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Snow cover and air temperature 1961–2025

Analysis based on observations from 23 Norwegian stations

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Photo: Ketil Isaksen

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Abstract
Seasonally averaged temperature and snow cover data from 23 stations for the period 1961–2025 were used to investigate three research questions: (1) Is there a robust connection between seasonal temperature and snow cover? (2) Can an albedo amplification explain differences in temperature trends between seasons? And (3) can the albedo effect explain differences in temperature trends between elevations?
We conclude that the connection between seasonal temperature and snow cover is relatively robust within a specific season, although, particularly in spring, it also depends on total precipitation during the cold season. Differences in temperature trends between summer and autumn/spring are at least to some degree, accounted for by an albedo amplification. The major differences between elevations are, however, not explainable by an albedo effect. Since the dataset is limited to elevations below 1000 m a.s.l., data from higher elevations might yield different conclusions.

Keywords
Seasonal snow cover, seasonal temperature, trends, correlation, albedo feedback

Disciplinary signature

Responsible signature

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Abstract

Seasonally averaged temperature and snow cover data from 23 Norwegian climate stations for the period 1961–2025 were used to produce time series of temperature and snow cover representing 17 sites. The series showed increasing temperature at all sites and across all seasons, and decreasing snow cover at all sites and seasons where average snow cover was not close to 0 or 100%. These time series were used to investigate three research questions:
(1) Is there a robust connection between seasonal temperature and snow cover?
(2) Can an albedo amplification explain differences in temperature trends between seasons?
And (3) can the albedo effect explain differences in temperature trends between elevations?

We conclude that the connection between seasonal temperature and snow cover is relatively robust within a specific season, but there are systematic differences between autumn and spring, as a given temperature is associated with lower snow cover in autumn than in spring. Furthermore, particularly in spring, the relationship also depends on total precipitation during the cold season.

Regarding seasonal differences in temperature trends between summer and autumn/spring, these are, to some degree, accounted for by an albedo effect. The substantial warming during winter is, on the other hand, not explainable by albedo amplification. Instead, winter warming may be explained by systematic changes in atmospheric circulation, which have led to a warmer winter climate in our region.

The investigation of trends at different elevations was restricted to South-East Norway, to reduce the influence of other geographical factors. The major temperature trend differences between elevations found in this region cannot be explained by differences in snow cover trends. The dataset is, however, limited to elevations below 1000 m a.s.l. Data from higher elevations might yield different conclusions.

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1 Introduction

1.1 Background

In Norway, the temperature on average increased by about 1 °C from the previous standard normal period (1961–1990) to the present (1991–2020), and the temperature increase is projected to continue (Dyrrdal et al., 2025). The temperature increase impacts snow conditions, and several studies have examined the historical development of snow amounts or "snow cover depth" (Dyrrdal and Vikhamar-Schuler, 2009; Dyrrdal et al., 2013; Nilsen et al., 2025). Snow amounts are of interest for e.g. the water power industry, the transport sector and for winter tourism. It also impacts ecosystems, particularly affecting species like rodents and ptarmigan, who use the snow cover as shelter during the winter.

In some connections, however, snow cover itself is important. Whether the ground is snow covered or not influences ecosystems by affecting the survival of animals that change coat or feather colours as an adaptation to the snowy environment, e.g. ptarmigan and hares. It also impacts the albedo, and can thus affect the surface energy balance by locally amplifying temperature trends ("albedo effect"; see https://npolar.no/en/fact/albedo/). Satellite data on snow cover exists (e.g. https://cryo.met.no/en), but only from the late 1970s, and the distinction of snow from clouds is still a problem. For Norway, daily snow conditions are also calculated by a hydrological model (https://www.senorge.no/). However, the model basically calculates amounts of snow, and the resulting "snow cover" is thus sensitive to a chosen threshold value. Dyrrdal and Vikhamar-Schuler (2009) analysed the historical development of snow cover duration based on observations from 41 weather stations with long-term series (33 series covering more than 100 years). They concluded that the length of the snow season has decreased, but that there are regional variations. In this report, we will analyse the historical connection between temperature and snow cover in Norway in different seasons based on snow cover and temperature observations during the period 1961 to 2025.

Basic research questions are:

- R1: Is there a robust connection between seasonal temperature and snow cover?
- R2: Can the albedo effect explain differences in temperature trends between seasons?
- R3: Can the albedo effect explain differences in temperature trends between elevations?

1.2 Structure of the report

The data and methods we have used are presented in Section 2, while the results are presented in Section 3. In Section 4, we discuss the results in context of our research questions. We sum up our final conclusions in Section 5.

2 Data, definitions and methods

2.1 Data and definitions

Though Norway has an extensive network of weather stations measuring temperature (T), the network of stations with long term observation of snow cover (SC) is limited, especially during the later couple of decades, when many manual stations have been replaced by automatic measurements. In this report, we have applied data from 23 stations (Table 1 and Figure 1) for the period 1961 to 2025. Note that none of the stations are situated above 1000 m a.s.l. High mountain areas are thus not represented in this report.

Table 1. Station data applied in the analyses.

Station		**Elevation**	**Data**	
No.	Name	(m a.s.l.)	Temperature (T)	Snow cover (SC)
700	Drevsjø	672	Some missing	To 2019; some missing
7010	Rena – Haugedalen	240	To 2013	To 2013
7950	Rena flyplass	255	From 2013	No
10380	Røros lufthavn	625	From 2002	From 2002
10400	Røros	628	To 2001	To 2001
16610	Fokstugu	973	Complete	Complete
18700	Oslo-Blindern	94	Complete	Complete
24880	Nesbyen - Skoglund	167	To 2005	To 2005
24890	Nesbyen - Todokk	166	From 2006	From 2006; some missing
25630	Geilo - Oldebråten	772	Complete	No
25640	Geilo	841	No	Some missing data
31570	Møsvatn-Haug	945	No	1976 to 2018
31610	Møsstrand	948	1964-1975	1964-1975
31620	Møsstrand II	997	From 1975	No
37230	Tveitsund	252	Complete	To 2008
50540	Bergen – Florida	12	Complete	Complete
50310	Kvamskogen – Jonsh.	455	Complete	To 2016; some missing
69100	Værnes	12	Complete	To 2016; some missing
82290	Bodø VI	16	Complete	To 2021; some missing
90450	Tromsø	100	Complete	Complete
93900	Sihccajavri	382	Complete	Some missing data
97350	Cuovddatmohkki	286	From 1967	From 1967
98550	Vardø radio	10	Complete	To 2017

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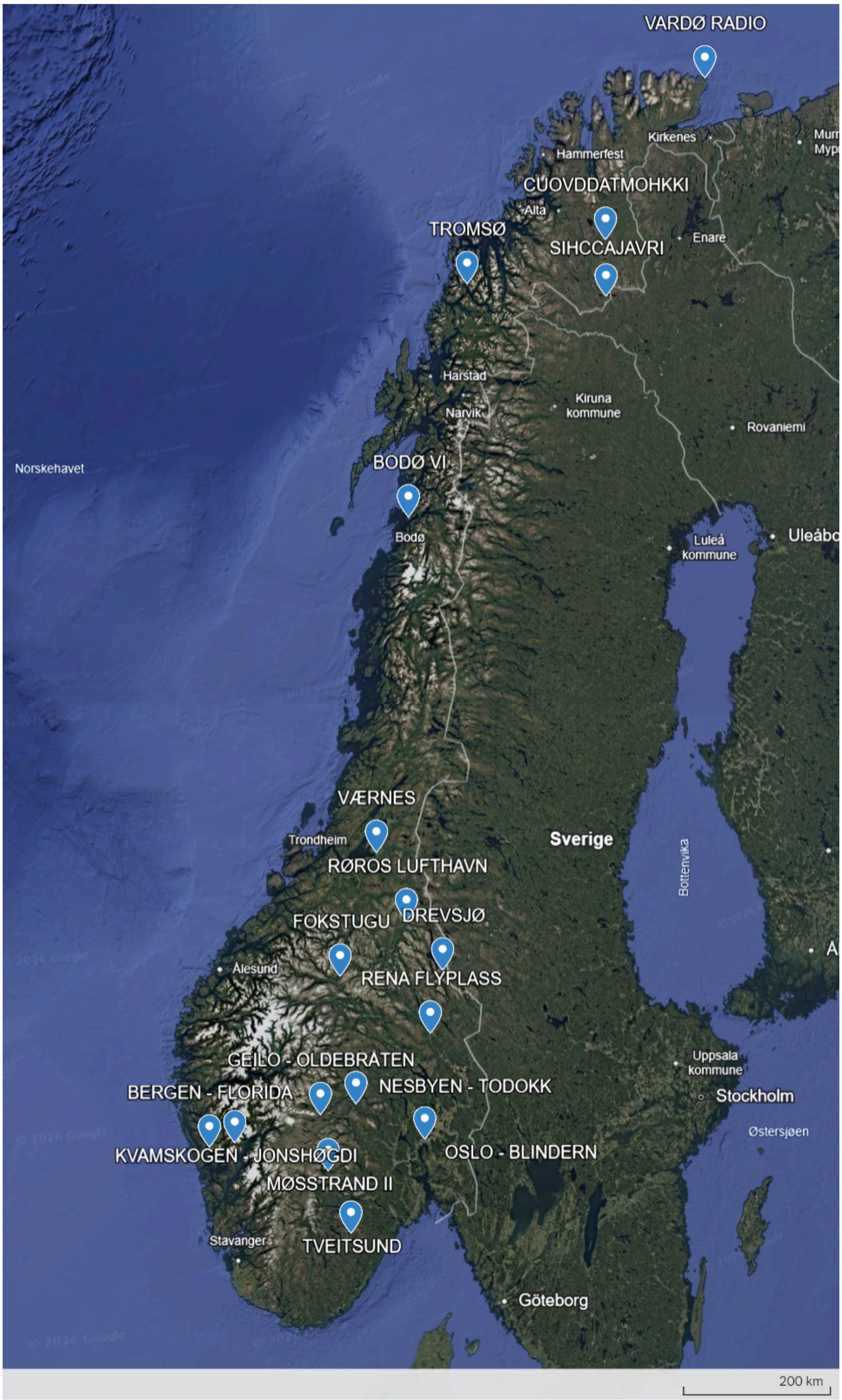

Figure 1. Map showing the position of the 23 stations representing the 17 sites analysed in this report. Source: Google Earth, Map data: IBCAO, Landsat / Copernicus, SIO, NOAA, U.S. Navy, NGA, GEBCO, LDEO-Columbia, NSF, NOAA, USGS. Imagery: 2015-2021.

Monthly data were downloaded from SeKlima (https://seklima.met.no/observations/) and combined to represent 17 sites (Table 2 and Figure 1). For Rena, Røros, Nesbyen, Geilo and Møsstrand, data from two or three stations were combined. Homogenised temperature series representing the presently active station were downloaded for these sites, and the elevation in Table 2 refers to the elevation of that station. For snow cover, we simply combined the time series from the different stations. Snow cover is observed manually and reported as the fraction of ground covered by snow on a scale of 0 to 4 (representing quarters of cover) within a 1 km radius of the station, restricted to areas within a +/- 50 m elevation range relative to the station. The values are thus less affected by the exact elevation of the stations. On the other hand, while the quality control routines for the temperature values are thorough, the routine check of the snow cover values is less systematic. Further, the snow cover series are more affected by missing values. Missing single values usually have limited influence on long-term averages, but gaps may be critical for trend calculations, especially when occurring towards the ends of the time series. In Norway, we find a strong positive temperature trend from around 1980 to present (Dyrrdal et al., 2025), and when data are missing during the later years, the trend will not be representative for the whole period.

Table 2. Sites included in the present study (also shown in Figure 1). When series are combined, elevation of the latest position of temperature measurements is given. The first column indicates the geographical region for each site, as some analyses are based on southeastern sites only.

