Climate Teleconnections Influencing Historical Variations, Trends, and Shifts in Snow Cover Days in Finland

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Abstract

Snow cover days (SCDs), the number of days with snow water equivalent (SWE) greater than a given threshold, play a vital role in the climate system, hydrological cycle, and sustainable development in cold regions. This study used long-term (1951-2022) simulated daily SWE time series based on a temperature-index snowmelt model at Kaisaniemi, Kajaani, and Sodankylä stations in the south, center, and north of Finland, respectively. Days with simulated SWE > 1 mm were defined as possible (PSCDs), > 2.5 mm as shallow (SSCDs), and > 7.5 mm as deep (DSCDs) snow cover days. The Mann-Kendall trend free pre-whitening (MK-TFPW) test to detect statistically significant ($p<0.05$) trends and the sequential *t*-test analysis of regime shift (STARS) to determine possible transitions in annual PSCDs, SSCDs, and DSCDs in Finland were used. On average, annual PSCDs, SSCDs, and DSCDs were about 130, 125, and 114 days at Kaisaniemi; 187, 183, and 173 days at Kajaani; and 216, 212, and 204 days at Sodankylä, respectively. At all these three stations, annual PSCDs, SSCDs, and DSCDs showed statistically significant ($p<0.05$) decreasing trends (ranging from 0.31 to 0.94 days $year^{-1}$) during the water years (September-August) 1951-2022. In Finland, 1988 was a negative shift point for annual PSCDs, SSCDs, and DSCDs, by about 18.8-22.4 days. Such variability, trends, and shifts in annual PSCDs, SSCDs, and DSCDs were mainly controlled by the effects of wintertime surface air temperature (SAT) and precipitation fluctuations in different phases of climate teleconnections on snowpack hydrological processes (SHPs). In both northern and southern Finland, accordingly, annual SCDs were most strongly influenced by the Arctic Oscillation (AO). In central parts, however, the East Atlantic/West Russia (EA/WR) was the only influential climate teleconnection for interannual variations in SCDs over time.

Keywords: Arctic Oscillation; East Atlantic/West Russia, Sequential *t*-test; Snowmelt model; Snow water equivalent; Finland.

1 Introduction

Snow cover plays a crucial role in modulating the land surface energy, atmospheric circulation, regional weather patterns, hydrological processes, aquatic and terrestrial ecosystems, and socio-economic systems around the world, particularly in cold climate regions (e.g., Mankin and Diffenbaugh, 2015; Jin *et al.*, 2023). In boreal environments, like Finland (de Castro *et al.*, 2007), snowpack significantly influences land surface hydrology by storing water during winter and gradually releasing it as snowmelt in spring and early summer (Pohl *et al.*, 2005). Such snowmelt controls annual peak river flow and provides a primary water resource for both terrestrial and aquatic ecosystems as well as different human activities (e.g., agriculture, forestry, and energy generation) at high latitudes (Jylhä *et al.*, 2008). In general, snowmelt water not only provides up to 12.5% of the global drinking water but also supports 25% of the world's gross domestic product, hydropower generation, and irrigation (Bormann *et al.*, 2018). Likewise, the snow cover is important for regional planning and development, including winter sports, the tourism industry, and pasture and livestock management. However, global warming in response to significant increases in anthropogenic emissions of greenhouse gases to the Earth's atmosphere is substantially altering climatic conditions (IPCC, 2021), controlling both quantity and temporal characteristics of snowpack in cold regions (Irannezhad *et al.*, 2016b), and thereby seriously challenging local, regional, and global sustainability (IPCC, 2019).

In winter, warmer surface air temperature (SAT) results generally in less icing days, snowfalls, snow accumulations, and snow cover extension in boreal environments (Irannezhad *et al.*, 2016b). The warmer SAT can reduce the number of icing days (days with maximum SAT < 0ºC) (Irannezhad *et al.*, 2018) and less snow can reduce the maximum retention capacity of snowpack, both together leading to less refreezing of wintertime meltwater (Irannezhad *et al.*, 2016b). These changes in snowpack hydrological processes (SHPs) (Irannezhad *et al.*, 2015c) can decrease snow water equivalent (SWE), reduce spring snowmelt (Irannezhad *et al.*, 2022b), decline early summer groundwater level, and consequently increase the risk of summertime drought in cold climate regions (Okkonen and Kløve, 2010). On the other hand, less SWE can fundamentally decrease the number of days with snow cover (hereafter, snow cover days: SCDs), inducing lower albedo feedback and thereby intensifying SAT warming in snow-dominant areas (Serreze and Francis, 2006), as seen across the north-east United States (Leathers *et al.*, 1995). However, all these effects can be offset by a significant increase in wintertime precipitation that amplifies snowfall intensity and consequently increases SCDs (Irannezhad *et al.*, 2017c). Under global warming, hence, less or more snow days in cold environments are mainly dependent on the balance between regional SAT and precipitation patterns.

In general, large-scale regional oceanic-atmospheric circulation patterns (e.g., the North Atlantic Oscillation) control variations in climatic conditions, particularly SAT and precipitation, across different regions around the world (Dogar and Almazroui, 2022). Such patterns refer to steady, frequent, and widespread modes of atmospheric pressure variances describing the primary airflow over an extensive geographical region (Chen and Chen, 2003). They also expose the continuing variations in the natural occurrence of chaotic behaviors in the global climate system (Glantz *et al.*, 2009). These patterns are principally quantified by numerical indices, which reflect the power and effect of oceanic-atmospheric circulations on climatic conditions across a specific region during a particular period of the year (Glantz *et al.*, 2009). Hence, such numerical indices are commonly expressed by the "climate teleconnections" term. There are many studies focusing on the key descriptions and features of such climate teleconnections (Glantz *et al.*, 2009) and their influences on regional SAT, precipitation patterns, snow resources, and river flow regimes (Stewart *et al.*, 2005; Bartolini *et al.*, 2010; Hoy *et al.*, 2013; Wang *et al.*, 2015; Dogar *et al.*, 2017a; Irannezhad *et al.*, 2020; Ghasemifar *et al.*, 2022; Irannezhad and Liu, 2022), including Finland (Rödel, 2006; Irannezhad *et al.*, 2016b, 2016a, 2017c, 2022b; Kiani *et al.*, 2018; Irannezhad, 2020). Although a few previous studies have analyzed SCDs throughout mountains (Marty, 2008; Yi *et al.*, 2021; Sadeqi *et al.*, 2024), understanding the role of climate teleconnections in historical variability, trends, and shifts in annual SCDs at high latitudes like Finland is still lacking.

The overall aim of this study was to investigate the historical SCD regime in Finland and its relationships with the well-known large-scale climate teleconnections. Accordingly, the specific objectives were to: (1) analyze variability and trends in annual SCDs in Finland during 1951-2022; (2) evaluate regime shifts in these long-term time series of annual SCDs; and (3) identify different climate teleconnections strongly influencing such variability, trends, and regime shift in annual SCDs throughout the country. Such studies can improve our understanding of global warming and climate change impacts on cold regions, where snow plays a key role in water-energy-food-ecosystem nexus (WEFE Nexus) (Cimmarrusti *et al.*, 2021; Irannezhad *et al.*, 2022a), thereby acting towards achieving the 2030 United Nations Agenda for Sustainable Development adopted in 2015 (UN, 2015).

