Assessing snow cover changes in the Kola Peninsula, Arctic Russia, using a synthesis of MODIS snow products and station observations.

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Abstract. The very high albedo of snow means that changes in its coverage have a significant impact on the Earth's global energy budget. Thus, Northern Hemisphere snow cover, which comprises approximately 98% of the global total area of seasonal snow, is responsible for the largest annual and inter-annual contrasts in land surface albedo. Here, we examine recent changes in snow cover (2000-2016) in the western mountain regions (hereinafter WMR) of the Kola Peninsula in Arctic Russia, an area that has undergone significant climate change in recent decades. Future changes in snow cover have the potential to have a major socio-economic impact in this region, which is primarily dependent on mining and tourism for its economy. We used a combination of remote sensing data, the first time it has been used to assess snow cover in this region, and meteorological observations in our analysis. The snow cover products were processed to maximise the number of cloud-free days. First and last days of snow cover were derived for each year from snow depth observations at meteorological stations. MODIS-derived snow cover dates were compared to these station-derived dates to look for systematic biases in the satellite data. We find that for 85.8 % of pixels investigated the deviation between the MODIS-derived and station-derived snow cover start and end dates is less than 20 days. These 'locally calibrated' MODIS data were then used in combination with data from meteorological stations to determine the trends and variability in the duration of the snow season in the WMR in the past half century. Snow cover was found to be highly variable both spatially and at inter-annual timescales. Overall, the duration of the snow season decreased at higher altitudes and increased in valleys and plains. High spatial variability in trends in the snow cover season and snow depth across the region can be partially explained by the effect of orography and wind scouring. Between 2000 and 2016, opposing trends in the duration of the snow cover season occur at different stations within the WMR, though more consistent trends appear over a 25-year common interval wherein the snow cover duration has decreased statistically significantly at four of five stations. Finally, MODIS is shown to provide a highly reliable snow dataset for assessing regional snow cover changes, being able to identify correctly the only statistically significant trend observed at meteorological station.

1 Introduction

30   Snow cover has a direct impact on human life in many parts of the world. It affects engineering, irrigation, travel, recreation, hydrology, while associated floods and avalanches can pose significant natural hazards (Robinson et al., 1993; Tedesco, 2015). For example, 90% of the annual water supply in the Colorado Rockies results from snowfall (Singh and Gan, 2000) and, in Norway, where 98% of electricity production comes from hydropower, 50% of the input flow is derived from melted snow (Storvold et al., 2006). Snow also affects mountainous ecosystems and plant survival (e.g. Keller et al., 2005).

35   Snow is the largest component of the terrestrial cryosphere by area (e.g. Lemke et al., 2007) and 98% of seasonal snow is located in the Northern Hemisphere (NH) (Armstrong and Brodzik, 2001), with the proportion of snow-covered land ranging from 7 to 40% over an annual cycle (Singh and Gan, 2000). With its low thermal conductivity, snow also effectively insulates the underlying soil, which means it affects permafrost extent (Zhang, 2005; Lawrence and Slater, 2010; Gouttevin et al., 2012).

40   In addition, snow has more indirect effects, though no less important, through its physical characteristics. Snow has high albedo, high infra-red emissivity and low thermal conductivity. Therefore, it has a strong impact on the Earth's energy balance by altering the energy flux between the atmosphere and the material beneath the snow (e.g. Dewey, 1977; Walland and Simmonds, 1997; Vavrus, 2007; Field et al., 2014). Importantly, snow's albedo leads to a positive feedback loop. Fresh snow has a very high albedo, meaning it reflects radiation back out to space, thus maintaining a cool Earth's surface. As snow

45   melts from a warming of the atmosphere, more radiation can be absorbed by the surface, leading to further warming and so more snow melt. Snow albedo is the third most important climate feedback after water-vapour and cloud feedbacks (e.g. Bony et al., 2006).

         Another important aspect of snow is its interactions with vegetation. Snowmelt is often the source of water that enables the survival and governs the productivity of vegetation (Fagre et al., 2003; Trujillo et al., 2012). Additionally, the

50   thermal barrier caused by thick snow cover may reduce or even prevent soil frost, thus protecting plants during winter. However, too much snow in spring will tend to negatively affect plants by reducing the growing season length. Conversely, vegetation itself may also have an impact on snow cover (Broxton et al., 2014). Indeed, tree canopies can intercept significant amounts of falling snow in forested environments. This snow may then sublimate before reaching the snowpack on the ground (Essery et al., 2003; Molotch et al., 2007). In contrast, increased shrub vegetation captures and holds more snow, and may thus

55   lengthen the snow-covered period and extend the supply of melt-water (Vajda et al., 2006).

         For these many reasons, the timing of snowfall and snow cover persistence are very important parameters, and it is essential to have a good understanding of how snow has been changing over the past decades and how it is likely to change over the next century. Arctic snow is especially likely to be affected by climate change as a result of Arctic Amplification: the Arctic has warmed faster than anywhere else on the planet (Serreze et al., 2009; Serreze and Barry, 2011) and climate

60   projections suggest that this is likely to continue (IPCC, 2014). Several factors are believed to contribute to the amplification (Cohen et al., 2014) including the decline in terrestrial spring snow cover (Serreze and Barry, 2011; Matsumura et al., 2014).

Studying arctic snow is problematic due to its high spatial variability (Liston, 2004) and the relative scarcity of ground-based measurements. Studies looking at changes in snow over the past century have focussed predominantly on the trends in snow cover extent. These trends have been negative across the Northern Hemisphere as a whole for the past few decades (e.g. Dye, 2002; Lemke et al., 2007, Peng et al., 2013), especially in spring (Brown and Robinson, 2011). Tedesco and Monaghan (2009) noted that, in the 1979 to 2008 interval, the duration of the melt season in the Northern Hemisphere was shortening by 6.0 days/decade. However, these are the large-scale trends and at a smaller, regional, scale, snow cover trends are not uniform and have greater inter-annual variability (Robinson and Frei, 2000; Bormann et al., 2018).

Decreases in both snow depth and snow water equivalent have been observed in North America, in contrast to increases in these two parameters across much of Eurasia until 1980, after which they started to decline in parts of this region too (Bulygina et al., 2009; Shmakin, 2010; Callaghan et al., 2011). For example, Gregow et al. (2008), in their study of the impacts of climate change on snow- and wind-induced risk to Finnish forests, found that the risk of heavier snow loads increased during 1961–2000. Another example of regional variability in the response of snow cover to climate change is an increase in the number of snow-covered days each year in China since 2000, where the average snow depth increased annually despite snow depth decreasing in all seasons but spring (Huang et al., 2016). This study also emphasizes the significant regional differences in the variation of snow cover in China. Due to such high spatial and temporal variability in the response of snow cover to climate change, studying snow cover at a regional level is clearly essential.