Region	**Site**	**Elevation** (m a.s.l.)	**Comments on temperature (T) and snow cover (SC) series**
South-East Norway	Drevsjø	672	Some missing T and SC, SC to 2019
	Rena	255	Composite; T complete, SC to 2013
	Røros	625	Composite; T and SC complete
	Fokstugu	973	T and SC complete
	Oslo	94	T and SC complete
	Nesbyen	166	Composite; T complete, some missing SC
	Geilo	772	Composite; T complete, some missing SC
	Møsstrand	997	Composite; T complete, SC to 2018
	Tveitsund	252	T complete, SC to 2008
West- and Mid-Norway	Bergen	12	T and SC complete
	Kvamskogen	455	T complete, SC to 2016
	Værnes	12	T complete, SC to 2016
Northern Norway	Bodø	16	T complete, SC to 2021
	Tromsø	100	T and SC complete
	Sihccajavri	382	T complete, some missing SC
	Cuovddatmohkki	286	T and SC from 1967
	Vardø	10	T complete, SC to 2017

2.2 Methods

Based upon the downloaded monthly temperature and snow cover values, we calculated seasonal temperature and snow cover values as well as the correlations between them based upon all available data in the period 1961–2025 for the sites given in Table 2. We also calculated linear trends for temperature and snow cover, but only for the 50-year period 1967–2016. Linear trends depend highly on the choice of start- and endpoint, and several series are missing data towards the ends – in particular snow data. Limiting the trend calculation to the period 1967–2016 makes the trends more comparable. Note that still, the snow cover series from Rena and Tveitsund stop even earlier (2013 and 2008, respectively), and several other snow cover series also include gaps.

We analysed the results for the four seasons where autumn is defined as September, October, November (SON), winter is December, January, February (DJF), spring is March, April, May (MAM), and summer is June, July, August (JJA). Selected results were also analysed for individual months.

All data were applied for investigating the research questions R1 and R2. For research question R3, however, it was necessary to restrict the analyses to one geographical region, in order to reduce the influence of other geographical factors than elevation. Thus, the first column in Table 2 gives a regional attribution for all sites. As most sites are situated in South-East Norway, the investigation of R3 was limited to this region.

3 Results

As critical conditions for the formation and maintenance of a snow cover, namely temperature and solar radiation, vary throughout the year, we present the results on a seasonal basis. The basic results are presented in subsection 3.1. In the following subsections, covariation between some of the key variables are illustrated in different figures.

3.1 Basic results

3.1.1 Autumn

The basic results for autumn (SON) are presented in Table 3. The average autumn temperature varies from below -1 °C at the northern inland sites Sihccajavri and Cuovddatmohkki to +8.6 °C in the west-coast city Bergen.

Table 3. Basic results for the autumn (SON). The averages are based upon all available values in the period 1961–2025. Trends are given for the period 1967–2016.The sites are colour-coded according to the regions given in table 2: South-East is red; West- and Mid-Norway is green, Northern Norway is blue.

Site	**Elevation** (m a.s.l.)	**T-mean** (°C)	**SC-mean (fraction** 0–4)	**Corre-lation**	**trend T** (°C/dec.)	**trend SC** (fraction/dec.)
Drevsjø	672	1.2	1.26	-0.68	0.45	-0.10
Rena	256	2.9	0.94	-0.56	0.55	-0.05*
Røros	625	1.0	1.34	-0.68	0.41	-0.14
Fokstugu	973	0.6	1.49	-0.65	0.31	-0.17
Oslo	94	6.6	0.37	-0.69	0.35	-0.11
Nesbyen	166	3.2	0.88	-0.67	0.37	-0.05
Geilo	772	1.8	1.48	-0.55	0.33	-0.04
Møsstrand	997	2.0	1.40	-0.57	0.20	-0.08
Tveitsund	252	6.1	0.51	-0.70	0.31	-0.14*
Bergen	12	8.6	0.13	-0.51	0.30	-0.03
Kvamskogen	455	5.1	0.84	-0.66	0.30	-0.02
Værnes	12	6.2	0.46	-0.68	0.27	-0.12
Bodø	16	5.7	0.55	-0.68	0.45	-0.10
Tromsø	100	3.5	1.44	-0.68	0.37	-0.15
Sihccajavri	382	-2.0	1.90	-0.58	0.58	-0.07
Cuovddatmohkki	286	-1.4	2.15	-0.62	0.58	-0.08
Vardø	10	2.4	1.08	-0.76	0.51	-0.16

*: At Rena the SC series ends in 2013, and at Tveitsund in 2008

The average snow cover is at minimum (below 5%) in Bergen and at maximum (around 50% cover) at Sihccajavri and Cuovddatmohkki. The correlation between average temperature and snow cover varies from -0.51 in Bergen to -0.76 in Vardø in the northeast. The temperature trends 1967–2016 are positive everywhere, and highest at the northern inland sites Cuovddatmohkki and Sihccajavri, but also at the southeastern inland site Rena. The lowest temperature trends are found at the high-elevation station Møsstrand in southeastern Norway, but there are also low values along the western coast. The trends in snow cover are negative at all sites. The largest negative trends are seen at Fokstugu, 973 m a.s.l. in southern Norway, and at the coastal sites Vardø and Tromsø in northern Norway. The smallest change in snow cover is found at the western sites Kvamskogen and Bergen.

Figure 2 shows examples of autumn time series. Bergen and Tromsø represent coastal sites in southern and northern Norway, respectively. Fokstugu and Sihccajavri represent inland sites in southern and northern Norway, and they also represent relatively high elevation snow observations in their respective regions. The average autumn snow cover is low in Bergen. Around the other stations, however, snow normally starts to accumulate in autumn, and there is a considerable variation from year to year.

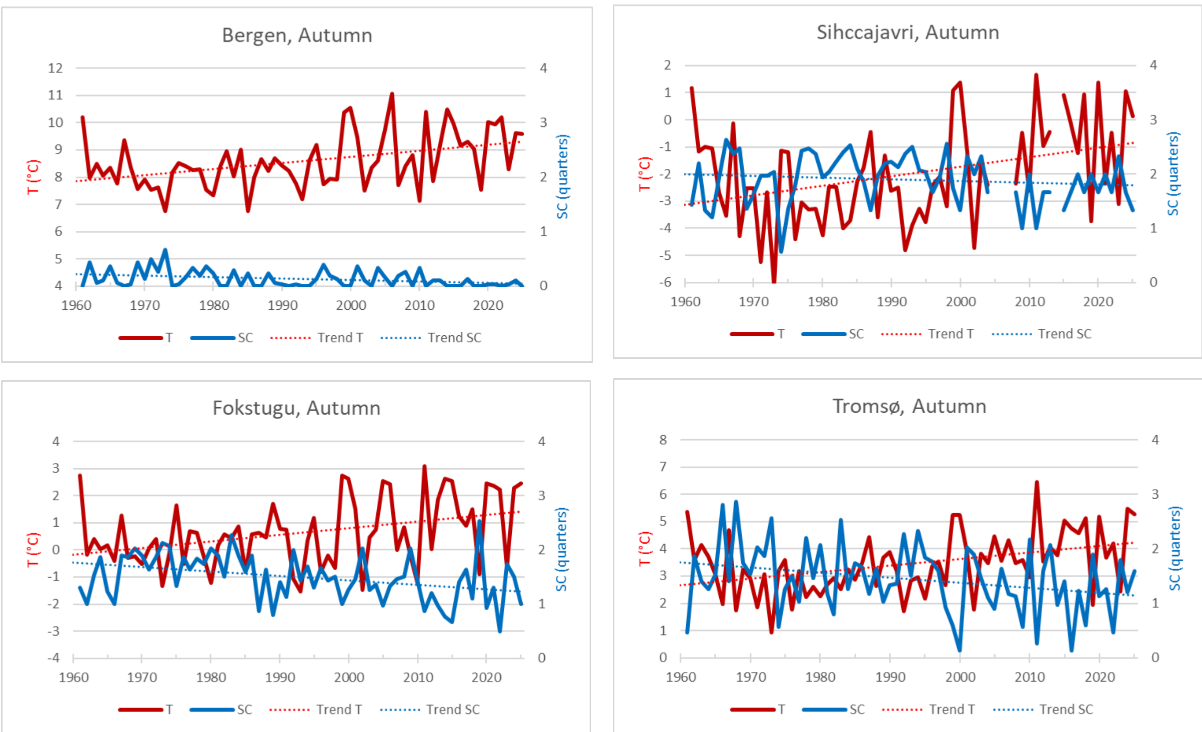

Figure 2. Autumn time series of temperature (red) and snow cover (blue) for Bergen, Fokstugu, Tromsø and Sihccajavri for the period 1961–2025.

3.1.2 Winter

The basic results for winter (DJF) are presented in Table 4. The average winter temperature varies from below -13 °C at the northern inland sites Sihccajavri and Cuovddatmohkki to +2.3 °C in the west-coast city Bergen. The average snow cover is at minimum in Bergen (below 40% cover) while Sihccajavri and Cuovddatmohkki had full snow cover throughout the winter during the whole period. The correlation between average temperature and snow cover is non-positive everywhere and varies from 0 at the sites with full snow cover to -0.86 in Bergen.

Table 4. Basic results for the winter (DJF). The averages are based upon all available values in the period 1961–2025. Trends are given for the period 1967–2016. The sites are colour-coded according to the regions given in table 2: South-East is red; West- and Mid-Norway is green, Northern Norway is blue.

Site	**Elevation** (m a.s.l.)	**T-mean** (°C)	**SC-mean (fraction** 0–4)	**Corre-lation**	**trend T** (°C/dec.)	**trend SC** (fraction/dec.)
Drevsjø	672	-9.5	3.94	-0.19	0.56	-0.07
Rena	240	-8.6	3.90	-0.13	0.77	-0.07*
Røros	625	-9.4	3.95	-0.17	0.55	-0.02
Fokstugu	973	-7.5	3.93	-0.32	0.42	-0.02
Oslo	94	-2.7	3.14	-0.73	0.44	-0.19
Nesbyen	166	-8.1	3.69	-0.53	0.62	-0.04
Geilo	772	-6.8	3.99	-0.38	0.30	0.00
Møsstrand	997	-6.5	3.97	-0.28	0.33	-0.01
Tveitsund	252	-2.5	3.38	-0.68	0.50	-0.19*
Bergen	12	2.3	1.43	-0.86	0.19	-0.19
Kvamskogen	455	-2.1	3.70	-0.38	0.26	-0.03
Værnes	12	-1.5	2.71	-0.73	0.27	-0.23
Bodø	16	-0.9	2.70	-0.62	0.32	-0.15
Tromsø	100	-3.0	3.51	-0.60	0.23	-0.10
Sihccajavri	382	-13.9	4.00	0.00	0.55	0.00
Cuovddatmohkki	286	-13.4	4.00	0.00	0.46	0.00
Vardø	10	-3.9	3.59	-0.54	0.47	-0.13

*: At Rena the SC series ends in 2013, and at Tveitsund in 2008

The temperature trends are positive everywhere, and highest in the southern inland sites Rena and Nesbyen, and lowest at the coastal sites Bergen and Tromsø. The trends in snow cover are zero in areas where the average snow cover is 4, but negative elsewhere. The largest negative trends are seen in Bergen and Oslo and at Tveitsund. Note that the Tveitsund series ends already in 2008 and thus is not directly comparable to other series.

Figure 3 shows some examples of winter time series from Bergen, Tromsø, Fokstugu and Sihccajavri. In Sihccajavri, there is full snow cover all through the winter. There are also only minor deviations from full snow cover in Fokstugu. The coastal stations show more interannual variation. In Bergen, the average winter snow cover varies from almost 0 to above 74%; while it varies from about 60% to full snow cover in Tromsø.