2 Material and Methods

2.1 Study Area and Data Description

Finland is a long country (extending about 1320 km in the south-north direction) located in the boreal environment of northern Europe (Figure 1a). Accordingly, both annual mean SAT and precipitation increase from north to south, while annual snow cover duration decreases (Figure 1b-d). On average, annual SAT and precipitation in Finland for the latest normal climate period (1991-2020) were about 2.9˚C and

609 mm, respectively (Jokinen *et al.*, 2021). For this period (1991-2020), the annual snow cover duration was typically more than 225 days in the north of Finland, while less than 85 days along the coastal areas in the southwest and west (Figure 1d). Compared to the previous normal climate period (1980-2010), in Finland, mean annual SAT and precipitation increased by 0.6˚C and 2% (or about 12 mm), respectively, while annual snow cover duration decreased by 7-14 days, through the years 1991-2020 (Jokinen *et al.*, 2021).

Daily SAT and precipitation records at three hydrometeorological measurement stations of Kaisaniemi, Kajaani, and Sodankylä in southern, central, and northern Finland (Figure 1), respectively, were obtained from the Finnish Meteorological Institute (FMI). These stations were selected because of (1) recording daily SAT and precipitation from more than 100 years ago; (2) located in three different snow cover classes of maritime in Kaisaniemi, alpine in Kajaani, and taiga in Sodankylä; and (3) covering spatial SAT, precipitation, and SWE patterns in Finland (Sturm *et al.*, 1995). For this study, daily snow water equivalent (SWE) time series recorded biweekly (or every 16 days) at the Sodankylä Vuotso station located 84 km north of Sodankylä, the Kajaani Vuolijoki station located 34 km west of Kajaani, and the Kaisaniemi Vantaaa station located 36 km north-east of Kaisaniemi, were also obtained from the FMI for the past 30-70 years. The full details regarding the geographical coordinates, general climatic conditions, measuring devices, and techniques for correcting inhomogeneity in precipitation records mainly due to different instruments employed at these stations over time are explained in Irannezhad *et al.* (2015c, 2016a).

Previous studies (Dogar *et al.*, 2017b; Irannezhad *et al.*, 2017b, 2017a, 2018; Dogar and Sato, 2018) have indicated that the Arctic oscillation (AO), East Atlantic (EA), East Atlantic/West Russia (EA/WR), North Atlantic Oscillation (NAO), Polar/Eurasian (POL), and Scandinavian (SCA) patterns are the primary climate teleconnections influencing SAT and precipitation variations across the Middle East, North Africa, and Europe, particularly in its northern regions, including Finland. A summary of all these climate teleconnections is given in Table 1. Standardized monthly values of these climate teleconnections from January 1950 were freely obtained from the Climate Prediction Center (CPC) at the National Oceanic and Atmospheric Administration (NOAA) in the USA (http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml). For the present study, the annual value of climate teleconnections for a water year (WY) was defined as the average of such standardized monthly datasets for the period from 1 September to the following 31 August.

2.2 Possible, Shallow, and Deep Snow Cover Days

The FMI generally measures daily SWE in Finland biweekly or every 16 days. Hence, such daily SWE time series would lead to inaccurate calculation of SCDs in Finland. To overcome this issue, the present study applied long-term daily SAT and corrected precipitation (Irannezhad *et al.*, 2016a) datasets as input to a temperature-index snowmelt model (developed by Irannezhad *et al*. (2015c)) to simulate daily precipitation forms (rainfall and snowfall) and SHPs (meltout, refreezing, and SWE) at stations studied during 1951-2022. Based on Irannezhad *et al*. (2015c), next, the model was calibrated and validated using 30-70 years of daily SWE records measured biweekly (or every 16 days) at the Kaisaniemi, Kajaani, and Sodankylä stations in Finland. Over both calibration and validation phases, the model goodness was indicated by statistical comparisons between simulated and observed daily SWE based on: (i) the determination of coefficient (R^2), (ii) the percentage deviation (PBIAS), and (iii) the regression line slope (S) (Irannezhad *et al.*, 2015c). At all three stations of Kaisaniemi, Kajaani, and Sodankylä during both calibration and validation periods, the model performed practically well (Irannezhad *et al.*, 2015c), with R^2 = 0.64 to 0.85, PBIAS = -7.5 to 10.5%, and S = 0.76 to 1.1. This could further justify our decision to apply the simulated values of daily SWE, rather than its biweekly (or 16 days) measurements, for more accurate estimation of SCDs in Finland. Hence, three different categories of possible (PSCDs), shallow (SSCDs), and deep (DSCDs) snow cover days were defined as the number of days with simulated SWE of more than 1, 2.5, and 7.5 mm, respectively. Finally, the annual values for PSCDs, SSCDs, and DSCDs were calculated as their occurrences during each water year from 1951 (1 September 1950 to 31 August 1951)-2022 (1 September 2021 to 31 August 2022).

2.3 Statistical Analyses

Historical variations in annual PSCDs, SSCDs, and DSCDs were evaluated by plotting anomalies, which are deviations from the long-term (1951-2022) mean values. The positive/negative anomalies principally represent higher/lower annual PSCDs, SSCDs, and DSCDs than their normal values (long-term average). To detect statistically significant trends ($p<0.05$) in such annual PSCD, SSCD, and DSCD anomalies, it is generally recommended to use the Mann-Kendall (MK) non-parametric test (Mann, 1945; Kendall, 1948) associated with the Sen's slope method (Sen, 1968). However, the MK non-parametric test requires serially independent time series (Helsel and Hirsch, 1992), and unfortunately, most hydrometeorological parameters (e.g., SCDs and climate teleconnections) are controlled by autocorrelated physical processes (Katz and Brown, 1991). The existence of such autocorrelation in time series can modify the variance of MK statistics while keeping their central tendency and distribution type unchanged. Hence, the positive autocorrelation in hydrometeorological time series can increase the possibility of rejecting the null hypothesis of no trend in the MK, while the null hypothesis is true. It means the positive serial correlation in hydrometeorological time series leads the MK to detect statistically significant trends, whereas really none might exist (Yue *et al.*, 2002). Hence, this study used the MK-trend free pre-whitening (MK-TFPW) method (developed by Yue *et al.* (2002)) to eliminate such effects of autocorrelation on detecting statistically significant ($p<0.05$; i.e. 5% significance level or 95% confidence interval) trends in annual SCDs throughout Finland during the water years 1951-2022. The Sen's slope method (Sen, 1968) was accordingly employed to estimate the magnitude of such statistically significant ($p<0.05$) trends. The sequential *t*-test analysis of regime shift (STARS) (Rodionov, 2004; Marty, 2008; Irannezhad *et al.*, 2015c) was also used to examine significant ($p<0.05$) transitions in annual PSCD, SSCD, and DSCD time series for Finland. Additionally, the Spearman's rank correlation coefficient (ρ) (Helsel and Hirsch, 1992) was applied to measure the relationships of annual PSCD, SSCD, and DSCD in Finland with annual values of climate teleconnections during the water years 1951-2022. The Benjamini-Hochberg (B-H) Procedure was finally employed to address the issue of multiplicity arising from simultaneous conduct of such multiple statistical tests (Benjamini and Hochberg, 1995). This issue primarily increases the likelihood of Type I errors, leading to the incorrect rejection of true null hypotheses (Benjamini and Hochberg, 1995). To mitigate these challenges, the B-H Procedure controls the False Discovery Rate (FDR), which represents the expected proportion of false positives among the rejected hypotheses. Hence, the B-H Procedure maintains high statistical power while effectively managing the rate of false discoveries, thereby ensuring its suitability for analyses involving numerous tests (Benjamini and Hochberg, 1995; Storey, 2002).

