Climate change in Arctic terrestrial ecosystems with particular attention to the vegetation of Svalbard

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Abstract

In the last four decades, warming in the Arctic has been much faster than in the rest of the World. The average air temperature in the Arctic has already risen at a rate of almost four times the global average. On average, the Arctic is now approximately 3°C warmer than it was in 1980. Different Arctic regions – Svalbard in particular – warm faster than any other region on Earth. Such warming has consequences for terrestrial ecosystems. Since plant growth and development are closely linked to the temperature of spring and summer, the early onset of vegetation is one of the most remarkable consequences. Moreover, recent evidence from satellite data suggests there is a temperature-induced increase in growth rate and biomass production of Svalbard vegetation; plant species that dominate the tundra communities are growing taller and more densely. In this chapter, we present an analysis of climatic characteristics recorded at the Adventdalen weather station (operated by The University Centre in Svalbard) with particular attention to vegetation cover. In Adventdalen, community types form five groups of vegetation: (a) sparsely vegetated areas on dry subsoil, (b) sparsely vegetated areas on moist substrate, (c) densely vegetated areas on dry substrate, (d) densely vegetated areas on substrate and (e) areas of organic material. The period of 2011–2020 was analysed, and relations between climatic drivers were evaluated. The presented data support the idea of fast ongoing warming of the Svalbard terrestrial ecosystems.

Keywords: climate warming, Adventdalen, *Dryas octopetala* ridges, moss-dominated tundra, greening/browning scenario

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The Arctic climate

Climatically, the Arctic is defined by an average air temperature in July (isotherm) of +10°C, which well describes the condition of a short cool summer. The cold climate is conditioned by low precipitation, the presence of permafrost and frozen water surfaces for most of the year, which are among the characteristic features of the natural environment of the Arctic.

Recent warming – reality and future scenarios

Climate change and an associated rise in air temperature have been reported in the Arctic in recent decades. The average annual air temperature in the Arctic region (defined by 60°N) increases three to four times faster than the global average (*source*: Intergovernmental Panel on Climate Change report[1]). In addition to the growing body of meteorological data, analyses of satellite imagery have contributed to fundamental insights into the spatial distribution of air temperature in the Arctic. These have confirmed that, in contrast to the central Arctic Ocean, the marginal seas (Kara or Chukchi Seas) and the subarctic regions of the continents are warming at the fastest rate.

Several other factors contribute to the recent trend of climate warming in the Arctic. Among them, changes in atmospheric circulation caused by changes in the strength of the Aleutian and Icelandic pressure lows are of great importance. As the Aleutian cyclone deepens, the southerly flow intensifies in the Alaska region, bringing relatively warm air masses from lower latitudes. Conversely, when the Aleutian low weakens, the northerly (colder) flow from the Arctic Ocean strengthens (Láska 2026a,b - *in press*). The variation in the intensity of the Icelandic cyclone and the Azores anticyclone, known as the North Atlantic Oscillation, is another interacting factor. As the Icelandic cyclone weakens, the westerly flow transports warmer air from the Atlantic and cooler air from higher latitudes to coastal Russia and adjacent marginal seas, respectively.

Within the last four decades, the Arctic has warmed almost four times faster than the rest of the world (Rantanen et al. 2022). This means that the region is on average approximately 3°C warmer than it was in 1980. Regionally, the most significant warming since the mid-20th century has been recorded in the Kara Sea region, where the average annual temperature has increased by 1.13°C per decade. Over the last 30 years, air temperature has increased most rapidly in the central part of West Svalbard. At the Svalbard Airport station, mean annual temperatures have increased by 1.66°C and mean spring temperatures by 3.20°C every 10 years.

Exceptional warming has occurred over the northern Barents Sea area, where the High Arctic Svalbard Archipelago is located, due to the strong decline in sea ice cover. Isaksen et al. (2022) reported temperature increases of up to 2.7°C per decade at the isolated island (Karl XII-øya, located at 80°39′ N), north of the major islands of the north-eastern part of the archipelago. Such warming is unprecedented in this region and exceptional in the Arctic and even on a global scale. The importance of summer temperatures for Arctic (and especially High Arctic) plant growth and distribution is well known (*e.g.* Elmendorf et al. 2012, Walker et al. 2005). In Svalbard, a high correlation between measurements of vegetation growth and June–July temperatures is found (van der Wal and Stien 2014). From a broad-scale bioclimatic zonation study in Arctic Canada, Edlund and Alt (1989) concluded that environmental factors other than summer temperatures were almost insignificant by comparison. Further illustrating the strong relationship between vegetation and temperature in the Arctic, Karlsen and Elvebakk (2003) showed that the distribution of vascular plants in a topographically diverse study area in Greenland could be used to map in detail the local climatic mosaic in terms of growing season temperatures. However, the response of vegetation to higher temperatures is also mediated by other factors, most notably the hydrological conditions (Campbell et al. 2021, Myers-Smith et al. 2015).