Here, we focus on the western mountain regions (hereinafter WMR) of the Kola Peninsula in Arctic Russia (see Fig 1.). Temperatures in Russia are rising faster than average, especially in its northern Arctic regions (Olofinskaya et al., 2009). The WMR, as defined for this paper, contains both lower elevation plains and the highest orography of the Kola Peninsula. The definition of these high altitude areas is based on Blinova and Chmielewski (2014): three main high altitude areas are included in the WMR (see Fig. 1) and these are the Khibiny Mountains (1,191 m), the Lovozero Mts (1,120 m) and the combined Volchji (955 m), Monche (965 m) and Chuna Tundras (1,114 m) hereafter the VMC Tundras (Blinova and Chmielewski, 2014). These mountains are extremely rich in mineral resources and also make the WMR a popular winter sports tourist destination, making it a very economically valuable Russian region. The work in this paper follows on from a strong culture of Russian snow research in North-West Russia (e.g. Kitaev et al., 2007) and in the Khibiny Mountains (Glazovskaya, 2000; Sapunov et al 2006; Troshkina et al., 2005; Troshkina et al., 2009; Vikulina, 2009; Zyuzin et al., 2006), mainly focussing on snow microphysics and avalanche processes. This regional Russian snow research was summarised in 2013 with a comprehensive analysis of past changes in the Khibiny Mountains (Zaika et al., 2013). In addition to this, some papers published in English have studied past climatic variations in the area (Kozlov and Berlina, 2002; Demin and Zyuzin, 2006; Demin and Zyuzin, 2009; Blinova and Chmielewski, 2014; Marshall et al., 2016) but none specifically focussed on snow cover. This work distinguishes itself by its wider spatial scope, comparing the snow cover in the mountains to the surrounding region, and, importantly, is the first to use remotely-sensed snow cover data to add to the availability of data from meteorological stations in the area.
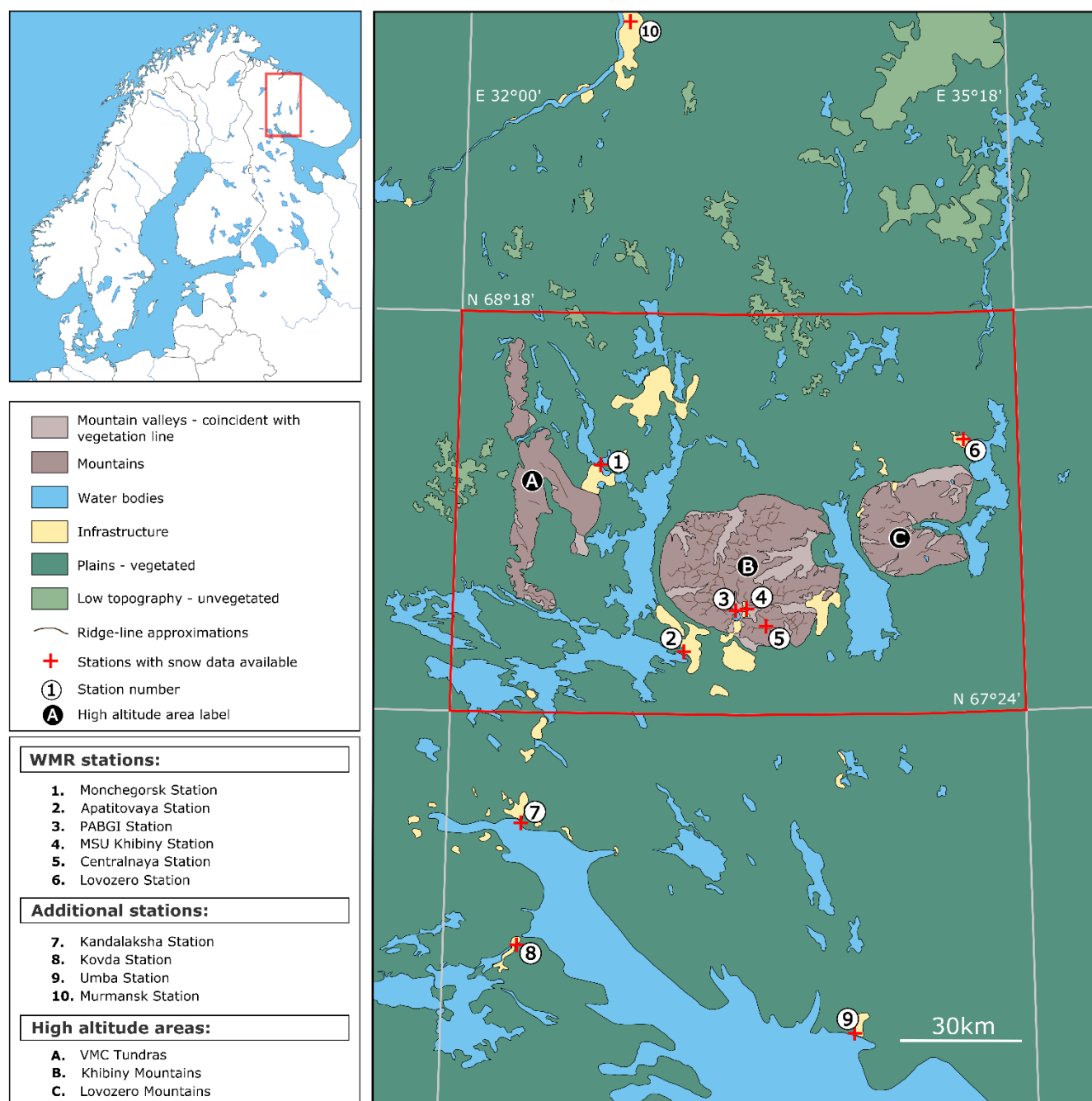
95   The Moderate Resolution Imaging Spectroradiometer (MODIS) snow cover product has been used to study snow cover changes in many regions (Zhang et al., 2010; Dietz et al., 2012; Huang et al., 2016; Malnes et al., 2016). Here, we describe the first analysis to employ MODIS NDSI snow cover data to study snow cover in the WMR of the Kola Peninsula. The MODIS snow product lends itself well to snow cover studies within mountainous regions due to its high spatial (500 m) and temporal (daily) resolution (Bormann et al., 2018). We use a method based on Malnes et al. (2016), who processed the

100   daily MODIS snow product using multi-temporal interpolation to eliminate cloud effects and derived the first and last snow-free day in northern Norway between 2000 and 2010. In this paper we demonstrate that this method is applicable to other Arctic regions and, with a longer time series of MODIS data available to us, we are able to develop the methodology further by utilising the output to analyse recent trends in WMR snow cover from 2000-2016.

         In Sect. 2, we provide a brief introduction to the climate of the WMR, including a summary of the current

105   understanding of the region's snow cover. In the following Sect. 3, the methods employed in this analysis are detailed, focussing on the validation of the MODIS data and the processing used to derive MODIS snow cover maps. In Sect.4, the results are summarised and discussed: trends in the snow cover start (SCS), snow cover end (SCE) and snow cover duration (SCD) are given for all of the available meteorological stations as well as SCS, SCE and SCD datasets of the entire WMR derived from MODIS data. Finally, Sect. 5 comprises the conclusions.

110 **2 Climate of the Western Mountain Regions (WMR)**

Figure 1: Map showing the WMR and its location on a map of Fennoscandia. The WMR is the area delimited in red by the four grid lines. Red crosses show the locations of the ten meteorological stations with readily available snow data.

