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No significant trends in snow free days at three long-term monitoring sites in the high-, mid- and low- Arctic Greenland as seen by MODIS Terra from 2000-2025

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Abstract. Snow cover is a key component of Arctic ecosystems, regulating both biotic and abiotic processes such as plant phenology, soil thermal regimes, greenhouse gas fluxes, and the timing of glacier melt. We present a 26-year (2000-2025) record of snow-free days derived from the MODIS Terra cloud-gap-filled snow cover product at three long-term monitoring sites in high, mid, and low-Arctic Greenland. The MODIS-derived counts correlated well with in situ observations, most strongly at the high-arctic site, the only location where a direct comparison to in situ observations was possible. The mean snow-free season length is 76, 78 and 103 days at high-, mid-, and low-Arctic respectively, with a standard deviation of approximately two weeks at each site despite their contrasting latitudinal positions. We find no statistically significant trends in the number of snow-free days at any site over the record, consistent with the absence of significant trends in Northern Hemisphere snow cover in the Greenland and North American sector over the same period. The dominant driver of interannual variability shifts along the latitudinal gradient: snowfall was the dominant predictor of snow free day counts at the high arctic site, positive degree-days become co-limiting alongside snowfall at the low-Arctic site and at the mid-Arctic site positive degree-days are the only significant predictor, allthought snowfall and positive-degree-days together explain little of the interannual variance there, which point to additional physical controls. The high interannual variability in snow-free season length underscores the necessity of monitoring records spanning multiple decades in order to detect climate-change signals in snow cover and the many Arctic ecosystem processes that depend on it.

1 Introduction

In seasonally snow-covered regions, the duration and amount of snow strongly influence ecosystem processes. For example, snow regulates the surface energy balance at both local (Lund et al., 2017) and larger scales (Flanner et al., 2011). Snow regulation of the surface energy balance influences ground temperature and permafrost dynamics and, through the albedo feedback, contributes to Arctic amplification of global warming. Snow depth and snow cover duration affect vegetation characteristics

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(Callaghan et al., 2011; Pedersen et al., 2016; Kankaanpää et al., 2018; Assmann et al., 2019), as well as other biotic processes such as plant flowering phenology and arthropod phenology (Schmidt et al., 2023). In addition, snow cover affects greenhouse gas fluxes between the ground and the atmosphere (Kolstad et al., 2021; Mastepanov et al., 2013; Zona et al., 2022) and shapes streamflow (Binder et al., 2026) with consequences for marine ecosystems (Sejr et al., 2022). More broadly, changes in snow cover directly affect water availability for communities dependent on meltwater resources (Calvin et al., 2023).

On large scales, Northern Hemisphere snow cover extent has shown a general decrease since the 1970s (Box et al., 2024). The key drivers of this decrease is temperature (Brutel-Vuilmet et al., 2013; Mudryk et al., 2017) and to a lesser degree total precipitation (Sospedra-Alfonso and Merryfield, 2017), rising temperatures shift the partition between snow and rain, reducing the snow fraction precipitation (McCrystall et al., 2021). In the Arctic, tendencies of increased snowfall has been balanced by earlier spring melt, and delayed autumn snowfall, all contributing to a longer snow free period (Khani et al., 2022). However, these trends are spatially heterogeneous and primarily driven by changes in Eurasia (Box et al., 2024). Snow cover is furthermore highly variable in space and time at local scales, and regional to local ecosystem-scale impacts of snow cover can only be understood with observations at local spatial scales.

The Greenland Ecosystem Monitoring (GEM) program is a long-term, integrated ecosystem monitoring program at three main sites in Greenland: Zackenberg (high-Arctic, established 1995), Disko (mid-Arctic, from 2017), and Kobbefjord near Nuuk (low-Arctic, from 2007). At these sites, GEM monitors a wide range of biotic and abiotic variables as well as their interactions, making it possible to evaluate ecosystem responses to environmental change. Snow cover is a fundamental driver of ecosystem dynamics at these sites, and the aim of this study is to quantify the duration of the snow-free season in these three areas based on satellite remote sensing observations in order to characterize local-scale variability and trends in snow cover and identify their key climatic drivers. Using daily MODIS Terra cloud-gap-filled (CGF) snow cover fraction maps, we quantify the duration of the snow-free period in the areas surrounding the GEM sites spanning the full 26-year MODIS Terra record (2000-2025). These satellite-derived time series are evaluated against in situ measurements and compared with key climatic drivers of snow cover duration, namely snowfall and positive-degree-days. All derived data products are openly accessible through the Greenland Ecosystem Monitoring data portal (https://data.g-e-m.dk/).

2 Data and methods

2.1 Area of interest and topography

We define an area of interest (AOI) for each of the three GEM sites (Figures 1, 2, 3 and 4). The AOIs varies in size and were delineated based on a subjective assessment of the area relevant to the ecosystem monitoring at each site.

For elevation-related analysis we use the digital digital elevation model ArcticDEM v4.1 Mosaic at 32 m resolution (Porter et al., 2023), hereafter referred to as ArcticDEM. The elevation distributions of the three sites derived from the ArcticDEM are shown in Figure 5.

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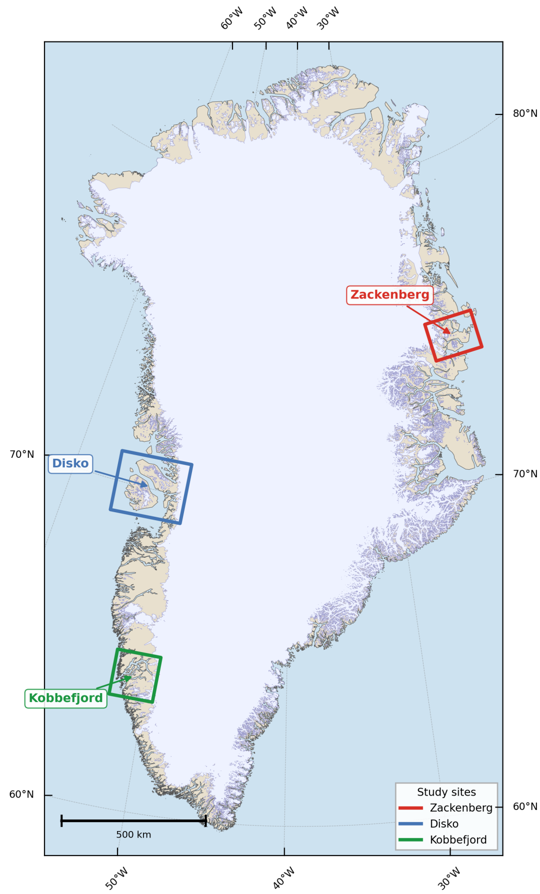

Figure 1. Red: The high-Arctic Zackenberg site. Blue: The mid-Arctic Disko site. Green: the low-Arctic Kobbefjord site. The background are vector maps from Danish Agency for Climate Data (https://dataforsyningen.dk/data/985) available under the Creative Commons Attribution 4.0 International (https://creativecommons.org/licenses/by/4.0/). The map is projected in UTM 24N.

2.2 MODIS Terra CGF snow cover maps and snow free days

For this study, we utilize the NASA Earth Observing System (EOS) Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Terra satellite. MODIS Terra was launched in late 1999 with the first images available from 24 February 2000 and has an orbit that enables daily repeated images over most of the Earth.

The National Snow and Ice Data Center (NSIDC) at NASA the Making Earth System Data Records for Use in Research Environments (MEaSUREs) data collection provides Level 3 MODIS data available as cloud gap filled daily snow cover data (Hall and Riggs, 2020). More specifically the Level 3 data is daily maps of the Normalized Difference Snow Index (NDSI) ranging from 0 (no snow in a pixel) to 100 (pixel fully snow covered). The NDSI is a relationship between both infrared and visible bands, and while it can clearly distinguish clouds from snow, clouds will still obstruct the view to the surface and thus

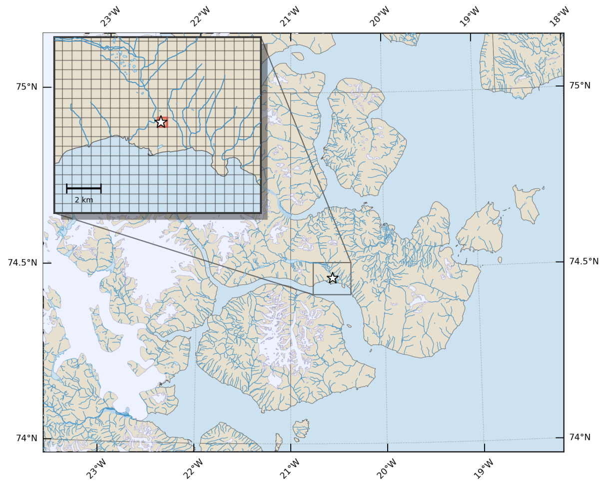

Figure 2. The Zackenberg Area of Interest (AOI) in UTM 27 N projection. The insert shows the main monitoring area with the reprojected MODIS grid overlain to illustrate the resolution of the MODIS data. The star indicates the location of the main climate mast and the orange shaded pixel is the pixel where the MODIS data is extracted for comparison with the main climate mast. MODIS imagery is from NASA and the background are vector maps from Danish Agency for Climate Data (https://dataforsyningen.dk/data/985) available under the Creative Commons Attribution 4.0 International (https://creativecommons.org/licenses/by/4.0/)

cloud cover creates observational gaps. MEaSUREs provides a cloud gap filled dataset to overcome this, where the data gaps caused by cloud cover are simply filled using the most recent available observation. While this forward-fill approach effectively removes cloud gaps, it may introduce biases during extended periods of persistent cloud cover. The cloud cover persistence is therefore also part of our analysis. For the remainder of this paper we will refer to the MODIS Terra CGF snow cover maps as "MODIS".