3 Results

During the water years 1951-2022, the lowest (highest) annual snow days were generally observed in the south (north) of Finland. The long-term average values for annual PSCDs, SSCDs, and DSCDs were about 130.6, 125.5, and 114.8 days at the Kaisaniemi station in southern Finland, respectively (Figure 2). This station experienced the highest rate of historical variations in annual snow days throughout Finland. Such variations in annual PSCDs, SSCDs, and DSCDs at Kaisaniemi were about 187 days (from 2 days in 2020 to 189 days in 1957), 183 days (from 1 day in 2020 to 184 days in 2020), and 178 days (from 0 day in 2020 to 178 days in 1953), respectively (Figure 2). This indicated that the high (low) numbers of annual snow days at this station were generally seen during the early 1950s (2020s). Hence, annual PSCDs, SSCDs, and DSCDs significantly ($p<0.05$) decreased by 0.88, 0.93, and 0.94 days year^{-1}, respectively, at Kaisaniemi during the water years 1951-2022 (Figure 2).

On average, annual PSCDs, SSCDs, and DSCDs were about 187.5, 183.6, and 173.1 days at the Kajaani station in central Finland, respectively (Figure 3). At this station, annual PSCDs ranged from 39 days in 2016 to 232 days in 1974 during the water years 1951-2022 (Figure 3a). The lowest and highest annual SSCDs (123 and 230 days) and DSCDs (92 and 230 days) at this station were also observed in 2016 and 1974, respectively (Figure 3b and c). At this station (Kajaani), such variations were accordingly higher in annual DSCDs (138 days), SSCDs (108 days), and PSCDs (93 days) (Figure 3). However, significant

($p<0.05$) trends in annual PSCDs (-0.31 days year^{-1}), SSCDs (-0.36 days year^{-1}), and DSCDs (-0.46 days year^{-1}) indicated substantial decreases in the number of snow cover days at the Kajaani station during the water years 1951-2022 (Figure 3).

The Sodankylä station in northern Finland generally experienced 216.3, 212.8, and 204.6 days of annual PSCDs, SSCDs, and DSCDs during the water years between 1951 and 2022, respectively (Figure 4). At this station, the interannual variability was about 84 days for PSCDs, 89 days for SSCDs, and 101 days for DSCDs (Figure 4). The annual PSCDs ranged from 178 days in 2006 to 262 days in 1969 at Sodankylä (Figure 4a). Similarly, the lowest annual SSCDs (173 days) and DSCDs (161 days) were seen in 2006, while the highest ones (262 days for both annual SSCDs and DSCDs) were in 1969 (Figure 4b and c). Hence, a higher number of snow days was recorded in the earlier than later decades during 1951-2022. Similarly, significant decreasing trends were found in annual PSCDs (-0.32 days year^{-1}), SSCDs (-0.34 days year^{-1}), and DSCDs (-0.34 days year^{-1}) at the Sodankylä station in northern Finland during the water years 1951-2022 (Figure 4).

In general, annual snow days in Finland shifted from high to low mode in 1988 (Figure 5). The range of such shifts in annual PSCDs, SSCDs, and DSCDs was about 18.8-22.4 days. On average, annual PSCD was about 185.1 days before 1988 in Finland, but about 166.3 days afterward (Figure 5a). The country experienced the high (181.2 days) and low (161.7 days) modes of annual SSCD during the water years 1951-1987 and 1989-2022, respectively (Figure 5b). In 1988, the annual DSCDs also shifted from its high (172.5 days) to low (150.1 days) mode (Figure 5c). At all Kaisaniemi, Kajaani, and Sodankylä stations, wintertime (2 Oct to 7 May based on Irannezhad *et al.* (2016b)) was generally warmer (1.6-1.8 ºC) in the low (1989-2022) than the high (1951-1987) annual SCDs mode (Table 2). At Kaisaniemi in southern Finland, the low mode of annual SCDs was also associated with less (about 37.7 mm) wintertime precipitation and snowfall (about 52.8 mm), resulting in a substantial reduction (about 59.3 mm) in annual maximum SWE (Table 2). At Kajaani, although wintertime precipitation slightly decreased (about 2.0 mm) during the low mode of annual SCDs, a significant decrease in SWE (23.9 mm) was primarily related to the considerable increases in the rate of wintertime snowpack meltout (48.7 mm) in response to warmer SAT (1.7 ºC) (Table 2). However, at Sodankylä, an increase in wintertime snowpack meltout (40.3 mm) along with a reduction in wintertime snowfall (about 21.6 mm), both in response to warmer wintertime SAT (1.8 ºC), resulted in less (about 23.1 mm) SWE during the low mode of annual SCDs (Table 2).

The AO was the strongest climate teleconnection influencing variations in annual SCDs at the Kaisaniemi (ρ ranged from -0.58 to -0.60) and Sodankylä (ρ ranged from -0.32 to -0.35) stations in southern and northern Finland during the water years 1951-2022, respectively (Figure 6). Annual PSCD, SSCD, and

DSCD time series also showed significantly negative (positive) correlations with the EA (SCA) at both Kaisaniemi and Sodankylä stations, with ρ ranging from -0.30 (0.23) to -0.47 (0.35) (Figure 6). At these two stations, likewise, significant negative relationships between the NAO and annual PSCDs (ρ = -0.25 to -0.31), SSCDs (ρ = -0.23 to -0.30), and DSCDs (ρ = -0.23 to -0.32) were found (Figure 6). However, at Kajaani, all annual PSCDs, SSCDs, and DSCDs showed statistically significant correlations only with the EA/WR, with ρ = 0.35 to 0.36, during the water years 1951-2022 (Figure 6).

4 Discussion

4.1 Less Annual Snow Days

The present study found that the annual SCDs decreased in Finland during the water years 1951-2022. Similarly, previous studies reported substantial reductions in the annual number of SCDs in different parts of Europe (Jylhä *et al.*, 2008; Lehtonen *et al.*, 2013; Luomaranta *et al.*, 2019) in recent decades. In particular, Luomaranta *et al.* (2019) concluded that the wintertime (DJF) number of days with snow depth of more than 1 (N1), 15 (N2), and 25 (N25) cm decreased throughout Finland during 1961-2014. Although the long-term (1961-2014) average values for N25 and N15 were lower than N1 in Finland, their decreasing rates were substantially higher (Luomaranta *et al.*, 2019). Our results also showed that the decreasing trends in annual SSCDs and DSCDs were higher than in annual PSCDs throughout southern, central, and northern Finland, where all naturally experience lower annual number of SSCD and DSCD than PSCD. Similar to Luomaranta *et al.* (2019), moreover, this study identified that the decreasing trends in annual PSCDs, SSCDs, and DSCDs were stronger in southern than northern Finland. Lehtonen *et al.* (2013) also concluded that annual SCDs decreased most (least) in the coastal (mountainous) regions in northern Scandinavia during 1981-2010.

Finland experienced a shift from a high to a low mode of annual SCDs in 1988, reflecting substantial decreasing trends found in historical snow days throughout the country. This regime shift was mainly influenced by wintertime SAT and precipitation controlling different SHPs (Irannezhad *et al.*, 2015b, 2016b; Mudryk *et al.*, 2017). At the Kaisaniemi station in southern Finland, warmer SAT and less precipitation during wintertime periods played the most important roles in the low mode of annual SCDs by decreasing the amount of snowfall. Similarly, Brown and Mote (2009) reported that changes in both or one of wintertime SAT and precipitation can lead to substantial alterations in snow cover, particularly in regions with wintertime SAT close 0ºC, like Kaisaniemi. Future projections also concluded increases (decreases) in rainfall (snowfall) in southern Finland (Bintanja and Andry, 2017), where its maritime and mild winters make snow cover more sensitive to climate change when compared to more northern locations like Kajaani and Sodankylä (Callaghan *et al.*, 2011). At Kajaani, the present study found slight decreases in wintertime precipitation, but significant reductions in SWE before and after 1988. This might be related to substantial decreases in snowfall and increases in snowpack meltout rates in response to warmer SAT during the winter seasons in recent decades. Luomaranta *et al.* (2019) also reported slight changes in precipitation, but fewer ice (potential snowfall) days in the inland areas of Finland. Similarly, Räisänen (2016) projected less frequent snowfall days in Finland during the 21st century. At Sodankylä, however, warmer wintertime SATs decreased snowfall, increased snowpack meltout, and consequently reduced SWE during the water years after 1988.

