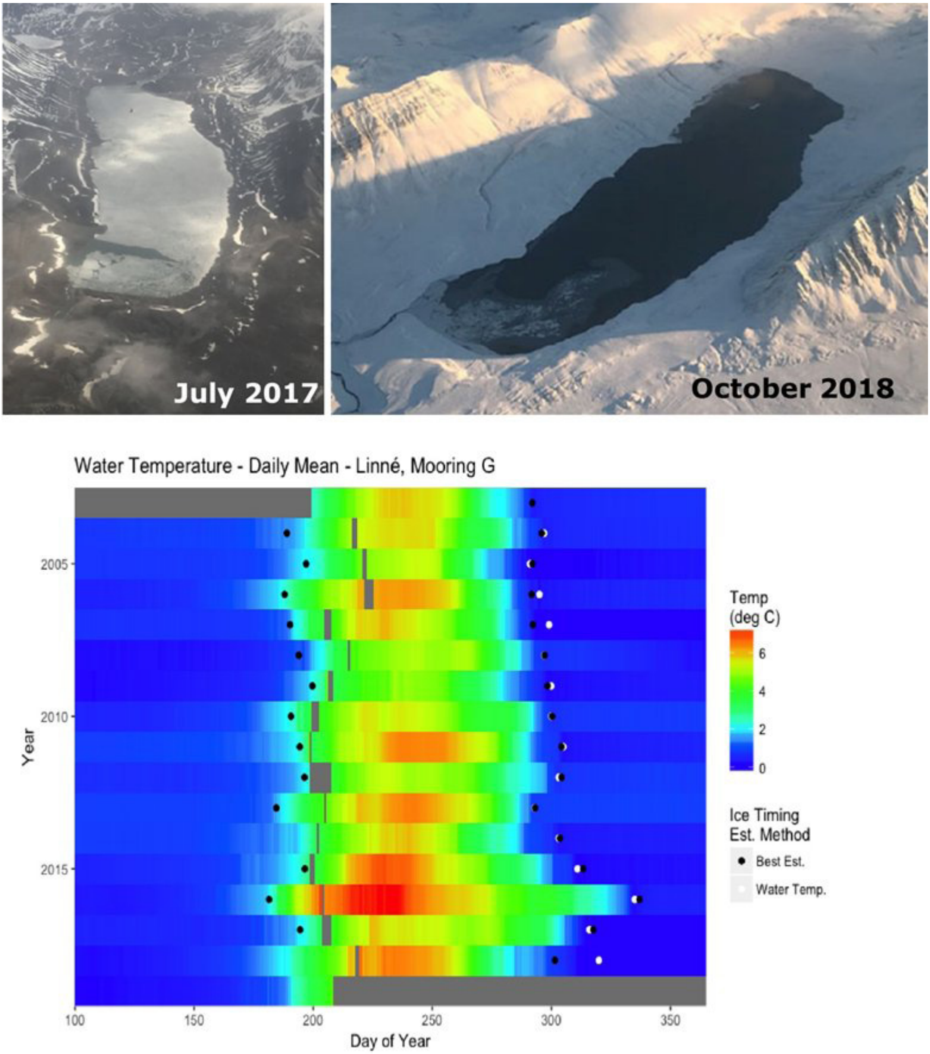


Figure 8: **Upper:** Photographs of Linnévatnet from commercial air flight 3 July 2017 and 9 October 2018 during breakup and freeze-up respectively. **Lower:** Plot of Linnévatnet. Daily mean water temperature 2003-2018 and best estimates of breakup and freezeup (dots). View to the south and southeast respectively.

also used to identify ice-on and ice-off dates, after correcting for satellite view angle effects. These results support an overall decrease in annual duration of lake ice cover in this part of Svalbard (Figure 8 lower panel). Contrary to patterns described for elsewhere in the Arctic (e.g. Šmejkalová et al. 2016; Magnuson et al. 2000), we do not see significant trends in the timing of summer lake ice breakup (breakup has occurred between 3rd week of June and the middle of July). However, we see significant changes in the timing of lake ice formation in the autumn. Prior to 2013, lake ice cover always formed during the second half of October. Since 2013, we have observed several years in which lake ice cover did not form until late November or early December. Our ongoing work is exploring relationships between Kapp Linné area air temperature and Linnévatnet ice cover, and possible influences of the Arctic and North Atlantic Oscillations.