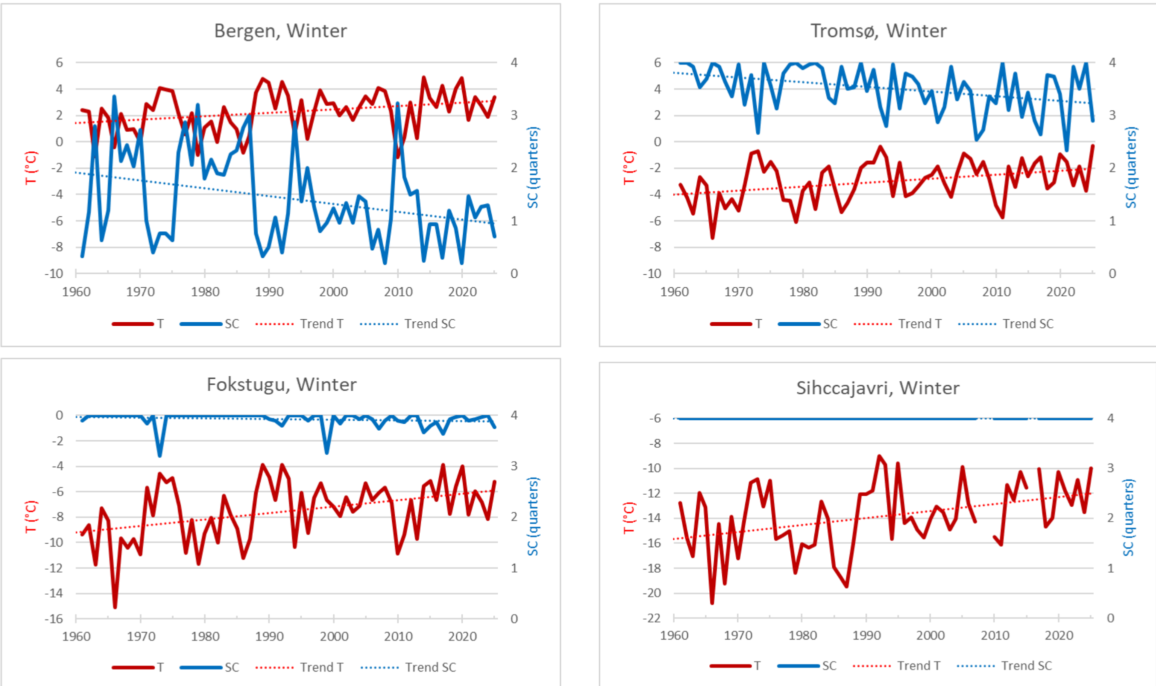

Figure 3. Winter time series of temperature (red) and snow cover (blue) for Bergen, Fokstugu, Tromsø and Sihccajavri.

3.1.3 Spring

The basic results for spring (MAM) are presented in Table 5. Average spring temperature varies from around -4 °C at the northern inland sites Sihccajavri and Cuovddatmohkki to above +6 °C at the southern coastal stations Bergen and Oslo.

The average snow cover is at minimum in Bergen (about 10% cover) while several northern stations (Sihccajavri, Cuovddatmohkki and Tromsø) on average had more than 75% snow cover in spring. The correlation between average temperature and snow cover varies from -0.37 in Sihccajavri to -0.81 in Tveitsund. The temperature trends from 1967 to 2016 are positive everywhere and vary from 0.16 °C per decade in Værnes to 0.48 in Cuovddatmohkki. The trends in snow cover are negative and vary from -0.03 quarters per decade in Røros to -0.24 quarters per decade in Vardø.

Table 5. Basic results for the spring (MAM). The averages are based upon all available values in the period 1961–2025. Trends are given for the period 1967–2016. The sites are colour-coded according to the regions given in table 2: South-East is red; West- and Mid-Norway is green, Northern Norway is blue.

Site	**Elevation** (m a.s.l.)	**T-mean** (°C)	**SC-mean fraction** (0–4)	**Correl-ation**	**trend T** (°C/dec.)	**trend SC** (quart./dec.)
Drevsjø	672	-0.1	2.90	-0.42	0.45	-0.06
Rena	256	2.8	2.31	-0.56	0.41	-0.09*
Røros	625	-0.1	2.70	-0.54	0.36	-0.03
Fokstugu	973	-1.0	2.82	-0.69	0.32	-0.10
Oslo	94	6.2	1.08	-0.74	0.40	-0.16
Nesbyen	166	4.0	1.52	-0.68	0.41	-0.14
Geilo	772	0.3	2.82	-0.70	0.46	-0.13
Møsstrand	997	-0.5	3.31	-0.53	0.43	-0.12
Tveitsund	252	4.4	1.93	-0.81	0.40	-0.23*
Bergen	12	6.9	0.38	-0.65	0.27	-0.07
Kvamskogen	455	3.2	2.62	-0.65	0.23	-0.18
Værnes	12	5.0	1.12	-0.61	0.16	-0.14
Bodø	16	3.4	1.30	-0.68	0.24	-0.12
Tromsø	100	1.4	3.23	-0.76	0.24	-0.11
Sihccajavri	382	-4.3	3.62	-0.37	0.41	-0.08
Cuovddatmohkki	286	-3.4	3.38	-0.59	0.48	-0.11
Vardø	10	-0.1	2.72	-0.77	0.47	-0.24

*: At Rena the SC series ends in 2013, and at Tveitsund in 2008

Figure 4 shows some examples of spring time series from Bergen, Tromsø, Fokstugu and Sihccajavri. The average spring temperature has increased at all sites, and most at Sihccajavri. The average snow cover on the other hand, has decreased at all sites except Sihccajavri, where it varied between 75 and 100% during the entire period.

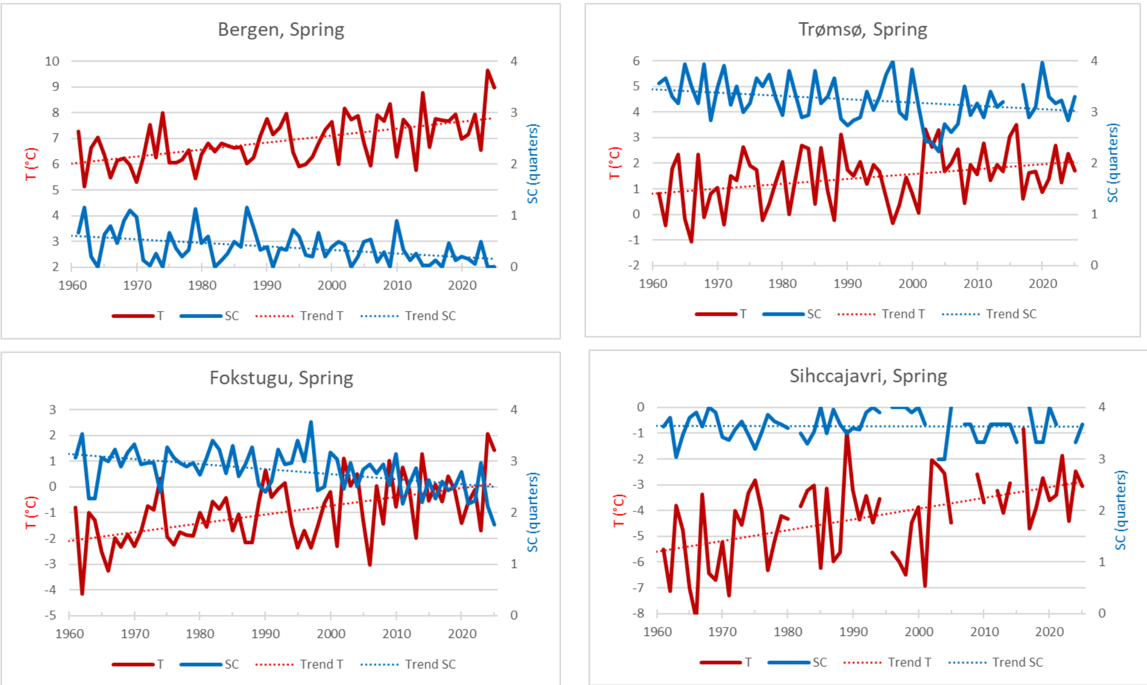

Figure 4. Spring time series of temperature (red) and snow cover (blue) for Bergen, Fokstugu, Tromsø and Sihccajavri.

3.1.4 Summer

The main results for the summer (JJA) are presented in Table 6. The average summer temperature at the selected sites varies from +8.7 °C at the northernmost coastal site Vardø to +16.3 °C in Oslo. Most of the sites report no snow cover in summer during the entire period, while occasional SC > 0 has been observed at the northernmost stations and some high-elevation stations further south. Still, the average values are very low (2.5% or less). The temperature trends from 1967 to 2016 are positive everywhere and vary from 0.04 °C per decade in Tromsø to 0.29 in Vardø. The trends in snow cover are non-positive and vary from 0 quarters per decade in sites with no snow to -0.04 quarters per decade in Sihccajavri, where there still is some snow in the early summer.

Table 6. Basic results for the summer (JJA). The averages are based upon all available values in the period 1961–2025. Trends are given for the period 1967–2016. The sites are colour-coded according to the regions given in table 2: South-East is red; West- and Mid-Norway is green, Northern Norway is blue.

Site	**Elevation** (m a.s.l.)	**T-mean** (°C)	**SC-mean fraction** (0–4)	**Correl-ation**	**trend T** (°C/dec.)	**trend SC** (quart./dec.)
Drevsjø	672	11.1	0.02	-0.14	0.07	0.00
Rena	256	13.8	0.00	0.00	0.16	0.00*
Røros	625	10.8	0.00	-0.08	0.12	0.00
Fokstugu	973	9.5	0.02	-0.13	0.13	0.00
Oslo	94	16.3	0.00	0.00	0.10	0.00
Nesbyen	166	14.7	0.00	0.00	0.11	0.00
Geilo	772	10.8	0.00	-0.22	0.11	0.00
Møsstrand	997	10.2	0.05	-0.15	0.08	-0.01
Tveitsund	252	14.6	0.00	0.00	0.08	0.00*
Bergen	12	14.5	0.00	0.00	0.27	0.00
Kvamskogen	455	11.8	0.00	-0.20	0.12	0.00
Værnes	12	13.9	0.00	0.00	0.18	0.00
Bodø	16	12.3	0.00	0.00	0.19	0.00
Tromsø	100	11.1	0.02	-0.27	0.04	-0.01
Sihccajavri	382	10.7	0.10	-0.32	0.14	-0.04
Cuovddatmohkki	286	11.1	0.02	-0.28	0.15	-0.02
Vardø	10	8.7	0.03	-0.37	0.29	-0.02

*: At Rena the SC series ends in 2013, and at Tveitsund in 2008

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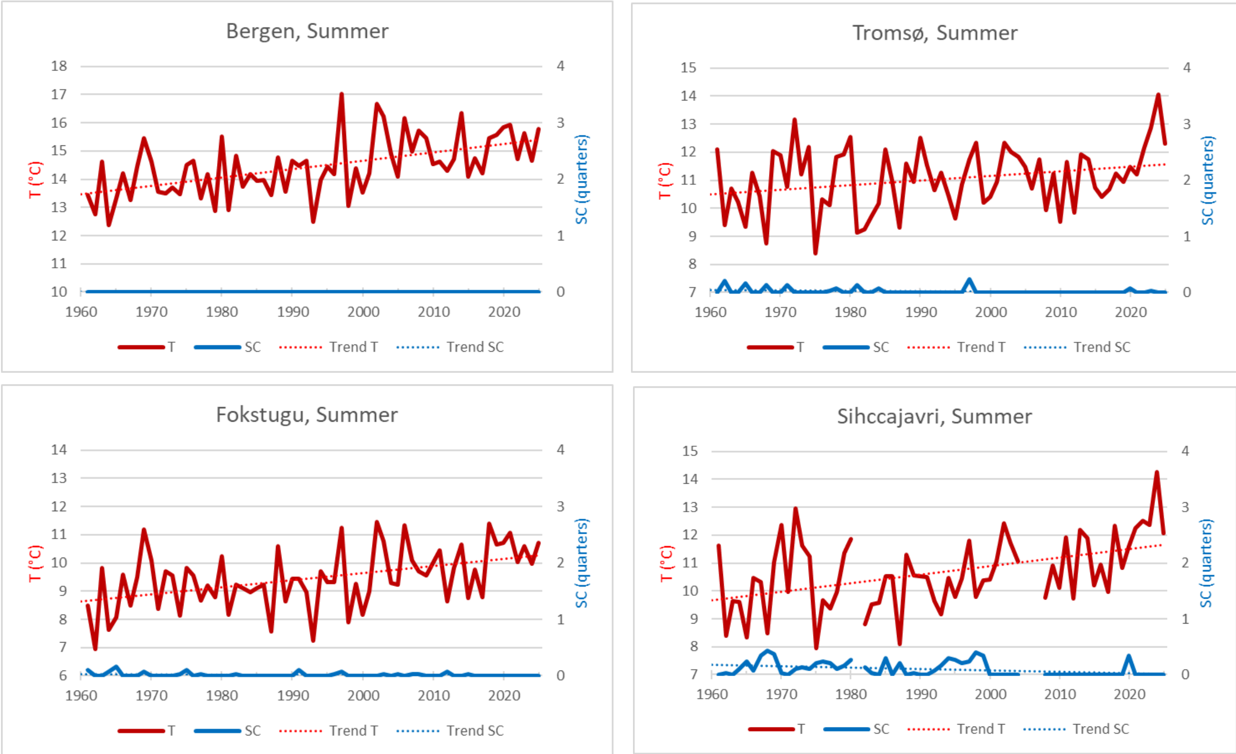

Figure 5. Summer time series of temperature (red) and snow cover (blue) for Bergen, Fokstugu, Tromsø and Sihccajavri.

