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Active layer thickening and controls on interannual variability in the Nordic Arctic compared to the circum-Arctic

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Abstract

Active layer probing in northern Sweden, northeast Greenland, and central Svalbard indicates active layer thickening has occurred at Circumpolar Active Layer Monitoring (CALM) sites with long-term, continuous observations, since the sites were established at these locations in 1978, 1996, and 2000, respectively. The study areas exhibit a reverse latitudinal gradient in average active layer thickness (ALT), which is explained by site geomorphology and climate. Specifically, Svalbard has a more maritime climate and thus the thickest active layer of the study areas (average ALT = 99 cm, 2000–2018). The active layer is thinnest at the northern Sweden sites because it is primarily confined to superficial peat. Interannual variability in ALT is not synchronous across this Nordic Arctic region, but study sites in the same area respond similarly to local meteorology. ALT correlates positively with thawing degree days in Sweden and Greenland, as has been observed in other Arctic regions. However, ALT in Svalbard correlates with freezing degree days, where the maritime Arctic climate results in relatively high and variable winter air temperatures. The difference in annual ALT at adjacent sites is attributed to differences in snow cover and geomorphology. From 2000 to 2018, the average rate of active layer thickening at the Nordic Arctic CALM probing sites was 0.5 cm/yr. The average rate was 1 cm/yr for Nordic Arctic CALM database sites with significant trends, which includes a borehole in addition to probing sites. This range is in line with the circum-Arctic average of 0.8 cm/yr from 2000 to 2018.

KEYWORDS
active layer thickness, CALM, climate change, degree days, Nordic Arctic, permafrost

1 | INTRODUCTION

Active layer thickness (ALT) is dependent on meteorological and site variability, including substrate, topography, hydrology, vegetation, and snow cover. ALT and the thermal state of permafrost are the two permafrost-related Essential Climate Variables (ECVs) designated by the Global Climate Observing System.[1] ALTs across the Arctic have increased since the Circumpolar Active Layer Monitoring (CALM) program began in 1995, with maximum and near-maximum thicknesses occurring during 2016–2018.[2–4] The present study examines the increase in ALT observed through 2018 at five CALM probing sites in the Nordic Arctic, specifically in northeast Greenland, central Svalbard,
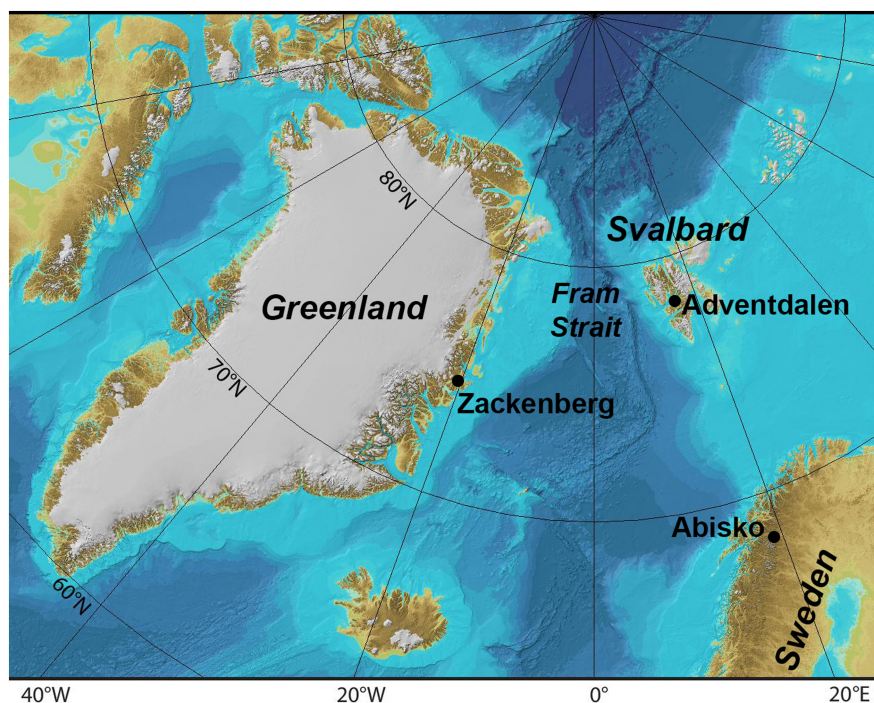
FIGURE 1 The Nordic Arctic and Subarctic, with locations of the CALM grids studied in northeast Greenland, central Svalbard, and northern Sweden. Basemap from Jakobsson et al.[63] [Colour figure can be viewed at wileyonlinelibrary.com]

and northern Sweden (Figure 1). These CALM sites have been operated consistently as part of different monitoring programs, resulting in 41 years of data in northern Sweden, 23 years in northeast Greenland, and 19 years in central Svalbard. Existing in-depth analyses of these data series are over a decade old, and have never been compared in a regional study.

The Nordic region encompasses a continuum of permafrost types. Isolated permafrost exists in palsas and peat hummocks in Iceland, Norway, Sweden, and Finland,[5,6] while permafrost is continuous in the periglacial landscapes of Svalbard and most of northern Greenland.[7–10] Mean annual ground temperatures (MAGTs) in permafrost in this region are higher than in other high-Arctic locations because of the climatic influence of the warm Norwegian Current, which extends into the West Spitsbergen Current in the eastern side of the Fram Strait.[11,12] However, Greenland has a relatively cold climate and thus thinner ALT due to more extensive sea ice and the cold East Greenland Current flowing south along Greenland's shelf.[13,14] The contrast of these currents and their influence results in a large climatic gradient across the Fram Strait. The purpose of the present study is to assess how this climatological setting, in addition to site geomorphology, affects ALT, and to determine the magnitude and variability in active layer thickening at the Nordic CALM probing sites with continuous, long-term records. These results are contextualized in the circum-Arctic through the analysis of ALT data from all Arctic sites in the CALM database.[15]