Analysis of meteorological data, time-lapse imagery and detailed grain size analysis of sediment traps has been used to characterise each year of sediment trap deployment (Figure

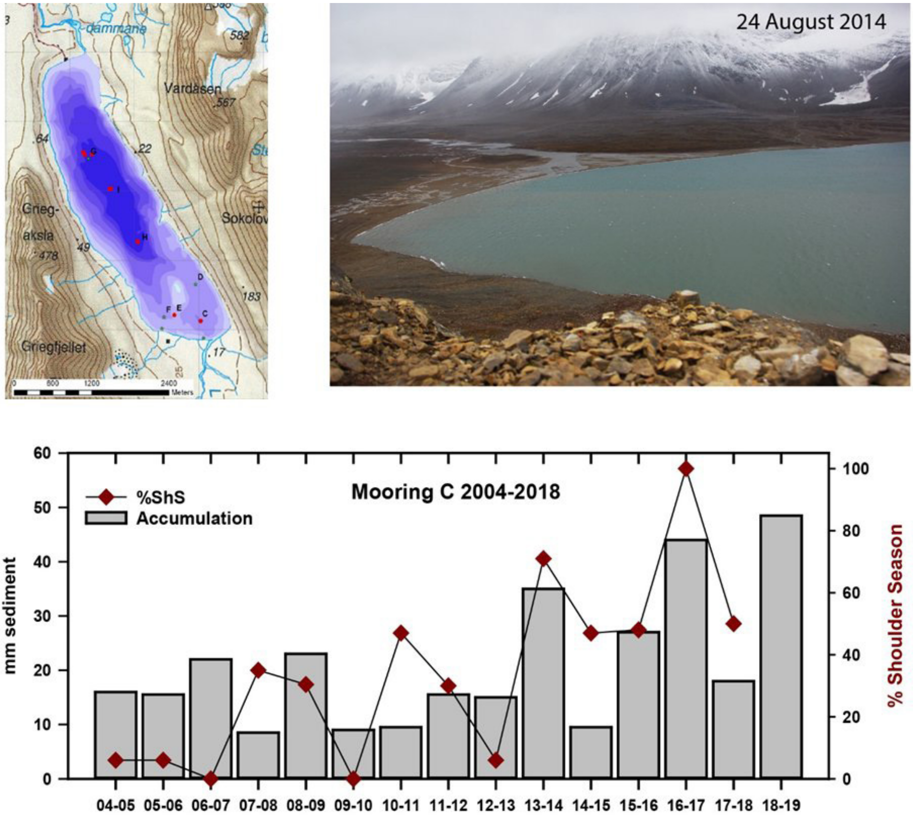


Figure 9: Upper left: Bathymetry of Linnévatnet and location of moorings (red dots). **Upper right:** Linnévatnet, view to the southwest from the "Plumecam" during river discharge event in late August 2014. **Lower:** Plot of accumulation from 2004 to 2018 in sediment trap from delta proximal mooring C. Red diamonds indicate percentage of accumulation in late summer-fall "shoulder season" (%ShS).

9 Top left), ca. 1 August to 31 July. Over the period 2013 to 2018 the general hydrological regime has shifted from one where peak discharge and lake sedimentation occurring during spring and early summer snowmelt (Schiefer et al. 2017) to one in which peak flow occurs during late summer and fall "shoulder season" as a result of intense late-season rainstorms (Nowak and Hodson 2013). In 2005, 2006, 2008, 2009, and 2012, the spring snowmelt processes were dominant; however the late-season mode has been the dominant mode in 6 of the past 8 years (Figure 9 bottom panel). In September 2015, approximately 70% of the annual sediment accumulation in sediment traps occurred over the course of 36 hours during a late summer rain event. Two storms in October and November 2016 produced floods and debris flows in the Linnédalen watershed with sediment yield exceeding all of the previous 13 years of observation. The late-season storms generally occur when the active layer is thickest at the end of the summer and sediments are easily mobilised along with residual sediment in stream channels.

Remote Sensing: Remote sensing techniques based on satellite Synthetic Aperture Radar (SAR) and optical images are powerful tools to upscale the investigation of large and hard-to-access Arctic environments. Past and on-going research projects in Svalbard have shown that remote sensing is valuable for A) the investigation of ground dynamics in periglacial areas using SAR Interferometry (InSAR) (Rouyet et al. 2019), B) the study of wet snow, ice cover on lakes and freeze/thaw cycles using SAR backscatter analysis (Eckerstorfer et al. 2017), and C) the mapping of vegetation (Johansen et al. 2012) and the onset of the growing season (Karlsen et al. 2014) using multi-spectral optical images.