The NDSI (given in percent) has been shown by (Salomonson and Appel, 2004) to be a measure for the snow cover fraction (SCF) on ground via the relation:

$$\mathrm{SCF} = (0.06 + 1.21 \cdot \mathrm{NDSI}) \tag{1}$$

However, since the focus of this study is variability in snow free days and not specifically snow cover fraction the main analysis in this study is for simplicity based on the NDSI values directly, and only use this relation for comparison with similar studies that published on the SCF and not the NDSI.

The MODIS data is published in a sinusoidal grid of, approximately 500 x 500m, in order to provide a good spatial coverage over the entire globe. For the purpose of this study we reproject the MODIS snow cover tile to the local UTM coordinate system for the different sites and then cut out the area of interest. The MODIS product covers both land and ice, however, the distinction between snow, firn and ice can be a problem with the NDSI (Hall et al., 1995). So, for snow cover statistics we mask out glacier ice and oceans (vector masks are from the Danish Climate Agency https://dataforsyningen.dk/data/985, data is available under the Creative Commons Attribution 4.0 International https://creativecommons.org/licenses/by/4.0/).

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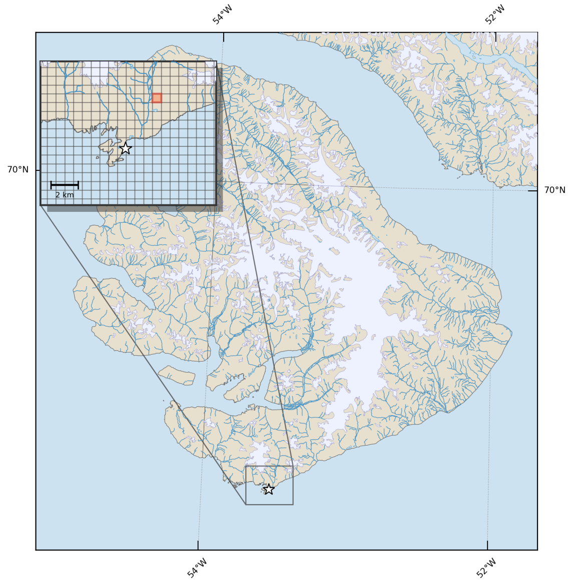

Figure 3. The Disko Area of Interest (AOI) in UTM 27N projection. The insert shows the main monitoring area with the reprojected MODIS grid overlain to illustrate the resolution of the MODIS data. The star indicates the location of the main climate mast and the orange shaded pixel is the pixel where the MODIS data is extracted for comparison with the main climate mast. MODIS imagery is from NASA and the background are vector maps from Danish Agency for Climate Data (https://dataforsyningen.dk/data/985) available under the Creative Commons Attribution 4.0 International (https://creativecommons.org/licenses/by/4.0/)

Since the NDSI depends on the visual spectrum it is not possible to obtain NDSI from MODIS during polar night. For this reason it is more robust to identify snow free days which most commonly occur during the periods where the sun is above the horizon, instead of snow covered days and thus the study focusses on the number of snow free days.

A snow-free day is defined as a day on which a pixel exhibits only fractional snow cover i.e. a NDSI value below 100 %. To asses the sensitivity of the results to the specified threshold snow free days are computed for thresholds of of 10, 20, 30, 40, 50, 60, and 70%. For each year and threshold, the number of snow-free days was counted per pixel and then averaged spatially across the area of interest to yield a single annual time series. This average count is also done for elevation bands of 100 m using the ArcticDEM.

For validation against in situ observations and for investigating snow cover conditions at the main ecological research sites, we extract the time series of NDSI values at a single pixel at each GEM site, ideally the pixel directly covering the main climate mast. A direct pixel-to-mast comparison is only possible at Zackenberg, where the mast location falls within a usable MODIS pixel (Figure 2). At Disko, the climate mast is located on a small peninsula very close to the coast, and MODIS pixels covering substantial water bodies do not contain usable land surface data. We therefore select a pixel further inland, in the valley where the main ecological monitoring activities are concentrated, though this pixel is at a distance of approximately 4 km from the climate mast (Figure 3). At Kobbefjord, the climate mast is located adjacent to a large lake, which similarly affects the usability

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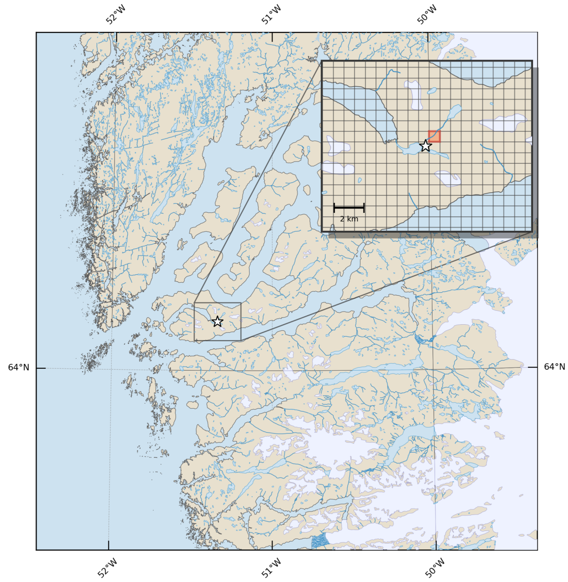

Figure 4. The Kobbefjord Area of Interest (AOI) in UTM 27 N projection. The insert shows the main monitoring area with the reprojected MODIS grid overlain to illustrate the resolution of the MODIS data. The star indicates the location of the main climate mast and the orange shaded pixel is the pixel where the MODIS data is extracted for comparison with the main climate mast. MODIS imagery is from NASA and the background are vector maps from Danish Agency for Climate Data (https://dataforsyningen.dk/data/985) available under the Creative Commons Attribution 4.0 International (https://creativecommons.org/licenses/by/4.0/)

of the corresponding MODIS pixel. In this case, however, a single diagonal shift to a neighbouring pixel is sufficient to obtain valid data, placing the chosen pixel much closer to the mast than at Disko (Figure 4).

2.3 In situ data

We use in situ data to validate both the MODIS snow cover observations and the reanalysis data used to quantify the key drivers of snow cover variability. For validation of the MODIS-derived snow-free days, we use in situ albedo measurements from the climate masts at each GEM site, defining snow-free conditions as days with albedo below 0.4. We assess agreement between the in situ and MODIS-derived snow-free day counts using Pearson correlation and mean bias. We furthermore use in situ observations of air temperature and snow depth to validate the CARRA reanalysis data used to derive snowfall and positive degree days as described in the following section. A climate mast at each GEM site provides all the variables needed for this validation (https://data.g-e-m.dk/).

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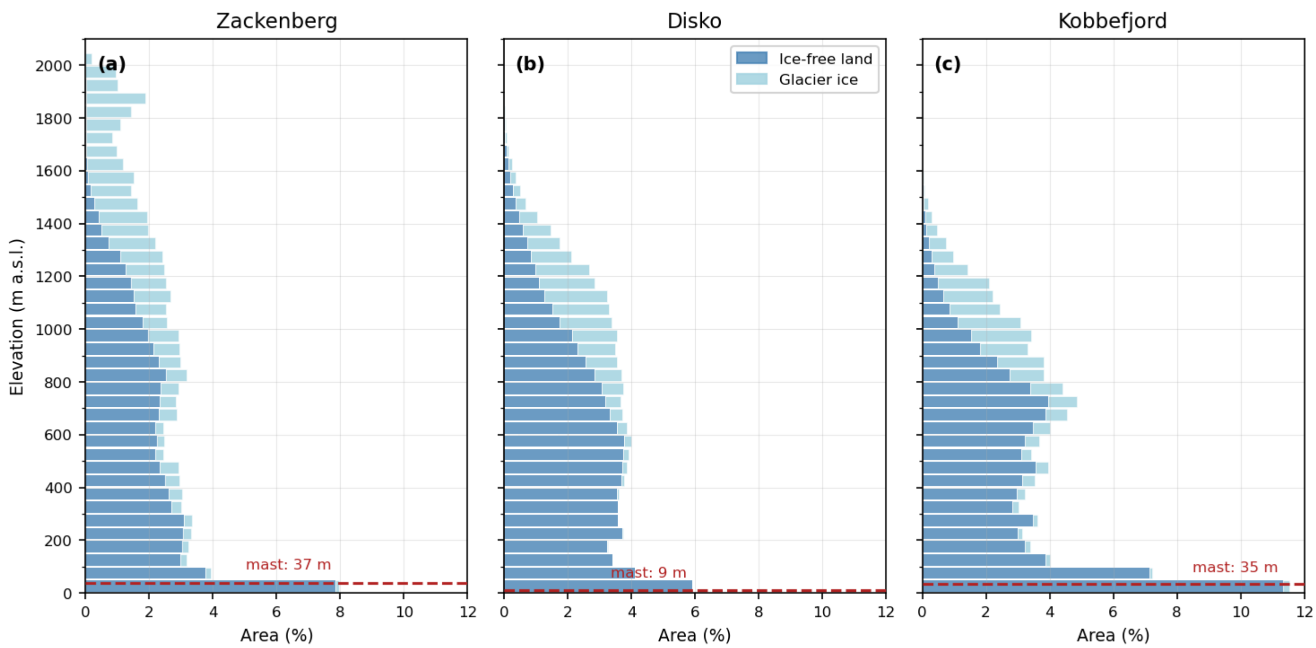