1.1 | Study areas

There are six active CALM sites in the Nordic region; this study uses data from the five sites that have active, continuous mechanical

probing data series of at least 10 years. These five sites are operated in fine-grained sediments or peat, allowing the probing technique to be used, and are located within three study areas. The utilized data series are 19–41 years long, allowing for the assessment of meteorological control on ALT trends and interannual variability. All data are available through the CALM database.[15]

1.2 | Adventdalen, Svalbard

The UNISCALM site is located at 78°N in central Spitsbergen, Svalbard, in the Adventdalen sediment-infilled fjord-valley (Figure 2). Permafrost is continuous in Svalbard's periglacial landscape, which exhibits several permafrost-controlled landforms including pingos and ice wedges.[9] Svalbard has a maritime Arctic climate, with winter air temperatures substantially higher than those at other Arctic sites of the same latitude.[16,17] Mean annual air temperature (MAAT) at the Svalbard Airport, located ~10 km northwest of the UNISCALM site, was −5.9°C from 1971 to 2000, and mean annual precipitation during the same period was 196 mm.[18] In 2018, MAAT was −1.8°C and annual precipitation was 177 mm.[19] From 1971 to 2017, MAATs at Svalbard meteorological stations increased 3–5°C, with the largest seasonal temperature increase occurring during winter and the smallest during summer.[18] During this same period, precipitation has generally increased in autumn and winter, and decreased in spring and summer, although few of these trends are significant.[18]

UNISCALM is located 10 m a.s.l. in a loess deposit on a flat terrace of the Adventelva river plain.[20] At this site, the loess is ~2.5 m thick and consists of laminated silt and well-sorted fine- to very fine-grained sand that has been bioturbated by plants.[21] The site has patchy vegetation consisting of dwarf willow, sedges, and mosses.[22]

FIGURE 2 UNISCALM in Adventdalen, central Svalbard; ZEROCALM1 and ZEROCALM2 in Zackenberg, northeast Greenland; and the Storflaket and Heliport sites at Abisko, in northern Sweden. [Colour figure can be viewed at wileyonlinelibrary.com]

Winds are funneled through Adventdalen, resulting in thin (<30 cm) snow cover over the measurement grid in winter.[23] From January to March 2013, snow depth averaged 18 cm at this site[24]; this snow depth is considered representative of other years based on field observations.

The UNISCALM site grid is 100 × 100 m with 10 m node spacing, resulting in 121 measurement points. The UNISCALM grid is probed periodically during the thawing season, typically from May to the end of September or beginning of October. From 2000 to 2018, thaw depths were measured eight times during the thawing season, on average, corresponding to an approximate frequency of 2 weeks.

Some years have less frequent measurements, but the grid has always been measured multiple times each year since 2000.[20]

1.3 | Zackenberg, northeast Greenland

Two CALM sites have been operating in Zackenberg, northeast Greenland (74°N) since 1996: ZEROCALM1 and ZEROCALM2. Zackenberg lies in the zone of continuous permafrost on Greenland's northeast coast, ~60 km east of the margin of the Greenland Ice Sheet. The CALM sites are located in the Zackenberg valley, which

contains Quaternary glacial and periglacial landforms including moraines, meltwater plains, a raised delta, and large alluvial fans.[25–27] From 1996 to 2015, MAAT at Zackenberg was −9°C and mean annual precipitation was 218 mm.[28] From 1997 to 2014, the highest monthly mean air temperature was 6.3°C in July and the lowest was −19.8°C in February.[29] Thus, Zackenberg has a lower MAAT than central Spitsbergen, with colder winters and slightly cooler summers.

The ZEROCALM1 grid is 100 × 100 m with 10 m node spacing, resulting in 121 measurement points. ZEROCALM2 also has 10-m node spacing, but is 120 × 150 m to accommodate a snow patch, and thus has 208 measurement points. Thaw progression in the ZEROCALM grids has been monitored from late May or early June to early September since 1996, as part of Zackenberg Ecological Research Operations (ZERO). The complete thaw depth data series are available from the GeoBasis program of the Greenland Ecosystem Monitoring database.[30] Christiansen[31] has described the two ZEROCALM sites in detail and presented snow cover and grid thaw progression data for 1996–2002. ZEROCALM1 is located 36–37 m a.s.l. on a slightly sloping (0–2°) ground moraine, consisting of fine-grained sediments with occasional cobbles and few boulders. The site is vegetated with a homogeneous heath cover. Between 1998 and 2002, maximum snow depth in the southern part of ZEROCALM1 ranged from 40 to 105 cm. The ZEROCALM2 site contains two fluvial bar deposits (10–12 and 20–22 m a.s.l., respectively) with a 14° south-facing slope between them; a snow patch >1.2 m deep accumulates on this slope and persists into the summer, impacting thaw depths. Distinct vegetation zonation of shrubs, dwarf willow, mosses, and grasses at ZEROCALM2 reflects snow cover extent and duration in the different parts of this site.[31]

1.4 | Abisko, northern Sweden

Abisko is located in northern Sweden in the Torneträsk region (68°N), where discontinuous and sporadic permafrost occurs.[32–34] Discontinuous permafrost is widespread in the mountains surrounding Abisko above 800–1000 m a.s.l.,[35] while permafrost is sporadic at lower elevations, occurring in peat mires.[36] From 1985 to 2010, MAAT at Abisko was 0.02°C and mean annual precipitation was 330 mm.[37] Abisko has a continental, subarctic climate, meaning the coldest month has a mean temperature <0°C and the warmest month has a mean temperature >10°C.

ALTs have been reported from mechanical probing at multiple sites in the Abisko area,[33] and data from 11 sites are averaged into one annual ALT value for Abisko in the CALM database. Data from the individual Heliport (378 m a.s.l.) and Storflaket (383 m a.s.l.) sites are presented here, as these sites have standardized 100 × 100 m grids with 121 measurement points (10 m node spacing), and the longest and most continuous data series from the study region. The Storflaket site is an ~1 km² peat plateau with Sphagnum peat 60–90 cm thick.[38] The Heliport site is a slightly smaller peat plateau. The active layer was previously confined to the upper peat layer at both sites,[39] but recently includes part of the underlying fine-grained

sediment. These grids are measured once annually around the time of maximum thaw depth, typically the third week in September.[33] Probing data exist for Heliport and Storflaket since 1978, but the 121-point grids were not established until 1994. From 1978 to 1986, probing was done in a transect, and from 1987 to 1993 measurements were made in a smaller 10 × 10 m grid. The two sites are located relatively close to the meteorological observatory of the Abisko Scientific Research Station.