Figure 5 shows some examples of summer time series from Bergen, Tromsø, Fokstugu and Sihccajavri. The average summer temperature has increased in all sites. The average snow cover fraction is 0 in Bergen, and constantly below 0.5 in all sites throughout the whole period.

3.2 Research question 1

Is there a robust connection between seasonal temperature and snow cover? To illuminate this, we have looked at the connection between seasonal average snow cover and temperature.

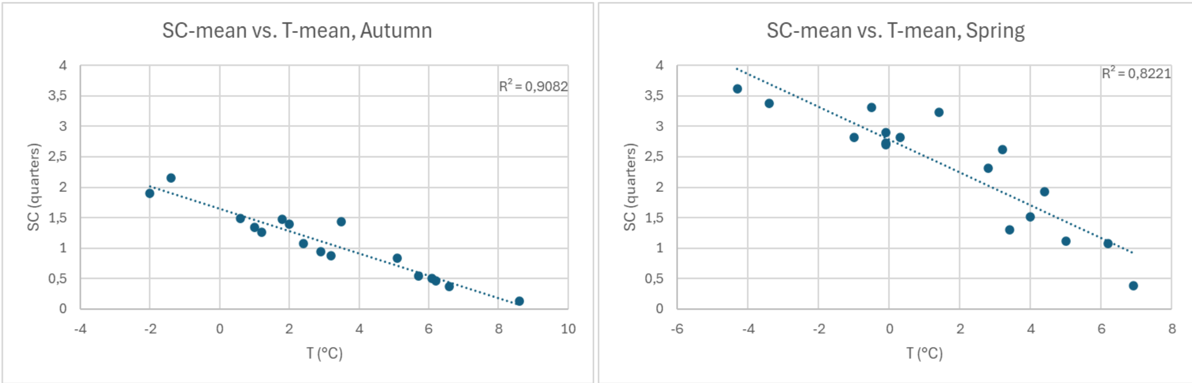

Figure 6. Crossplot of average seasonal snow cover (SC) and temperature (T) in autumn (left panel), and spring (right panel), see Tables 3 and 5. The dotted lines show linear trend lines.

The connection between average snow cover and temperature has a seasonal dependency. In autumn, the connection can be described well as linear (R^2=0,91), from SC=0 for seasonal temperature around + 8 to 9 °C to SC=2 for seasonal temperature around -2 °C (Figure 6, left panel). The linear fit is somewhat poorer in spring (R^2=0,82; Figure 6, right panel). Further, the slope is steeper, and the snow cover is in general larger for a given temperature than it is in autumn (Figure 6, right panel).

All seasons combined, the snow cover dependency of temperature may be described by a hysteresis (Figure 7). In autumn, the snow cover starts building up when precipitation falls at sufficiently low temperatures. In spring, on the other hand, snow does not start to melt until temperatures are sufficiently high. There is therefore a time lag that depends on how much snow has to melt, i.e. the snow depth. Differences in precipitation amounts in the cold season lead to differences in the time lag, and can thus explain why the spread is larger in spring than in autumn. For example, the average spring snow cover fraction is rather similar in Tromsø and Møsstrand (3.2 vs. 3.3), even though the average spring temperature in Tromsø is almost 2 °C higher than at Møsstrand (+1.4 vs. -0.5 °C). Climatology maps for winter precipitation (e.g. Figure 3.3.2a in Dyrrdal et al., (2025)) show that winter precipitation normally is much higher in Tromsø than at Møsstrand.

In winter, the connection fits rather well a polynomial trendline (R^2=0,91; not shown) that resembles the common trend line shown in Figure 6. The largest deviation from the trendline is found at Kvamskogen (SC-mean: 3.7 and T-mean: -2.1). Kvamskogen is situated in an area with very high winter precipitation (Dyrrdal et al., 2025). In summer, average snow cover is close to 0 in all these sites.

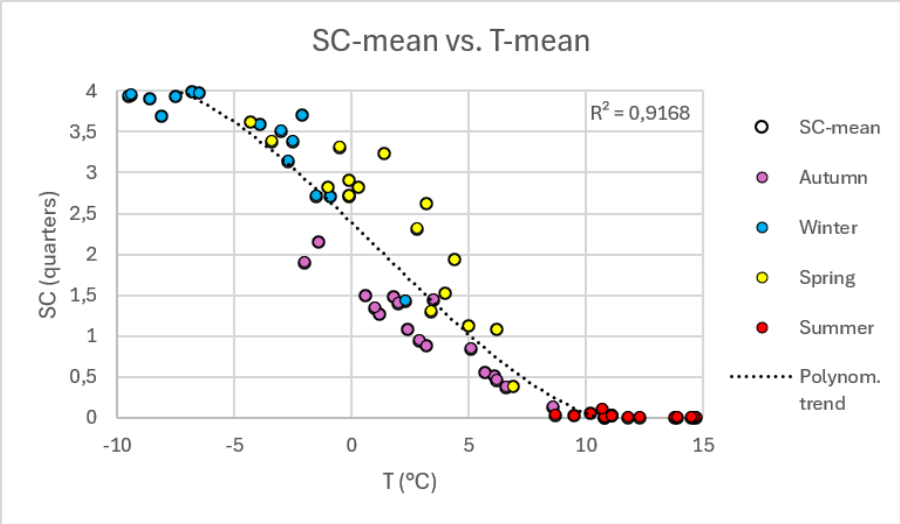

Figure 7. Crossplot of average seasonal snow cover and temperature in autumn (purple), winter (blue), spring (yellow), and summer (red), based upon the values in Tables 3–6. The dotted black line shows a third-degree polynomial trend line for the whole dataset.

3.3 Research question 2

Can the albedo effect explain differences in temperature trends between seasons? To illuminate this question, we performed several analyses. The direct comparison of temperature trends and snow cover trends (Section 3.3.2) is central, but as many factors affect these trends, additional analyses are performed.

3.3.1 Correlation SC-T vs. T-mean and SC-mean

The correlation between seasonal snow cover and temperature is primarily driven by the fact that temperature defines whether a snow cover can exist. However, snow cover also feedbacks on temperature by reducing the absorption of solar radiation, and capping the maximum surface temperature at 0 °C. Finding the temperature range and the snow cover range where there is a considerable correlation coefficient between snow cover and temperature will thus indicate the range in seasonal values of when the snow cover trend might affect the temperature trend. This is relevant background information for the discussion of our second research question.

In general, the negative SC-T correlation with temperature increases from 0 in seasons with average temperature below -10 °C or so, to values between -0.5 and -0.9 when the seasonal temperature is between 0 and +5 °C, then decreases towards 0 when the seasonal temperature exceeds +12 °C (Figure 8).

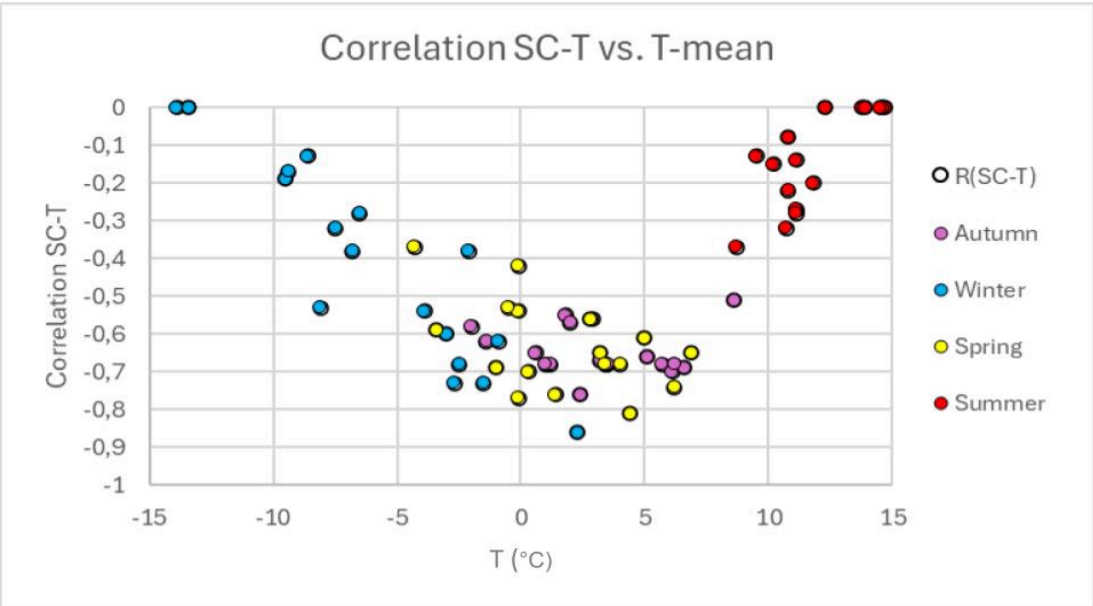

Figure 8. Crossplot of correlation between seasonal snow cover and temperature versus average seasonal temperature in autumn (purple), winter (blue), spring (yellow), and summer (red), based upon the values in Tables 3 – 6.

There is a considerable spread in the data, especially in winter and spring. Correlations better than -0.5 are mainly found for seasons with average temperatures between -5 and +8 °C. The average autumn temperatures lie mostly in this interval, and the SC-T correlations in autumn are better than -0.5 at all sites. The best individual correlation values are still found in winter (Bergen: -0.86 for T=+2.3 °C) and in spring (Tveitsund -0.81 for T=+4.4 °C). In summer, all sites have average temperatures above +8 °C, and none of the negative correlation exceeds -0.4.

While Figure 8 indicates a slightly skewed V-shape, Figure 9 indicates more of an U-shape for the connection between snow cover - temperature correlation and snow cover. From no correlation for seasons with average zero or full snow cover, the negative correlation between SC-T and mean snow cover changes quite rapidly with increasing or decreasing average snow cover, respectively . The correlation between snow cover fraction and temperature is -0.5 or better for most sites and seasons when the average snow cover fraction is between 0.1 and 3.7.