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The WMR (see Fig. 1) is part of Murmansk Oblast (Region) (66–70° N), which essentially comprises the Kola
115 Peninsula. Almost all of the Murmansk Region is situated north of the Arctic Circle, but the Gulf Stream makes its climate
milder than in nearby areas east of the Kola Peninsula (Blinova and Chmielewski, 2014). A number of papers have analysed
climatological trends in the Kola Peninsula (Anisimov and Reneva, 2006; Demin, 2012; Demin et al., 2014; Demin et al.,
2015; Blinova and Chmielewski, 2014; Marshall et al., 2016).

The Kola Peninsula is climatically heterogeneous. The regional mean annual air temperature is ~0 °C (Marshall et al
120 2016) and falls to −2 °C in the WMR (Blinova and Chmielewski, 2014) due to higher average altitude and the lack of warming
oceanic influence. The snow cover period extends from the middle of October until the end of May, and the thermal growing
season from early June until the middle of September (Koroleva, 1994; Blinova and Chmielewski, 2008; Blinova, 2011).
Annual surface air temperature in the Kola Peninsula has increased by 2.3 ± 1.0 ℃ over the past 50 years. Seasonally,
statistically significant warming has taken place in spring and autumn, although the largest trend has occurred in winter
125 (Marshall et al., 2016). Spring has become significantly wetter and autumn drier, though annual precipitation has not undergone
any significant change (Marshall et al., 2016). There has also been an overall trend towards stronger winds (Roshydromet,
2005). Within the WMR, at the highest altitudes of the Khibiny Mountains, air temperature increased in all the seasons by 0.22
to 0.54°C per decade between 1965 and 2015 (Demin and Volkov, 2017).

Using phenology (the study of the seasonal development of plants), Kozlov and Berlina (2002) find that the length of
130 the summer in the Kola Peninsula decreased by 15 to 20 days in the 1930 to 1998 interval. This is supported by the 44%
increase in winter precipitation recorded over the Northern taiga forests in the Kola Peninsula (Høgda et al., 2001). However,
Bulygina et al. (2009) argue that snow cover duration has been decreasing in north-west Russia since 1966. Additionally,
Blinova and Chmielewski (2014) demonstrated shifts in the timing of the growing season and its mean prolongation by 18.5
days in the 1951 to 2012 interval. In this period, the onset of the growing season advanced by 1.1 days/decade, while the end
135 was extended by 1.8 days/decade. This matches the pattern observed in Fennoscandia but it has not been detected in the rest
of Europe (Karlsen et al., 2009; Høgda et al., 2013). In this paper, we try to reconcile these opposing findings by focusing in
on the rate of change of the snow season and its spatial variability in the WMR.

3 Data and methods

3.1 Station data

140 ### 3.1.1 WMR stations

There are six meteorological stations with readily available snow data in the WMR (see Table 1), although only two
of these stations have a record that covers the entire period of MODIS availability (2000-2016). Data from the Khibiny
Avalanche service is difficult to obtain and, as a result, we only use the maximum annual snow depth recorded at Centralnaya
between 1962 and 2005, as used by Zaika et al. (2013). It is worth noting throughout this study that snow depth measurements

145 from the stations within higher altitude areas (MSU Khibiny and PABGI Khibiny) are likely affected by false precipitation issues as a result of wind-blown snow (Demin, personal communication). However, as this paper focuses on spatial and temporal changes in snow distribution rather than snow depth, this markedly lessens the impact of such errors on our findings.

Station Name	Latitude (°N)	Longitude (°E)	Elevation (m)	Dates	Data used in this study
Apatitovaya	67.55	33.36	135	2010 - present	Daily snow depth.
Centralnaya	67.63	33.88	1050	1962-2005	Yearly maximum snow depth.
Lovozero	68.00	35.03	162	1992 - present	Daily snow depth.
Monchegorsk	67.97	32.88	131	2005 - present	Daily snow depth.
Moscow State University (MSU) Khibiny Research and Education	67.64	33.72	330	1984 - 2016	Monthly average and maximum snow depth. And snow cover start and end dates.
Polar-Alpine Botanical Garden Institute (PABGI) - Khibiny	67.64	33.67	310	1991 - 2014	Monthly snow depth.

Table 1: Description of the WMR stations and available snow depth data.

3.1.2 Western Murmansk Region stations

150 Snow depth data from additional stations with longer records in the western Murmansk Region (Table 2) are used for the validation of the MODIS data (Sect. 3.3.2) and for a wider understanding of snow cover changes in the western Kola Peninsula.

Station Name	Latitude (°N)	Longitude (°E)	Elevation (m)	Dates	Data used in this study
Kandalaksha	67.13	32.43	40	1936 – present	Daily snow depth.
Kovda	66.70	32.88	18	2005 – present	Daily snow depth.
Murmansk	68.98	33.09	96	1945 – present	Daily snow depth.
Umba	66.68	34.35	1	1966 - present	Daily snow depth.

Table 2: Description and available snow depth data of the four additional stations used in this study, the western Murmansk Region stations.

Station observations were checked for gross errors by simply plotting the data. Potentially incorrect values in the 21st century

155 were cross-checked against other available sources (e.g. https://rp5.ru) and changed if confirmed as incorrect. Earlier likely incorrect values and recent values where a more likely alternative could not be located were considered to be missing data.

However, very few values were removed in this process so it will not have significantly impacted the calculated trends. Snow depth observations at the stations were made to the nearest centimetre.

3.2 MODIS

160 ### 3.2.1 General information

The satellite data used in this study comprise the MODIS snow product from both satellites: Terra (MODIS/Terra Snow Cover Daily L3 Global 500m Grid, Version 6) and Aqua (MODIS/Aqua Snow Cover Daily L3 Global 500m Grid, Version 6). These datasets were downloaded from http://reverb.echo.nasa.gov/reverb on 21/02/17. Data were used from their earliest availability, 2000 for Terra and 2001 for Aqua, until August 31st 2016, taken as the end of the 2015/2016 snow cover

165 season. The specific dataset used in this study is the Normalised Difference Snow Index (NDSI) snow cover dataset. This is a snow cover index that directly relates to the presence of snow in a pixel and is a more accurate description of snow detection compared to Fractional Snow Cover (FSC) products (https://nsidc.org/). NDSI is calculated from the MODIS bands 4 (B4) and 6 (B6):

(1) $NDSI = (B4 - B6) / (B4 + B6)$

170 Salomonson and Appel (2004) present various equations relating NDSI and FSC. Since the span of these equations includes the simple 1:1 correspondence (FSC ≈ NDSI), we simply adopt the NDSI as a straightforward proxy for FSC.

3.2.2 Data processing

The MODIS data were processed for long-term trend analysis. Before any data processing, the Aqua and Terra data comprised 52.6 % and 50.97 % cloud cover respectively. Merging both datasets together is the first step to replacing cloudy

175 pixels with snow cover data (Dietz et al., 2012, Foppa and Seiz, 2012; Husler et al., 2014; Malnes et al., 2016). As the satellites have slightly different overpass times, a cloudy pixel in the data of one of the satellites may contain NDSI data in the other. For each pixel, each day, if there existed an NDSI value in one of the Aqua or Terra data sets, then this value was inserted. If a value existed in both satellite data sets then the average of the two was used. When a pixel had no value in either Aqua or Terra, a weighted average of the two nearest values within the previous five and following five days from either satellite was

180 used to determine an NDSI value. If only one value could be found pre- or post- empty pixel, then this value was applied. Using this technique, over half of missing NDSI data were filled and the resulting combined dataset comprises only 23% missing data as a result of cloud cover.