In general, SCDs influence economic, social, and environmental sustainability in a Nordic country in different ways. In Finland, fewer SCDs during winter have a high negative economic impact in terms of recreation and tourism (Kaarina Tervo-Kankare and Saarinen, 2013; Hall, 2014; Neuvonen *et al.*, 2015). During the years with a reduced number of SCDs, however, less financial supports are required for preparing and maintaining sufficient snow removal equipment (Lehtonen, 2015), facilitating traffic and power supply in Finland (Juga *et al.*, 2014; Vajda *et al.*, 2014; Lehtonen, 2015). As snow is a challenging habitat for life in northern ecosystems, such significant alterations in SCDs can also affect animals and vegetation in Finland. For example, less SCDs can be associated with the reduction of basal ice formation (Rasmus *et al.*, 2018), providing more ground-growing lichens that are vitally important for reindeer grazing and herding (Hansen *et al.*, 2014; Rasmus *et al.*, 2016; Turunen *et al.*, 2016), as a traditional livelihood in Finland. On the other hand, with the reduced number of SCDs, both frost-free (Wypych *et al.*, 2017) and growing seasons (Irannezhad and Kløve, 2015) can be lengthened, and consequently affect boreal agriculture and forestry in Finland (Bjerke *et al.*, 2014; Peltonen-Sainio *et al.*, 2016).

4.2 Influential Climate Teleconnections

Similar to our findings, previous studies reported significant negative relationships of AO and NAO teleconnections with snow cover throughout the Northern Hemisphere (Bamzai, 2003), northern Europe (Bartolini *et al.*, 2010; Henderson and Leathers, 2010), northern Eurasia (Ye and Wu, 2017), and southern and northern Finland (Irannezhad *et al.*, 2016b). The AO expresses the circumpolar vortex power (Thompson and Wallace, 1998), while the NAO describes the intensity of westerly airflow coming from the North Atlantic to the Atlantic sector of Europe (Hurrell, 1995). The negative (positive) phase of both AO and NAO naturally corresponds to the weakening (strengthening) of westerly circulation, bringing cold (mild maritime) airflow across the northern parts of Europe, particularly in wintertime periods (e.g., Gormsen *et al.*, 2005; Jaagus, 2006). Accordingly, the NAO is considered as a major component of the AO (Serreze *et al.*, 2000). In recent decades, both AO and NAO showed significant increasing trends of 0.26 and 0.20 decade^{-1}, respectively (Wang *et al.*, 2005). Based on the negative correlations of annual SCDs with both AO and NAO, such increases in these two climate teleconnections resulted in milder winters (Irannezhad *et al.*, 2015a) and consequently less annual PSCDs, SSCDs, and DSCDs in Finland. These decreases in the annual number of snow days were statistically significant at the Kaisaniemi and Sodankylä stations in southern and northern Finland, respectively, which are located closer to the Baltic Sea compared to the Kajaani station in central areas. Similarly, Callaghan *et al.* (2011) and Luomaranta *et al.* (2019) reported that those areas with more maritime environment and milder winters are expected to show a higher sensitivity of snow cover to global warming and climate change than the inland parts in Finland. On the other hand, scientists argue that SAT warming at high latitudes during winter was experienced following strong tropical volcanism. Accordingly, previous studies concluded different causes for such regional wintertime warming: (i) the volcanic-induced positive NAO phase (Banerjee *et al.*, 2021), (ii) the El Niño-Southern Oscillation (ENSO) variability (Polvani and Camargo, 2020), (iii) Concurrent El Niño and volcano activities (Coupe and Robock, 2021). The most recent study by Dogar *et al.* (2024), however, reported that the post-eruption wintertime warming across Eurasia was only caused by volcanic-induced positive NAO phase.

At Kaisaniemi and Sodankylä, the EA was another climate teleconnection negatively influencing annual SCDs during 1951-2022. This climate teleconnection (EA) is expressed as the second dominant mode of low frequency variations across the North Atlantic (Barnston and Livezey, 1987). The EA is commonly interpreted as a south-eastward shifted NAO because of better describing the intensity of westerly airflow over the south and center of Europe. The positive phase of EA generally describes the positive pressure anomalies across subtropics, bringing warm airflow to Europe during all months of the year (Henderson and Leathers, 2010). Similar to our findings, hence, such a positive EA phase results fundamentally in above-average mean SAT (Irannezhad *et al.*, 2015a), less snowfall to precipitation ratio (Irannezhad *et al.*, 2017c), and consequently decreases in snowpack accumulation (Irannezhad *et al.*, 2015b) in Finland. Likewise, several previous studies concluded such negative relationships between the EA and SCDs throughout Europe (Henderson and Leathers, 2010), particularly across Fenno-Scandinavia (Bartolini *et al.*, 2010). On the other hand, these studies also reported significant positive correlations between the SCA and SCDs over northern Europe. In parallel, the present study found such positive relationships between the SCA and annual PSCDs, SSCDs, and DSCDs in both Kaisaniemi and Sodankylä stations in Finland during 1951-2022. This climate teleconnection (SCA) consists of a main anomaly center across the Scandinavian Peninsula and a large segment of the Arctic Ocean in northern Siberia (Barnston and Livezey, 1987). Its two other circulation centers, with opposite sign of pressure anomalies, are located across the north-east Atlantic (Western Europe) and western China (Mongolia) (Barnston and Livezey, 1987). The positive (negative) SCA phase describes high (low) pressure airflow associated with the warmer and drier (colder and wetter) climate than normal conditions across the Scandinavian Peninsula, Norwegian Sea, and Greenland (Bueh and Nakamura, 2007). Hence, such a positive phase of SCA can increase SAT (Irannezhad *et al.*, 2015a), decrease SWE (Irannezhad *et al.*, 2015b), and consequently reduce SCDs throughout Finland.

At Kajaani in central Finland, however, the EA/WR was the only climate teleconnection, positively controlling annual SCDs during the water years 1951-2022. In winter, it has two centers of pressure anomalies over the west of Europe and the Caspian Sea. However, during spring and autumn, the main pressure anomaly centers, with opposite signs, are characterized across western/northwestern Russia and northwestern Europe. With the same sign, the third center is located across the Portuguese coast during spring, but in Newfoundland through autumn (Barnston and Livezey, 1987). The EA/WR positive (negative) phase is typically associated with north-westerly (south-easterly) and northerly (southerly) atmospheric circulations across the East European plain and the Baltic Sea (Lim and Kim, 2013). Hence, during the positive EA/WR phase, colder and drier (warmer and wetter) climate than normal conditions are experienced over large parts of western Russia, northeast Africa, and the Arctic area (east Asia) (Lim and Kim, 2013). For Kajaani station located close to the western parts of Russia, such colder and drier climate associated with the recent positive trend in the EA/WR (Krichak *et al.*, 2002) could not offset anthropogenic SAT warming but slightly decreased wintertime precipitation, resulting in the reduction of snowfall and consequently less SCDs over time. Similarly, previous studies reported significant positive correlations between the EA/WR and SCDs in northern Europe (Bartolini *et al.*, 2009), particularly in Finland (Irannezhad *et al.*, 2016b, 2017c).