Figure 5. The elevation distribution at (a) the Zackenberg AOI, (b) the Disko site AOI and (c) the Kobbefjord site, according to ArcticDEM v. 4.1. Red dashed lines Indicate the elevation of the main climate mast at the three sites.

2.4 Reanalysis data

To assess how snowfall and positive degree days influence the length of snow-free conditions, we require gap-free records spanning the full analysis period 2000–2025. Since the climate masts at Kobbefjord and Disko do not extend back to 2000, we use data from the Copernicus Arctic Regional Reanalysis (CARRA) to produce a complete, cross-site consistent dataset.

CARRA provides precipitation (snow and rain) and 2 m air temperature on a 2.5 km × 2.5 km grid, from which we extracted values at the grid cell covering the climate mast at each site.

The CARRA dataset includes a snow water equivalent (SWE) variable that has been shown to describe seasonal snow cover duration well (van der Schot et al., 2024), however Rutishauser et al. (2025) identified an issue where SWE is reset to zero at specific dates, prohibiting the use of this the CARRA SWE variable for this study. We therefore follow the approach of Rutishauser et al. (2025) and derive snowfall directly from the temperature and precipitation fields, assuming that all precipitation falling when the 2 m temperature is below 0 °C is snow. Daily snowfall contributions are then summed over the hydrological year (1 October – 30 September) to obtain total snowfall for each year. Since CARRA output is not downscaled to the elevation of each mast, the absolute precipitation amounts will carry some elevation-related bias, but as the analysis focuses on inter-annual variability rather than absolute totals, this is not expected to affect the conclusions.

To quantify the influence of air temperature on snow cover duration, we use positive degree days (PDD). Sub-daily 2 m air temperature values from CARRA were first averaged to daily means, after which PDD was computed as the sum of positive

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daily mean temperatures over each calendar year, with negative values set to zero before summation. CARRA-derived PDD was validated against in situ temperature records from the climate masts at each GEM site. Although absolute values differ between the reanalysis and in situ records, the inter-annual variability correlates well, with R^2 values of 0.831, 0.884, and 0.912 at Zackenberg, Disko, and Kobbefjord respectively. Since the analysis focuses on variability rather than absolute magnitudes, we consider this level of agreement adequate.

2.5 Statistical analysis

To answer the question if there are any trends in snow free days over the observational period, trends in snow-free days and climate predictors were assessed using the non-parametric Mann-Kendall test with Sen's slope estimator, at a significance level of $p = 0.05$.

Prior to analysis, the normality of annual snow-free day counts was assessed using the Shapiro–Wilk test to verify the appropriateness of the standard deviation as a summary statistic and to confirm that the assumptions of ordinary least squares regression were met.

To determine how much of the variability in snow free days can be predicted by the two main climate drivers: snowfall and PDD we examined the relationships between snow-free days and climate drivers using Pearson correlation by assuming that

$$\text{snow\_free\_days} = \text{intercept} + \beta_{pdd} \cdot \text{PDD} + \beta_{snow} \cdot \text{snowfall} + \text{error} \quad (2)$$

and then using an ordinary least-squares (OLS) multiple regression to find coefficients β_{pdd} and β_{snow} that best predicts the number of snow free days.

To determine the relative importance of each driver we standardised the drivers to have a mean of 0 and standard deviation of 1, and then performed OLS multiple regression again to compute the standardised regression coefficients (β weights). All analyses were conducted in Python using the `xarray`, `statsmodels`, and `pingouin` libraries.

3 Results

The number of snow free days counted from MODIS NDSI naturally varies depending on which NDSI threshold is being used to define snow free conditions as seen in panel (a) in Figures 6, 7 and 8. However, it is also clear that there is a convergence in the number of snow free days determined by an NDSI of 40 % or less. Thus, for trend and driver analysis we decided to use the 40 % threshold. Converted into SCF according to equation 1 an NDSI value of 40 % corresponds to a SCF of 50 %. Thus using the NDSI threshold of 40 % is in accordance with the 50 % SCF threshold used by Vickers et al. (2020) and Gauthier et al. (2024).

Table 1 summarises the statistics for the number of snow-free days across NDSI thresholds from 10 to 70% at the three GEM sites. At Zackenberg the mean number of snow-free days at the 40% threshold is 76.5 days with a standard deviation of 14.5 days. At Disko the values are similar, with a mean of 78.3 days and a standard deviation of 12.3 days. As expected, the southernmost site Kobbefjord has a longer snow-free season, averaging 102.9 days with a standard deviation of 15.8 days.

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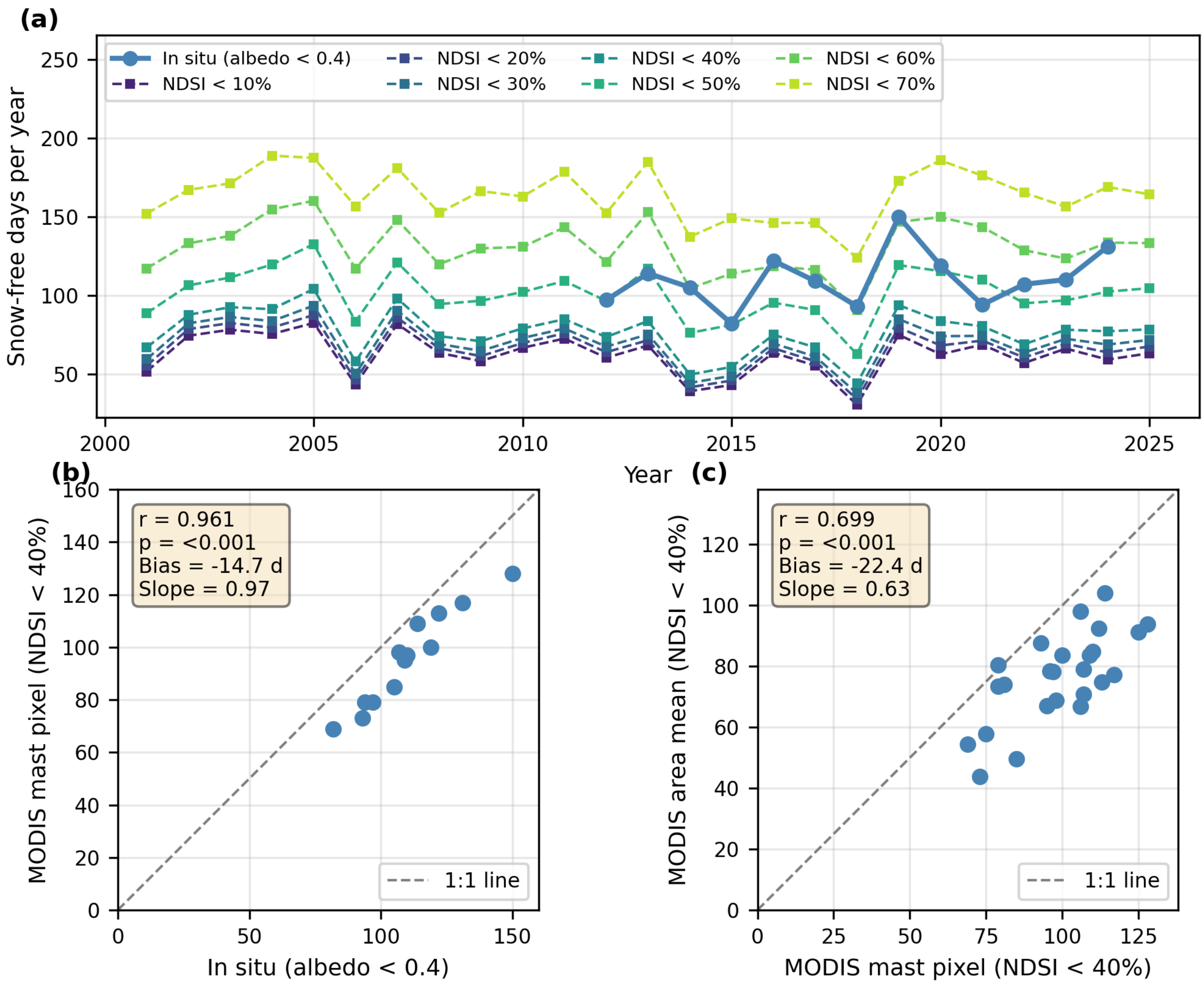

Figure 6. Zackenberg: (a) The timeseries of the mean annual count of snow-free days derived using different NDSI thresholds and the in situ observations of snow-free days. (b) Correlation between snow-free days observed at the main climate mast and MODIS-derived snow-free days at the pixel covering the mast location, where a snow-free day is defined as a day with an NDSI value below 40%. (c) Correlation between the snow-free day count at the MODIS pixel covering the main climate mast and the mean snow-free day count across the AOI, both using an NDSI threshold of 40 %.