The first and last snow-free days for each year in the 2000 to 2016 interval were calculated following the method used by Malnes et al. (2016). A cutoff value for the NDSI data of 50 (equivalent to 50 % pixel FSC) was taken to evaluate the

185 start and end of the snow cover. The snow cover start (SCS) is defined as the first day when a 50 % FSC value is reached for more than 5 days in a row. The snow cover end (SCE) is defined as the first snow-free day when an FSC value falls below 50

% for more than 10 days in a row. This difference in cutoff time is due to the high cloud cover in autumn which hinders MODIS' snow cover retrieval ability over longer periods of time than in spring.

190   Earliest and latest SCS and SCE dates were set for the analysis (Malnes et al., 2016). These dates were selected based on snow cover start and end dates at stations and on the dates of the Polar night in the region (Dec 2nd to January 10th) to avoid problems due to low solar angles. The SCS was set as being able to occur between September 1st and November 17th. The SCE was set as being able to occur between March 15th and August 31st. The snow cover duration (SCD) is the number of days with snow cover and the MODIS SCD dates were calculated from the SCS and SCE maps, following equation 2, with DiY being the number of days in the year (365 or 366).

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(2) SCD = (DiY – SCS) + (SCE – 1) (as the end of snow cover is the first day with no snow)

4 Results and Discussion

4.1 Station data

4.1.1 Snow cover depth

200   Plots of daily snow cover depth at the Apatitovaya, Lovozero and Monchegorsk stations located in the WMR for the entirety of their available record (see Table 3) are shown in Fig. 2. The inter-annual range in snow depth at these three stations is considerable, especially for the two latter stations, with longer records. The largest inter-annual differences in snow depth can be seen at the end of the snow season. For example, in some years, such as 2016/17, the snow depth was at its highest peak or only just starting to melt out at the time of the median SCE (Figure 2). Thus at Lovozero station, the highest inter-annual

205   depth range can be seen in late April when the snow depth ranges from 0 to 88 cm. However, at Apatitovaya and Monchegorsk stations the maximum inter-annual difference is observed in early May, where the range is just over and just under 80 cm, respectively. Note that late season snowfall can be observed at Lovozero station, where a renewed snow depth peak appears at the end of the snow season. This is not seen at the other two stations but is likely to be simply a result of the longer record at Lovozero station, as all late season snowfall on record there occurred between 1996 and 2001.

210   The inter-annual difference in SCS and SCE dates at these three stations is also clearly seen in these figures and is summarized in Table 3.

Station	Dates of available data	SCS inter-annual variability	SCE inter-annual variability
Apatitovaya	2011 - 2017	October 13th - November 5th	April 30th - May 24th
Lovozero	1992 - 2017	October 1st - November 5th	April 22nd and June 6th
Monchegorsk	2005 - 2017	October 14th - November 16th	April 30th - June 4th

Table 3: Inter-annual differences in SCS and SCE dates at the Apatitovaya, Lovozero and Monchegorsk stations.
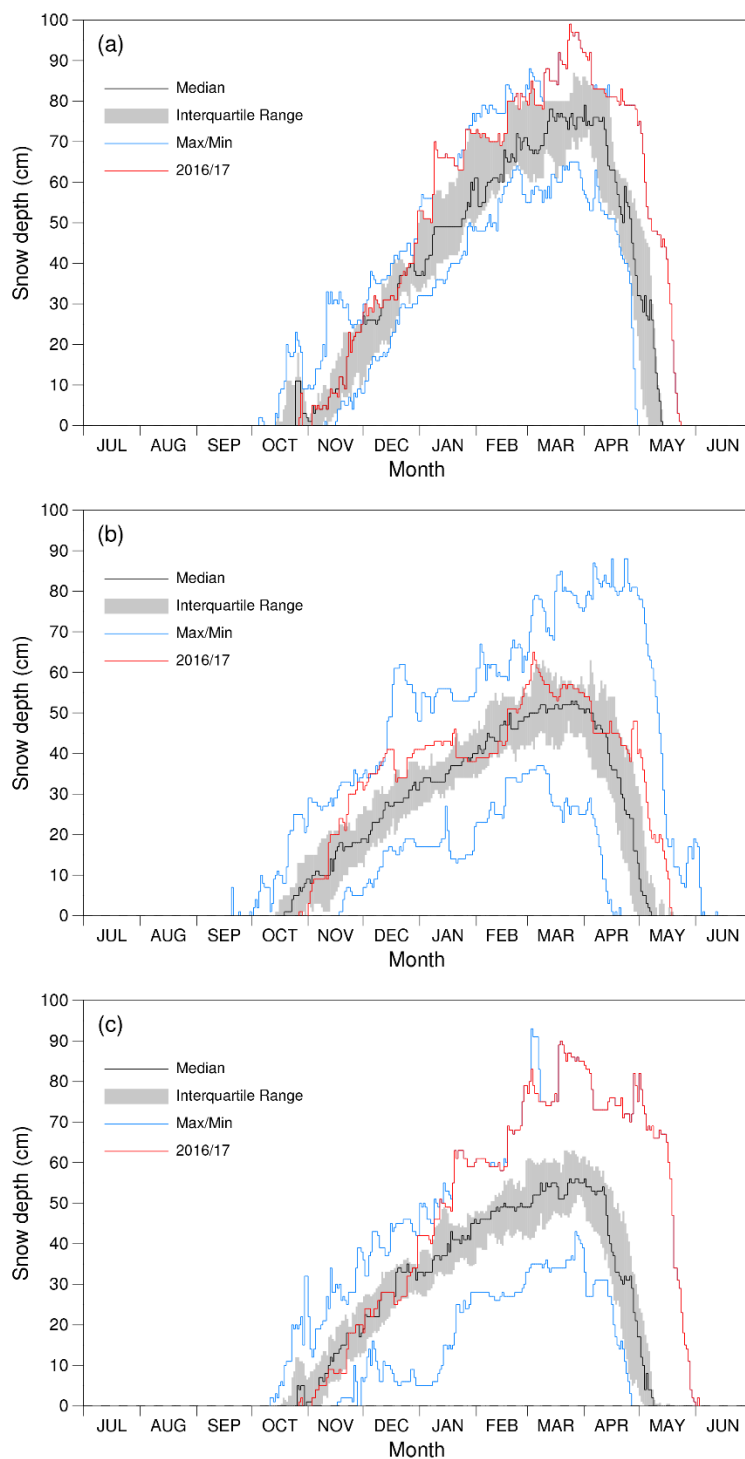
Figure 2: Snow depth range at (a) Apatitovaya station, (b) Lovozero station, (c) Monchegorsk station.
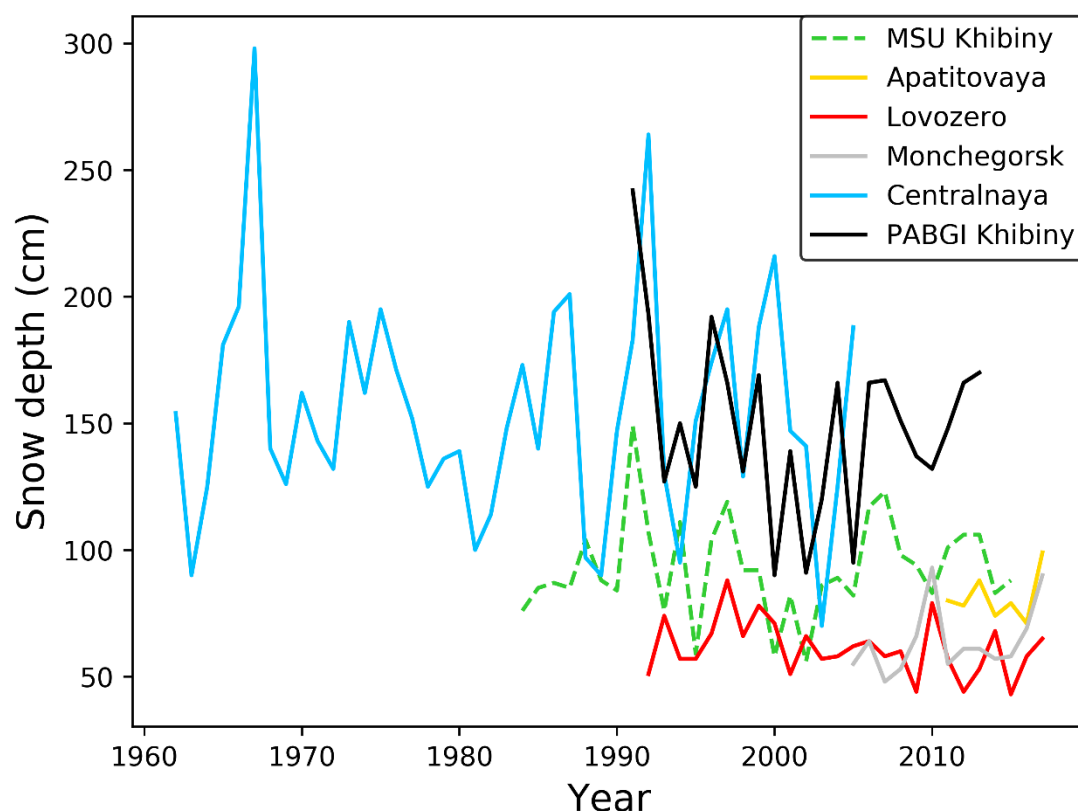
Figure 3: Maximum snow depth in centimetres at the Centralnaya station, MSU Khibiny station, PABGI Khibiny station, Lovozero station, Monchegorsk station and Apatitovaya station. The data from Centralnaya station was collected by the Khibiny avalanche service.