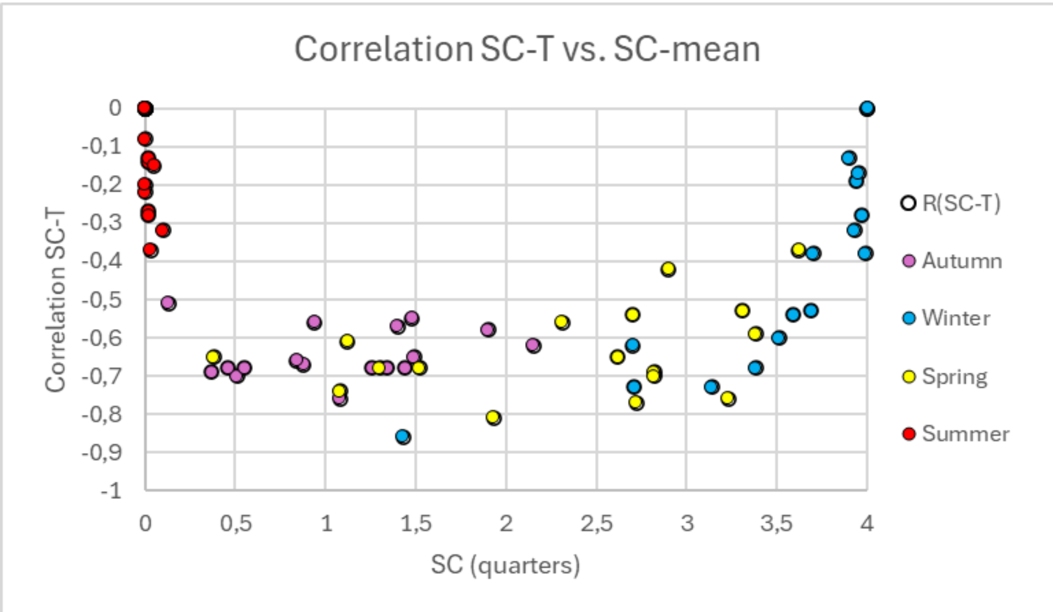

Figure 9. Crossplot of correlation between seasonal snow cover and temperature versus average seasonal snow cover in autumn (purple), winter (blue), spring (yellow), and summer (red), based upon the values in Tables 3 – 6.

3.3.2 T-trend vs. SC-trend

If the positive temperature trends we find in historical data locally have been amplified by an albedo effect, we expect to see the larger positive temperature trends at sites and in seasons with large negative snow cover trends. Figure 10 shows that the linear connection between the trends in temperature and snow cover is very weak. The worst fit is during winter, and when skipping the winter data (Figure 11), the fit increases to some degree (R^2=0.33). Still, the strongest temperature trends in autumn are found in Rena, Sihccajavri and Cuovddatmohkki, where the negative trends in snow cover are moderate. Further, the weakest temperature trends in spring are found at sites with medium-range negative snow cover trends.

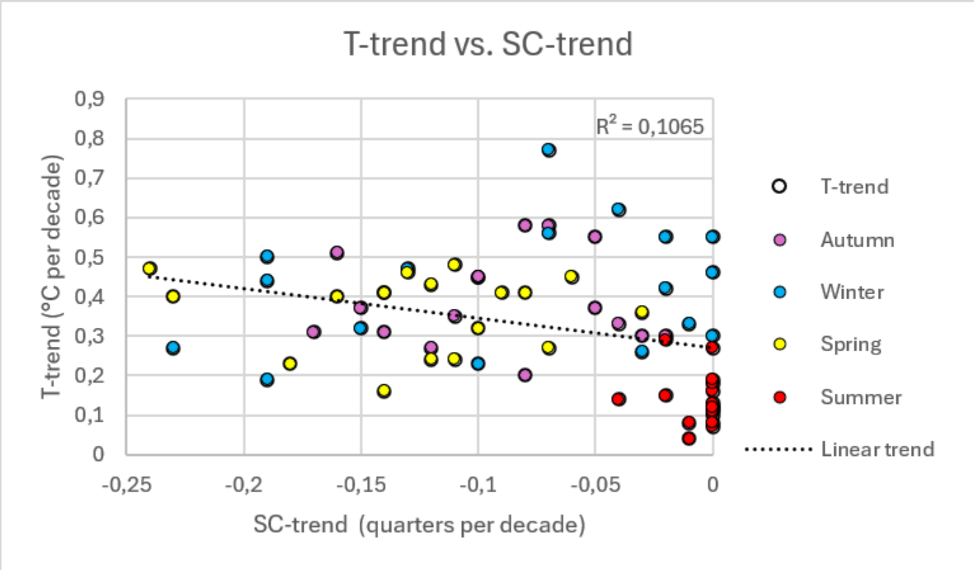

Figure 10. Cross plot of temperature trends versus trends in snow cover in autumn (purple), winter (blue), spring (yellow), and summer (red), based upon the values in Tables 3 – 6. The dotted black line shows the linear trend line for the whole dataset.

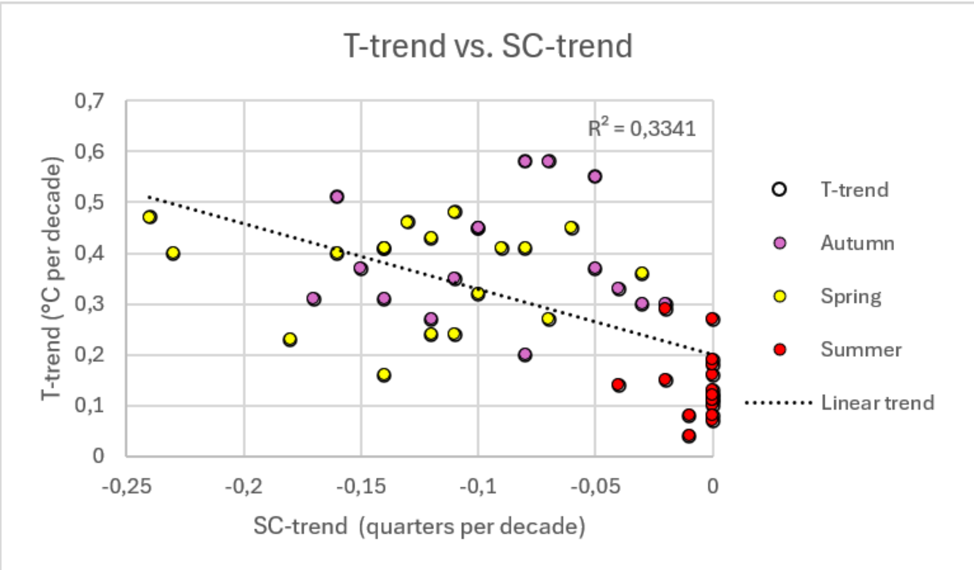

Figure 11. As Figure 10, but without winter.

Concerning seasonal differences, the lowest average temperature increase is found in summer (0.14 °C per decade, based upon Table 6). The largest average is seen in winter (0.43 °C per decade; Table 4), while the increase has been slightly lower for autumn (0.39; Table 3) and spring (0.36; Table 5).

3.3.3 T-trend vs. SC-mean and T-mean

Trend calculations are sensible to single values, especially towards the ends of the series (see section 2). Although we have restricted the trend calculations to the period 1967–2016, when snow cover has been observed at most sites, there are some gaps in the SC series. We also know that the quality of the snow cover data is varying. As average values are more robust towards missing or erroneous single values than trends, we have here plotted the temperature trend versus the seasonally averaged snow cover values (Figures 12 and 13) and temperature values (Figures 14 and 15).

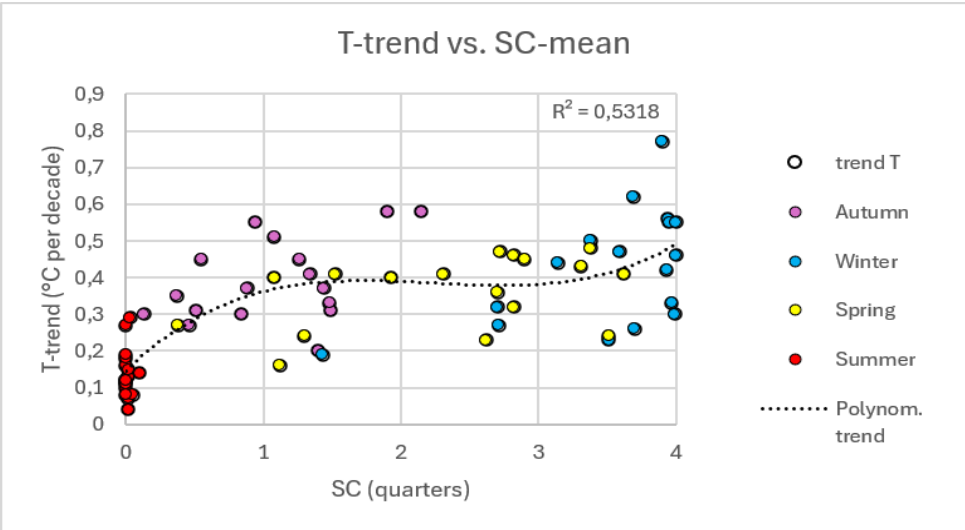

Figure 12. Cross plot of temperature trends versus average snow cover in autumn (purple), winter (blue), spring (yellow), and summer (red), based upon the values in Tables 3–6. The dotted black line shows a third-degree polynomial trend line for the whole dataset.

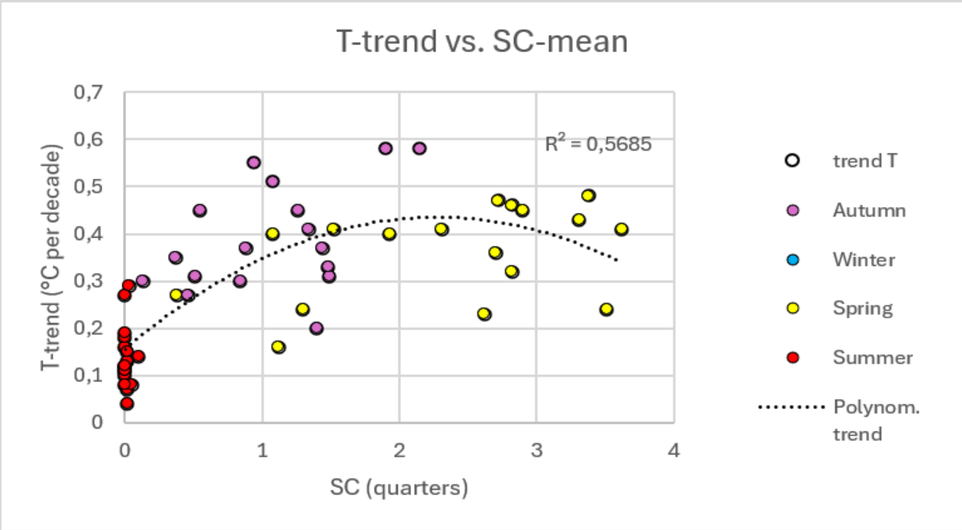

Figure 13. As Figure 10, but without winter, and with a second-degree polynomial trend line.

When considering all seasons (Figure 12), the dataset tends to show low temperature trends for SC=0, increasing to higher values for snow cover fraction around 1. Between snow cover fraction 1 and 3, there is no clear trend, however, for snow cover fraction values above 3, there is a new tendency for increasing temperature trends, mainly caused by high temperature trends at some sites in winter. When skipping the winter (Figure 13), the tendency for increased temperature trends at sites with snow cover fraction above 3 disappears.