Response of Arctic plants to elevated temperature

Arctic vegetation has developed many anatomical, morphological and physiological adaptations to survive harsh, cold growing conditions. Recent warming brings a new aspect into plant ecophysiology in a great variety of Arctic terrestrial ecosystems, since the plants' responses to a generally warmer and drier microclimate are mostly unknown and hardly predictable. In the field, the major question is whether or not vegetation cover area increases or decreases in response to environmental warming of particular Arctic ecosystems (wet and dry tundra and others). Several manipulated warming field experiments have been conducted over the last few decades (*e.g.* Callaghan et al. 2011, Myers-Smith et al. 2020), indicating a clear trend of increase or decrease in vegetation cover according to the temperature resistance of particular species. However, monitoring studies focused on the vegetation response to naturally rising air temperature brought much more mixed and complex responses (Bjorkman et al. 2020). In general, the recent rapid global warming in the Arctic has brought an increase in air and soil temperature; this leads to a prolongation of the growing season for vegetation, resulting in the phenomenon of 'greening' (for review *see* Frost et al. 2025) of Arctic terrestrial ecosystems. The greening is mainly attributed to an increase in the number of shrubs and the area they cover and to their vigorous growth and biomass production. The latter is caused by environmental warming-induced permafrost thaw (Thoman et al. 2023), which results in promoted water and nutrient availability in the soil profile occupied by the root system of the shrubs (Mekonnen et al. 2021).

Recently, intensive research on the responses of vascular plants to Arctic warming has been conducted to predict vegetation changes resulting from the warming and/or the predicted climate change in the next few decades.

In the Arctic, mosses play a key role in the terrestrial ecosystems, where, together with lichens, they form a large part of the vegetation cover. In the tundra, their cover can reach up to 100%. Mosses are also an important component of food chains in the Arctic. Carpets of mosses and lichens in extreme environments host a variety of other organisms, such as microorganisms, fungi, small invertebrates, algae and cyanobacteria. Mosses serve as indicators of climate change because they are sensitive to changes in the environment and competition. Warming of terrestrial environments may bring a change in the share between bryophytes and lichens on the one hand and vascular plants on the other.

For lichens, another constituent of non-vascular autotrophs of vegetated areas, a negative impact on lichen communities is expected. In contrast to the fact that lichens are tolerant to winter warming stress (Finne et al. 2025), many lichen species are vulnerable to extinction as a result of changing climate conditions: specifically, increased temperature and altered liquid water availability. Moreover, macrolichens in the Arctic ecosystems exposed to environmental warming may decline if global warming causes an increase in the abundance of vascular plants (Cornelissen et al. 2001).

The climate warming-induced phenomenon ‘greening of the Arctic’ means an increase in the growth of herbs and shrubs in tundra environments. The phenomenon is linked to increased tundra plant productivity (*e.g*. Raynolds et al. 2011) and attributed to rising air temperature due to climate change (*e.g*. Berner et al. 2020). Analyses of satellite data (available since around 1980), in particular the normalised difference vegetation index (NDVI), have revealed a widespread tundra advance consistent with recent global warming (Ingrosso et al. 2025). Analysis of the period of 2000–2022 (Karlsen et al. 2024) produced evidence that the overall highest greening was found in 2022. This shows a rapid recent greening of Svalbard that is very strongly linked to the temperature increase and consequent increase in the growth and development of vascular plants. The study, however, points out regional differences in ‘the greening’. The eastern parts of Svalbard show the largest variability between years, most likely due to variability in the timing of sea-ice breakup in adjacent areas.

Such changes may result in a reduction in the moss cover area and changes in their species composition and distribution. Reduction of native plant species represents another consequence of warming in the Arctic. The decline of some cold-loving and less competitive bryophytes in the polar regions is thought to be a consequence of the gradual warming of the planet. The warming-induced invasion of non-native plant species from the south to the Arctic regions represents another consequence. A recent study (Speed et al. 2024) suggests that many non-native plant species have a broader macroclimatic niche on Svalbard than they currently occupy.