2 | METHODS

2.1 | Active layer probing and Nordic CALM grid data

ALT has been determined at all the sites using mechanical probing, according to the monitoring methods defined by the CALM program.[1] In this method, a steel rod is inserted perpendicular to the ground surface until complete resistance is met at the top of the frost table. Thaw depth is defined as the depth the rod is inserted into the ground; measurements are recorded at the grid nodes. A grid thaw depth average was calculated from all grid point values for each day with thaw depth measurements. ALT is the maximum grid thaw depth average in any given year for the Zackenberg and Svalbard sites. For the sites at Abisko, ALT is assumed to be the thaw depth average in the grid during annual measurement in the second half of September, which is the period of maximum thaw in this area.[33] It should be acknowledged that the reliability of ALT data from probing can be impacted by operator strength, interference of buried clasts, and the potential difference between the frost table and the 0°C isotherm[40]; however, these issues are not considered to be significant at the selected Nordic sites given site geomorphology and the authors' probing experience.

2.2 | CALM database and Arctic ALT trends

Annual ALT data from Arctic sites in the CALM database[15] were analyzed to compare the Nordic results to the entire Arctic. The CALM summary data span the years 1990–2018 and include both Arctic and lower-latitude sites in the Subarctic, Alps, and Tibetan plateau. In these data, ALT has been determined through mechanical probing, frost-tube measurements, or ground temperature interpolation from borehole measurements. There are three Svalbard sites in the CALM database that are not individually discussed in this paper (IT1, N1, and S1), as they did not fit the criteria of having active, continuous mechanical probing data series of at least 10 years. These sites are Ecogrid (IT1), a newer probing grid with only six years of data, Janssonhaugen (N1), a borehole in bedrock, and Kapp Linné (S1), an inactive probing site with noncontinuous data. Additionally, Abisko is listed as one site in the CALM database, but has been subdivided into two sites for the CALM summary analysis, given that the full Heliport and Storflaket grid data are available. Annual ALT values from

all sites above the Arctic Circle (66°33′N) with at least 10 consecutive years of ALT data within the periods 1990–2018 (79 sites) and 2000–2018 (75 sites) were used to assess regional ALT variability and long-term trends. Shiklomanov et al.[41] also required 10 consecutive years of data for their determination of long-term, regional active layer trends. The Arctic sites that meet these criteria are located in nine different regions: the Alaska North Slope, Canada (which is not further subdivided in the CALM database), northwest Russia, western Siberia, central Siberia, northeast Siberia, central Svalbard, northeast Greenland, and northern Sweden. Reported regional averages are the mean of all annual ALT values of all sites within a region. The rate of change in ALT (cm/yr) was calculated for the Arctic sites using linear regression. Trends were considered significant for p-values ≤0.05. CALM summary data processing and the computation of ALT trends and statistics were done in MATLAB version R2019b.[42]

2.3 | Meteorological data

Daily mean air temperatures were used for the determination of freezing and thawing degree days. Daily mean air temperatures for Svalbard Airport, located ∼10 km northwest of the UNISCALM site, were obtained from eKlima, the online meteorological database hosted by the Norwegian Meteorological Institute.[19] Daily mean air temperatures from the meteorological station at the Abisko Scientific Research Station were obtained from the Swedish Polar Research Secretariat.[43] Hourly air temperatures for Zackenberg were downloaded from the GEM database (ClimateBasis program)[30] and were used to calculate daily mean air temperatures. Air temperatures for all three locations were measured 2 m above the ground. The daily mean air temperatures were also used to calculate MAAT during the study period.

ALT and air temperature are commonly related by a variant of the Stefan equation (Equation 1):

$$Z = E\sqrt{TDD} \qquad (1)$$

where Z is ALT, TDD is the thawing degree days, and E is the edaphic factor, which is a scaling parameter dependent on site conditions.[1,44] Thawing degree days were calculated by summing positive daily mean air temperatures during each thawing season. The start and end dates of thawing seasons were defined by the local minimum and maximum of the summation curve of daily air temperatures from each calendar year.[45] FDD values were calculated by summing negative daily mean air temperatures during each freezing season, starting after the local maximum in the summation curve of daily air temperatures from each calendar year, and ending at the local minimum. Because the resulting value is negative, the absolute value of FDD was used to compute the square root. The edaphic factor, E, was calculated using Equation 1 given the known ALT and $\sqrt{TDD}$ values. Trends in ALT relative to year, MAAT, $\sqrt{TDD}$, and $\sqrt{FDD}$ were determined by fitting linear regression models to the available data using the least-squares method; this was done in R version 3.6.2.[46]

3 | RESULTS

3.1 | Nordic ALT and climate

Of the studied Nordic probing sites, the active layer is thickest at UNISCALM, typically ranging between 90 and 110 cm with an average of 99 cm (standard deviation = 8 cm) from 2000–2018 (Figure 3). The active layer is thinnest in the mires near Abisko: 47–81 cm at Storflaket and 44–91 cm at Heliport. Average ALT from 1978 to 2018 is 63 cm at Storflaket (standard deviation = 9 cm) and 64 cm at Heliport (standard deviation = 14 cm). ALT at ZEROCALM2 is of similar magnitude, ranging from 44 to 75 cm with an average of 64 cm (standard deviation = 8 cm) from 1996 to 2018. The active layer at ZEROCALM1 is somewhat thicker than at ZEROCALM2 and the Abisko sites; it ranges from 58 to 85 cm with an average of 73 cm (standard deviation = 8 cm) from 1996 to 2018. Over the period 2000–2018, when there are ALT data for all five sites, average ALT is as follows: 99 cm at UNISCALM, 70 cm at Storflaket, 78 cm at Heliport, 75 cm at ZEROCALM1, and 66 cm at ZEROCALM2. Over this same period, standard deviation was 8 cm for Heliport and UNISCALM, 7 cm for both ZEROCALM sites, and 5 cm for Storflaket.