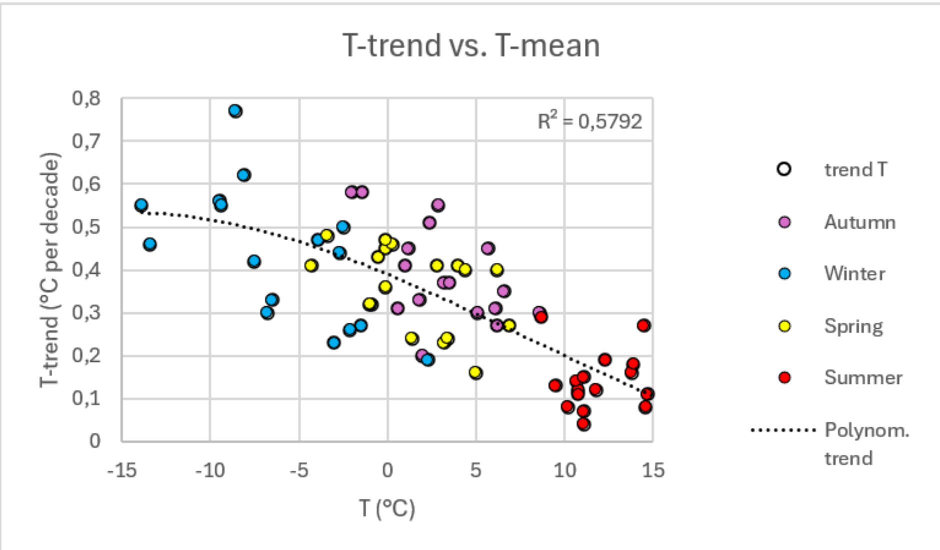

Figure 14. Cross plot of temperature trends versus average temperature in autumn (purple), winter (blue), spring (yellow), and summer (red), based upon the values in Tables 3–6. The dotted black line shows a third-degree polynomial trend line for the whole dataset.

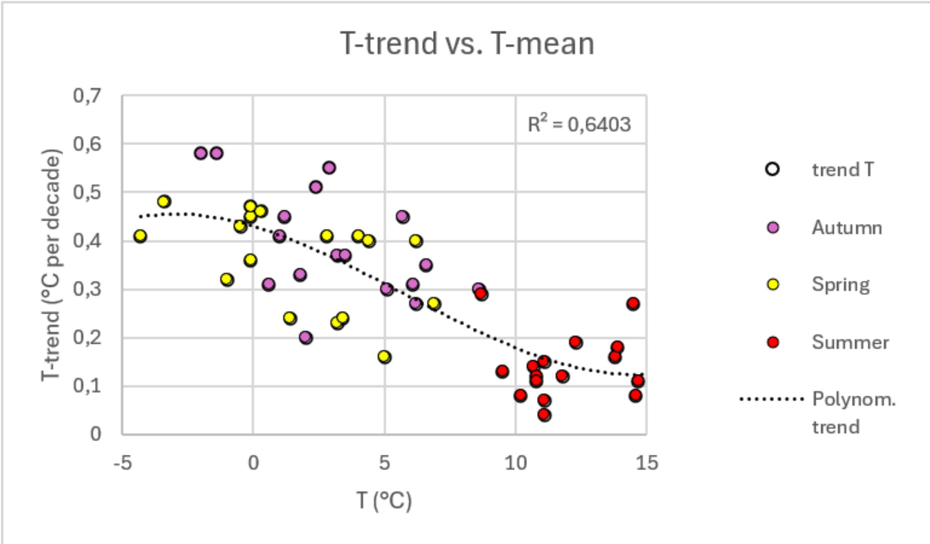

Figure 15. As Figure 14, but without winter.

The connection between temperature trend and temperature mean is illustrated in Figures 14 and 15. There is a general tendency towards higher trends in sites and seasons with low average temperature (Figure 14). However, when skipping the winter data (Figure 15), the tendency seems to culminate around a couple of degrees below zero.

3.4 Research question 3

Can the albedo effect explain differences in temperature trends between elevations? As a background for discussing this question, we have analysed the variation with elevation of several variables by season. However, as shown below, temperature variation with latitude and distance from coast makes it necessary to restrict such analyses to more homogeneous regions in order to minimize the influence of latitudinal as well as coast to inland variability. Hanssen-Bauer et al. (2020) defined seven temperature regions in Norway. South-East Norway ("Østlandet") is represented by nine of the 17 sites (see Table 2). These sites are marked with red colour in Tables 3 to 6.Three stations represent Mid- or West-Norway (green in Tables 3 to 6), while five stations represent the four temperature regions in Northern Norway (blue in Tables 3 to 6).

3.4.1 T-mean vs. elevation

Crossplots of temperature versus elevation are shown in Figures 16 to 19 for autumn, winter, spring and summer, respectively. In general, at the same elevation, the western sites (green colour) are warmest in autumn, winter and spring, while the southeastern sites (red colour) are warmest in summer. The northern sites (blue colour) are in general coldest, though the northern coastal station Bodø on average is milder than the Værnes in Mid-Norway in winter.

In autumn, winter, and spring, the five northernmost sites (blue colour) indicate a temperature drop with elevation that is far beyond the "standard atmosphere" gradient of -0.65 °C per 100 m. In summer, on the other hand, there tends to be a weak temperature increase with elevation. This spatial variability is to a large degree related to temperature contrasts between coastal and inland sites. In autumn, spring, and especially in winter, the maritime influence leads to a relatively mild climate at the three coastal stations, while the inland sites have a more continental climate. In summer, on the other hand, the temperature at the coastal sites is restricted by the relatively cold sea. There are also considerable differences between the more southern and westerly exposed site Bodø and the easternmost coastal site Vardø. According to Hanssen-Bauer et al. (2020), the five northern stations belong to three different temperature regions, and they are thus not suitable as a basis for calculating a common vertical temperature gradient.

The three sites in West- and Mid-Norway (green colour in Figures 16–19), indicate a temperature drop with elevation of 0.5 to 0.62. Restricting the analysis to the two sites in the western temperature region as defined by Hanssen-Bauer et al. (2022) would bring the vertical temperature gradient even closer to the "standard atmosphere" lapse rate. However, two sites obviously give a too poor basis for a study of average temperature gradient with elevation.

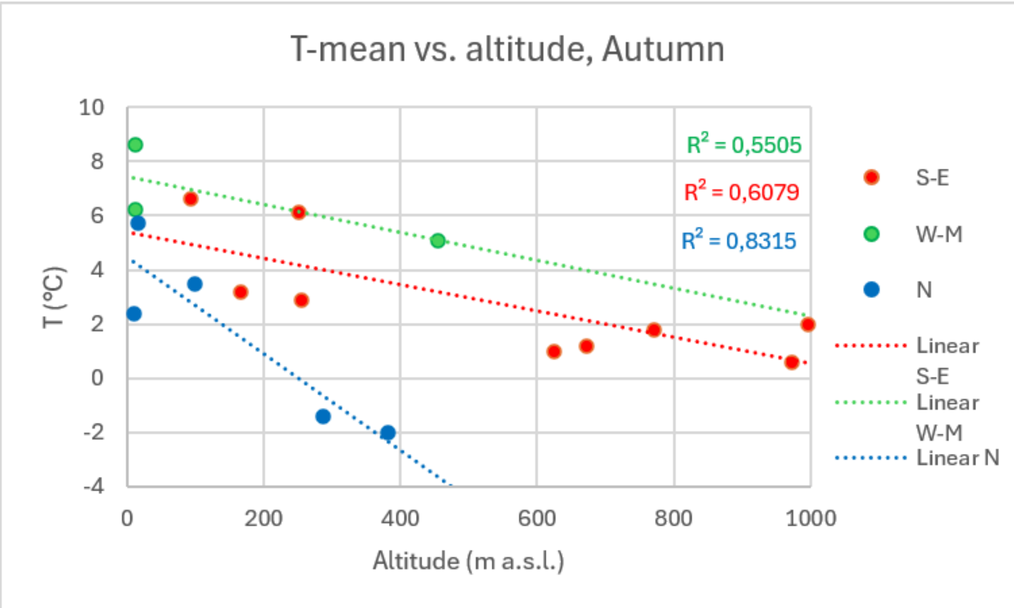

Figure 16. Cross plot of temperature versus elevation in autumn, based upon the values in Table 3. The blue dots and regression line represent the 5 northernmost sites, while green represent sites in West- and Mid-Norway, and red represents the southeastern sites.

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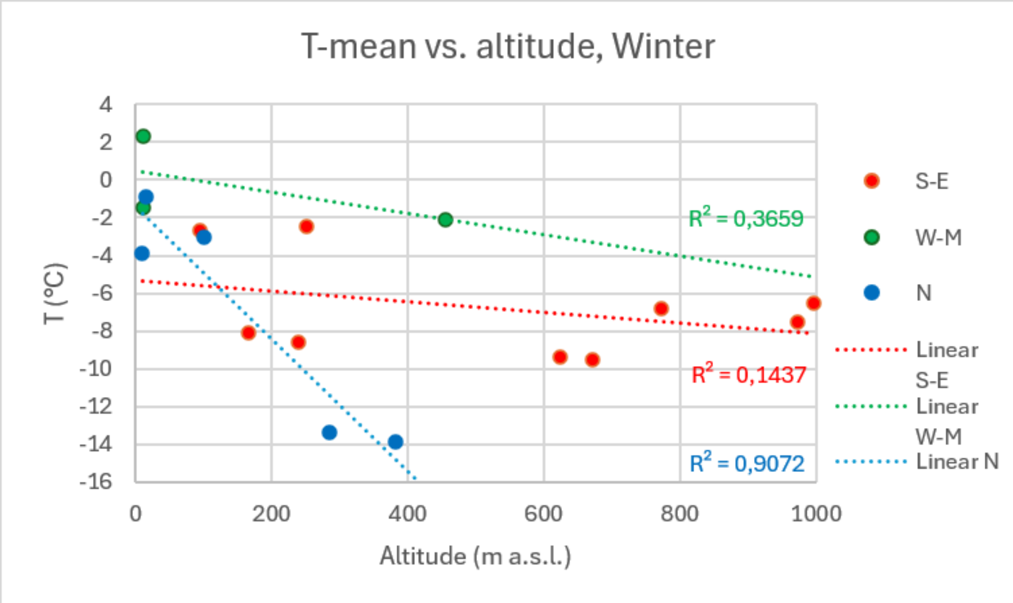

Figure 17. Cross plot of temperature versus elevation in winter, based upon the values in Table 4. The blue dots and regression line represent the 5 northernmost sites, while green represent sites in West- and Mid-Norway, and red represents the southeastern sites.

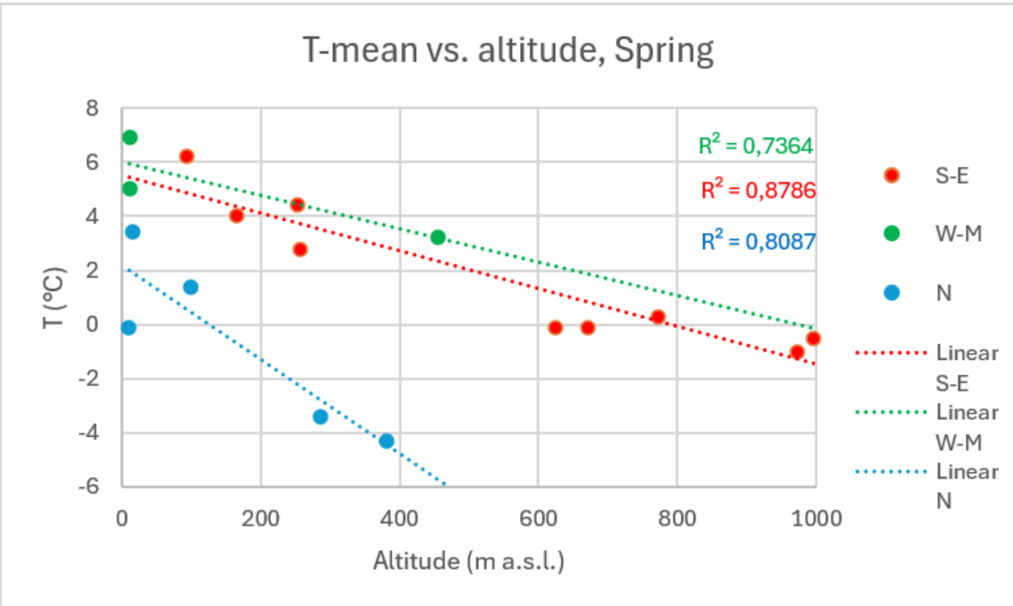

Figure 18. Cross plot of temperature versus elevation in spring, based upon the values in Table 5. The blue dots and regression line represent the 5 northernmost sites, while green represent sites in West- and Mid-Norway, and red represents the southeastern sites.