Response of the vegetation of Svalbard to climate warming

A general trend of climate warming in the Arctic, causing early snowmelt and a prolonged growing season, is thought to be beneficial for vascular plant growth and development. Our study aimes to overview recent state of plant research in Svalbard (*see* Fig. 1) in respect to ongoing climate warming.

Vegetation of Adventdalen

Adventdalen is one of the valleys located close to Longyearbyen, Svalbard.The town, with a population of approximately 2,300, is nestled in a narrow, steep-sided valley on the southern side of the Adventfjorden, the entrance to the larger Isfjord that opens into the Atlantic Ocean on the western side of Svalbard.

Two pivotal factors, namely the extent of open waters in Isfjorden and the persistence of cyclonic atmospheric circulation patterns, shape the local climate in Longyearbyen and neighbouring Adventdalen (Frank et al. 2023).

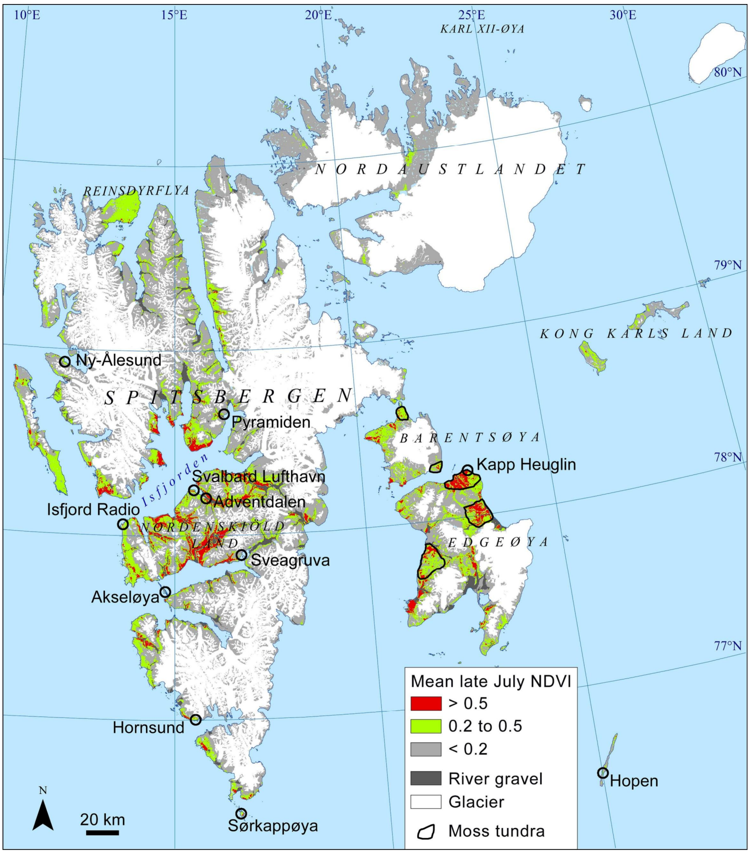

Fig. 1. Map of vegetation-dominated areas in Svalbard. Rich plant communities are indicated by a high value of the normalised difference vegetation index (NDVI higher than 0.2) (indicated by the green and red areas). Adopted from Karlsen et al. (2024).

The region is characterised by the co-ordinates 78° 09′ 55″–78° 10′ 20″ N and 16° 00′ 00″–16° 05′ 00″ E. The vegetation in the lower flat areas is dominated by bryophyte-rich fens and marshes, whereas the more elevated, exposed and dry areas have plant communities dominated by *Salix polaris*, *Cassiope tetragona* or *Dryas octopetala* (Tømmervik et al. 2014). The vegetation types formed in Adventdalen include shrubs and graminoids. The two most common types are mesic meadows and dry heath (Gillespie and Cooper 2022). Vegetation cover is composed of numerous moss and vascular plant species (Rønning 1996, Speed et al. 2010). The dominant vascular species are *D. octopetala, Eriophorum scheuchzeri, Equisetum arvense, C. tetragona* and *S. polaris*. Recently, vegetation components of Adventdalen have been studied using a wide range of methods, including traditional taxonomy and vegetation science (Elvebakk 1994) and more advanced methods, such as aerial photography-based vegetation mapping, Landsat satellite data (Johansen et al. 2012) and remote sensing imagery. The latter approach uses hyperspectral analysis to develop a spectral library for Arctic vegetation (*e.g.* Yang et al. 2023).