Both MAAT (Figure 4) and ALT (Figure 3) have increased at all the sites during the period of CALM measurements. Utilizing each site's full time series, ALT increase was statistically significant at all of the sites except ZEROCALM2, with p ≤ 0.01 at the Abisko and ZEROCALM1 sites, and p ≤ 0.05 at UNISCALM. Assessed through linear regression over each site's full time series, ALT has increased 0.7 cm/yr at UNISCALM and ZEROCALM1, 0.4 cm/yr at ZEROCALM2, 0.6 cm/yr at Storflaket, and 1.0 cm/yr at Heliport. Using the common period 2000–2018, Heliport and UNISCALM maintain the highest rates of ALT increase and exhibit the same rates of increase over 2000–2018 compared to the sites' full time series (1.0 cm/yr for Heliport and 0.7 cm/yr for UNISCALM). Over this shorter period, the rate of ALT increase is greatly reduced for Storflaket (0.3 cm/yr), ZEROCALM1 (0.4 cm/yr), and ZEROCALM2 (0.0 cm/yr) and is not significant based on a p-value ≤ 0.05. The average of all five 2000–2018 rates is 0.5 cm/yr. Over the period 2000–2018, based on linear regression, increase in ALT was 17 cm at Heliport, 13 cm at UNISCALM, 7 cm at ZEROCALM1, 6 cm at Storflaket, and 1 cm at ZEROCALM2.

The running averages of MAAT at each study area (Figure 4) show the same broad pattern in recent years with a peak in air temperatures from 2005 to 2007, and a relative minimum following in 2009–2012. Svalbard MAAT increased ∼5.2°C from 1980 to 2018 (assessed by linear regression), a substantially greater increase than at the other sites. There is some synchronicity in MAAT extremes between the locations, particularly between the two high Arctic sites of Svalbard and northeast Greenland, both of which have the highest MAAT on record in 2016. This extraordinarily warm year in the high Arctic is reflected in relative maxima in ALT at UNISCALM, ZEROCALM1, ZEROCALM2, and Storflaket (Figure 3). Aside from this example, interannual variability in ALT between the three study areas is not contemporaneous. However, there is synchronicity between
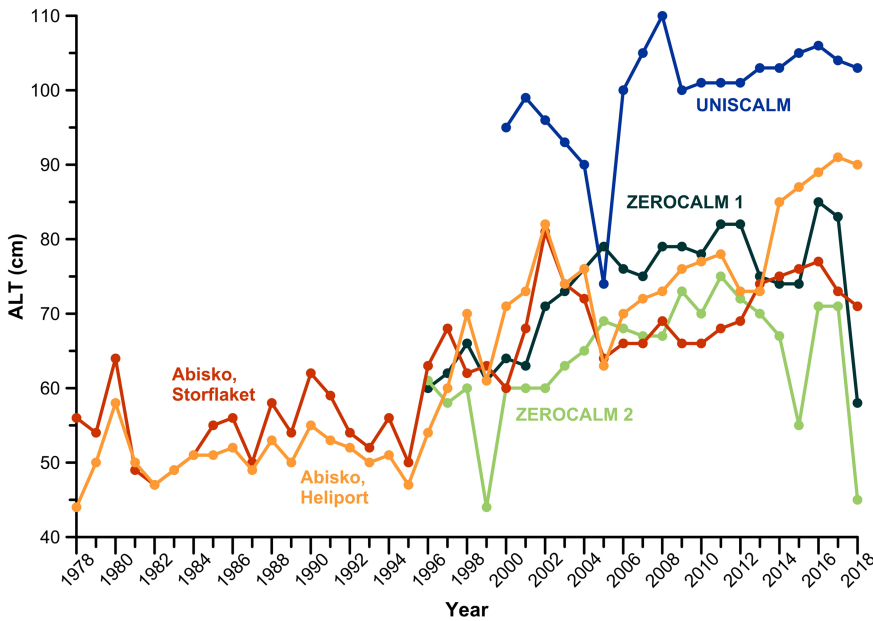
FIGURE 3 Active layer thickness (ALT, cm) at the studied Nordic Arctic CALM sites. [Colour figure can be viewed at wileyonlinelibrary.com]
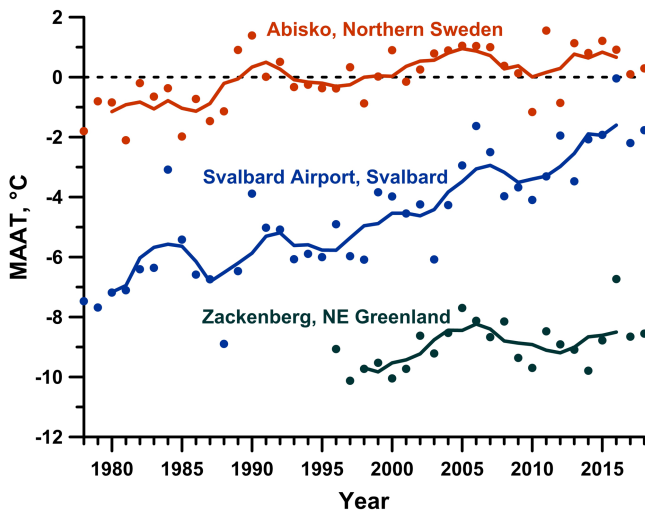

FIGURE 4 Mean annual air temperature (MAAT) at the three study areas from 1978 to 2018. Air temperature data for Zackenberg are available from August 1995, so this MAAT record starts from 1996. The lines show the MAAT 5-year moving average. [Colour figure can be viewed at wileyonlinelibrary.com]

the paired grids' data series at both Zackenberg and Abisko, where both grids in the same area generally have the same years of ALT maximum and minimum. This is especially true for the ZEROCALM sites. In 2018, both ZEROCALM sites had minimum or near-minimum ALT; the 2018 thawing season also had the lowest TDD value of the Zackenberg observation period (Figure 5).