Conclusions

The present study analyzed variability, trends, shifts, and links to the well-known large-scale climate teleconnections of annual SCDs in Finland during the water years 1951-2022. The highest and lowest numbers of annual SCDs were naturally seen at the Sodankylä and Kaisaniemi stations in northern and southern Finland, respectively. In the country, all annual PSCDs, SSCDs, and DSCDs shifted by 18.8-22.4 days from high to low mode in 1988. In southern, central, and northern Finland, all annual PSCDs, SSCDs, and DSCDs were significantly reduced by about 22-68 days over the study period. Such variations, shifts, and trends were most strongly controlled by warmer wintertime SAT, less snowfall, and more snowpack meltout rates, particularly in the northern parts of Finland. Such changes in regional SAT, precipitation form, and SHPs were naturally influenced by different large-scale climate teleconnections, predominantly the AO (EA/WR) at Kaisaniemi and Sodankylä (Kajaani). Generally speaking, the strong positive phases of AO declined all annual PSCDs, SSCDs, and DSCDs in Finland, mostly in southern and northern areas, by prevailing a mild maritime airflow (i.e., warmer SAT causing less snowfall and SWE) in cold months. Over the Fenno-Scandinavian region, although the positive phase of EA/WR decreases SAT but could not neutralize the anthropogenic climate warming, which resulted in less snowfall, higher snowpack meltout rates, and consequently significant decreases in SCDs. Such findings can lay a foundation for future studies focusing on different economic (e.g., tourism industry), social (e.g., traffic management), and environmental (e.g., surface energy balance and atmospheric circulation) sustainability risks of SCD changes in cold regions, particularly at high latitudes in northern Europe.

Author Contributions

Conceptualization, M.I. and Z.A.; methodology, M.I. and Z.A.; software, Z.A. and A.S.; validation, Z.A. and A.S.; formal analysis, M.I. and Z.A.; investigation, M.I. and A.S.; resources, M.I.; data curation, Z.A. and A.S.; writing—original draft preparation, M.I. and Z.A.; writing—review and editing, M.I. and A.S.; visualization, M.I., Z.A. and A.S.; supervision, M.I.; project administration, M.I.; funding acquisition, M.I. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

All datasets analyzed during this study are publicly available through the references given in the manuscript.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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List of Figures

Figure 1. Maps of (a) Finland in northern Europe and the location of hydrometeorological stations of Sodankylä, Kajaani, and Kaisaniemi, (b) mean annual SAT in ˚C, (c) mean annual precipitation in mm, and (d) mean annual snow cover duration in days, during the latest normal climate period (1991-2020). Compiled based on Jokinen *et al.* (2021).

Figure 2. Annual (a) PSCD, (b) SSCD, and (c) DSCD anomalies with their significant ($p<0.05$) trend lines at the Kaisaniemi station in southern Finland during the water years 1951-2022.

Figure 3. Annual (a) PSCD, (b) SSCD, and (c) DSCD anomalies with their significant ($p<0.05$) trend lines at the Kajaani station in central Finland during the water years 1951-2022.

Figure 4. Annual (a) PSCD, (b) SSCD, and (c) DSCD anomalies with their significant ($p<0.05$) trend lines at the Sodankylä station in northern Finland during the water years 1951-2022.

Figure 5. Variability and regime shift in annual (a) PSCD, (b) SSCD, and (c) DSCD at the Kaisaniemi, Kajaani, and Sodankylä stations in southern, central, and northern Finland, respectively, during the water years 1951-2022.

Figure 6. The Spearman's rank correlations (ρ) of annual PSCD, SSCD, and DSCD with climate teleconnections at the Kaisaniemi, Kajaani, and Sodankylä stations in southern, central, and northern Finland, respectively, during the water years 1951-2022. The given values show statistically significant ($p<0.05$) correlations.

Table 1. Summary of climate teleconnections selected for this study (source: CPC).

No.	Climate Teleconnection	ID	Action Centers	Reference
1	Arctic Oscillation	AO	A dipole between the adjacent zonal ring centred along 45°N and the polar cap area	(Thompson and Wallace, 1998)
2	East Atlantic	EA	South-North dipoles in the North Atlantic	(Barnston and Livezey, 1987)
3	East Atlantic/West Russia	EA/WR	Western Europe, north-west Europe and Portugal in spring and autumn, Caspian Sea in winter and Russia	(Barnston and Livezey, 1987; Lim and Kim, 2013)
4	North Atlantic Oscillation	NAO	Ponta Delagada (Azores) and Stykkisholmur (Iceland)	(Barnston and Livezey, 1987)
5	Polar/Eurasia pattern	POL	North Pole, Europe and north-eastern China	(Barnston and Livezey, 1987)
6	Scandinavia pattern	SCA	West of Europe, Mongolia and Scandinavia	(Barnston and Livezey, 1987; Bueh and Nakamura, 2007)

Table 2. Long-term average values for observed SAT (ºC) and corrected total precipitation (mm) records as well as for simulated (by a temperature-index snowmelt model) rainfall (mm), snowfall (mm), meltout (mm), refreezing (mm), and maximum SWE (mm) during wintertime period (2 Oct to 7 May based on Irannezhad *et al.* (2016b)) at the Kaisaniemi, Kajaani, and Sodankylä stations before and after 1988, corresponding to the high (1951-1987) and low (1989-2022) modes of annual SCDs in Finland, respectively.

Hydrometeorological Measurement Station	Hydrometeorological Variable	Period	
		1951-1987 (High Annual SD Mode)	1989-2022 (Low Annual SD Mode)
Kaisaniemi	Observed SAT (ºC)	-0.76	0.83
	Corrected total precipitation (mm) records	607.9	570.2
	Simulated rainfall (mm)	428.8	443.9
	Simulated snowfall (mm)	179.1	126.3
	Simulated meltout (mm)	158.1	144.8
	Simulated refreezing (mm)	1.4	0.87
	Simulated maximum SWE (mm)	140.3	81.0
Kajaani	Observed SAT (ºC)	-5.49	-3.77
	Corrected total precipitation (mm) records	277.1	275.1
	Simulated rainfall (mm)	99.9	126.5
	Simulated snowfall (mm)	177.2	148.6
	Simulated meltout (mm)	119.4	168.1
	Simulated refreezing (mm)	40.4	47.5
	Simulated maximum SWE (mm)	170.4	146.5
Sodankylä	Observed SAT (ºC)	-8.77	-6.97
	Corrected total precipitation (mm) records	275.1	268.3
	Simulated rainfall (mm)	67.5	82.3
	Simulated snowfall (mm)	207.6	186.0
	Simulated meltout (mm)	36.8	77.1
	Simulated refreezing (mm)	24.2	25.3
	Simulated maximum SWE (mm)	206.9	183.8