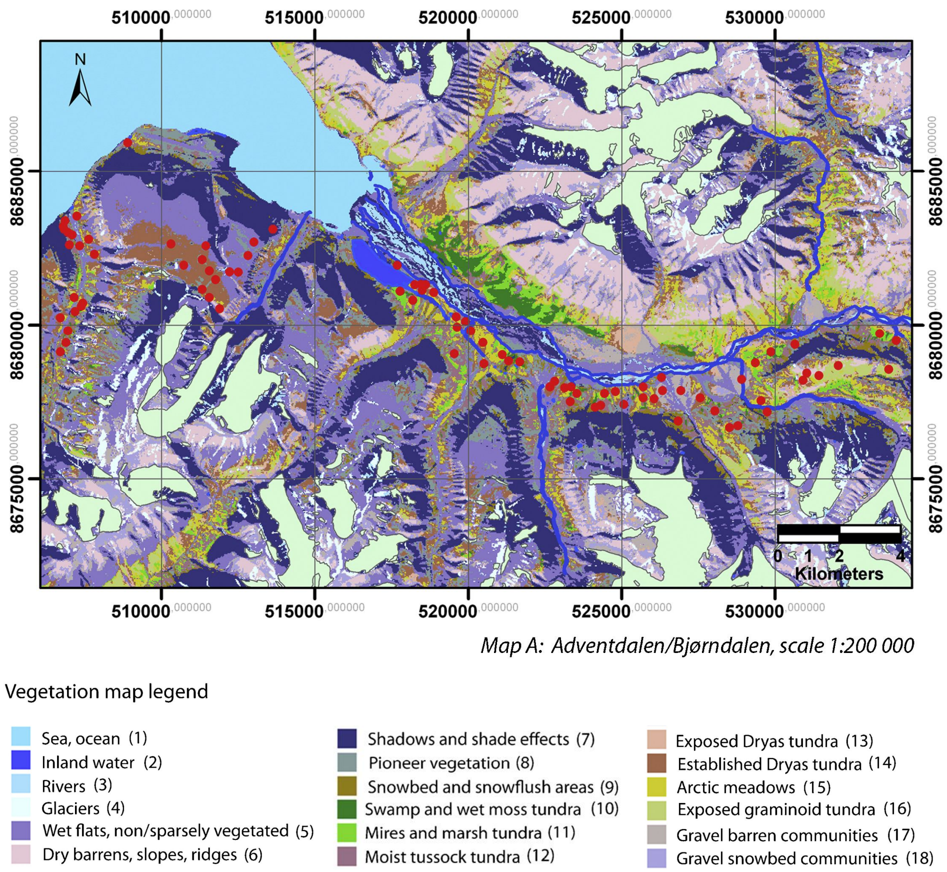

Fig. 2. Map of vegetation components in Adventdalen (Svalbard). The location of the University Centre in Svalbard weather station is indicated by an asterisk. Red dots indicate biomass recording sites. Adopted from Johansen and Tommervik (2014).

The effects of local warming on plants and plant communities in Asventdalen have been studied using numerous approaches. To evaluate the photosynthetic performance of plants forming a tundra community and the effect of warming on permafrost, CO_2 fluxes and net ecosystem exchange were measured in typical plant communities (Cannone et al. 2019, Giamberini et al. 2025). The study confirmed that an increased temperature-induced drying trend could switch ecosystems from sinks to sources of carbon. Manipulated warming by open top chambers and artificial heaters was also used in three plant species (*S. polaris*, *Alopecurus ovatus* and *Bistorta vivipara*) in Adventalen (Iveland 2023, Andersen et al. 2025), indicating that the number of leaves increased with manipulated warming at the end of the growing season (August) due to delayed leaf senescence in the three species.

In Adventdalen, a great variety of moist microenvironments can be found, ranging from relatively dry *D. octopetala*-dominated sites (the Dryas ridges) to moss communities-dominated wet tundra. Recently, a drone-based study of the two vegetation cover types based on NDVI evaluation was performed in Adventdalen (Paulsen et al. 2025).