In Kapp Linné, ground dynamics products document the distribution and timing of ground displacements along the line-of-sight of the SAR sensors during the snow-free season. Figure 10A shows the distribution of thaw subsidence in flat areas and creep on west-facing slopes between June and September 2018. Snow and ice cover products provide information about the distribution of wet snow and ice on water surfaces, useful to detect rain-on-snow events during the winter, the onset of the snow melting in spring and the timing of ice cover on lakes. Figure 10B is a snapshot for the 17th of July 2017 when snow is getting wet in the upper slopes and the ice covering Linnévatnet is melting. Vegetation products document the occurrence and distribution of the flora in the study area. Figure 10C shows the 18-units vegetation map in Kapp Linné based on Landsat TM/ETM+ imagery from 1987-2002.

Permafrost and Periglacial Geomorphology: Since 2004 observations of active layer temperatures in the most widespread periglacial landforms such as a beach ridge (43 in Figure 1), a snowpatch site (42 in Figure 1), a rock glacier (45 in Figure 1) and a solifluction sheet (41 in Figure 1) have been carried out primarily in the northern part of the strandflat in the study area. In 2008 as part of the IPY Thermal State of Permafrost (TSP Norway) project three boreholes were drilled into the permafrost for ground thermal monitoring

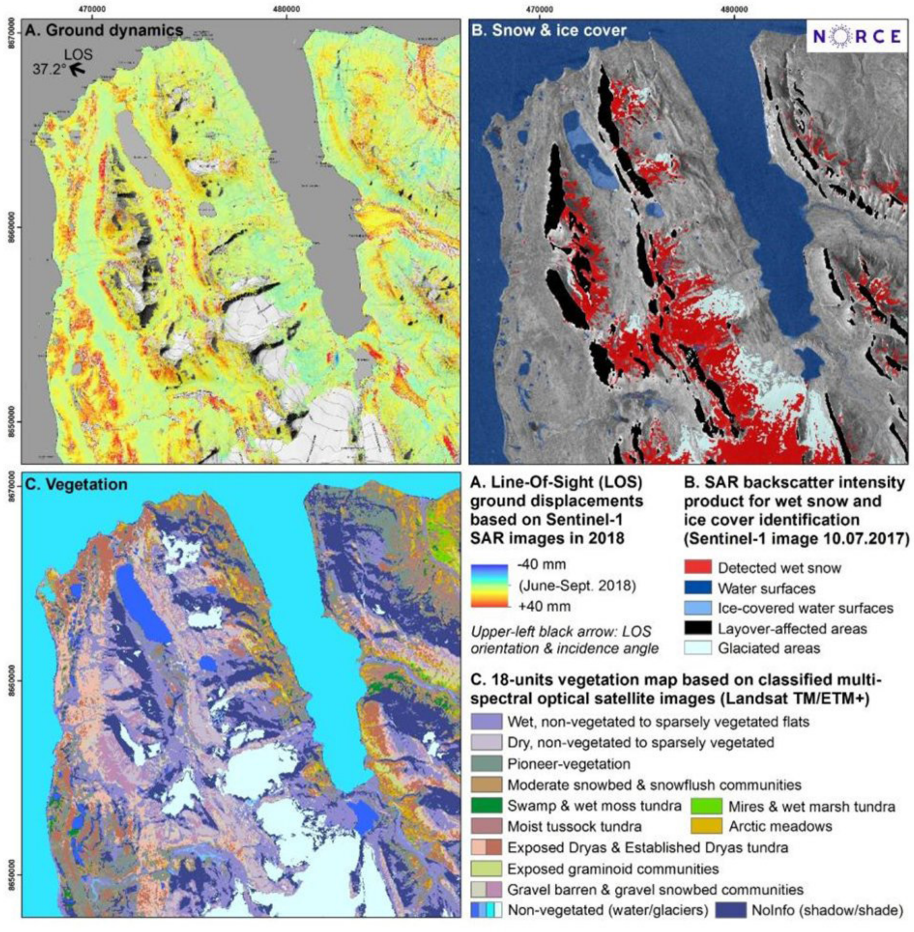


Figure 10: Examples of satellite remote sensing products in Kapp Linné.