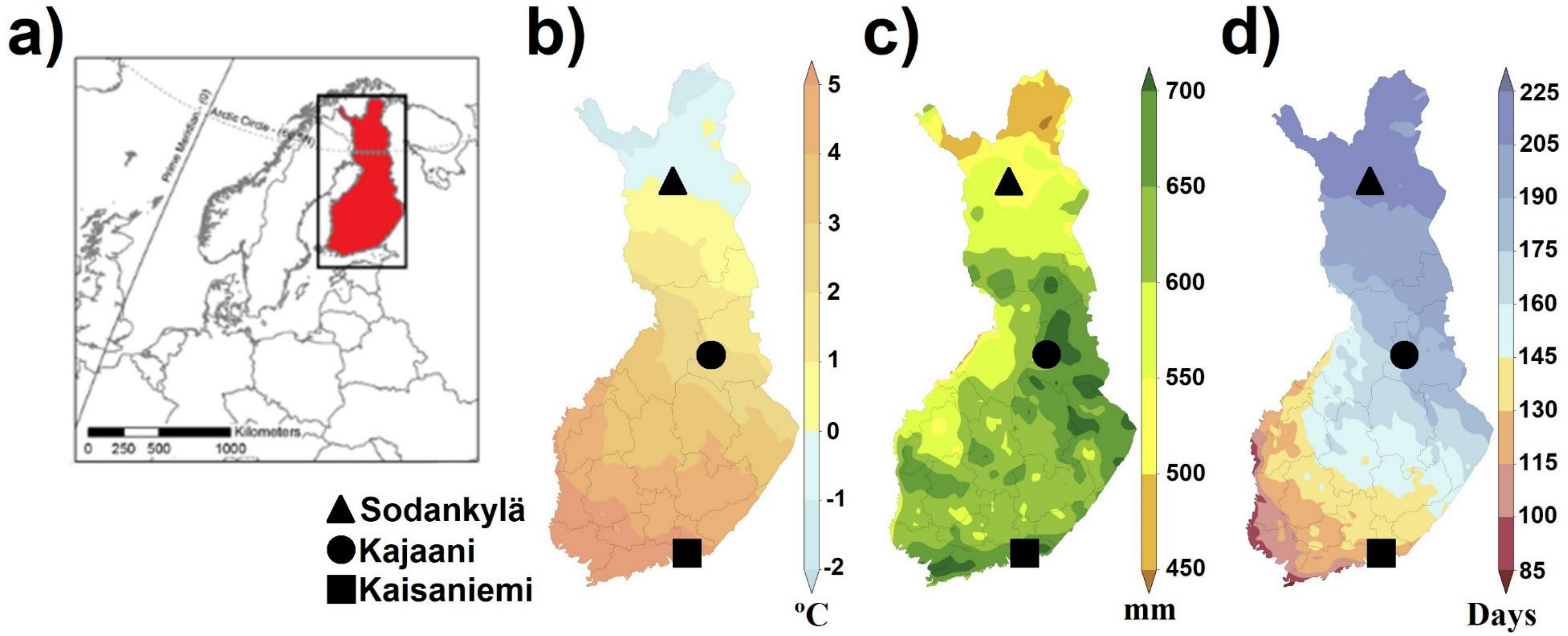
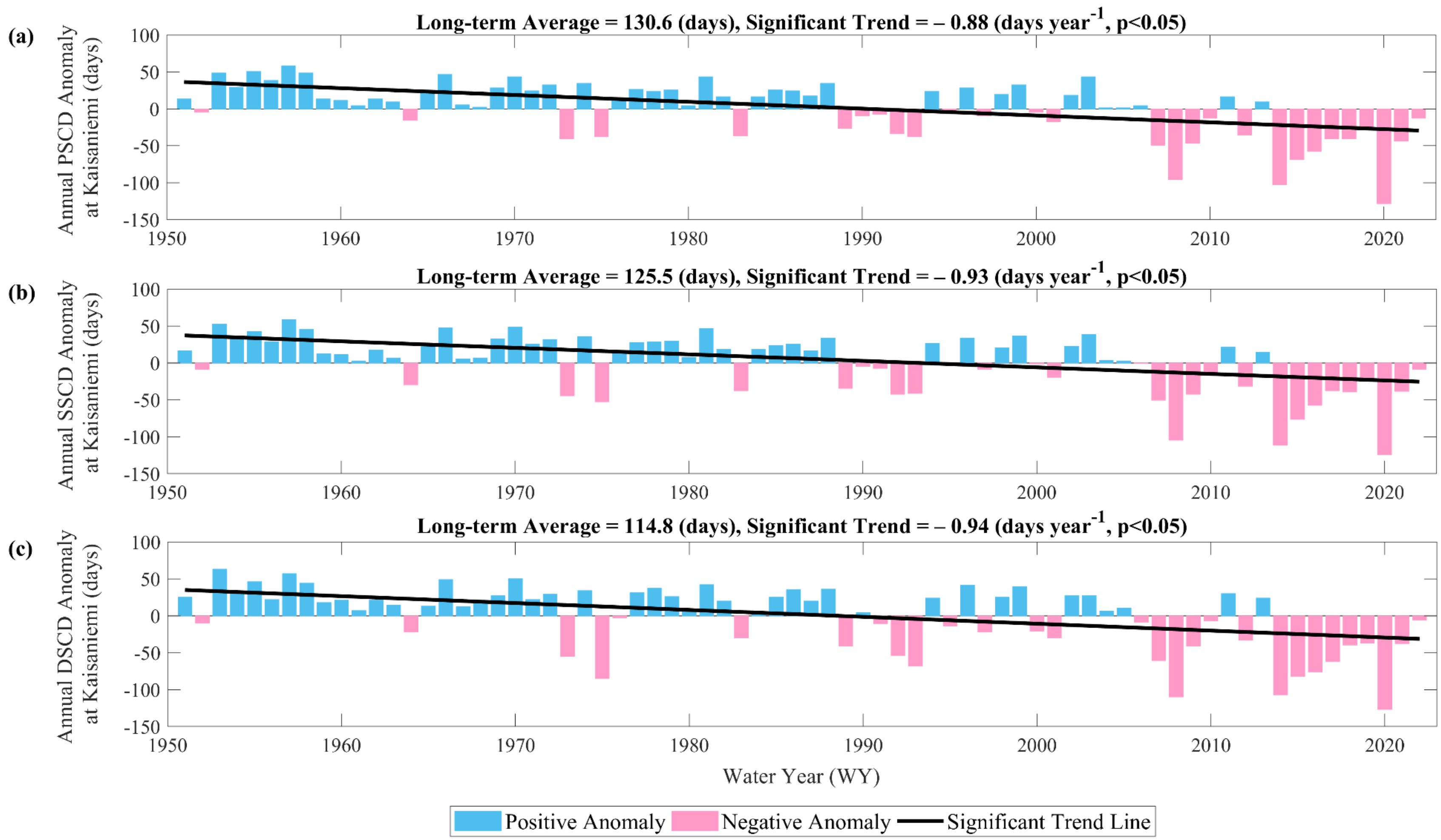


Figure 1. Maps of (a) Finland in northern Europe and the location of hydrometeorological stations of Sodankylä, Kajaani, and Kaisaniemi, (b) mean annual SAT in ˚C, (c) mean annual precipitation in mm, and (d) mean annual snow cover duration in days, during the latest normal climate period (1991-2020). Compiled based on Jokinen *et al.* (2021).