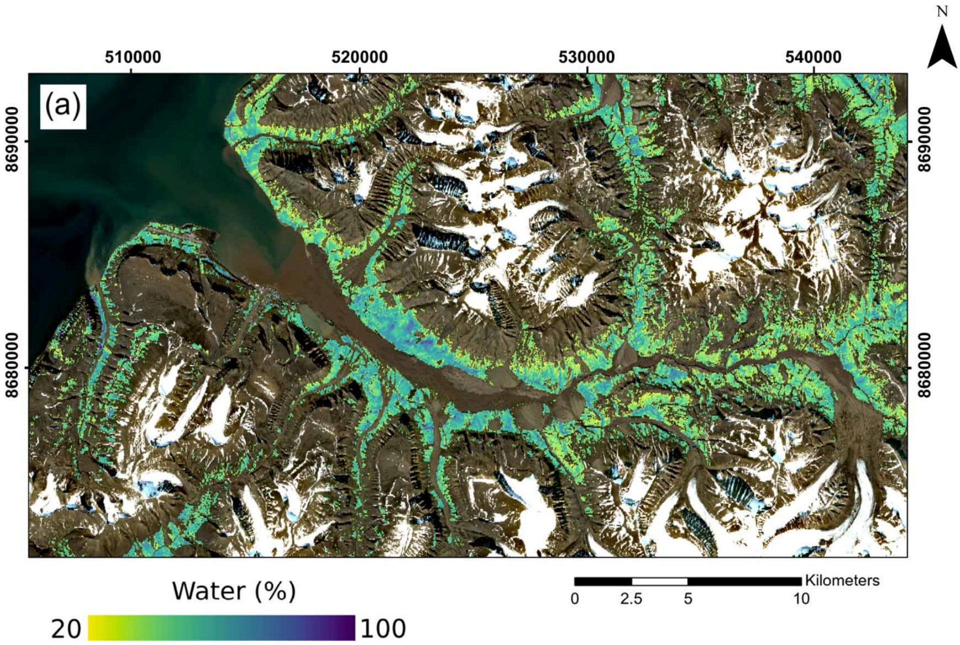

Fig. 3. A map of vegetation water content (false colour scale ranging from 0% to 100%) in Adventdalen created by autonomous underwater vehicle data calibrated by a Sentinel-specific partial least squares regression model (adopted from Thomson et al. 2021).

The study found evidence that the NDVIs derived from the Sentinel-2 mission reached higher values than those acquired with drones in the years 2018–2021. The study also reported that the NDVI differed between the two vegetation covers. It reached 0.4 in the Dryas ridge and 0.6 in the moss tundra. The effect of warming on the NDVI and vegetation biomass was not clear, since the authors reported that, contrary to expectations, the record-warm summers experienced in Svalbard in recent years had no clear association with the NDVI in the corresponding years. Therefore, summer ground temperatures did not have a positive effect on the NDVI. The data indicate that summer ground temperatures in Svalbard may have reached a level that is hampering, rather than enhancing, vegetation.

Material and methods

Trends in the climate – analysis of Adventdalen data

The study area is located in the Adventdalen (Figs. 2, 3), on the Spitsbergen Island of the Svalbard Archipelago (78° 09′ 55″–78° 10′20″N and 16° 00′00″–16° 05′00″E). Adventdalen is a large trough valley surrounded by steep mountains and glaciers with a few side valleys. The area around the river Adventelva has become a large, important wetland area (Barr 2021). The annual mean surface temperature and precipitation are 6°C and 190 mm, respectively.

Fig. 4. Vegetation cover of the Adventdalen: A – Central part of the valley, B – University Centre in Svalbard (UNIS) meteorological station located close to the Adventelva river, C – Wet tundra with patchy stagnant water dominated by mosses (*Sphagnum*). Photos credit: K. Láska (MU Brno).

Since 2009, the weather station of the University Centre in Svalbard (UNIS) has been operating in Adventdalen. The station measures 10 climate parameters (*see* Supplementary materials) and the datasets gained by the station are accessible in the Open database[2]. In our study, data from the period of 2010–2018 were analysed in order to evaluate the markers that indicate most sensitively the ongoing climate change on a local scale. Data from UNIS are acknowledged as the source for analysis. The weather station is located 15 m above sea level (78° 12′ 10″ N, 15° 49′ 51″ E) (Fig. 4).

Climate data processing

Air temperature at the height of 5 (AirT5), 8 (AirT8), and 9 m (AirT9) above ground was analysed. Monthly and yearly mean values were calculated from original data sets measuring the three parameters in 10-m intervals (AirT = [AirT5 + AirT8 + AirT9] / 3). Calculations were made by the EMS software (Mini32 for Win XP/8/10/11, Environmental Measuring Systems, Brno, Czech Republic). Regression analysis was applied to evaluate the relation between AirT5, AirT8, AirT9 and AirT. Vertical air temperature profile data were analysed, and those representing contrasting climatic situations were presented and discussed.