ALT at both the ZEROCALM sites and the Abisko sites correlated positively with $\sqrt{TDD}$ ($p \leq 0.01$). ALT at these four sites did not correlate with $\sqrt{FDD}$. Conversely, ALT at UNISCALM did not correlate with $\sqrt{TDD}$ ($p = 0.13$, $R^2 = 0.13$, $n = 19$), but correlated weakly with $\sqrt{FDD}$ ($p = 0.05$, $R^2 = 0.21$, $n = 19$) (Figure 6). The relationship with $\sqrt{FDD}$ is statistically significant based on a p-value ≤ 0.05. The

edaphic factor (E) was lowest at the Abisko sites: 1.7 at Storflaket and 1.8 at Heliport. E was highest at UNISCALM (4.0) and was 3.4 for ZEROCALM1 and 3.0 for ZEROCALM2. Standard variation in E was relatively low and consistent across the five sites, ranging from 0.2 to 0.3.

3.2 | Nordic ALT in the context of Arctic ALT

There is considerable variation in all the ALT values at Arctic CALM database sites from 1990 to 2018 (Figure 7a). ALT ranged from a minimum of 23 cm at the Barrow CRREL plots (site U2, CALM database) in the Alaska North Slope in 1991 and 1992, to a maximum of 197 cm at the Janssonhaugen borehole, Svalbard (site N1, CALM database) in 2016. Average ALT during the period 1990–2018 was highest in Svalbard (mean = 126 cm) and lowest in the Alaska North Slope (mean = 48 cm). The circum-Arctic average ALT (average of the nine regional ALT averages) was 80 cm. The average of the Nordic region ALT averages was 87 cm (including all Nordic Arctic CALM sites, not just the probing sites, as described in the Methods). The spread in ALT values is lowest for northeast Greenland and northern Sweden, as these areas only have two CALM sites each, with adjacent sites in the same field area.

In total, 84% of the Arctic sites (66 of 79) exhibited positive trends in ALT during the period 1990–2018, and 91% of sites exhibited positive trends when the period is restricted to 2000–2018. Significant trends ($p \leq 0.05$) in ALT were observed at 42% of sites (33 of 79) from 1990 to 2018, and 49% from 2000 to 2018 (Figure 7b,c). All of the significant trends were positive, indicating active layer thickening, except at Taglu in the Mackenzie Delta in Canada (site C4 B in the CALM database), where a decrease in ALT was observed. More than 50% of sites in northwest Russia, northeast Siberia, Svalbard, and northern Sweden exhibited significant trends during 1990–2018, although the number of sites varies greatly
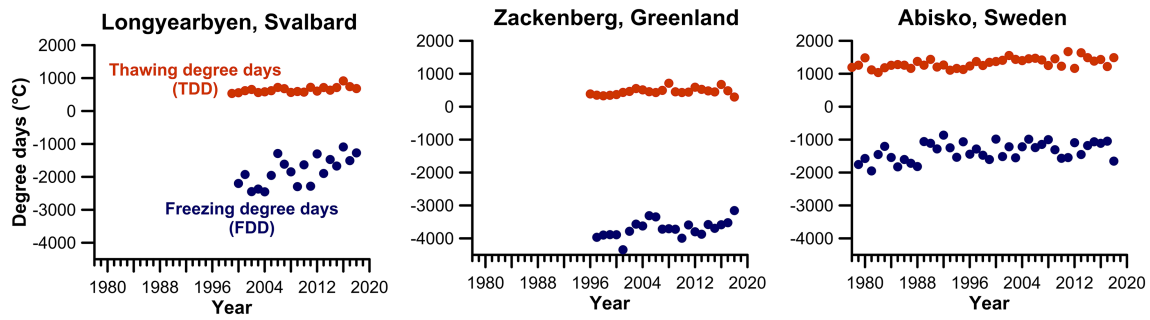
FIGURE 5 Thawing and freezing degree days at the three Nordic Arctic study areas during the years of CALM measurements. [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 6 Active layer thickness and square root of FDD and TDD at the studied Nordic CALM sites. Regression lines and R^2 values are indicated for significant linear regressions; black regression lines have p-values ≤ 0.01 and the dotted regression line (UNISCALM) has a p-value ≤ 0.05. [Colour figure can be viewed at wileyonlinelibrary.com]
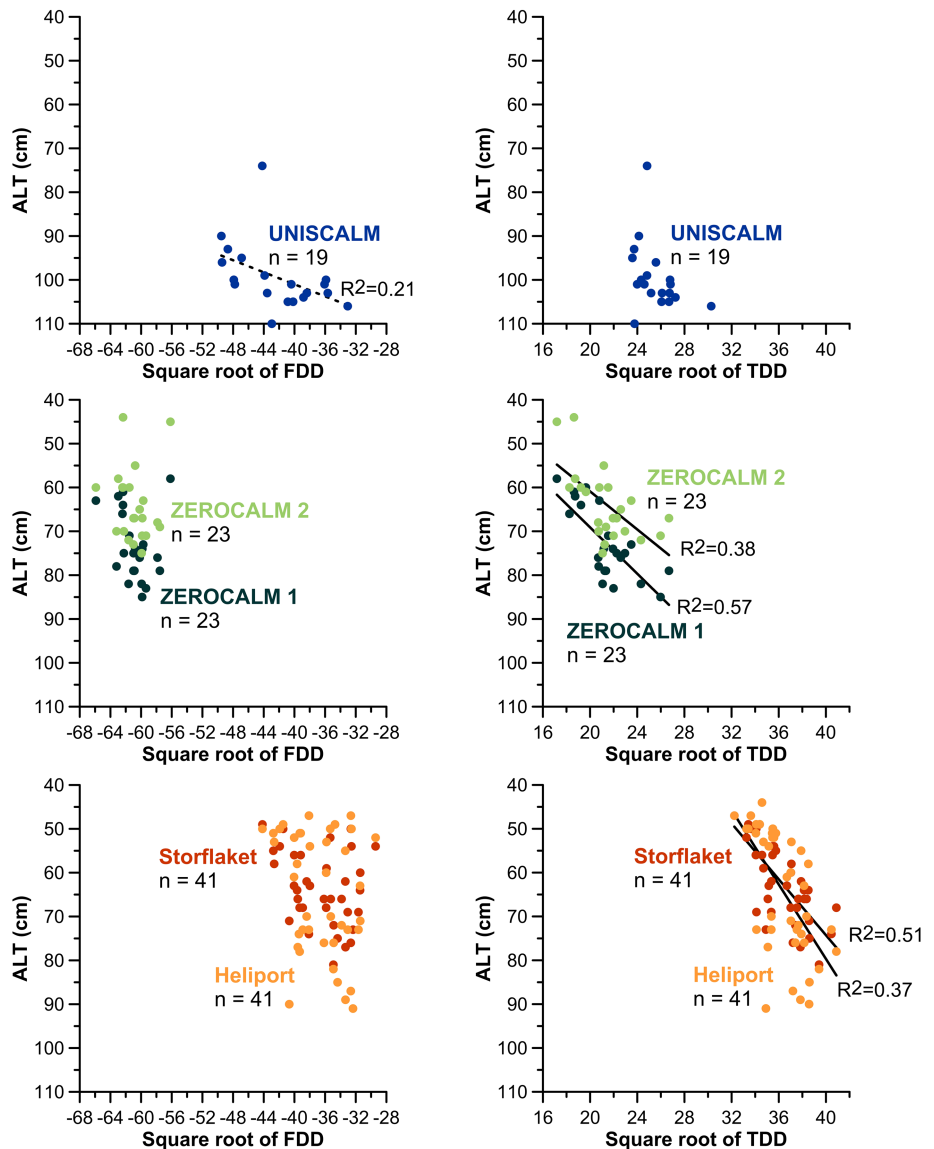
between these regions (from $n = 2$ in northern Sweden to $n = 13$ in northeast Siberia). At the Alaska North Slope, the region with the most sites, 40% of sites had significant trends during 1990–2018 and 66% of sites had significant trends during 2000–2018. The largest rate of ALT increase (3.7 cm/yr, 1990–2018) was observed at Talnik in northwest Russia. For both the 1990–2018 and the 2000–2018