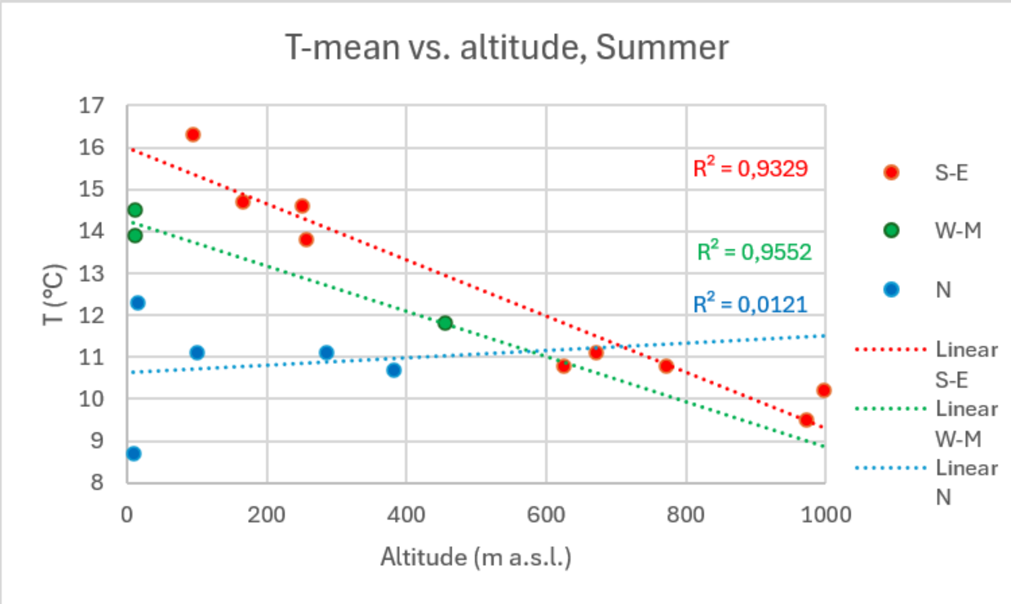

Figure 19. Cross plot of temperature versus elevation in summer, based upon the values in Table 6. The blue dots and regression line represent the 5 northernmost sites, while green represent sites in West- and Mid-Norway, and red represents the southeastern sites.

The nine sites in southeastern Norway (red colour in Figures 16–19), indicate a vertical temperature gradient rather close to the standard atmosphere in spring (-0.70 °C per 100 m) and summer (-0.67 °C per 100 m). The linear fit is good in these seasons (R^2 around 0.9). In autumn, and especially in winter, the average temperature fall with elevation is smaller (-0.48 °C and -0.28 °C per 100 m, respectively), and the fit is poorer (R^2 = 0.61 in autumn and only 0.14 in winter). The main explanation for this is low temperatures relative to elevation at Nesbyen, Rena, Røros and Drevsjø. The low temperatures are caused by cold air production, drainage and pooling. Under clear skies and during periods of limited solar radiation, radiative cooling leads to the formation of cold air, which pools in low-lying areas and drains through valleys. The effect is strongest at the valley sites Nesbyen and Rena, which are known for pooling and draining cold air from large areas. In winter, the temperatures at these sites are comparable to the conditions at sites in the northern regions.

In spite of the local influence of cold air pooling and drainage in autumn and winter, we regard the nine southeastern sites as belonging to the same region, and use the measurements from these stations in the further analyses.

3.4.2 Average SC vs. elevation

Figure 20 shows variations of seasonal average snow cover with elevation. Except for summer, when the average snow cover is 0 or very close to 0 everywhere, the tendency is that snow cover increases with elevation. In winter, the ground is nearly or completely snow-covered (100 % snow cover) at elevations above 600 m a.s.l. In autumn and spring, the tendency to increase with elevation continues up to the highest sites. Oslo in general has lower snow cover than the trendline indicates, while Rena has higher snow cover. This may be caused by differences in distance from the coast. For Rena, pooling of cold air may also allow for a longer snow season.

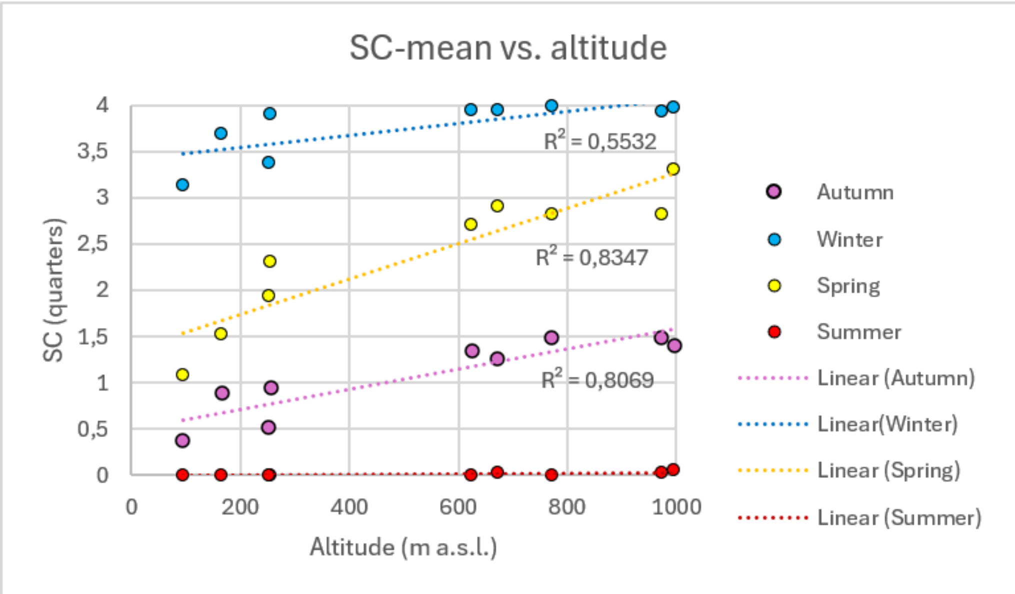

Figure 20. Cross plot of mean snow cover versus elevation in autumn (purple), winter (blue), spring (yellow), and summer (red), based upon values from the nine first sites in Tables 3–6. The dotted lines show the linear trend lines for each season.

3.4.3 T-trend vs. elevation

Figure 21 shows how the seasonal temperature trends vary with elevation. In winter, the trends tend to decrease with elevation, and the lowest trends are seen at the higher stations. There is, however, a considerable spread. The trend in Oslo is relatively low, while the temperature trend at Rena is far above the regression line. Also in autumn, the temperature trend tends to decrease by elevation for sites above 600 m, but not for the lower stations. In spring and summer, the temperature trend seems not to depend on elevation.

The general level of the historical temperature trends is at all sites at minimum in summer. For the sites below 700 m elevation, they are at maximum in winter. For the higher station the maximum trend is seen in spring or winter.

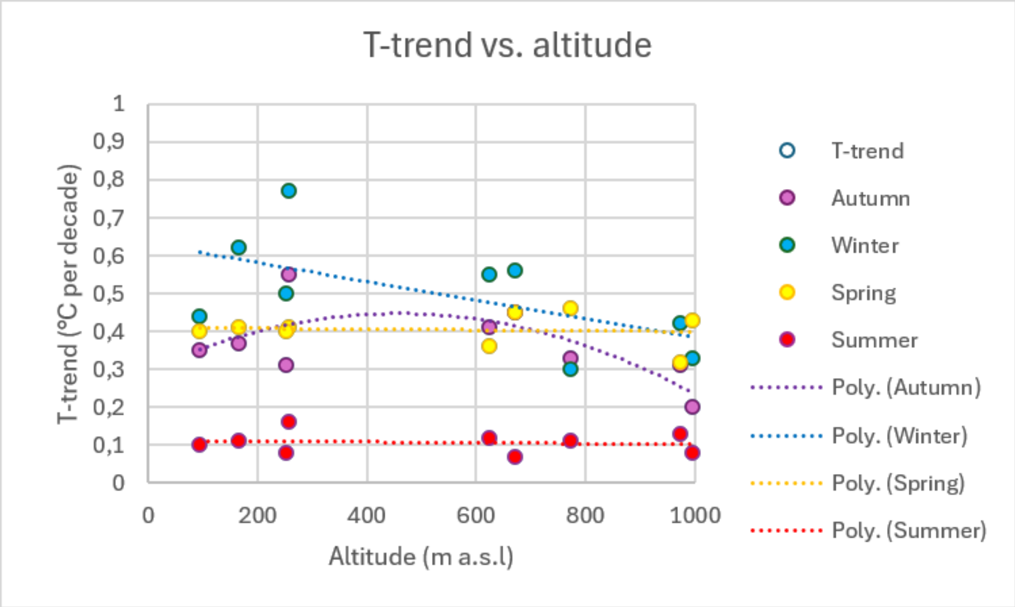

Figure 21. Cross plot of the temperature trend versus elevation in autumn (purple), winter (blue), spring (yellow), and summer (red), based upon values from the nine first sites in Tables 3–6. The dotted lines show a second-degree polynomial trend line for each season.

4 Discussion

4.1 Research question 1

Is there a robust connection between seasonal temperature and snow cover?

The analyses in Section 3.2 are based on all 17 sites given in Table 2. Figure 7 shows that within each season, and especially in autumn, the relationship is described fairly well by a polynomial, or even a linear regression line. However, there are systematic differences between the seasons, as the same seasonal temperature is associated with a larger average snow cover in spring than in autumn. This is explained by the fact that the autumn starts out with snow-free ground, while there in general is more or less snow on the ground when the spring season starts, and it needs energy to melt away. There is also a spread within each season, and especially in spring. This can be explained by differences in precipitation amounts during the cold season, and thus in snow accumulation.

As some of the following discussion will focus on sites in southeastern Norway (the first nine in Table 2), we performed a similar analysis on a monthly basis for these stations only (Figure 22). The main impression is the same as from the seasonal values from all sites. We can see that there is a reasonably good relationship between snow cover and mean temperature within each season, but that the same temperature is associated with larger snow cover in spring than in autumn. In the winter months, it tends to be somewhere in-between.

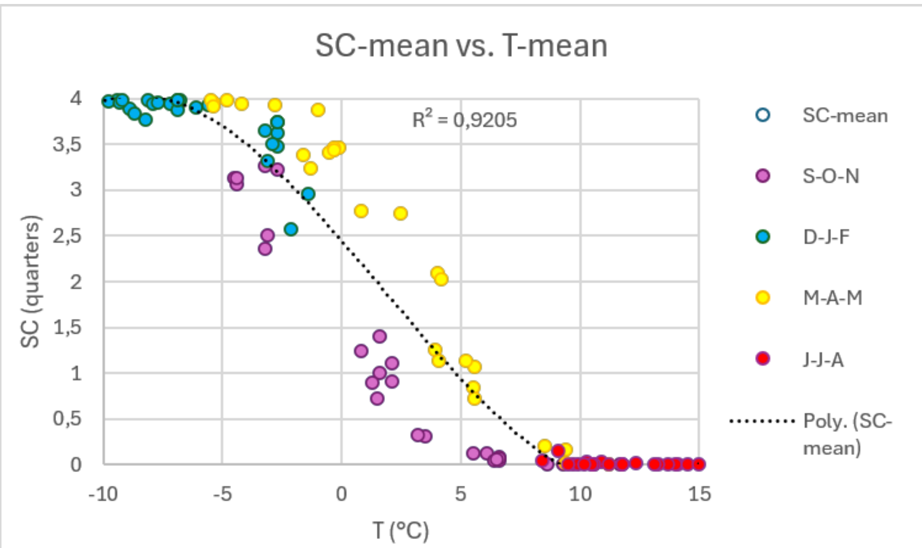

Figure 22. Crossplot of average monthly snow cover and temperature in Sep, Oct and Nov (purple), Dec, Jan and Feb (blue), Mar, Apr and May (yellow), and Jun, Jul and Aug (red), based upon the first nine sites in Tables 3–6. The dotted black line shows a third-degree polynomial trend line for the whole dataset.