Figure 3 shows a comparison of yearly maximum snow depth at all six stations from the WMR used in this study.
220 The maximum snow depth at the stations within the Khibiny Mountains (Centralnaya, PABGI Khibiny and MSU Khibiny stations) is on average higher than those in the surrounding plains (Apatitovaya, Lovozero and Monchegorsk stations). The station at the highest altitude, Centralnaya station, also has the greatest snow depth. Over the common period of 1991 to 2005, the yearly average maximum snow depth is 13.3 cm deeper than at PABGI Khibiny station. At Centralnaya station, maximum snow depth varies markedly, from 100 to 300 cm, between 1962 and 2005 but does not have a statistically significant trend
225 over this long time period. This inter-annual variability in snow depth is likely explained by differences in air temperature, wind speed and solid precipitation (Demin, personal communication). The inter-annual variability in maximum snow depth is less for stations at lower altitudes, and there are no statistically significant trends here either.

It is interesting to compare the MSU Khibiny and PABGI Khibiny stations, as both are at similar altitudes in valleys within the Khibiny Mountains and are located only 2 km apart. Yearly maximum snow depth is consistently much higher at
230 PABGI Khibiny station than for MSU Khibiny station, by 56.5 cm on average. This is likely explained by wind scouring. The

MSU Khibiny station is situated at a highly exposed point in the central-east valley, to the east of the largest lake in the mountains. In contrast to this, the PABGI Khibiny station is located on the lee side of the western Khibiny Mountains and has more cover from surrounding vegetation, and, as such, is shielded from the predominant westerly winds. This spatial variability in snow depth shows the importance of orography and other local factors in determining snow cover characteristics in the WMR.

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4.1.2 Seasonal snow cover trends

4.1.2.1 Full time series

Station	Dates of available data	Parameter	Trend full time series (days/decade)
Apatitovaya	2011 - 2017	SCS	-1.7
		SCE	11.1
		SCD	11.4
Lovozero	1992 - 2017	SCS	3.8
		SCE	-4.4
		SCD	-9.4**
Monchegorsk	2005 - 2017	SCS	-5.1
		SCE	-3.6
		SCD	2.9
MSU Khibiny	1984 - 2016	SCS	-2.3
		SCE	2.4
		SCD	4.6
Kandalaksa	1936 - 2017	SCS	-1.0
		SCE	1.2***
		SCD	2.3***
Murmansk	1945 - 2017	SCS	-0.4
		SCE	1.8**
		SCD	2.9**
Umba	1966 - 2017	SCS	1.9
		SCE	-2.8***
		SCD	-5.4***

Table 4: Trends in days per decade, and their significance, of the Snow Cover Start (SCS), Snow Cover End (SCE) and Snow Cover Duration (SCD) at the WMR and the western Murmansk Region stations over both their full available time-series and the MODIS common period (2000-2016). Statistically significant trends are marked with asterisks: * = p < 0.1, ** = p < 0.05, ***= p < 0.01.

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From the daily snow depths recorded at the meteorological stations, we calculated the start, end and duration of each snow season (see Table 4). Over the 2005 to 2017 interval of data collected at Monchegorsk, the snow cover season has not undergone any statistically significant trends. However, over the time period also covered by MODIS (2005 to 2016), a statistically significant trend is identified in the SCE (p < 0.01), wherein the snow cover season has been ending earlier at a

245 rate of 1.45 days/decade. This is a result of the year 2017 being a very anomalous year (see Fig. 2), thus the inclusion of such an outlier year decreases the statistical significance of the trend. Data from the MSU Khibiny station shows a notable increase in the duration of the snow cover season since the start of the record in 1984, but none of the trends at MSU Khibiny are statistically significant. Finally, the Lovozero data shows an increasingly early start and end of the snow free season over the past 25 years, but only the trend in its SCD is statistically significant ($p < 0.05$): the SCD has been shortening by 9.4

250 days/decade since 1992.

It is also interesting to look at trends at some of the longer datasets in the western Kola Peninsula in order to set the trends in the WMR in a longer temporal context (see Table 4). The daily snow depth dataset from Kandalaksha station is one of the longest available from the region and shows significant trends in SCE and SCD since 1936: overall the snow season has lengthened by 2.3 days/decade. At Murmansk station, the trends in the SCE and SCD are significant over the entire time-

255 series. The snow cover season has been lengthening over the past 71 years at the rate of 2.9 days/decade. The SCS has changed very little over time (-0.4 days/decade; not statistically significant), so the extension of the snow cover season is primarily due to a much later end to the average snow cover season (1.8 days days/decade; significant at $p < 0.05$). At Umba station, in contrast, the snow cover season has been getting shorter over the past 39 years, at the rate of 5.4 days/decade. The delay in the start of the snow cover is not statistically significant, however the increasingly early end to the snow cover season (-2.8

260 days/decade) is ($p < 0.01$).