study periods, the mean ALT rate of change of all sites with significant trends, regardless of region, was 0.8 cm/yr. The Nordic subset of the CALM summary sites with significant trends had a mean ALT rate of change of 1 cm/yr, also for both the full and the shortened time period. This Nordic subset of CALM summary sites with significant trends includes the Janssonhaugen borehole on Svalbard (site N1), in
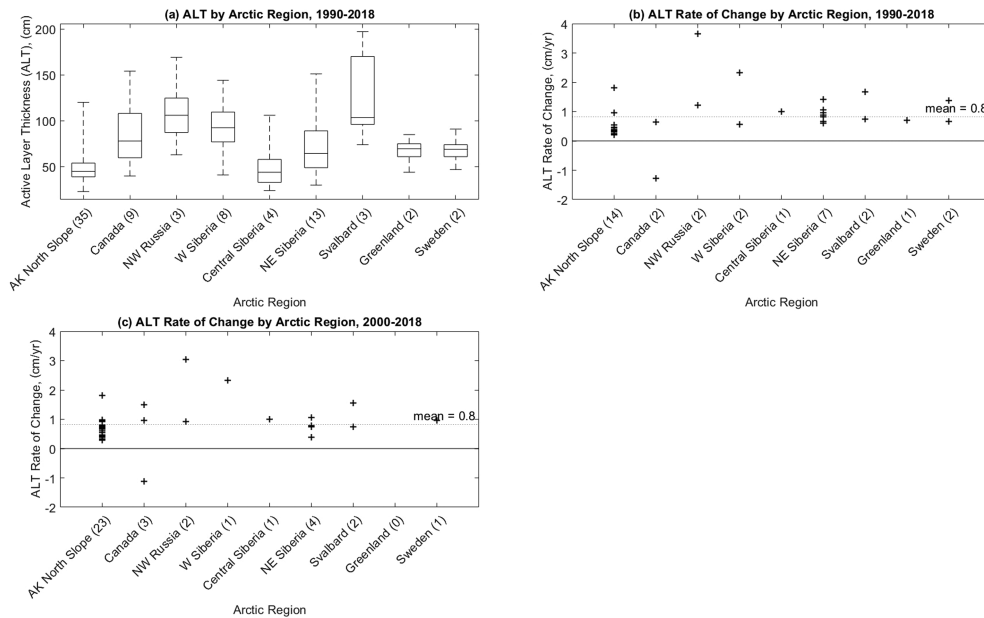
FIGURE 7 (a) Box plots showing all reported ALT values from all Arctic sites in the CALM database with at least 10 consecutive years of data during 1990–2018, separated into the nine designated Arctic regions. The box center lines indicate median ALT, the box top and bottom edges indicate the 25th and 75th percentiles, respectively, and the dotted whisker lines extend to the minimum and maximum values. (b) ALT rate of change (cm/yr) in the nine Arctic regions over the period 1990–2018; only the 33 significant trend rates ($p \leq 0.05$) are shown. (c) ALT rate of change (cm/yr) in the nine Arctic regions over the period 2000–2018; only the 37 significant trend rates ($p \leq 0.05$) are shown. For all three panels, the numbers in parentheses on the x-axis indicate the number of observations per region

addition to the probing grids presented in this study. At Janssonhaugen, where thaw depth is inferred from borehole temperature measurements in bedrock, ALT increase was 1.6 cm/yr from 2000 to 2018, a higher rate of change than observed at any of the probing grids.