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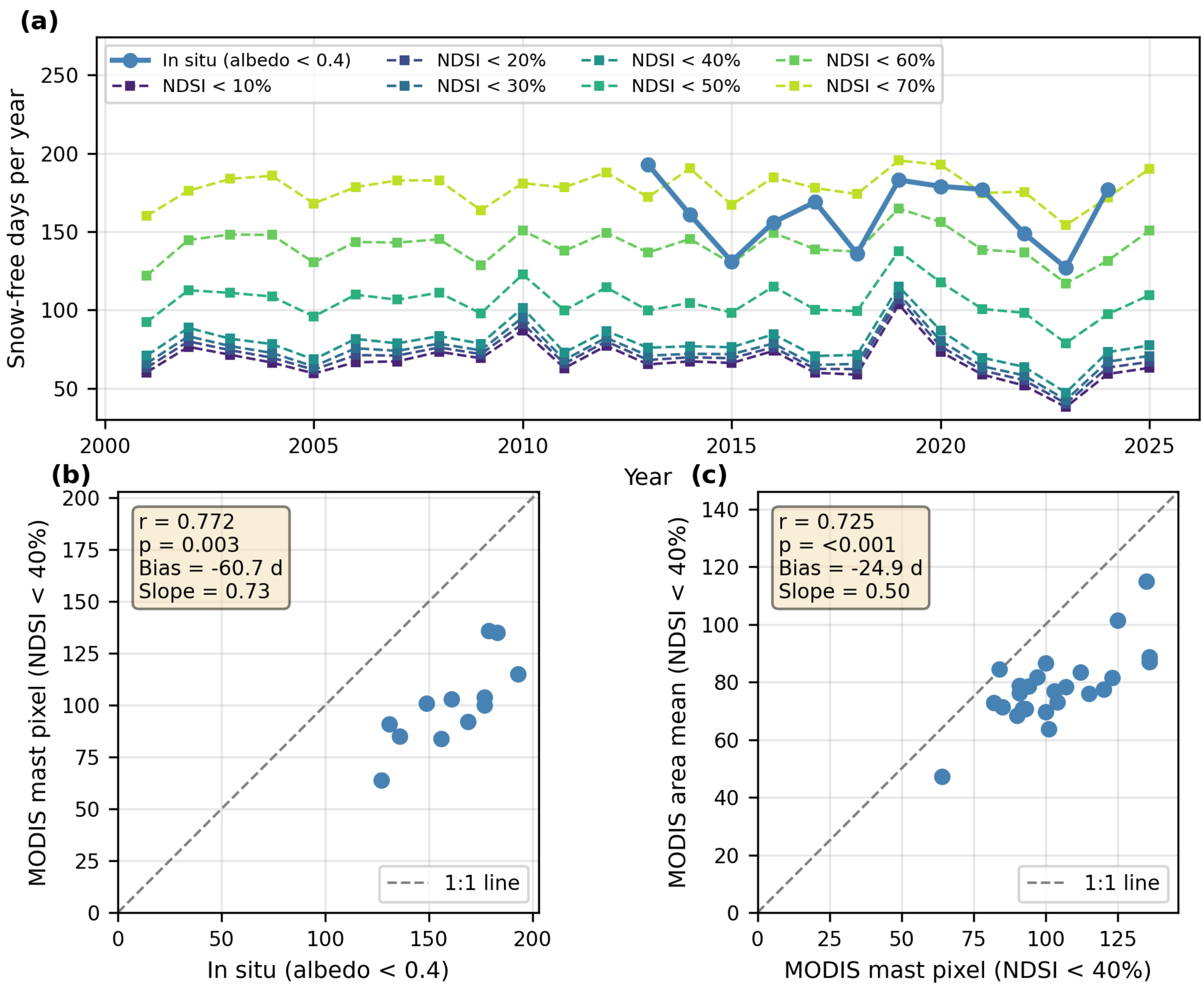

Figure 7. Disko: (a) The timeseries of the mean annual count of snow-free days derived using different NDSI thresholds and the in situ observations of snow-free days. (b) Correlation between snow-free days observed at the main climate mast and MODIS-derived snow-free days at the pixel close to the mast location, where a snow-free day is defined as a day with an NDSI value below 40%. (c) Correlation between the snow-free day count at the MODIS pixel close to the main climate mast and the mean snow-free day count across the AOI, both using an NDSI threshold of 40 %

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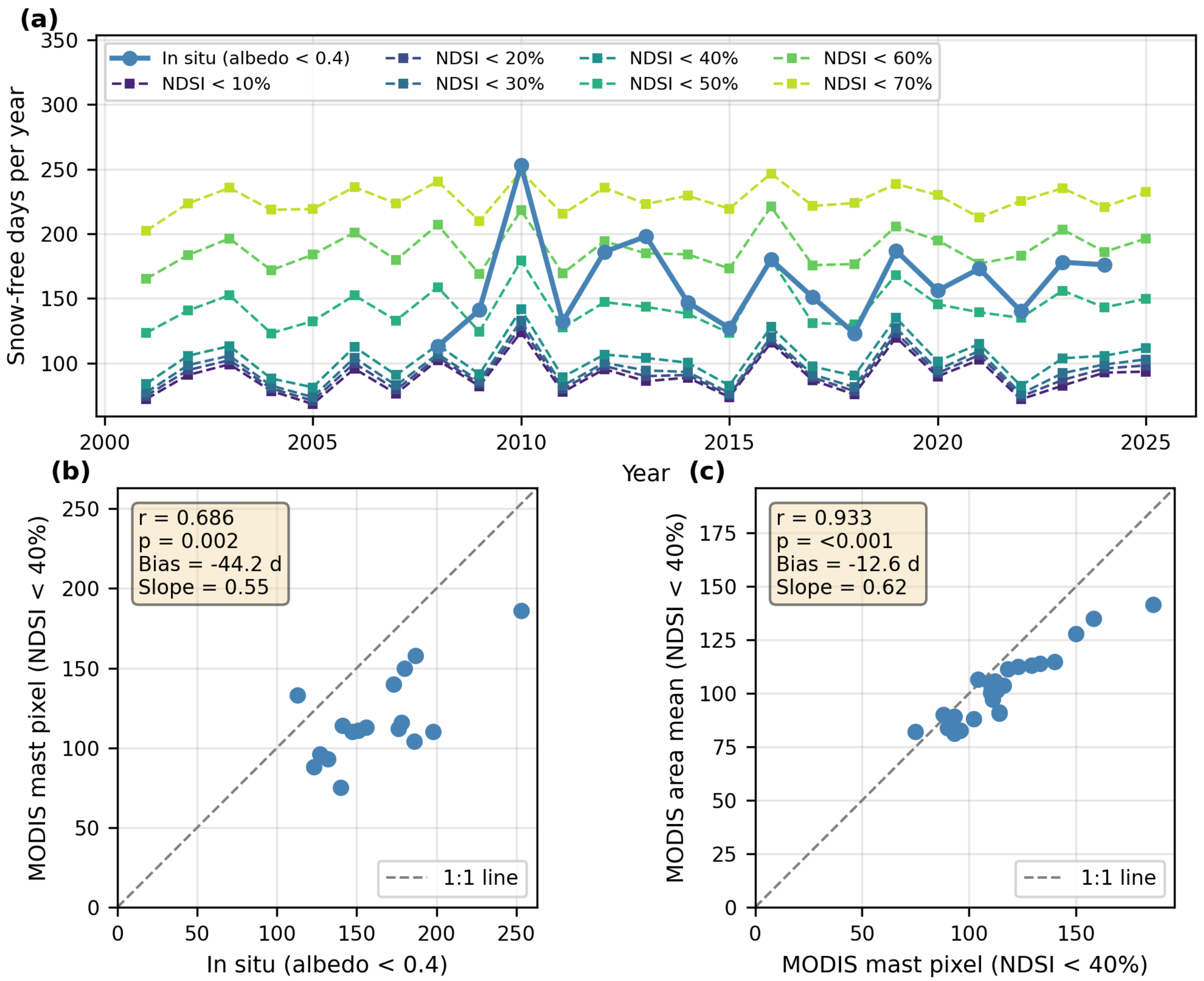

Figure 8. Kobbefjord: (a) The timeseries of the mean annual count of snow-free days derived using different NDSI thresholds and the in situ observations of snow-free days. (b) Correlation between snow-free days observed at the main climate mast and MODIS-derived snow-free days at the pixel close to the mast location, where a snow-free day is defined as a day with an NDSI value below 40 %. (c) Correlation between the snow-free day count at the MODIS pixel close to the main climate mast and the mean snow-free day count across the AOI, both using an NDSI threshold of 40 %

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Notably, the standard deviation is close to two weeks at all three sites. For comparison the mean number of snow-free days at the 70% threshold is 163.7, 178.0 and 226.7 days at the Zackenberg, Disko and Kobbefjord sites respectively.