(Christiansen et al. 2019). One borehole is 30 m deep and drilled into a bedrock outcrop (25 in Figure 1), another borehole is 39 m and drilled into beach ridge sediments laying over bedrock (26 in Figure 1). The third borehole was drilled 4 m through organic deposits and into beach ridge sediment (27 in Figure 1) but has been destroyed by a polar bear. These three boreholes are located approximately 1 km south of Isfjord Radio and are 200 m apart. Permafrost conditions in the two deep boreholes are compared to other permafrost observation sites in Svalbard in Christiansen et al. (2019) and in Christiansen et al. (2020). Generally the permafrost along the west coast in the study area is relatively warm as discussed for the last two hydrological years. This is reflecting the location close to the sea, with the top permafrost temperatures higher than -2°C and the deeper permafrost temperatures (15-20 m) higher than -3°C recorded in both the strandflat at Kapp Linné and in the marine terrace in the Barentsburg area (Christiansen et al. 2019). The active layer varies from around 3 m thickness in the bedrock to approximately 1.5 m in sediments in the study area including data from both Kapp Linné and the Barentsburg area (Christiansen et al. 2020). Frost heave, thaw settlement, and downslope displacement of soil is measured at a solifluction station at the western flank of Griegfjellet (41 in Figure 1). A time-lapse camera takes daily photographs of the solifluction station, allowing for the assessment of snow conditions and ground heaving and settling. The ground temperature and solifluction station data have been used together with remote sensing backscatter data for improved process dynamics assessing ground deformation and subsidence in the landscape around Kapp Linné (Eckerstorfer et al. 2017).

3. Unanswered questions

Groundwater and Surface Water Hydrology: There are several urgent research needs that must be addressed if we are to properly understand the response of Svalbard's water budget to the marked climate changes described above. These are: i) the precipitation gradient across Nordenskiöldland is virtually unknown for rainfall, making data products from modern climate models or real data from our sparse network of rain gauges very difficult to distribute over the mountain environment; ii) we have traditionally neglected change in any water store other than glacier ice, providing no basis for accounting for how ground-thaw and the loss of ground ice will contribute to water supply and geomorphic processes; and iii) research in Svalbard has greatly neglected groundwater as a water source and bio-geomorphic agent. Due to the complexity of cold region hydrological systems, a catchment response can vary depending on permafrost thawing and lead to an increased storage capacity of affected soils and a higher contribution of groundwater to river discharge. Hydrological modelling of polar catchments with varying active layer thicknesses requires analysis of non-stationarity of environmental conditions and their influence on simulated runoff. It should be taken into account for simulation of recent, past and future conditions. Developing our work in the Kapp Linné region via multi-institutional collaboration will, therefore, provide a much-needed alternative site to the now-defunct glacier-groundwater system studied in the past at Vestre Broggerbreen in Ny-Ålesund and unglaciated catchment Fuglebekken in Hornsund (Wawrzyniak et al. 2017). This new collaboration, first initiated in 2007 between UK and AARI and recently with IGF PAS researchers, will involve the instrumentation of four adjacent watersheds lying on identical rock types, yet with different lake or glacier cover proportions. Comparative watershed approaches have yielded significant insights into the influence of changing glacier cover in the past and is well-placed to provide empirical data resources for the future.

Paleoclimate/Paleohydrology: The annually laminated sediment record in Linnévatnet provides a long-term and high-resolution record of hydro-climatic variability for this part of Svalbard. Annual layering varies in thickness and structure in response to the amount and timing of sediment delivered by runoff from snow and glacier melt, and precipitation events. The sediment record provides a context for understanding the recent shift in hydrology by addressing two significant questions: (1) are there periods in the past ca. 1,000 years where lake sedimentation is similar to the current warm, wet Arctic scenario or (2) are we looking at a "new normal"? To address this important question, a new study, funded by U.S. NSF Polar Programs (R.S. Bradley, UMass, USA and M. Retelle, UNIS/Bates College USA) will use long term records of annually laminated sediments to reconstruct rainfall-related events and determine if and when similar conditions occurred in the past.

Paleoecology: The paleoenvironmental history of western Nordenskiöld land or Grønfjorden area has been studied by the RussianScientific Center on Spitsbergen, at Barentsburg, since 2015. The paleogeographical study is focused on landscapes, geomorphological features, Quaternary sediments, lake bottom sediment outcrops, etc. All are the key to understanding the environmental dynamics and climatic changes of the Late Pleistocene and Holocene. Taxonomic description of diatom complexes that are forming today in ecologically different environments (karst lakes, small lagoons, big lakes, streams, marine littoral zone, shore zone) will provide an accurate analogue for paleoecological reconstructions in the future. As a well-studied area, Linnédalen is the perfect location for environmental and paleoenvironmental monitoring.