4.1.2.2 25-year common time series

By comparing changes in snow cover variability at the WMR stations to those in the wider western Kola Peninsula over a common period, we can relate our findings to the broader regional spatial variability. Table 5 shows the trends in the SCS, SCE and SCD over a common 25-year time interval (1992-2016) for the five stations of both the WMR and the wider

265 western Murmansk Region with available data for that time. Data at four of the five stations show a positive trend in the SCS (increasingly late start to the snow cover), a negative trend in the SCE (increasingly early end of the snow season) and an overall decrease in the duration of the snow cover season. The station showing opposite results is MSU Khibiny station, located within the Khibiny Mountains and at a higher altitude than the other stations. Importantly, this opposite trend is also the only SCD trend that is not statistically significant. These results indicate a uniform regional signal of reduced SCD snow cover

270 across the lower altitudes of the western Murmansk Region between 1992 and 2016. They also imply an opposite trend in the snow cover season at higher altitudes, although more long-term data in the mountainous areas are needed to make robust conclusions on these higher-altitude zones. To resolve this issue, we use MODIS to obtain more spatially continuous data over the WMR in order to identify the spatial variability of the snow there.

Bulygina et al. (2009) found that snow cover duration has been decreasing in north-west Russia since 1966 and

275 Blinova and Chmielewski (2014) demonstrated the mean growing season has been has been prolonged since 1951 in the Murmansk Region. Similar patterns have been found in Fennoscandia (Karlsen et al., 2009; Høgda et al., 2013). In contrast to these findings, using phenological evidence, Kozlov and Berlina (2002) found that the length of the summer in the Kola

Peninsula decreased by 15 to 20 days in the 1930 to 1998 interval. Extracting the trends in the SCD at Kandalaksha station over comparable timescales to these two studies demonstrates that the contrasting conclusions of these previous studies can be
280   explained by the different time periods analysed. Kandalaksha station shows a statistically significant lengthening of the snow cover season in the 1936 to 1998 interval of 4.5 days/decade, thus a decrease of the length of summer similar to Kozlov and Berlina (2002). In the 1966 to 2007 interval, a shortening of the snow cover season of 1.9 days/decade is found, though it is not statistically significant. This trend supports the conclusions of Bulygina et al. (2009).

Station	Parameter	25-year trend 1992-2016 (days/decade)
Kandalaksha	SCS	4.2
	SCE	-4.0**
	SCD	-8.2***
Lovozero	SCS	3.8
	SCE	-4.4
	SCD	-9.4**
MSU Khibiny	SCS	-2.9
	SCE	4.0
	SCD	3.8
Murmansk	SCS	6.2**
	SCE	-1.2
	SCD	-7.5*
Umba	SCS	3.1
	SCE	-4.7**
	SCD	-7.3**

285   **Table 5: Trends in days per decade and their significance of the Snow Cover Start (SCS), Snow Cover End (SCE) and Snow Cover Duration (SCD) at the five stations with available data over the 25-year common interval (1992-2016). Statistically significant trends are marked with asterisks: * = p < 0.1, ** = p < 0.05, ***= p < 0.01.**

4.2 MODIS processed datasets

4.2.1 Missing data

Despite processing efforts to minimise missing data described in section 3.2.2, cloud cover remained a hindrance to
290   the extraction of SCS, SCE and SCD dates in the WMR. The number of missing years in each of the SCS, SCE and SCD datasets are shown in Fig. 4. Pixels of missing data make up 22.6 %, 5.9 % and 24.6 % of the SCS, SCE and SCD respectively. Water bodies have missing data in the SCS datasets for 12 to 16 years out of a possible 16 years. This can be explained by the fact that these areas will only return a SCS date when they have frozen over and started accumulating snow on this surface. The freezing process is slow and usually does not occur in time for the ice to be covered in snow before November 17th. In the
295   dry land section of the region, there is very little missing data in the SCE dataset and more missing data in the SCS data, especially for the plains. This is a result of the increased cloud cover in the autumn associated with the high snowfall. SCD is calculated from SCS and SCE and, as a result, has a combination of the missing data in those two datasets.
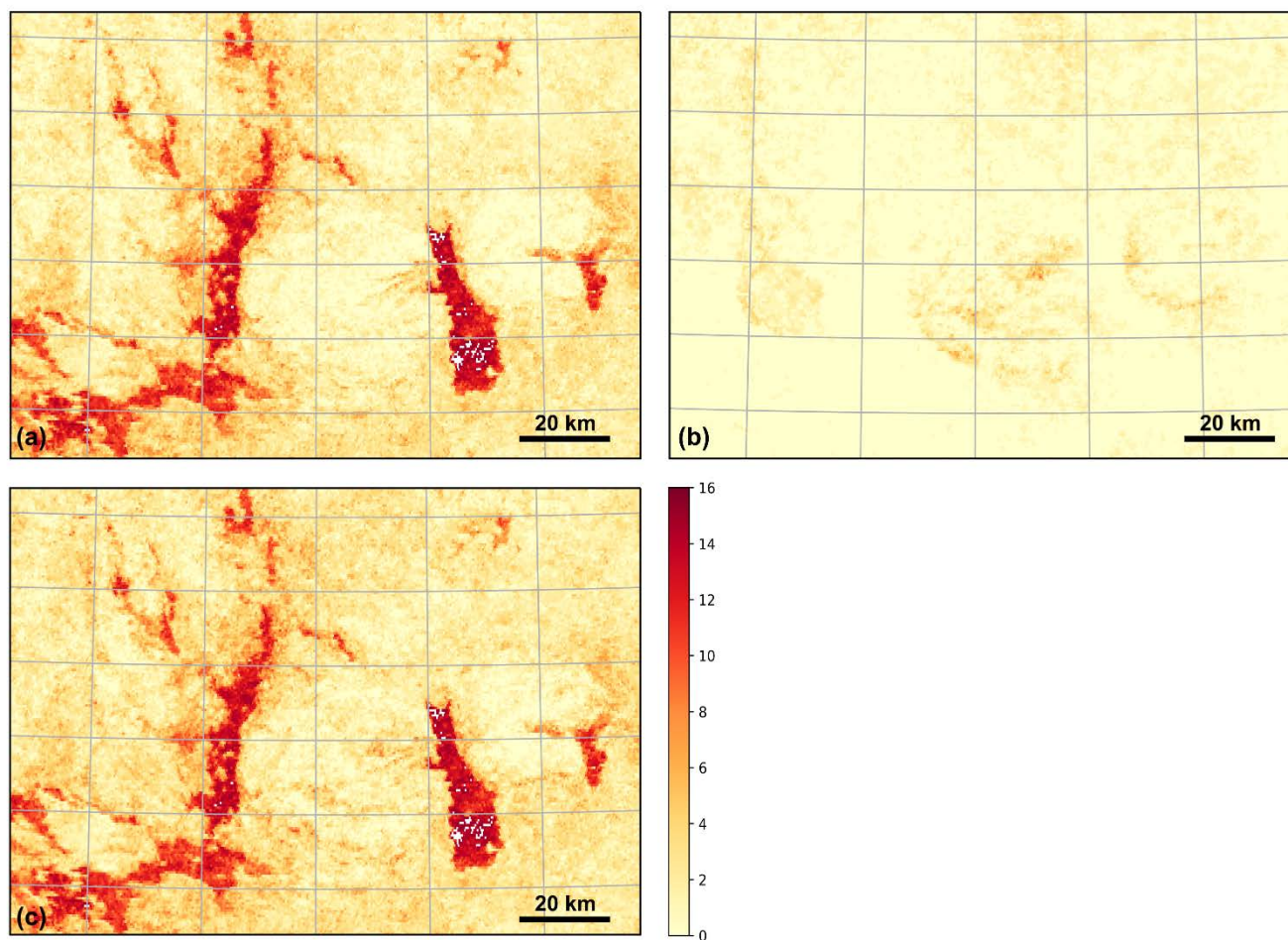
Figure 4: Number of years with missing a. SCS, b. SCE and c. SCD data over the 2000/2001 to 2015/2016 interval in the WMR.