We compared the MODIS-derived snow-free day count against in situ albedo-based counts at the pixel covering, or nearby to, each climate mast. At Zackenberg (Figure 6b), the correlation between in situ and MODIS-derived snow-free days is strong (r = 0.961), with MODIS underestimating snow-free days by 14.7 days on average. The slope of 0.97 indicates near-perfect agreement in interannual variability, suggesting the single MODIS pixel captures the amplitude of year-to-year fluctuations in snow-free days well at the Zackenberg climate mast. At Disko (Figure 7b), where no MODIS pixel directly covers the climate mast and a pixel approximately 4 km from the mast is used instead, the correlation is weaker (r = 0.772) and the underestimation considerably larger, with the MODIS pixel recording on average 60.7 fewer snow-free days than observed at the mast. The slope of 0.73 indicates a moderate compression of variability, meaning that the MODIS pixel captures approximately 27% less interannual amplitude than observed in situ. At Kobbefjord (Figure 8b), also compared against a nearby rather than directly overlapping pixel, the correlation is moderate (r = 0.686) and MODIS records on average 44.2 fewer snow-free days than observed in situ. The slope of 0.55 indicates stronger compression of variability, with the MODIS pixel capturing approximately 45% less interannual amplitude that observed in situ. The weaker agreement at Disko and Kobbefjord is somewhat expected given that the comparison pixel does not directly cover the mast location.

We compared the chosen MODIS pixel with the AOI mean to assess whether the snow-free day signal at each GEM site is representative of the broader area. At Zackenberg (Figure 6c), the mast pixel and AOI mean are moderately correlated (r = 0.699), with the mast pixel having on average 22.4 more snow-free days than the AOI mean. The slope of 0.63 indicates a compression of variability, with the AOI mean showing 37% less interannual amplitude than the mast pixel. At Disko (Figure 7c), the mast pixel correlates moderately with the AOI mean (r = 0.725), with the mast pixel having on average 24.9 more snow-free days than the AOI mean. The slope of 0.50 indicates a strong compression of variability, with the AOI mean showing 50% less interannual amplitude than the mast pixel. At Kobbefjord (Figure 8c), the correlation between the mast pixel and the AOI mean is strong (r = 0.933), with the mast pixel having on average 12.6 more snow-free days than the AOI mean. The slope of 0.62 indicates a compression of variability, with the AOI mean showing 38% less interannual amplitude than the mast pixel..

To assess the contribution of cloud gap-filling, we quantified the number of gap-filled days during the snow-free period. This was low at all three sites: 1.3 ± 1.8 days at Zackenberg (maximum 21 days; Table A1), 1.8 ± 2.3 days at Disko (maximum 20 days; Table A2), and 1.3 ± 1.8 days at Kobbefjord (maximum 13 days; Table A3)

We now turn to the climatic drivers. The key climatic drivers used in this study, total snowfall and PDD, are summarized in Table 2. The calculated snowfall based on CARRA precipitation and air temperature is highest at Kobbefjord (505 mm on average), intermediate at Zackenberg (357 mm), and lowest at Disko (216 mm). The ranking for PDD differs: Disko is the warmest (894 °C·d), followed by Kobbefjord (760 °C·d) and the high-Arctic Zackenberg (569 °C·d).

Prior to regression analysis, the normality of annual snow-free day counts and OLS residuals was assessed using the Shapiro–Wilk test. Snow-free day series were consistent with normality at all three sites (Zackenberg: W = 0.963, p = 0.469; Nuuk: W = 0.921, p = 0.055; Disko: W = 0.942, p = 0.164), supporting the use of the mean and standard deviation as summary statistics. Regression residuals also showed no significant departure from normality (Zackenberg: W = 0.977, p = 0.812;

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Table 1. Mean snow-free days per year by NDSI threshold at the three GEM sites.

	Zackenberg				Disko				Kobbefjord			
Threshold	Mean	Std	Min	Max	Mean	Std	Min	Max	Mean	Std	Min	Max
< 10%	62.3	13.0	30.4	82.4	67.0	11.9	38.0	103.5	89.6	14.7	68.3	123.8
< 20%	65.9	13.4	34.0	87.5	70.2	12.1	40.3	107.2	92.5	15.1	70.8	128.3
< 30%	69.7	13.8	37.7	93.4	73.1	12.3	42.5	110.3	95.6	15.4	73.6	132.7
< 40%	76.5	14.5	43.9	104.0	78.3	12.3	47.3	115.0	102.9	15.8	81.2	141.6
< 50%	101.1	15.6	62.5	132.6	105.6	11.3	78.9	137.7	143.0	16.0	123.0	180.2
< 60%	130.7	16.5	90.5	160.1	141.0	10.6	117.0	164.8	188.0	15.0	165.1	221.0
< 70%	163.7	16.3	123.7	188.8	178.0	10.1	154.2	195.5	226.7	11.1	202.3	248.1

Table 2. Mean ± standard deviation of annual positive degree days (PDD) and snowfall from CARRA at the three GEM sites, 2001 - 2025.

Site	PDD (°C·d)	Snowfall (mm)
Zackenberg	569 ± 87	357 ± 143
Disko	894 ± 123	216 ± 51
Kobbefjord	760 ± 153	505 ± 126

Nuuk: W = 0.979, p = 0.866; Disko: W = 0.967, p = 0.563), indicating that the assumptions underlying ordinary least squares regression were met at all sites.

Using OLS regression and the Mann-Kendall test, we found no statistically significant trends in the number of snow-free days at any of the tested NDSI thresholds. Trend analysis in 100 m elevation band similarly revealed no statistically significant trends. Despite the absence of statistically significant trends in snow-free days, trend analysis of the key drivers revealed a statistically significant cooling trend in positive degree days (PDD) at the Disko site of -8.06 °C·d/yr (p=0.008). All significant trends are summarized in Table 3.

Table 3. Significant trends from the Mann-Kendall trend analysis of snow-free days, and key drivers.

Metric	Sen's slope	p-value
Interannual variability in snow free days (5 yr) at Disko	0.42 d/yr	0.0063
PDD at Disko	-8.06 °C·d/yr	0.008

We assessed how much of the interannual variability in snow-free days can be explained by the two key climate drivers using OLS multiple regression. Results are summarised in Table 4. At Zackenberg, the two drivers together explain 58% of the variance, with total snowfall as the dominant and statistically significant predictor (β = -0.087 d/mm, p < 0.0001; standardised β = -0.74). The PDD term has the expected positive sign but is not statistically significant (p = 0.144). At Disko, the explanatory power of the model is considerably lower at only 16%, with PDD as the only statistically significant predictor (β = 0.070

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d/°C·d, p = 0.021) and snowfall contributing negligibly (p = 0.726). At Kobbefjord, the model explains 56% of the variance, with both PDD (p = 0.002) and snowfall (p = 0.016) as significant predictors. The standardised coefficients indicate that PDD is the stronger driver at this site (standardised β = 0.53 vs -0.39 for precipitation), in contrast to Zackenberg where precipitation dominates.

The observed and OLS-predicted snow-free day time series are compared in Figures A1, A2 and A3. At Disko in particular, several years, notably 2001, 2020 and 2023, fall well outside the model predictions, suggesting that additional drivers not captured by PDD and snowfall are influencing snow-free season length at this site. Liu et al. (2024) investigated drivers of seasonal transition dates at Disko using a distributed snow model that accounts for wind redistribution and terrain, and found that the combined effect of climate, snow cover, and terrain conditions explained 44 - 61% of the variance in seasonal transition dates, highlighting the complexity of local snow dynamics beyond simple temperature and precipitation forcing.

Table 4. Ordinary Least Square results (NDSI threshold < 40%).

Site	R^2	R^2-adj	β_{pdd} (p-value)	β_{snow} (p-value)	β_{pdd} standardized	β_{snow} standardized
Zackenberg	0.62	0.58	0.026 d/°C·d (p = 0.144)	-0.087 d/mm (p < 0.0001)	0.14	-0.74
Disko	0.23	0.16	0.070 d/°C·d (p = 0.021)	-0.024 d/mm (p < 0.726)	0.47	-0.067
Kobbefjord	0.59	0.56	0.045 d/°C·d (p = 0.002)	-0.051 d/mm (p < 0.016)	0.53	-0.39

4 Discussion

Despite its relatively coarse 500 m x 500 m pixel size, which makes thin or patchy snow layers difficult to detect and misses sub-pixel heterogeneity such as wind-drift accumulations or topographically shadowed patches (Hall and Riggs, 2020), MODIS provides a uniquely long and homogeneous time series. No currently operational sensor matches the 26-year continuity of the MODIS archive in terms of daily revisit frequency.