4. Recommendations for the future

1. It is vitally important to maintain and improve the network of environmental monitoring installations and environmental sampling in this critical region during this period of rapidly changing climate. In addition, we will strive to encourage an increase in interdisciplinary research. Some examples that are currently being pursued include long-term studies of both terrestrial and aquatic ecology and aquative microbiology and biogeochemistry.

2. Understanding regional variability in hydroclimate will be an increasingly important issue in Svalbard in the 21st Century. Poorly understood regional precipitation gradients, understanding the contributions of water storage in glacier ice and groundwater, and groundwater as a water source and a bio-geormorphic agent are significant issues that must be addressed.

3. The recent recognition of the Kapp Linné Environmental Observatory in the SIOS network provides the capability of linking with research in other High Arctic interdisciplinary observatories where similar hydroclimate, permafrost and limnological research is

undertaken including the Zackenberg station in Greenland (Mernild et al. 2007) and the Ward Hunt Island Observatory (Comte et al. 2018) and Cape Bounty Arctic Watershed Observatoriy (LaFrenière and Lamoureux 2019) in the Canadian High Arctic archipelago.

4. Continued support for the Kapp Linné Environmental Observatory provides an ideal training ground for the next generation of Arctic scientists who will take on the challenges of the 21st Century. The proximity to UNIS and the AARI Barentsburg Research Station provides a highly motivated and well-trained workforce for addressing critically important environmental research issues.

5. Synergy with other SIOS Programmes

The Kapp Linné Environmental Observatory is an interdisciplinary and international collaborative with a focus on hydroclimate, permafrost and periglacial research and education. Permafrost research at Kapp Linné is already a part of the Svalbard-wide network of permafrost boreholes and active layer monitoring stations however other natural connections can easily be forged with other SIOS research teams including hydrology (planned river discharge monitoring on Linnéelva), snow and glacier research, and terrestrial ecology.

6. Data availability

Data used in this report came from a wide variety of sources, including publicly accessible online databases. Table 3 lists datasets used in this report, data provider or owner, and notes on how to access data. A primary goal for KLEO project members is to make relevant data and metadata accessible through the SIOS data access point.

Table 3: Data used in this report and access information.

Data Category	Data descriptions	Temporal coverage	Location or spatial coverage	Data information, providers and access
Regional Climatology	Meteorological stations on Svalbard	Varies by station	Svalbard	The Norwegian Meteorological Institute: http://eklima.met.no https://aisori.meteo.ru/ClimateR/ Institute of Geophysics Polish Academy of Sciences: https://monitoring-hornsund.igf.edu.pl/index.php/login
Groundwater and Surface Water Hydrology	Snow cover observations Water and sediment discharge Precip and surface water isotopic composition	2002 to present 2006 to present	Aldegonda-breen, Kongress, Bryde, Aldegonda watersheds Barentsburg station	Available by request to Anna Nikulina, Arctic and Antarctic Research Institute Hydrogen and oxygen isotopes in precipitation: https://www.iaea.org/services/networks/gnip
Linnédalen Watershed Hydroclimate data	Weather station temperature time series Water temperature times series Time lapse camera images Glacier mass balance measurements (2005-2010) Annual sediment trap grain size and mass accumulations	2003 to present	Linnédalen watershed	Most data are available at https://arcticdata.io/catalog/view/doi:10.18739/A2VH5CH5P See Schiefer et al., 2017 Additional data available by request to Steve Roof, Hampshire College
KLEO region Remote sensing	Synthetic Aperture Radar (SAR)	1987 to present	Kapp Linné region	See Rouyet et al., 2019
Permafrost	Borehole temperature records	2004 to present	Kapp Linné region	Global Terrestrial Network for Permafrost (GTN-P): https://gtnp.arcticportal.org/

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References

Barton BI, Lenn YD, Lique C (2018) Observed Atlantification of the Barents Sea causes the Polar Front to limit the expansion of winter sea ice. J Phys Oceanogr 48(8):1849-1866

Bøyum A, Kjensmo J (1970) Kongressvatn. A crenogenic meromictic lake at Western Spitsbergen. Arch Hydrobiol, 67:542–552

Bøyum A, Kjensmo J (1978) Physiography of Lake Linnévatn, Western Spitsbergen. In: Proceedings: 20th Congress, Internationale Vereinigung fur Theoretische und Angewandte Limnologie

Cao J, Roof S, Werner A, Gunn G, Bunting E, Tuttle S (2018) Comparison of Arctic Lake Ice Cover Timing on Svalbard Using Satellite and In-Situ Data. Am Geophys Ann Mtg, Washington DC, December 2018