4.2.2 Station validation

300

The MODIS data processing algorithm was tested by comparing the derived SCS and SCE dates with those recorded at meteorological stations. Only one (MSU Khibiny) recorded the start and end dates of the snow cover season, so a method of extracting SCS and SCE dates from snow depth data was used for the other stations. SCS (/SCE) was defined as the first day with more than 5 (/10) days in a row with snow cover depth higher(/lower) than 1cm at a station. SCS and SCE dates were

305 extracted from the SCS and SCE MODIS processed datasets for each of the following stations: Apatitovaya, Lovozero, Monchegorsk, MSU Khibiny, Murmansk, Kandalaksha, Kovda and Umba. The results of the comparison of these to the station data are shown in Table 6.

The difference between the SCS and SCE end dates from station data and MODIS processing was calculated for all years at all stations. This difference is taken as the station dates minus the MODIS dates and the results are shown in Table 6.

310   All annual 'maps' have missing data (see Fig. 4) and as a result, there is no MODIS data for some years at all stations. In one

extreme case, no SCS dates could be extracted at all for Kandalaksha (Table 6).

	SCS				SCE			
	Mean	Mean offset	Positive or negative offset	Number of missing years	Mean	Mean offset	Positive or negative offset	Number of missing years
Apatity	-3.5	3.5	Negative	2	4.4	4.4	Positive	0
Lovozero	-4.0	5.3	Both	4	11.1	11.1	Positive	1
Monchegorsk	0.7	10.4	Both	4	15.6	15.6	Positive	0
MSU Khibiny	7.9	12.4	Both	3	-1.6	6.2	Both	2
Murmansk	-3.6	10.5	Both	7	-5.9	12.9	Both	6
Kandalaksha				16	20.9	20.9	Positive	2
Kovda	7.4	10.4	Both	3	-8.0	8.0	Negative	0
Umba	-0.8	4.0	Both	7	-0.2	2.8	Both	0

Table 6: Summary statistics of the difference between dates determined from data collected at meteorological stations and from the MODIS processed datasets in the 2000/2001 to 2015/2016 interval for the SCS and SCE. This difference is taken as the station dates minus the MODIS dates, and the unit for the mean and mean offset columns are number of days.

315   On average, the difference is 8.6 and 10.4 days between the station and MODIS SCS and SCE dates respectively.

There is a slight bias in the MODIS dates with higher errors being positive, so finding an earlier date than the station data. On

average the mean bias of the SCS and SCE dates are + 1.2 days and + 5.0 days respectively. Overall, errors are larger in the

spring (SCE). This is probably a result of our methodology used to extract SCS dates combined with the higher proportion of

missing data in the SCS dataset. Indeed, for times with particularly extensive cloud cover, SCS is more likely not to return a

320   value rather than return a biased one.

        In the WMR, the MODIS dates are most representative of the Apatitovaya station data. The differences are uniform

and quite low for the MSU Khibiny station for the SCE, however errors are more inconsistent and reach higher values for the

SCS. The Lovozero station is the opposite, with consistent low differences in the SCS dates and higher more varied differences

in the SCE dates. In the WMR, the deviation between station and MODIS dates is largest at the Monchegorsk station.

325   In the wider western Murmansk region, the MODIS dates best replicate Umba station data, where MODIS is neither

consistently early nor consistently late. At Kovda station, the deviation between MODIS and station data SCS is highly variable

between years, reaching high values of over 30 days. The MODIS SCE dates there are all later than those recorded at the

station. Kandalaksha station values follow the opposite trend with the MODIS SCS dates being much earlier than the station

values for all years. The differences are highest for Kandalaksha station with an offset of up to 41 days. Though this offset is

330   very high, it is not unprecedented. Indeed, Dietz et al (2010) found that 10 % (/3 %) of their study area was characterised by

34 to 72 (/72+) days deviation between station data and MODIS SCD. In this analysis, we find that for 85.8 % of pixels

investigated (SCS and SCE combined) the deviation in the MODIS-derived dates is less than 20 days, 9.9 % of pixels have a

deviation between 20 to 30 days and only 4.3 % of pixels are characterised by a deviation between 30 and 41 days (Fig. 5).

Thus, despite the large magnitude of some errors, deviation between the station data and MODIS-derived snow cover season

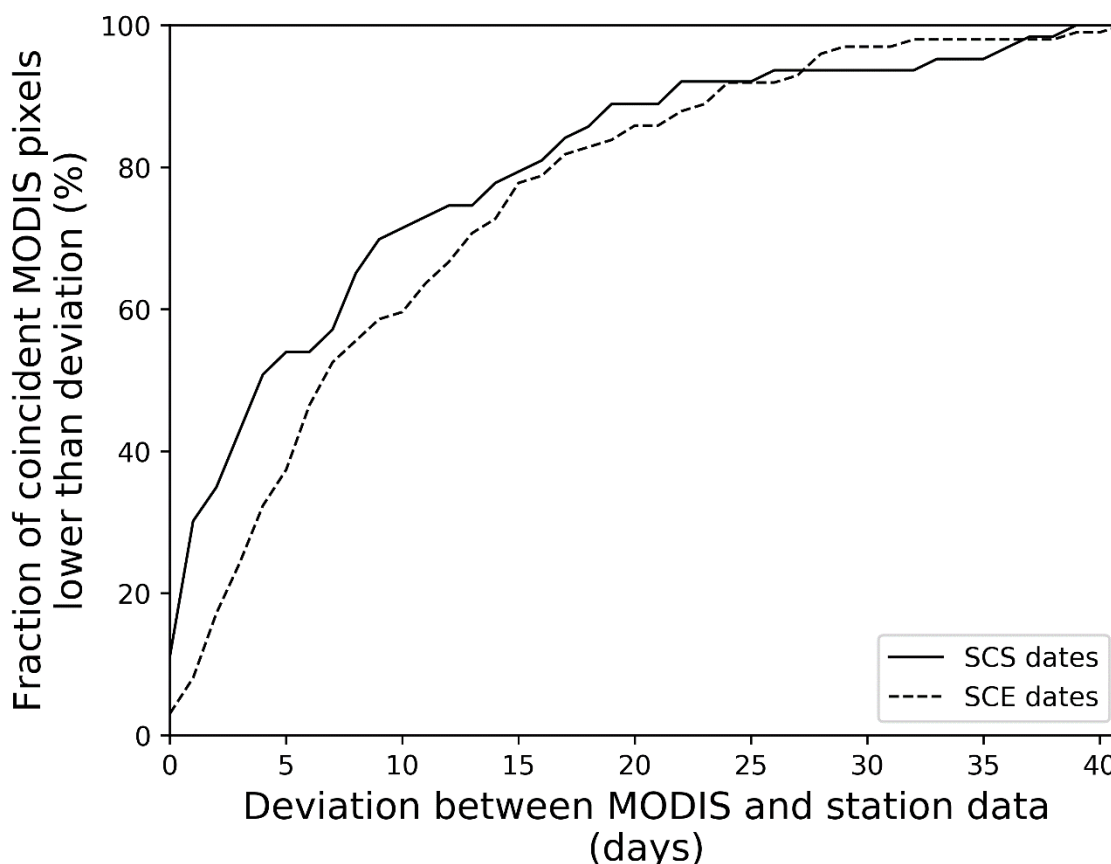335   dates are in fact lower than for some previous studies.