Results and discussion

The data presenting monthly means of AirT (Fig. 5) show that the warmest months are June and July in Adventdalen, when the monthly means are >5°C. However, interannual differences in the temperature of the two months exist, as seen when the warmest and coldest years of the investigated periods are compared. The highest annual mean is seen for the warmest year of 2016 (8.1°C), whereas only 7.3°C was achieved in the coldest year (2010). The mean annual temperature (Table 1) reached the highest value in 2016. The coldest years were 2010 and 2013 as documented by meanT in Table 1 and supported by the generally low values of AirT reached in the winter season (Fig. 5; *see* the bars for January, February, March and April 2010 and April 2013). The general trend of AirT in the period of 2010–2018 shows a slight increase (*see* the blue line in Fig. 5). The rate of AirT increase was found to be 0.37°C per year. Importantly, the highest temperatures are found in the most recent years as documented for the period 2012–2018 by Nordli et al. (2020). The authors reported that 2016 was the warmest year in the whole period and had an annual mean temperature of 0°C (data from the Longyearbyen airport station). The same authors reported that the number of days warmer than 0°C and 5°C has increased by 21% and 59% per year, respectively, for 1991–2018 compared with the 1961–1990 standard normal. These findings of a recent increase in air temperature for Adventdalen have consequences for vegetation cover structure in the area and its seasonal and interseasonal changes. This is consistent with recent findings summarised by Frost et al. (2025), who related the warming of northeast Svalbard to vegetation development evaluated by the NDVI. The authors conclude that due to an increase in mean summer temperature, maximum NDVI values increase in the summer months. Such a response of vegetation to summer warming is supported by the studies of Vickers et al. (2016) and Karlsen et al. (2024), which correlated the maximum value of NDVI with increasing summer warmth. However, rising summer temperatures may result in insufficient availability of water, at least in some parts of the vegetation season, which may consequently result in a reduction of photosynthetic and production processes. Such limitations may lead to the phenomenon of browning of vegetation cover, especially in woody species (for review *see* Phoenix and Bjerke 2016). The phenomenon is typically attributed to milder winters with frequent rain events during the winter period, causing the formation of thick ice layers in the snowpack (Hanssen-Bauer et al. 2019). This results in a later melting of snow and ice and, hence, later liquid water availability for plants, causing browning and damage/injury to different plant species (Bjerke et al. 2017). However, for Adventdalen vegetation, browning due to liquid water insufficiency is improbable since the valley bottom is well fed by water from several sources. For Arctic terrestrial ecosystems with vegetation cover, the probability of greening/browning scenario varies for particular sites and regions due to a complex coaction of environmental characteristics, including georelief and climate characteristics. Recently, a consensus has emerged that the causes and future dynamics of greening and browning trends are more complex, variable and scale-dependent than previously thought.

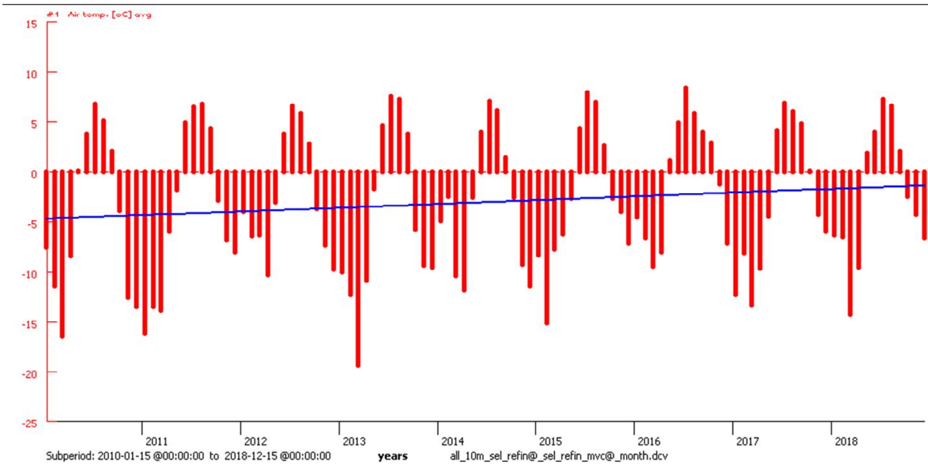

Fig. 5. Monthly means of air temperature (AirT, University Centre in Svalbard data pooled for the measuring heights of 5, 8 and 9 m above ground) recorded in Asventdalen (Svalbard) between 2010 and 2018. The blue line represents the increase in temperature calculated by the pooled measurements at 10 m height (for source, *see* Supplementary materials). For the period of 2010–2018, the rate of increase 0.39°C year^{-1}.