Christiansen HH, Gilbert GL, Demidov N, Guglielmin M, Isaksen K, Osuch M, Boike J (2019) Permafrost thermal snapshot and active-layer thickness in Svalbard 2016-2017. In: Orr et al (eds): SESS report 2018, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp. 26–47. https://sios-svalbard.org/SESS_Issue1

Christiansen HH, Gilbert GL, Demidov N, Guglielmin M, Isaksen K, Osuch M, Boike J (2020) Permafrost temperatures and active-layer thickness in Svalbard during 2017/2018. In: Van den Heuvel et al. (eds): SESS report 2019, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, 236 - 249 . https://sios-svalbard.org/SESS_Issue2

Comte J, Culley AI, Lovejoy C, and Vincent WF 2018, Microbial connectivity and sorting in a High Arctic watershed, ISME J, 12 2988-3000.

Dallmann WK (Ed.) (2015) Geoscience Atlas of Svalbard. Norsk Polarinstitutt.Report Series No. 148.

Dansgaard W (1964) Stable isotopes in precipitation. Tellus 16:436-468. https://doi.org/10.3402/tellusa.v16i4.8993

Eckerstorfer M, Christiansen HH (2011) The “High Arctic maritime snow climate” in central Svalbard. A Antarct Alp Res 43(1):11-21

Eckerstorfer M, Malnes E, Christiansen HH (2017) Freeze/thaw conditions at periglacial landforms in Kapp Linné, Svalbard, investigated using field observations, in situ, and radar satellite monitoring. Geomorphology. 293:433-447

Guilizzoni P, Marchetto A, Lami A, Brauer A, Vigliotti L, Musazzi S, Langone L, Manca M, Lucchini F, Calanchi N, Dinelli E (2006) Records of environmental and climatic changes during the late Holocene from Svalbard: palaeolimnology of Kongressvatnet. J Paleolimnol 36(4):325-351

Hamed KH, Rao R (1998) A modified Mann-Kendall trend test for autocorrelated data. J Hydrol. 204: 182–196

Holm TM, Koinig KA, Andersen T, Donali E, Hormes A, Klaveness D, Psenner R (2011) Rapid physicochemical changes in the high Arctic Lake Kongressvatn caused by recent climate change. Aqua Sci 74(3):385-395

Humlum O (2002) Modelling late 20th century precipitation in Nordenskiold Land, Svalbard, by geographic means. -Norw J Geog 56: 96-103

IAEA/WMO (2006) International Atomic Energy Agency/ World Meteorological Organization. Global Network of Isotopes in Precipitation. The GNIP Database. Accessible at: https://www.iaea.org/services/networks/gnip

Johansen BE, Karlsen SR, Tømmervik H (2012) Vegetation mapping of Svalbard utilising Landsat TM/ ETM+ data. Polar Rec 48(1):47-63

Karlsen S, Elvebakk A, Høgda K, Grydeland T (2014) Spatial and temporal variability in the onset of the growing season on Svalbard, Arctic Norway—measured by MODIS-NDVI satellite data. Remote Sens 6(9):8088-8106

Kendall MG (1975) Rank Correlation Methods. Charles Griffin: London

Lafrenière MJ, Lamoureux SF (2019) Effects of changing permafrost conditions on hydrological processes and fluvial fluxes. Earth Sci Rev 191:212-223.

Landvik JY, Mangerud J, Salvigsen O (1987) The Late Weichselian and Holocene shoreline displacement on the west-central coast of Svalbard. Polar Res 5(1):29-44

Lehnherr I, St. Louis VL, Sharp M, Gardner AS, Smol JP, Schiff SL, Muir DCG, Mortimer CA, Michelutti N, Tarnocai C, St. Pierre KA, Emmerton, CA, Wiklund, JA, Köck, G, et al. (2018) The world's largest High Arctic lake responds rapidly to climate warming: Nat Commun 9 https://doi.org/10.1038/s41467-018-03685-z

Magnuson, JJ, Robertson, DM, Benson, BJ, Wynne, RH, Livingstone, DM, Arai, T et al. (2000). Historical trends in lake and river ice cover in the Northern Hemisphere. Science 289:1743-1746

Mann H (1945) Nonparametric tests against trend. Econometrica 13(3):245–259

Mernild SH, Sigsgaard C, Rasch M, Hasholt B, Hansen BU, Stjernholm M, Petersen D. Climate, river discharge and suspended sediment transport in the Zackenberg River drainage basin and Young Sound/Tyrolerfjord, Northeast Greenland, 1995–2003. Carbon cycling in Arctic marine ecosystems. Case study Young Sound, ed. S. Rysgaard, RN Glud, and TM Roberts. 2007:24-43.