The length of the snow-free season at the three GEM sites varies with the choice of NDSI threshold, reflecting the significant sub-pixel heterogeneity of snow cover within a 500 m × 500 m pixel. Based on a convergence in snow-free day counts at NDSI < 40%, we adopted this threshold for further analysis, consistent with the thresholds used by Vickers et al. (2020) and Gauthier et al. (2024). At this threshold, some residual snow likely remains within a pixel, but the convergence suggests that this fractional cover disappears rapidly and is therefore unlikely to have a substantial effect on the local environment. Higher thresholds such as NDSI < 70% are reached considerably earlier in the season and may better capture the onset of snowpack thinning rather than near-complete snow clearance. The most appropriate threshold thus depends on the intended application: a high threshold is more suitable for studies of snow melt onset, while the 40% threshold and below better reflect the transition to a largely snow-free surface.

The comparison between the MODIS-derived snow-free days and in situ observations showed moderate to good correlation at all three sites. The best agreement was found at Zackenberg (r = 0.961), however, in situ observations recorded 14.7 more snow-free days than MODIS (Figure 6b). This bias is partly related to the choice of NDSI threshold, as the in situ snow-free

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day count aligns more closely with the NDSI < 50–60% thresholds (Figure 6a). The main cause of this discrepancy is likely MODIS pixel heterogeneity rather than a data mismatch - the 500 m pixel integrates over a mix of surface types, while the in situ albedo reflects conditions at a single point. The slope of 0.97 confirms a very high level of agreement in interannual variability. The moderate correlation between the mast pixel and the AOI mean (r=0.699, slope = 0.63) indicates considerable spatial variability across the AOI that is not captured at the mast pixel alone, which is expected given the valley location of the mast, the topographic relief of the AOI, and the varying distance to open ocean.

At Disko, direct validation against the main climate mast was not possible because the mast is located too close to the coast and the corresponding MODIS pixel does not contain usable data. We therefore compared against a nearby pixel covering the main ecological research area (Figure 3). The correlation between in situ and MODIS-derived snow-free days was moderate (r = 0.772), and the slope of 0.73 indicates that the interannual amplitude observed in situ is approximately 37% larger than captured by the chosen MODIS pixel (Figure 7b). The moderate correlation reflects the mast position close to the sea which is likely to affect snow cover conditions and while this comparison does not constitute a formal validation, it provides insight into how the in situ observations at the climate mast relate to snow cover conditions at the chosen MODIS pixel and, the correlation suggests that the two capture a broadly similar interannual signal even if the absolute counts and amplitude differ. The correlation between the mast pixel and the AOI mean (r = 0.725, slope = 0.5) indicates, as at Zackenberg, considerable spatial variability across the AOI likely driven by the topographical relief (Figure 5) and varying distance to the ocean.

At Kobbefjord, direct validation against the main climate mast is not possible because the mast is located too close to a large lake (Figure 4). Useable data was found in a neighbouring pixel, which is geographically closer to the mast than the comparison pixel at Disko. Despite this, the correlations between in situ and MODIS-derived snow-free days is only moderate (r = 0.686) with a slope of 0.55 indicating that in situ interannual variability is approximately twice that captured by the MODIS pixel (Figure 8b). The weaker correlation compared to Disko is likely related to local topographical differences. The chosen pixel is nonetheless strongly correlated with the AOI mean (r = 0.933, slope = 0.62), and the smaller bias between the two compared to the other sites is consistent with Kobbefjord having a higher proportion of its area close to sea level (Figure 5), reducing the elevation driven spatial variability in snow cover.

A primary source of uncertainty in our analysis is the cloud gap-filling procedure, in which cloud-obscured pixels are replaced with the most recent cloud-free observation. During the snow-free period, the mean number of gap-filled days was low at all three sites, ranging from 1.3 $\pm$ 1.8 days at Zackenberg and Kobbefjord to 1.8 $\pm$ 2.3 days at Disko. In individual years, however, the maximum gap-filled period reached 21, 20, and 13 days at Zackenberg, Disko, and Kobbefjord respectively, meaning that in the worst case a snow event of up to three weeks could pass undetected. This contributes to the systematic low bias in the MODIS-derived snow-free day counts relative to the in situ observations. Importantly, this bias appears stable through time, we find no statistically significant trend in the number of gap-filled days at any site, and the strong correlation between the MODIS-derived and in situ counts, particularly at Zackenberg where a direct pixel-to-mast comparison was possible (r = 0.961), gives confidence that the product reliably captures interannual variability even if absolute counts are underestimated.

The comparison with in situ observations highlight an important caveat. At Zackenberg, where a direct pixel-to-mast comparison was possible, agreement was strong (r = 0.961), giving confidence in the MODIS derive snow-free day counts at that site. At Disko and Kobbefjord, however, direct validation was not possible, and the indirect comparison suggest that MODIS captures only part of the interannual variability. A key difference between Zackenberg and the two southern sites is that snow-free conditions occur more frequently at the latter, including during winter, making the optical limitations of MODIS more consequential. The MODIS derived snow free day counts especially at Disko and Kobbefjord should therefore be interpreted with care considering that the snow free day counts is as seen from MODIS may differ from in situ conditions and further work is needed to better characterise the performance of MODIS at these sites. With this caveat in mind, we consider the interannual variability captured by MODIS sufficient to support the trend analysis presented below.

Trend analysis across all NDSI thresholds revealed no statistically significant trends in snow-free days at any of the three sites, a result that is consistent with the broader regional picture. While statistically significant decreasing trends in snow extent have been detected across the Northern Hemisphere as a whole, these are primarily driven by changes in Eurasia (Box et al., 2024). A trend analysis of the coarser Northern Hemisphere snow extent dataset of Robinson et al. (2012) confirms that no statistically significant trends are present in the North America and Greenland sector (longitude 0° to 180°W. Figure A4), either over the full record (1966-present) or over the MODIS period (2000-2025). The absence of significant trends is perhaps unsurprising given the high interannual variability in snow-free season length observed at the three sites. The standard deviation is approximately two weeks at each site, corresponding to a coefficient of variation around 18 % (76.5 ± 14.5 days) at Zackenberg and, 15 % and 16 % at Disko (78.3 ± 12.3 days) and Kobbefjord (102.9 ± 15.8 days) respectively. This level of variability is similar across all three sites despite their contrasting mean snow-free season lengths.

The OLS analysis reveals that the dominant predictor controlling interannual variability differs between the three sites. At Zackenberg, where the model explains 58 % of the variance, snowfall is the dominant and only significant predictor (standardised β = -0.74), while PDD carries the expected positive sign but is not significant. This suggests that at the cold, high-Arctic site the timing of melt-out is associated mainly with how much snow accumulated over winter, rather than by how much energy is available to remove it. At Kobbefjord, the wettest of the three sites, the model explains a comparable fraction of the variance (56 %), but here both drivers are significant and PDD is the stronger of the two (standardised β = 0.53 versus -0.39 for precipitation). The higher PDD at Kobbefjord (760 °C·d, against 569 °C·d at Zackenberg) appears sufficient for interannual differences in melt energy to become co-limiting alongside accumulation. Disko stands apart: it is the warmest of the three sites (894 °C·d) yet PDD is the only significant predictor, while snowfall contributes negligibly (p = 0.726). The most likely explanation is that Disko is also by far the driest site (only 216 mm snowfall from CARRA at the main mast location, against 357 mm at Zackenberg and 505 mm at Kobbefjord). With so little snow accumulating, year-to-year differences in accumulation have little leverage over melt-out timing, so the small explained signal falls on the energy term by default. The model as a whole performs poorly here (adjusted R^2 = 0.16), and several years fall well outside the prediction (Figure A2). Disko is also where our observational constraints are weakest: the comparison pixel does not directly overlie the climate mast, the in situ correlation is correspondingly lower (r = 0.772), and cloud persistence is the highest of the three sites (Table A2). Part of the unexplained variance may therefore reflect data quality rather than a genuine additional physical control.

Looking ahead, since MODIS is now a legacy sensor and will be decommissioned by the end of 2026, continuation of this snow cover record will require transitioning to newer sensors. The Visible Infrared Imaging Radiometer Suite (VIIRS), aboard

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the NASA/NOAA Suomi National Polar-orbiting Partnership (Suomi NPP), is the operational successor to MODIS offering comparable spatial resolution and daily revisit frequency and thus providing the most straightforward path to extending a consistent long-term record. The Ocean and Land Colour Instrument (OLCI) aboard ESA's Sentinel-3 constellation provides a complimentary option with daily Arctic coverage. The ESA Sentinel-2 constellation offers a third option: its considerably finer spatial resolution (10-20 m) would resolve much of the sub-pixel heterogeneity that MODIS misses, at the cost of a longer 4-6 days revisit cycle. The Sentinel-2 archive begins in 2016 and the Sentinel-3 archive in 2017, both providing substantial overlap periods over which cross-calibration against the MODIS record would be possible.