4 | DISCUSSION

4.1 | Climatic and geomorphological controls on ALT in the Nordic region

A reverse latitudinal gradient is observed in ALT among the three probing study sites, with UNISCALM, the northernmost site at 78°N, having the thickest active layer and the Abisko sites at 68°N having the thinnest. In addition, Svalbard has the largest mean ALT and highest observed ALT values of the nine Arctic regions in the CALM database, despite having the highest-latitude cluster of sites. This goes against the broad pattern in the Northern Hemisphere, where the active layer is thinnest near the pole and thicker in the Subarctic.[47] However, the difference between ALT at the three Nordic sites is well explained by a combination of geomorphology and climate. MAAT at Zackenberg is substantially lower than at Svalbard Airport (−8.6°C vs. −1.8°C in 2018), due to the large climatic gradient across the Fram Strait and Svalbard's maritime Arctic climate. Winters are substantially colder with lower FDD values at Zackenberg compared to Svalbard (Figure 5). These climatic differences are directly reflected in ALT, as ALT at UNISCALM is 26 cm thicker than at ZEROCALM1,

on average. Although MAAT at Abisko is higher than at the other two locations, ALT is relatively thin due to the Abisko site locations in peat plateaus, where the active layer is mostly confined to the surficial peat layer. The active layer is generally thin in poorly drained and well-vegetated areas, as at Abisko, and is thicker in areas of well-drained soil,[47] as at UNISCALM.

4.2 | Interannual variability and trends in ALT in the Nordic region

Interannual variability, inferred by standard deviation in ALT values, is of similar magnitude for the five sites from 2000 to 2018 (standard deviation ranges from 5 to 8 cm). When each site's full time series is used, variability in ALT is highest at the Abisko sites. Åkerman and Johansson (2008) noted an acceleration in ALT increase around Abisko from 1997 onwards, which they attributed to increased mean summer air temperatures and, to a lesser extent, snow depths.[33] This acceleration in ALT increase is reflected in the first and second halves of the 1978–2018 Abisko data series having noticeably different means and variability. It is also possible that changes in probing methods have impacted the data series; in 1994 standard CALM grids were established, whereas previous measurements were made in smaller 10 × 10 m grids or in transects. The similar interannual pattern in ALT within the ZEROCALM and Abisko grid pairs indicates that the active layer within an area responds synchronously to site meteorology, but the magnitude of ALT is dependent on characteristics within the grid where it is measured. Snow cover and duration is the primary

driver of ALT difference between the ZEROCALM sites,[31] while peat thickness, wetness, and microtopography all play a role in ALT differences within and between the Abisko sites.[33,38] The absence of an overall Nordic region-wide pattern in ALT is not surprising, given the substantial climate differences that exist between northeast Greenland, Svalbard, and northern Sweden, in addition to the sites' varying geomorphology.

The rate of increase in ALT is relatively similar for all the sites, ranging between 0.6 and 1.0 cm/yr at the sites with significant trends, and 0.4 cm/yr at ZEROCALM2. The difference in ALT increase between sites in the same study area also supports the importance of site-specific characteristics. The lack of a statistically significant trend at ZEROCALM2 can be attributed to substantial interannual variability caused by snow dynamics. Minimum ALT values in 1999, 2015, and 2018 are all due to the snow patch at this site persisting through the thawing season, precluding thaw in the portion of the grid that it covers.[31,48] In 2018, both ZEROCALM sites had minimum or near-minimum ALT; this is explained by an unusually large amount of snow and extraordinarily late snow melt at Zackenberg that year.[48] Åkerman and Johansson[33] found that ALT responded to snow depth at five of nine sites in the Abisko region, but this correlation was not as strong as that between ALT and TDD. Given that snow cover is consistently thin at UNISCALM,[23] snow depth is not thought to be a relevant forcing factor of ALT at this site. Comparable, regular snow measurements are not available for all of the Nordic sites, and thus it was not possible to calculate and report regression statistics for ALT and snow depth.

4.3 | Relationship between ALT, TDD, and FDD in the Arctic

ALT is usually assumed to be controlled by conditions during the thawing season, and thus is often positively correlated with TDD on the basis of the Stefan equation (Equation 1). Positive correlation between ALT and $\sqrt{\text{TDD}}$ has been observed in Alaska,[49,50] Canada,[51] and at Abisko.[33] ALT in the grids at Zackenberg and Abisko is statically significantly correlated with $\sqrt{\text{TDD}}$, and thus follows the commonly assumed relationship. These areas have a more continental climate than Svalbard, with a greater difference in summer and winter temperatures. The weaker correlation between ALT and $\sqrt{\text{TDD}}$ at ZEROCALM2 ($R^2 = 0.38$) compared to ZEROCALM1 ($R^2 = 0.57$) can be explained by the grid's snow patch, which results in a drawn-out snowmelt period throughout the summer and thus variations in the onset of thaw between grid points.[31]

The edaphic factors, which represent soil thermal properties (thermal conductivity, bulk density, water content, and latent heat effects) combined with the thawing season n factor,[52] indicate landscape and macroscale geomorphology differences between the three study areas. The edaphic factor is lowest at the Abisko sites (1.7 and 1.8), where there is a peat layer that insulates the ground in summer. The edaphic factor is highest at UNISCALM (4.0), where there is little vegetation and fine-grained mineral soils with relatively high thermal conductivity.