Mørk A, Worsley D (2006) The Festningen section. Norsk Geologisk Forening (NGF) Abstracts and Proceedings, 3: 31-35

Nilsen F, Skogseth R, Vaardal-Lunde J, Inall, M (2016) A Simple Circulation Model: Intrusion of Atlantic Water on the West Spitsbergen Shelf. J Phys Oceanogr 46:1209-1230

Nowak A, Hodson, A (2013) Hydrological response of a High-Arctic catchment to changing climate over the past 35 years: a case study of Bayelva watershed Svalbard. Polar Res, 32:0

Ohta Y, Hjelle A, Andresen A, Dallmann WK, Salvigsen O (1992) Geological map of Svalbard 1:100,000, sheet B9G Isfjorden, Temakart 16, Norsk Polarinstitutt, Oslo

Osuch M, Wawrzyniak T (2017) Inter- and intra-annual changes of air temperature and precipitation in western Spitsbergen. Int J Climatol 37:3082– 3097, https://doi.org/10.1002/joc.4901

Prowse T, Alfredsen K, Beltaos S, Bonsal B, Duguay C, Korhola A., McNamara J, Pienitz R, Vincent WF, Vuglinsky V and Weyhenmeyer GA (2011) Past and Future Changes in Arctic Lake and River Ice. AMBIO, 40(S1): 53–62. https://doi.org/10.1007/s13280-011-0216-7

Rouyet L, Lauknes TR, Christiansen HH, Strand SM, Larsen Y (2019) Seasonal dynamics of a permafrost landscape, Adventdalen, Svalbard, investigated by InSAR. Rem Sens Env 231:111236

Salvigsen O, Elgersma A (1985) Large-scale karst features and open taliks at Vardeborgsletta, outer Isfjorden, Svalbard. Polar Res 3(2):145-153

Schiefer E, Kaufman D, McKay N, Retelle M, Werner A, Roof S (2017) Fluvial suspended sediment yields over hours to millennia in the High Arctic at proglacial Lake Linnévatnet, Svalbard. Earth Surf Proc Land 43(2): 482-498

Sen PK (1968) Estimates of the regression coefficient based on Kendall's tau. J Am Stati Assoc 63: 1379–1389. https://doi.org/10.2307/2285891

Skakun AA, Chikhachev KB, Ekaykin AA, Kozachek AV, Vladimirova DO, Veres AN, Verkulich SR, Sidorova OR, Demidov NE (2020) Stable isotopic content of atmopsphericprecipitation and natural waters in the vicinity in the vicinity of Barentsburg (Svalbard). Ice and Snow (Led and Sneg) 60 (1): xx–xx. accepted [in Russian]

Šmejkalová T, Edwards ME, Dash J (2016) Arctic lakes show strong decadal trend in earlier spring ice-out: Sci Rep, 6: https://doi.org/10.1038/srep38449

Snyder JA, Werner A, Miller GH (2000) Holocene cirque glacier activity in western Spitsbergen, Svalbard: sediment records from proglacial Linnévatnet. The Holocene 10:(5)555-563

Wawrzyniak T, Osuch M, Nawrot A, Napiórkowski JJ (2017) Run-off modelling in an Arctic unglaciated catchment (Fuglebekken, Spitsbergen). Ann Glaciol 58 (75): 36–46. https://doi.org/10.1017/aog.2017.8

Wetzel K (1990) Isotopic Peculiarities of Meteoric Water in Polar Regions. Isotopenpraxis Isotopes in Environmental and Health Studies 26:11–13. https://doi.org/10.1080/10256019008624211

Williamson CE, Saros JE, Vincent WF, Smol JP (2009) Lakes and reservoirs as sentinels, integrators, and regulators of climate change. Limnol Oceanogr 54(6 part2): 2273-2282

Appendix

Metadata for Kapp Linné-Gronfjorden installations and instrumentation. Numbers refer to sites on Figure 1 in the text. Mooring sites are shown on map in Figure 9.