The high interannual variability in the snow-free season length documented here, combined with the absence of statistically significant trends over 26 years, has broad implications for ecosystem monitoring in the Arctic. Snow cover is a fundamental driver of a wide range of ecosystem processes at the GEM sites, from plant and arthropod phenology to soil thermal regimes, greenhouse gas flux, and glacier melt, and many of these processes are likely to inherit the high year-to-year- variability documented here. Detecting trends in snow-dependent ecosystem variables will therefore require monitoring records of comparable or greater length than those needed to detect trends in snow cover itself. The 26-year MODIS record presented here is a valuable baseline, but it also illustrates why sustained, multi-decadal monitoring programmes such at GEM are indispensable. As the MODIS era draws to a close, maintaining the continuity of snow cover observations through successor sensors will be essential not only for tracking snow itself, but for understanding the cascading effects of snow cover variability on the broader Arctic ecosystem.

5 Conclusions

We present a 26-year (2000-2025) record of snow-free days at the high-, mid- and low-Arctic Greenland derived from the MODIS cloud-gap-filled snow cover product. The MODIS-derived counts correlate well with in situ observations from the high-Arctic long term monitoring site Zackenberg, the only of the three GEM sites where a direct pixel-to-mast comparison was possible (r=0.961). At the mid- and low-Arctic sites Disko and Kobbefjord a direct validation was not possible, the MODIS-derived counts should be interpreted with some care. The mean snow free season length is 76, 78 and 103 days at the three sites respectively, with a standard deviation of approximately two weeks at each site despite their contrasting latitudinal positions.

No statistically significant trends in snow-free days were found at any site over the 26-year record, consistent with the absence of significant trends in the Northern Hemisphere snow cover in Greenland and North American sector over the same period. The dominant driver of interannual variability shifts along the latitudinal gradient: snowfall controls the snow free period in the cold, high-Arctic (Zackenberg) , positive-degree days become co-limiting alongside snowfall at the low-Arctic (Kobbefjord), and at the mid-Arctic (Disko) site, the warmest but driest of the three sites, PDD is the only significant predictor, though the model explains little of the variance there, pointing to additional physical controls not captured by simple temperature and precipitation forcing.

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The high interannual variability in snow-free season length, similar in magnitude across all three sites, means that records substantially longer than 26 years are required to detect a climate-change signal. Because so many Arctic ecosystem processes are governed by snow cover, detecting trends in these variables will demand monitoring records of comparable or greater length. This underscores the value of sustained, long-term monitoring programmes such as GEM. The snow-free day time series and the NDSI maps generated here will be continuously updated and made publicly available through the GEM database, and we intent to extent the record using complementary sensors as the MODIS era draws to a close.

Code and data availability. The dataset produced in this paper is considered living data, with annual updates. Daily NDSI maps for the three AOIs are available through the GEM database [link], and we intend to extend the record with the final MODIS image at the end of 2026 and continue it using VIIRS. The code to reproduce this work is available at https://github.com/GEUS-Glaciology-and-Climate/modis_snow_cover.

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Appendix A: Appendix

Table A1. Annual cloud persistence statistics at the climate mast pixel restricted to snow-free days (NDSI < 40%), Zackenberg. Values indicate the number of days since the last direct observation; 0 = directly observed.

Year	Mean (days)	Std (days)	Max (days)
2000	3.69	5.34	21
2001	1.71	2.28	10
2002	1.59	2.11	10
2003	1.18	1.66	8
2004	0.95	1.32	6
2005	1.83	2.70	13
2006	0.84	1.29	5
2007	0.75	1.25	6
2008	1.05	1.56	7
2009	1.33	1.91	9
2010	1.19	2.60	13
2011	0.80	1.35	6
2012	0.82	1.33	5
2013	1.24	1.82	7
2014	1.38	1.93	9
2015	2.00	2.28	8
2016	0.64	1.04	5
2017	1.20	1.65	6
2018	0.79	1.28	6
2019	0.67	1.12	6
2020	2.30	2.60	10
2021	0.78	1.16	5
2022	1.82	2.14	9
2023	1.00	1.42	6
2024	1.46	1.92	8
2025	1.01	1.64	7

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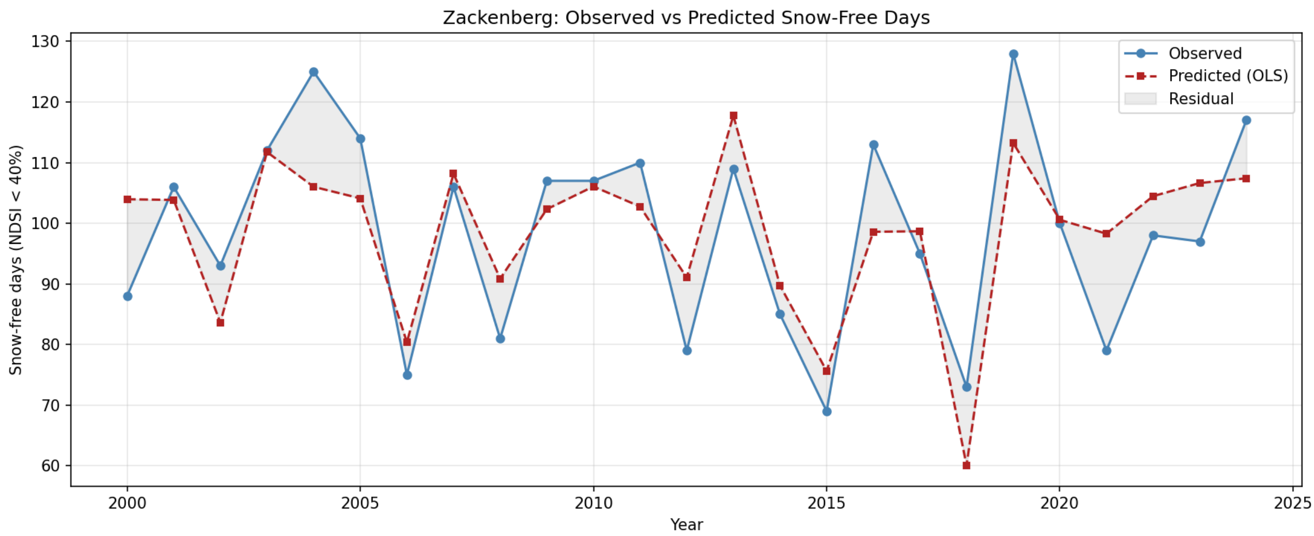

Figure A1. Zackenberg: Snow free days prediced in the mulitiple OLS regression analysis.

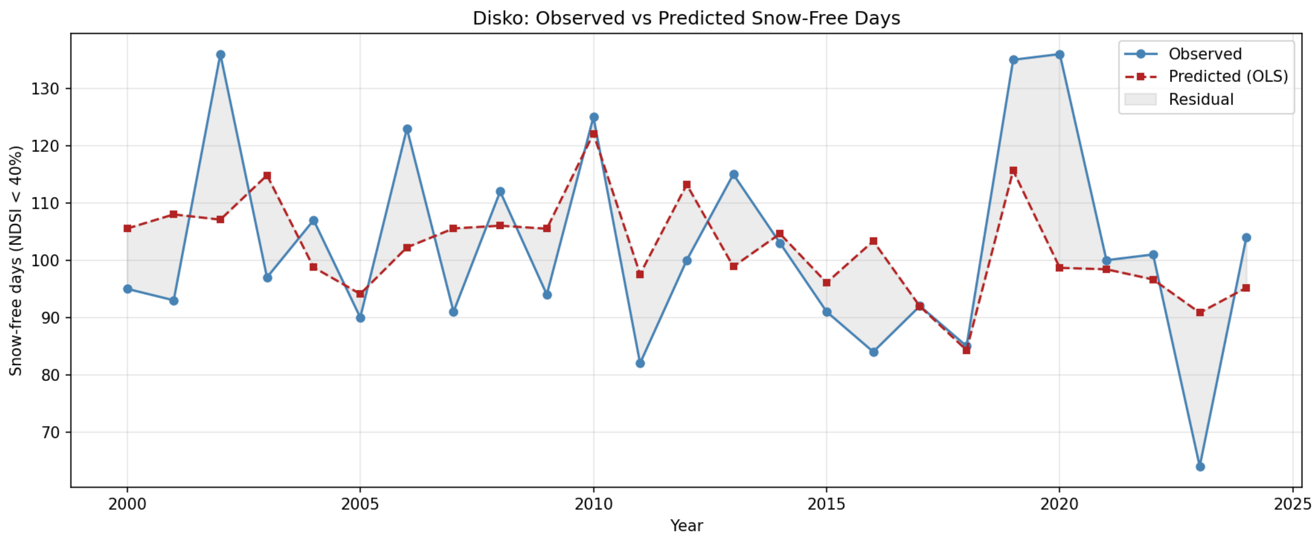

Figure A2. Disko: Snow free days prediced in the mulitiple OLS regression analysis.