4.2 Research question 2

Can the albedo effect explain differences in temperature trends within and between seasons?

If the albedo effect of the shrinking snow cover enhances the temperature trend, we expect to see the larger temperature increase at sites and seasons with maximum reduction in the snow cover. The direct comparison of temperature trends and snow cover trends (Section 3.3.2) shows that this tendency is very weak when including all seasons (R^2=0.11; Figure 10), but somewhat stronger when skipping the winter data (R^2=0.33; Figure 11).

An argument for omitting the winter data is that solar radiation reaches its minimum during winter, making the albedo feedback less significant than in other seasons. Nevertheless, even in autumn, the most pronounced temperature trends occur at sites where autumn snow cover trends are relatively weak (Rena, Sihccajavri and Cuovddatmohkki). For Rena, this may partly be caused by the fact that the snow cover series stops in 2013. We also know that the general quality control of the snow cover data has been limited (see Section 2). As average values are less influenced by single values than the trends are, we did additional analyses of the correlation between seasonal snow cover and temperature versus either average seasonal temperature or snow cover (Section 3.3.1). The results indicate that there is a “temperature window” for significant albedo effect from about -5 to +8 °C. This confirms that, though there may be an albedo effect at coastal sites during winter, the highest temperature trends are not caused by the albedo effect, as the average winter temperatures at the sites with largest temperature trends are well below -5 °C. Furthermore, the average winter snow cover at these sites is 100% or very close to it, while our analyses indicate that the influence of snow cover changes on temperature trends is minor when average snow cover is above 3.8 or below 0.1 (Figure 9).

Plots of trends for seasonal temperature versus average snow cover (Figures 12 and 13) show increasing temperature trends from low values at sites with low average snow cover to a level around 0.4 °C per decade for snow cover fraction between 1 and 3 (25–75% snow cover). When including all seasons, there is a new increase towards full snow cover, which disappears when excluding winter data. This supports that the albedo effect may explain at least parts of the increased temperature gradients in autumn and spring compared to summer, but there has to be another explanation for the fastest temperature increase which is seen at several sites during winter. Plots of seasonal temperature trends versus average temperature (Figures 14 and 15) also support this conclusion.

An explanation for increased temperature trends during winter may be systematic changes in the atmospheric circulation during the period 1967–2016. The North Atlantic Oscillation index (NAO-index; Hurrel, 1995 and 2003) is a simple index, which has been shown to account for temperature and precipitation variations in Norway, especially in the cold season (Tajet et al., 2024; Lutz et al., 2024). In winter and early spring, low NAO index is associated with clear weather, low temperatures and below average precipitation in Norway, while high NAO index is associated with more frequent frontal cyclones, and thus more cloudy weather with higher temperatures and more precipitation (Hurrel, 1995 and 2003). Tajet et al. (2024) compared the average NAO index between the periods 1961–1990 and 1991–2020. They found a substantial increase in the average NAO index in the winter months, while the signals were mixed in spring and autumn months. In summer, the NAO index is less relevant, as the correlation between the NAO index and Norwegian summer temperatures is low. Tajet et al. (2024) concluded that the winter warming from 1961–1990 to 1991–2020 was larger than expected from global warming alone, and that this was caused by differences between the two periods in typical atmospheric circulation. This is in line with the conclusion in a study from Finland (Ruosteenoja and Räisänen, 2021).

4.3 Research question 3

Can the albedo effect explain differences in temperature trends between elevations?

We restrict this discussion geographically to southeastern Norway, which includes nine of the 17 sites with sufficiently long observational series for snow cover. Temperature measurements from these sites indicate a dependence of elevation close to the “standard atmosphere” in summer (Figure 19). Then, the average temperatures are well above +8 °C at all elevations, and there is very little snow on the ground (Figure 20). Obviously, there can be no albedo effect from snow cover on the temperature trend at any elevation. Figure 21 shows that in summer the temperature trend from 1967−2016 was around 0.1°C per decade at all sites, which is well below the temperature trends in all other seasons, and there is no systematic variation with elevation. Regretfully, this study includes no series from elevations above 1000 m a.s.l. At higher elevations, there will be areas with snow at least in June. Then, the solar irradiation is at maximum and thus the potential for albedo feedback is large.

In autumn, the temperature measurements indicate, on average, a stably stratified atmosphere (Figure 16). However, there is a large spread in temperature for the sites below 300 m elevation. While Oslo and Tveitsund have average autumn temperatures between +6 and +7 °C, indicating near neutral stability, Nesbyen and Rena have average temperatures around +3 °C, which indicates pooling of cold air. The average snow cover fraction is about 0.5 in Oslo and Tveitsund, and twice as much at Nesbyen and Rena, and in general snow cover increases with elevation (Figure 20). At all sites, average temperature and snow cover values are within the range where there might be an albedo effect. Concerning the temperature trend, there is a weak tendency for higher values at intermediate elevations. However, this is mostly caused by the low value (0.2 °C per decade) at the highest site, Møsstrand, and the high value at the intermediate site Rena (0.55 °C per decade) while the all-over average is about 0.4 °C per decade. Møsstrand is close to the lake Møsvatn, which has a stabilising influence on the autumn temperatures, and might explain the slow temperature increase. Rena, on the other hand, is one of the sites exposed for temperature inversions, and the rapid temperature increase may be caused by a local weakening of the inversion. Note that the temperature trend is much lower at Tveitsund at a similar elevation. Additional analyses were made for September (not shown), as one might expect a larger potential for albedo feedback in the autumn month with the highest irradiation. However, snow cover is very sparse in September at elevations below 1000 m elevation, and the analyses did not give additional information. Altogether, we see no clear systematic dependence of the temperature trend on elevation in this dataset. As mentioned above, the albedo effect can still explain why the temperature trend at all sites is higher in autumn than in summer (Figure 21).

In spring, the temperature variation with elevation is close to the “standard atmosphere” (Figure 18). Average temperature and snow cover are at all sites in the “windows” where snow cover changes might have an amplifying effect on the temperature increase (Figure 20), and the average temperature trend is about 0.4 °C per decade, and shows no systematic variation with elevation (Figure 21). As in autumn, the difference between summer and spring temperature trends may very well be explained by an albedo feedback, however, this dataset shows no systematic variation in temperature trends with elevation below 1000 m a.s.l.

In winter, there is a tendency towards decreasing temperature trends with elevation (Figure 21). One might suspect this to be caused by an amplifying albedo effect at the lower sites. However, the sites with the largest temperature trends (Rena and Nesbyen) have on average winter temperatures outside the “window” that allows serious influence of decreasing snow cover (Table 4). The amplified warming at these sites compared to more elevated sites is probably connected to a weakening of the stable stratification. As noted in section 4.2, analyses in Norway as well as in Finland indicate that there have been systematic changes in typical atmospheric circulation in winter during the last six decades, leading to a general increase in winter temperatures which comes in addition to the general global warming. These changes probably include more cloudy weather, which again reduces the cold air production and pooling, and also more turbulence which destabilises the boundary layer. The stable stratification itself may also limit the amount of air in which temperature increases, and thus lead to an amplified warming in the lower part of the boundary layer. Similar conditions were registered by Maturilli and Kayser (2016), when analysing the warming and circulation changes in the atmosphere above Ny-Ålesund, Svalbard, during the period 1993–2014. They concluded that the warming during this period was caused by circulation changes, but it was amplified in the lower altitudes because of the stable stratification of the boundary layer.

5 Conclusions and final remarks

Analyses of seasonal time series of average temperature and snow cover from 17 sites in Norway during the period 1961–2024 led to the following conclusions:

1. **Is there a robust connection between seasonal temperature and snow cover?**
   The connection between seasonal temperature and snow cover is fairly robust within each season, but there are systematic differences between the seasons. In autumn, an average temperature of -2 °C corresponds to SC=2 (50%), while the same temperature in spring corresponds to SC>3 (above 75%). The spread between the different sites is larger in spring than in autumn. This is due to the differences in accumulation of snow during the cold season, and thus the amounts of winter precipitation.

2. **Can the albedo effect explain differences in temperature trends between the seasons?**
   The differences between the warming trends in different seasons can to some degree be explained by the amplifying albedo effect from snow cover.
   a. The albedo effect most likely contributes to the increased temperature trends in autumn and spring compared to summer. In these seasons, the average snow cover has decreased at all sites (on average 11% in autumn and 15% in spring from 1967 to 2016 according to the dataset), and the average temperature is at all sites within the "window" where the correlation between temperature and snow cover is good. When applying data from spring, summer and autumn, we find a linear connection ($R^2 = 0,33$) relating negative trends in snow cover and positive trends in temperature, indicating that one third of the variation in temperature trends is connected to variation in snow cover trends.
   b. In winter, on the other hand, though the negative trends in snow cover are considerable at some sites, especially along the coast, and thus may lead to increased warming there, the sites with the highest temperature trends have smaller or even no trend in snow cover. Further, average temperature is below the "window" where the correlation between temperature and snow cover is good at these sites. We conclude that the highest temperature trends in winter, compared to the other seasons, occur due to changes in typical atmospheric circulation during the period. Analyses of monthly NAO indices indicate a change from on average low NAO index associated with stable winter conditions in the period 1961–1990, towards higher NAO indices associated with more frequent frontal activity in the period 1991–2020.

3. **Can the albedo effect explain variation in temperature trends with elevation?**
   This analysis was limited to sites in southeastern Norway in order to minimise the influence from other geographical variables. Again, there are some seasonal differences

a. In summer, the snow cover at all sites is too small to account for an albedo effect. Note that at all our sites, the elevation is below 1000 m a.s.l. If we could include snow and temperature observations from higher elevations, where snow covered areas may exist at least early in the summer, we might get another result.

b. In autumn and spring, the snow cover, as well as the average temperature, are, at all elevations, within the “windows” where an albedo feedback is possible. The trend differences between elevations up to 1000 m a.s.l. are relatively small, and not systematic. Snow observations from higher elevations might change this picture, as there usually will be areas with full snow cover, at least in early spring.

c. In winter, only a couple of the low-elevation sites have average temperatures and snow cover in the window where the albedo effect occurs. The temperature trends at these sites are higher than at the most freely exposed high-elevation sites. The highest temperature trends are, however, found at sites exposed for pooling of cold air during winter, and the increased temperature trends at these sites imply a weakening of the winter temperature inversions. We conclude that this probably is associated with the general change in typical atmospheric circulation patterns described above, probably amplified at inversion exposed sites by change in stratification.

We conclude that the connection between average seasonal temperature and snow cover is good, though it depends on season, and particularly in spring also on the precipitation amount during the cold season.

The increased temperature trends in autumn and spring compared to summer is at least partly explainable by the albedo effect, but the highest temperature trends during winter are probably more connected to changes in the atmospheric circulation.

Concerning variation of temperature trends with elevation, the present study gives no clear indications. The variation with elevation is relatively small, except in winter, where changes in atmospheric circulation most probably have major influence. For the other seasons, snow data from elevations above 1000 m a.s.l. might help to detect an influence of the albedo feedback on temperature trends in different elevations. There is a lack of snow observations at these elevations, but model datasets (e.g. the 3-km Norwegian Reanalysis NORA3 (Haakenstad et al., 2022) might be used in further analyses. For temperature, there are also a few long-term observational series from Norwegian mountain areas. Though snow cover observations are missing at these sites, the present report indicates a “temperature window” in which an albedo feedback might be seen.

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