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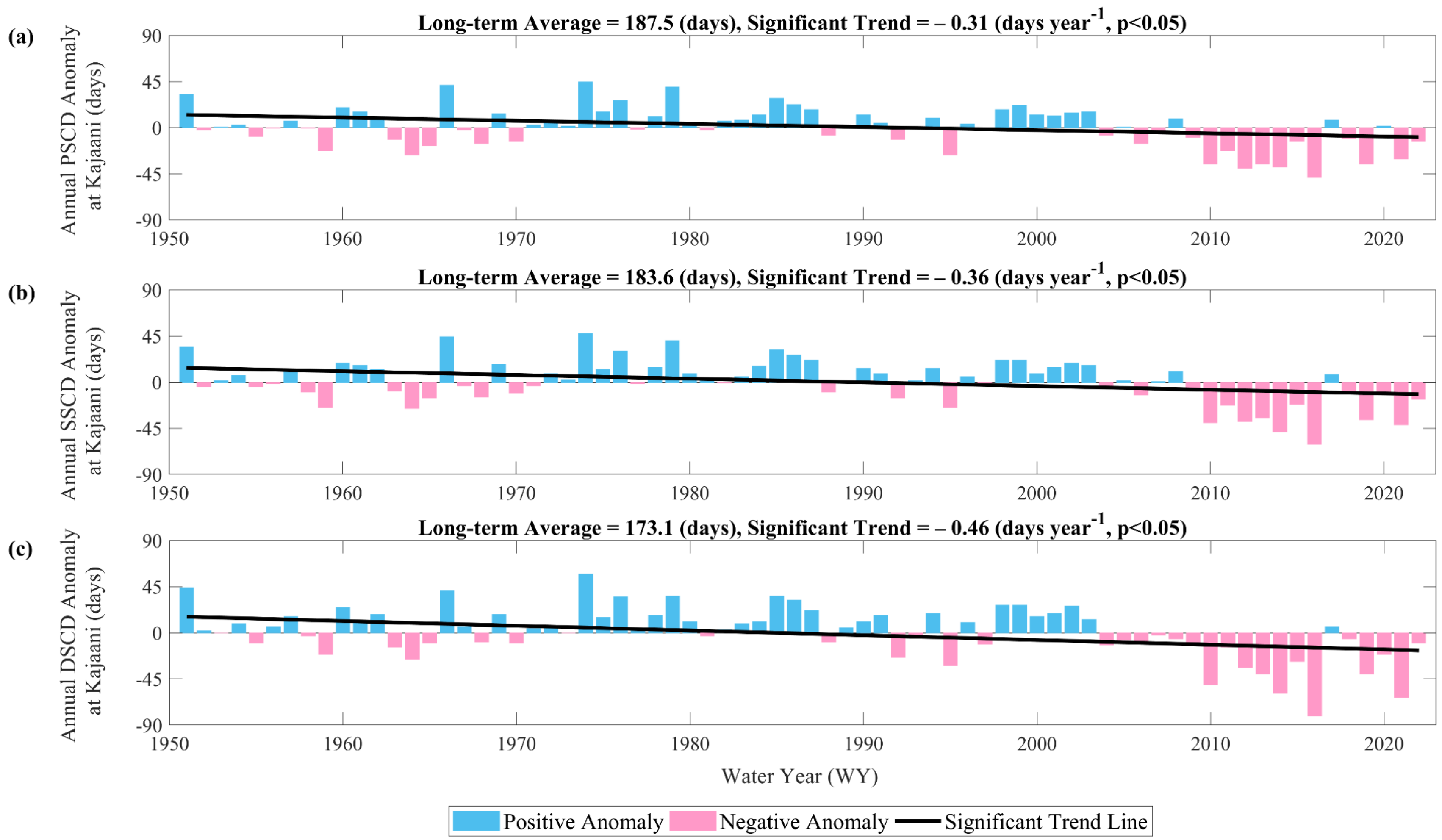


Figure 3. Annual (a) PSCD, (b) SSCD, and (c) DSCD anomalies with their significant ($p<0.05$) trend lines at the Kajaani station in central Finland during the water years 1951-2022.

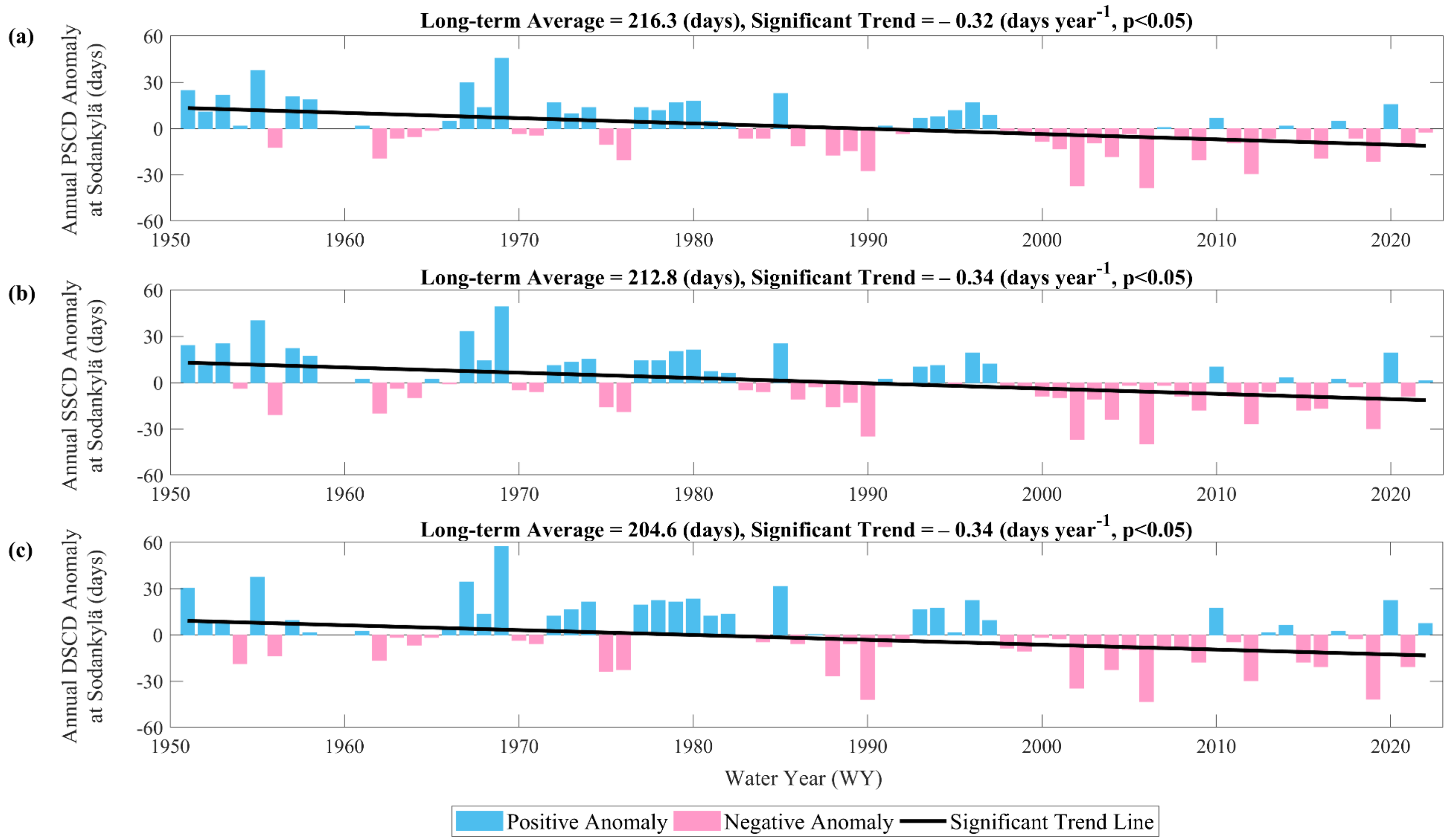


Figure 4. Annual (a) PSCD, (b) SSCD, and (c) DSCD anomalies with their significant ($p<0.05$) trend lines at the Sodankylä station in northern Finland during the water years 1951-2022.