LOCATION	Map #	Installation	Latitude	Longitude	Record Length
Linnédalen	1	Remote weather station	78,027	13,85	2003-2019*
	2	Air temperature	78,02435	13,80961	2003-2019*
	3	Air temperature	77,981	13,911	2003-2019*
	4	Air temperature	77,95876	13,88705	2003-2019*
	5	Air temperature	77,96721	13,904	2003-2019*
	6	Snow tree (snow depth)	77,98	13,911	2003-2019*
	7	Snow tree (snow depth)	78,016	13,881	2003-2019*
	8	Snow tree (snow depth)	78,02366	13,877	2003-2019*
	9	Stream temperature.	78,024	13,863	2004-2019
	10	Stream temperature	78,016	13,881	2004-2019
	11	Stream temp.	77,981	13,91	2004=2019
	12	Time lapse camera	78,02537	13,81784	2007-2019
	13	Time lapse camera	78,031	13,902	2007-2019
Linnévatnet Moorings	14	Mooring C	78,03217	13,86084	2003-2019
	15	Intervalometer	78,03206	13,86062	2003-2019
	16	Mooring C Spring deployment	78,03217	13,86084	2003-2019
	17	Mooring D	78,0373	13,85713	2003-2019
	18	Mooring E	78,03278	13,84386	2003-2019
	19	Mooring F	78,03257	13,83683	2003-2019
	20	Mooring G	78,05276	13,78557	2003-2019
	21	Mooring H	78,04241	13,81884	2003-2019
Linnébreen	22	ablation stake survey			2004-2013
	23	glacier margin GPS track			2004-2019
Kongressvatnet	24	Deep Hole mooring @ 55 meters	78,02126	13,96078	2003-2019

Kapp Linné Strandflat	25	Borehole KLB1	78,05588	13,63479	2008-2019
	26	Borehole KLB2	78,0544	13,63712	2008-2020
	27	Borehole KLB3	78,05313	13,63982	2008-2021
	41	Solifluction station	78,04522	13,72056	2004-2019
	42	Snowpatch active layer temperature	78,05739	13,74092	2004-2020
	43	Beach Ridge active layer temperature	78,05707	13,67991	2004-2021
	44	Isfjord Radio air temperature logger	78,06222	13,61662	2004-2022
	45	Rock glacier active layer temperature	78,04142	13,72658	2004-2023
Aldegondabreen	28	Snow cover survey	77,96976	14,05857	2001-2014 irregular 2015-2019 regular
		Chemical composition of snow	77,96976	14,05857	2015-2019
		glacier stake survey			2011-2019
	29	weather station A1	77,97991	14,10218	2015-2019
	30	weather station A2	77,96483	14,03276	2016-2019
Aldegonda river	31	water level	77,98707	14,18475	2001-2012
		water level; water temperature	77,98707	14,18475	2013-2014
		water level; water temperature	77,98707	14,18475	2015-2019
		water discharge	77,98707	14,18475	2001-2013 irregular, 2014-2019 regular
		sediment discharge	77,98707	14,18475	2001-2013 irregular, 2014-2019 regular
		Chemical composition of water	77,98707	14,18475	2015-2019
Bryde valley	32	Snow cover survey	78,00006	14,06926	2016-2019
		Chemical composition of snow	78,00006	14,06926	2016-2019
Bryde river	33	water level; water temperature	78,00371	14,1533	2016-2019
		water discharge	78,00371	14,1533	2003-2015 irregular, 2016-2019 regular

		sediment discharge	78,00371	14,1533	2003-2015 irregular, 2016-2019 regular
		Chemical composition of water	78,00371	14,1533	2015-2019
Kongressdalen	34	Snow cover survey	78,02422	14,03085	2016-2019
		Chemical composition of snow	78,02422	14,03085	2016-2019
Kongresselva	35	water level; water temperature	78,02833	14,12969	2016-2019
		water discharge	78,02833	14,12969	2003-2015 irregular, 2016-2019 regular
		sediment discharge	78,02833	14,12969	2003-2015 irregular, 2016-2019 regular
		Chemical composition of water	78,02833	14,12969	2015-2019
Vasstak river	36	water level; water temperature	78,0493	14,0724	2019
		water discharge	78,0493	14,0724	2019
		sediment discharge	78,0493	14,0724	2019
		Chemical composition of water	78,0493	14,0724	2019
Kongressvatnet	37	water level, temp.,chemistry, CTD	78,02092	13,95959	2017-2018 irregular, 2019
Stemmevatnet	38	water level, temp.,chemistry, CTD	78,0548	13,96539	2017-2018 irregular, 2019
Linnévatnet	39	CTD-measuments, chemical oomp.	78,04354	13,81572	2018 March
Kapp Linné small lakes	40	CTD-measuments, chemical oomp.			2016-2019; 2019 July