	2010	2011	2012	2013	2014	2015	2016	2017	2018
Mean AirT	−4.65	−3.84	−2.68	−4.59	−3.09	−2.62	−0.86	−3.02	−2.27
std	0.33	0.35	0.34	0.42	0.32	0.32	0.34	0.38	0.35

Table 1. Annual mean air temperature (calculated from pooled data for the measuring height of 5, 8 and 9 m above ground) for the climate station in Asventdalen (Svalbard) between 2010 and 2018. The highest air temperature was reached in the exceptionally warm year of 2016.

Vertical air temperature profiles are presented for a single winter day (Fig. 6) and summer day (Fig. 7) to document the seasonal differences. In the winter period, the typical profile has the lowest air temperature values at the height of 9 m, followed by the air temperature at 5 m, and the highest air temperature is found at 8 m above ground. The order of the air temperature(s) from the lowest to highest remains the same within a day (AirT9 < AirT5 < AirT8). For a fully sunny summer day, contrastingly, the order differs throughout the day. At 00:00, 04:00 and 20:00, the profile is similar to that in winter, following the order (AirT5 < AirT9 < AirT8), indicating that the highest air temperature is achieved at 8 m above ground. During daytime, at 08:00, 12:00 and 16:00, the minimum temperature is found at 8 m above ground, whereas the maximum is typically achieved at 9 m above ground. The order of temperature is (AirT8 < AirT5 < AirT9) for this period of the day.

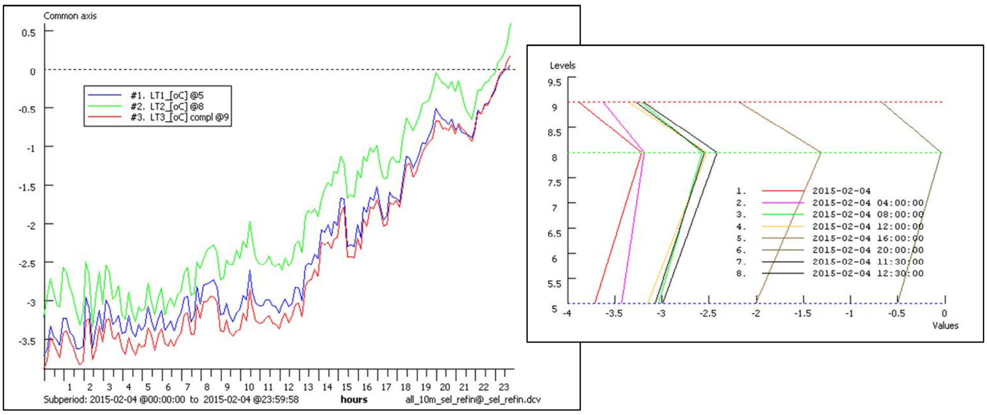

Fig. 6. Daily courses of air temperature measured at the height of 5, 8 and 9 m above ground (AirT5 – blue line, AirT8 – green line and AirT9 – red line) recorded in Asventdalen (Svalbard) for 2 February 2015 (left panel). Vertical air temperature profiles for different times of the day (00:00, 04:00, 08:00, 12:00, 16:00, 20:00) are presented in the right panel.