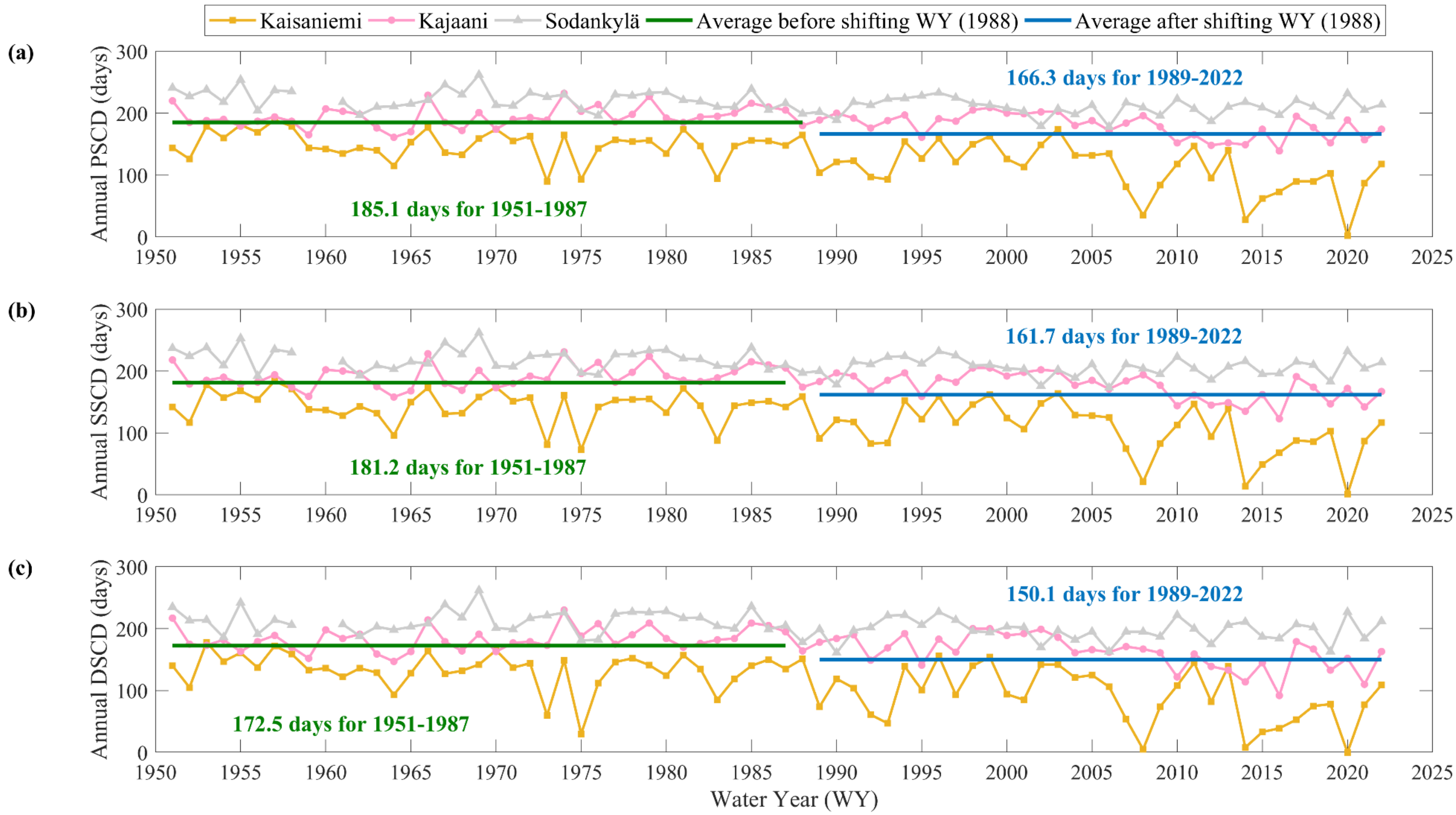
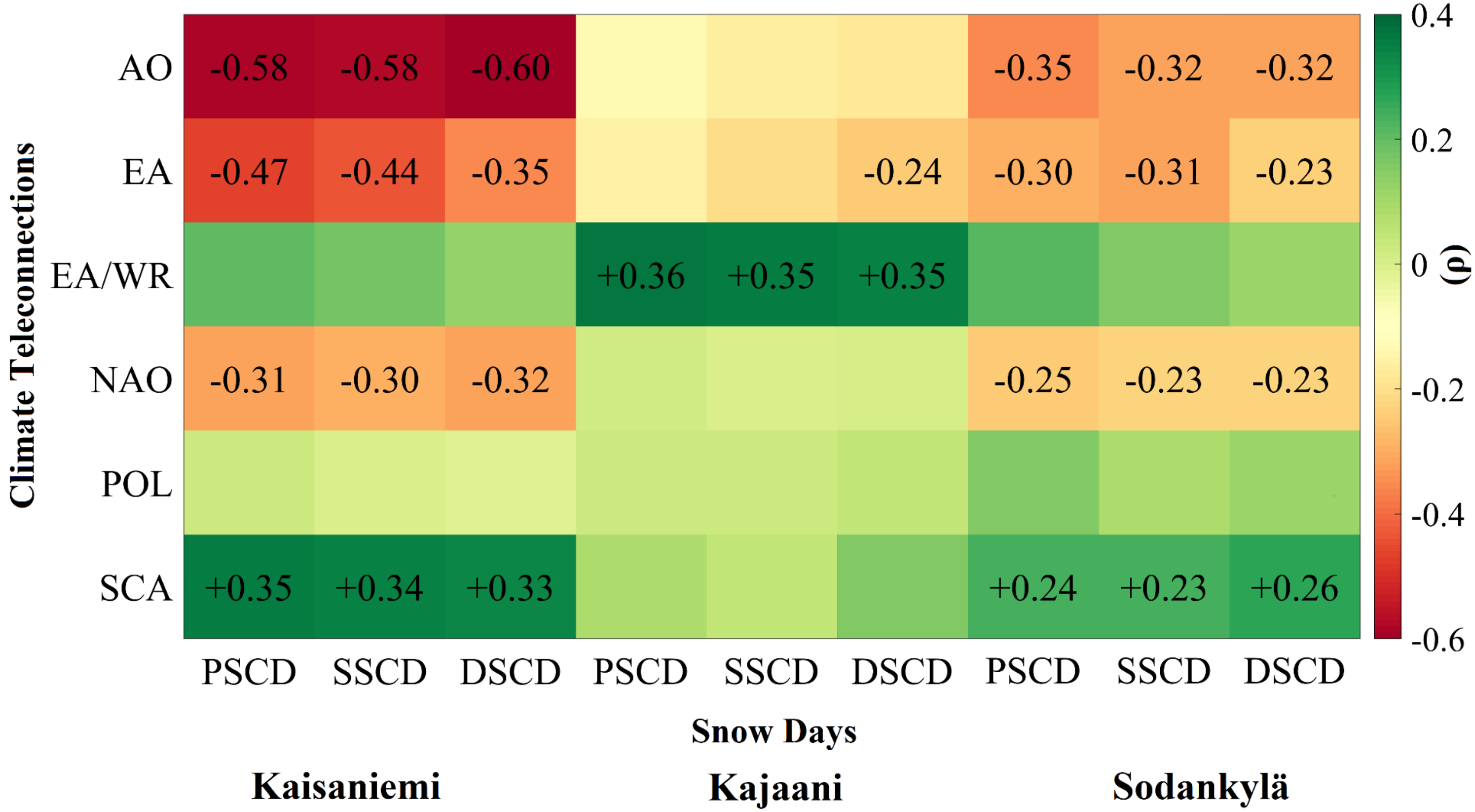


Figure 5. Variability and regime shift in annual (a) PSCD, (b) SSCD, and (c) DSCD at the Kaisaniemi, Kajaani, and Sodankylä stations in southern, central, and northern Finland, respectively, during the water years 1951-2022.



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