At UNISCALM, ALT does not correlate with $\sqrt{\text{TDD}}$ but has a weak correlation with $\sqrt{\text{FDD}}$, findings which are corroborated by previous analyses.[20,53] Since the establishment of the UNISCALM grid in 2000, winter air temperatures have increased more than summer air temperatures, and winter air temperatures exhibit greater inter-annual variability due to the maritime Arctic climate. This is reflected in the relatively wide spread of FDD values and their increase over time (Figure 5). The ground surface at UNISCALM has remained stable over the study period, as observed by the authors in the field, with no apparent changes in the site's patchy vegetation, relatively flat surface, absence of standing water in summer, shallow winter snow depths, and low ice content in the active layer. This observed lack of surface change is supported by a low standard deviation in E values. Given relatively little change in TDD and no apparent year-to-year ground surface changes at UNISCALM, interannual variability in ALT must be explained by some other combination of factors. Greater variability in FDD compared to TDD has been used to explain some of the interannual variability observed in ALT in the Mackenzie Valley, Northwest Territories, Canada.[54] The same study concluded that relatively warm conditions during winter may be a contributing factor to active layer development during the subsequent summer. This finding aligns with those of Schuh et al.,[53] who concluded that ALT at UNISCALM during 2000–2014 responded primarily to cumulative temperatures during the preceding winter, and that overall increase in ALT was controlled by consecutive years of winter warming. These conclusions are explained by warmer winters resulting in higher ground temperatures at the onset of the subsequent thawing season, meaning more energy can contribute directly to ground thaw relative to ground warming. In their study of the transient layer, Shur et al.[55] described maximum thaw depth as having a temporally integrated response to the components of ground surface energy balance, and specified that active layer soil water content during the autumn preceding thaw directly impacts the rate of thawing. For winter air temperatures (and FDD) to impact ALT, a thin snow cover is required. UNISCALM does have consistently thin snow cover due to significant wind-driven snow transport arising from channelized wind flow in Adventdalen.[23] Given the relatively weak correlation between ALT and $\sqrt{\text{FDD}}$ at UNISCALM ($p = 0.05$, $R^2 = 0.21$), it is evident that other environmental factors must still be considered. A site-specific study utilizing the thaw progression data, and thus thaw depth and meteorological data on a daily scale, could help to develop the process-based understanding of ALT, and is identified as an area for future work.

4.4 | Circum-Arctic trends in ALT

There is consensus that ALT has increased in the Northern Hemisphere since the 1990s, with the exception of some specific sites, namely in the Alaska North Slope and the Mackenzie River delta in Artic Canada.[2,41,56] In these latter two areas, an increase in ALT has been observed, but only more recently: since 2009 in the Alaska North Slope and since 2008 at the Mackenzie River delta.[4,57] The

average rate of increase in ALT for the Nordic probing sites discussed in this paper, 0.5 cm/yr (2000–2018), is of similar magnitude to the circum-Arctic CALM mean, 0.8 cm/yr (2000–2018), indicating that the active layer thickening observed in the Nordic region is representative of active layer thickening occurring across the Arctic. Shiklomanov et al.[41] found that there was no pronounced trend in ALT in the Alaska North Slope over the period 1995–2011, but more recent studies indicate active layer thickening has occurred at this location over the period 2009–2018.[4] The analysis presented here (Figure 7) shows that 40% of sites in the Alaska North Slope exhibit a statistically significant increase in ALT from 1990 to 2018, and 66% from 2000 to 2018. The comparison of these findings demonstrates the importance of the defined time series on trend determination, especially given particularly high Arctic air temperatures and ALT values in the most recent years, 2014–2018.[2–4]

In general, making regional and circum-Arctic interpretations of trends in ALT is complicated by a number of factors. Luo et al.[56] did not find consistent increasing ALT trends across the Northern Hemisphere, but acknowledged that uneven site distribution and inconsistent time series influenced their determination of ALT trends (or lack thereof). In areas with excess ice, ground surface subsidence caused by ice melt precludes a stable reference datum for ALT measurements made by mechanical probing, and thus can influence perceived trends in ALT.[58,59] Subsidence can explain why some sites do not exhibit trends in ALT, even given increased permafrost temperatures.[58–60] Based on field observations, subsidence is not thought to be a major issue within the Nordic sites discussed here, but subsidence does occur in these study areas[32,61,62] and thus the sites would benefit from monitoring using Differential Global Positioning Systems (DGPS) or Satellite Synthetic Aperture Radar Interferometry (InSAR).

5 | CONCLUSIONS

ALT in the studied Nordic Arctic CALM probing sites is controlled by a combination of geomorphology and climate. Although it is the most southern area in this study, the active layer in northern Sweden is the thinnest because the active layer is mostly confined to superficial peat. The active layer in central Svalbard is the thickest, compared to both the Nordic- and the circum-Arctic, due to the area's maritime Arctic climate, in contrast to the continental climates in Greenland and northern Scandinavia. Interannual variability in ALT is not consistent across the Nordic Arctic region; this is attributed to the substantial climate differences between the study areas and the large climatic gradient between central Svalbard and northeast Greenland, in addition to site-specific geomorphological controls. Differences in the magnitude of ALT between grids in the same area also arise from site-specific geomorphological controls, specifically snow dynamics and peat characteristics (at peatland sites).

Climate warming has caused active layer thickening at all three Nordic Arctic study areas. Seasonality in climate change has been identified as explaining differences in the relationship between ALT

and degree days between the three study areas. Specifically, increased summer air temperatures are responsible for increased ALT in the more continental climates of northern Sweden and northeast Greenland, while significantly increasing and variable winter air temperatures impact ALT in maritime central Svalbard. The ability of winter air temperatures to impact ALT is dependent on thin winter snow cover and the resulting coupling between winter air and active layer temperatures. We have found that ALT in central Svalbard correlates with FDD, but not with TDD. Here, there is relatively thin snow cover in the large valleys due to significant wind-driven snow redistribution. These findings add to our understanding of active layer sensitivity to climate, and show that ALT is not always correlated with TDD. Additionally, the impact of climate on ALT is superimposed on critical site-specific controls, such as the presence of peat and the timing and thickness of snow cover. Making accurate regional assessments of ALT trends is thus complicated by these unique site aspects, but also by varying lengths and inconsistencies in time series. However, there is consensus that Arctic ALT has been increasing, and we have found that the average rate of active layer thickening in the Nordic region is of the same magnitude as the average rate across the Arctic.

Data Availability Statement

The data that support the findings of this study are openly available in online repositories. The ALT data are publicly available in the CALM database at https://www2.gwu.edu/~calm/data/data-links.html. Zackenberg ALT, thaw depth, and meteorological data are available in the GEM Database at https://data.g-e-m.dk/. Svalbard Airport meteorological data are available through eKlima/the Norwegian Meteorological Institute at www.eklima.met.no. Abisko meteorological data are available upon request to the Swedish Polar Research Secretariat.

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