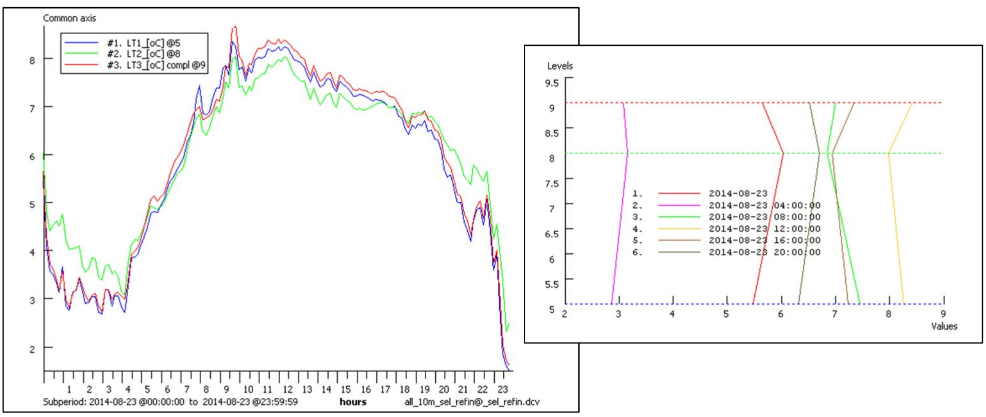

Fig. 7. Daily courses of air temperature measured at the height of 5, 8 and 9 m above ground (AirT5 – blue line, AirT8 – green line and AirT9 – red line) recorded in Asventdalen (Svalbard) for 23 August 2014 (left panel). Vertical air temperature profiles for different times of the day (00:00, 04:00, 08:00, 12:00, 16:00, 20:00) are presented in the right panel.

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Web sources / Other sources

[1] The Intergovernmental Panel on Climate Change (IPCC) Report (https://www.ipcc.ch/)

[2] Open database (https://www.unis.no/facilities/weather-stations/)

Supplementary material

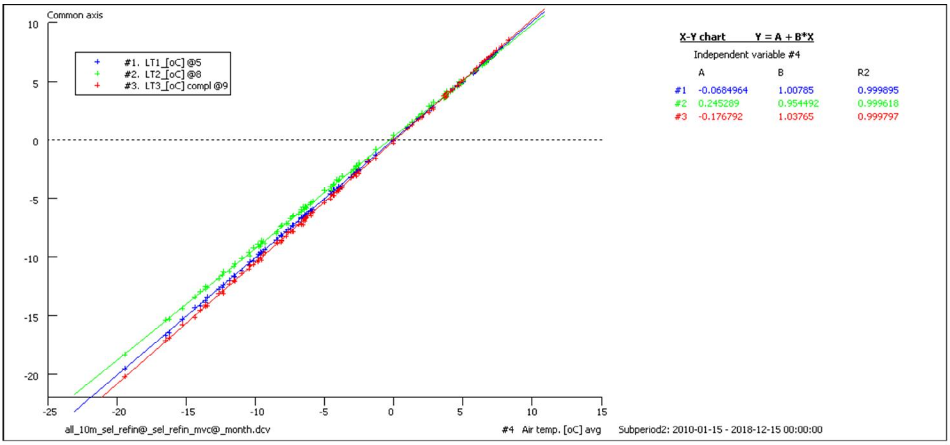

Fig. SM_1. Regression analysis of air temperature in Asventdalen (Svalbard) for the period of 2010-2018. Iindependent variable: average temperature calculater from pooled data for the measuring height of 5, 8, and 9 m above ground), dependent variables: air temperature measured at 5 (AirT5 – blue line), 8 (AirT8 – green line), and 9 m above ground (airT9 – red line). Regression coeficients (A,B) , and R^2 values are presented.

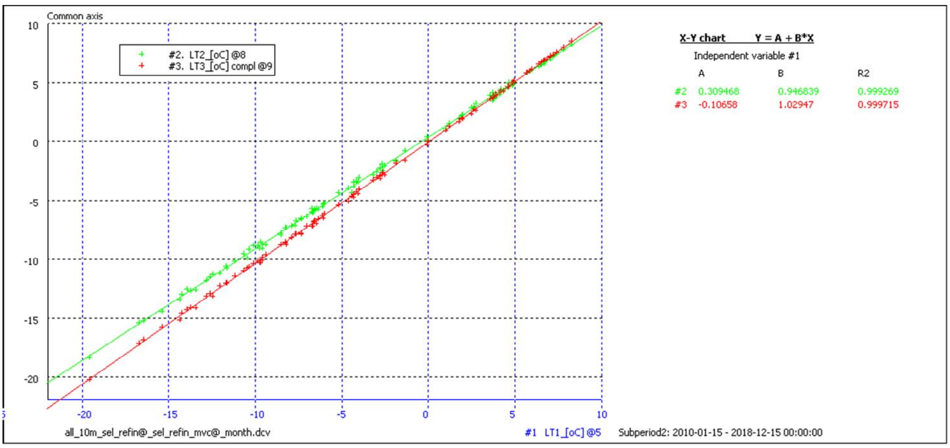

Fig. SM_2. Regression analysis of air temperature in Asventdalen (Svalbard) for the period of 2010-2018. Iindependent variable: air temperature measured at 5 (AirT5), dependent variables: air temperature measured at 8 (AirT8 – green line), and 9 m above ground (airT9 – red line). Regression coeficients (A,B) , and R^2 values are presented.