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Table A2. Annual cloud persistence statistics at the climate mast pixel restricted to snow-free days (NDSI $<$ 40%), Disko. Values indicate the number of days since the last direct observation; 0 = directly observed.

Year	Mean (days)	Std (days)	Max (days)
2000	2.94	3.27	12
2001	1.61	2.78	13
2002	2.36	3.74	18
2003	1.27	1.87	8
2004	1.94	2.50	11
2005	1.93	2.90	13
2006	3.06	3.94	18
2007	1.55	2.24	9
2008	1.13	1.37	5
2009	0.77	1.25	6
2010	1.13	1.58	8
2011	0.95	1.33	6
2012	1.21	1.67	7
2013	1.39	2.05	9
2014	1.22	1.51	7
2015	1.04	1.48	6
2016	0.63	0.98	4
2017	1.23	1.72	7
2018	1.75	1.88	8
2019	0.58	0.89	5
2020	2.10	2.59	12
2021	1.29	1.59	7
2022	5.20	5.73	20
2023	2.28	2.38	8
2024	2.84	4.22	18
2025	2.32	3.13	15

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Table A3. Annual cloud persistence statistics at the climate mast pixel restricted to snow-free days (NDSI $<$ 40%), Kobbefjord. Values indicate the number of days since the last direct observation; 0 = directly observed.

Year	Mean (days)	Std (days)	Max (days)
2000	2.10	2.95	13
2001	1.48	1.92	8
2002	1.23	1.61	7
2003	1.05	1.68	8
2004	1.19	1.60	7
2005	1.74	2.05	9
2006	1.41	1.93	9
2007	1.81	2.83	13
2008	1.42	2.35	11
2009	0.92	1.41	7
2010	1.91	2.98	15
2011	1.15	1.58	7
2012	0.95	1.37	6
2013	1.03	1.45	6
2014	1.18	1.78	8
2015	0.89	1.29	6
2016	1.21	1.99	11
2017	1.06	1.58	7
2018	1.50	1.84	7
2019	1.35	2.08	10
2020	1.36	1.98	9
2021	0.97	1.37	7
2022	1.39	1.92	9
2023	1.84	2.35	11
2024	1.21	1.64	7
2025	1.49	2.25	11

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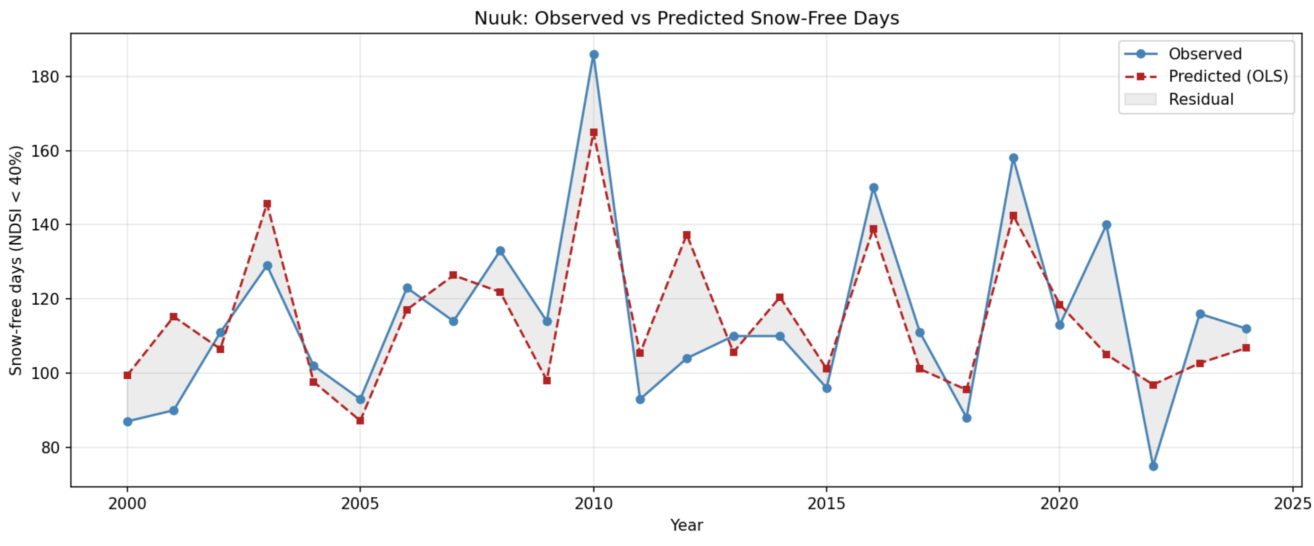

Figure A3. Kobbefjord: Snow free days prediced in the mulitiple OLS regression analysis.

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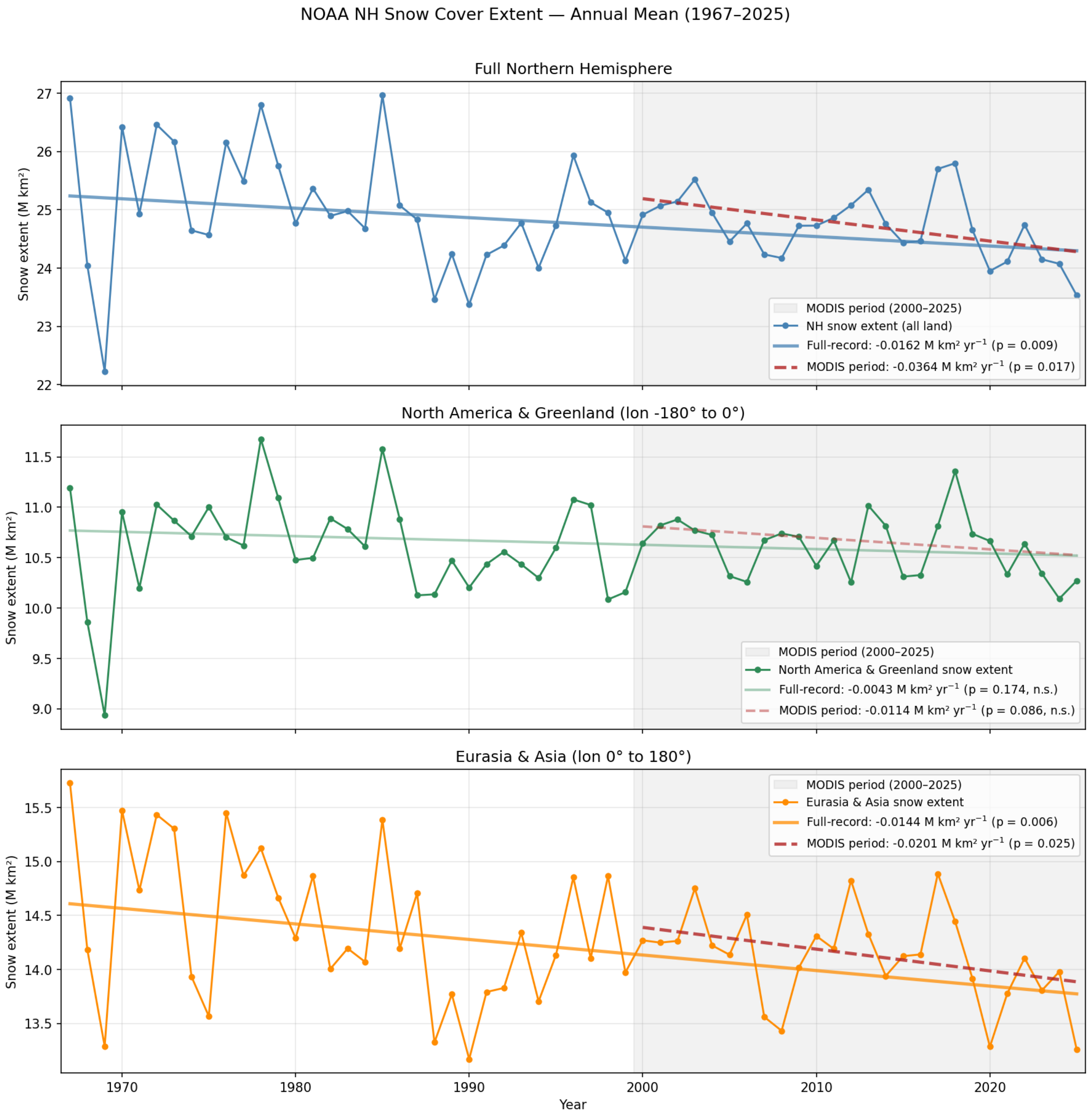

Figure A4. Snow exent variations on the Northern Hemispeher from Robinson et al. (2012).

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Author contributions. All authors where part of the idea development from start to end and all contributed to the writing of the manuscript. SHL wrote the code and lead the writing.

Competing interests. There are no competing interests

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