Figure 5: Graph showing the proportion of pixels with a deviation of lower than 0 to 41 days between the MODIS-derived and station data-derived SCS and SCE dates.
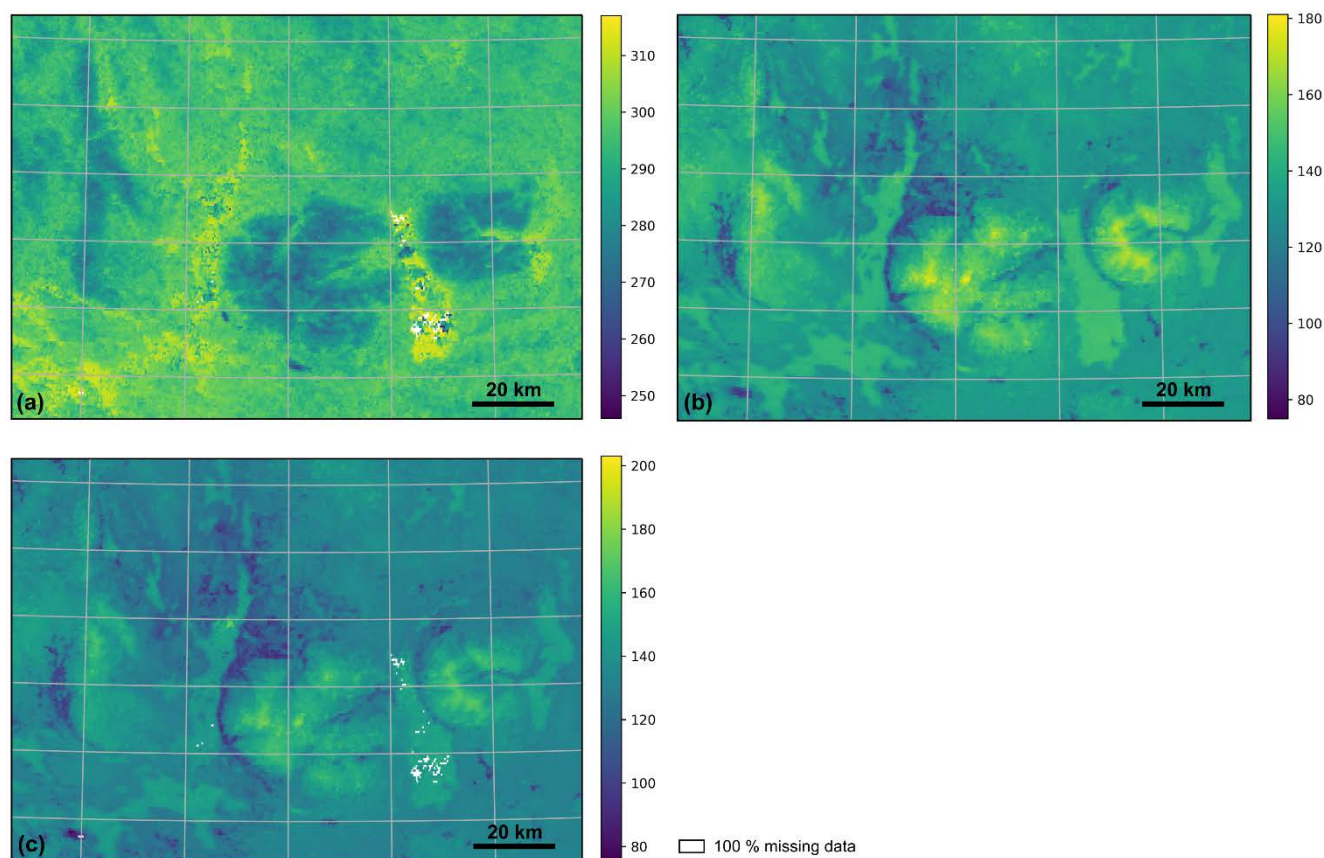
4.2.3 Mean SCS, SCE and SCD

340   Figure 6 shows the mean SCS, SCE and SCD dates over the entire MODIS period, 2000-2016, and illustrates the high spatial variability in the long-term snow cover distribution in the WMR.

Clear climatological differences between the mountainous areas and the surrounding plains can be seen. The snow cover season starts much earlier in the mountains than in the plains, and as expected it starts at the highest elevations first (around September 22nd on average) and then gradually moves to lower altitudes. For most years, the delay in the SCS in the

345   mountain valleys is ~30 days later than the highest elevations. The snow cover season then begins in the north-east of the WMR as defined in this study before arriving in the plains further south, surrounding the mountains. The SCS date for the

plains surrounding the higher elevations of the WMR is usually similar to those of the larger valleys within the mountains (~October 21ˢᵗ).

Figure 6: Three MODIS maps showing the (a) mean snow cover start, (b) mean snow cover end, and (c) mean snow cover duration of the WMR. Scales on (a) and (b) are the day of year, and for (c) the scale is of the number of days.

The SCS is slightly more uniform across the whole Khibiny and Lovozero mountains than the SCE, which is more gradual and follows altitude. The SCE is earliest at the lowest altitudes (~May 20ᵗʰ) while it occurs at the highest elevations around June 29ᵗʰ on average. This results in a very clear link between altitude and SCD, with the highest altitudes having the longest snow cover season in the entire area (~180 days) and the duration of the snow cover season decreasing with lowering elevation. Thus the snow season in the plains surrounding the mountains is much shorter than in the higher altitude areas (by approximately 50 days). Within the plains, the SCE is earliest on the western side of the two high mountain ranges and VMC Tundras. As a result, this area has the shortest snow cover season in the region, between 95 and 100 days long.

Finally, the water bodies have a very noticeable difference with the land around them, which sees them having a much later snow cover start than any other area in the region, but also have a later snow cover end. In 2015, the water bodies did not return snow cover end dates (see Fig. A1o in the Appendix). In most other years, the water bodies which had frozen and were

18

covered in snow, remained so until later in the year (~May 30th) than the surrounding plains (~May 15th). This is probably due to the snow on ice taking longer to melt out than the surrounding snow on top of ground, due to the higher heat capacity and reflectance of ice than soil.
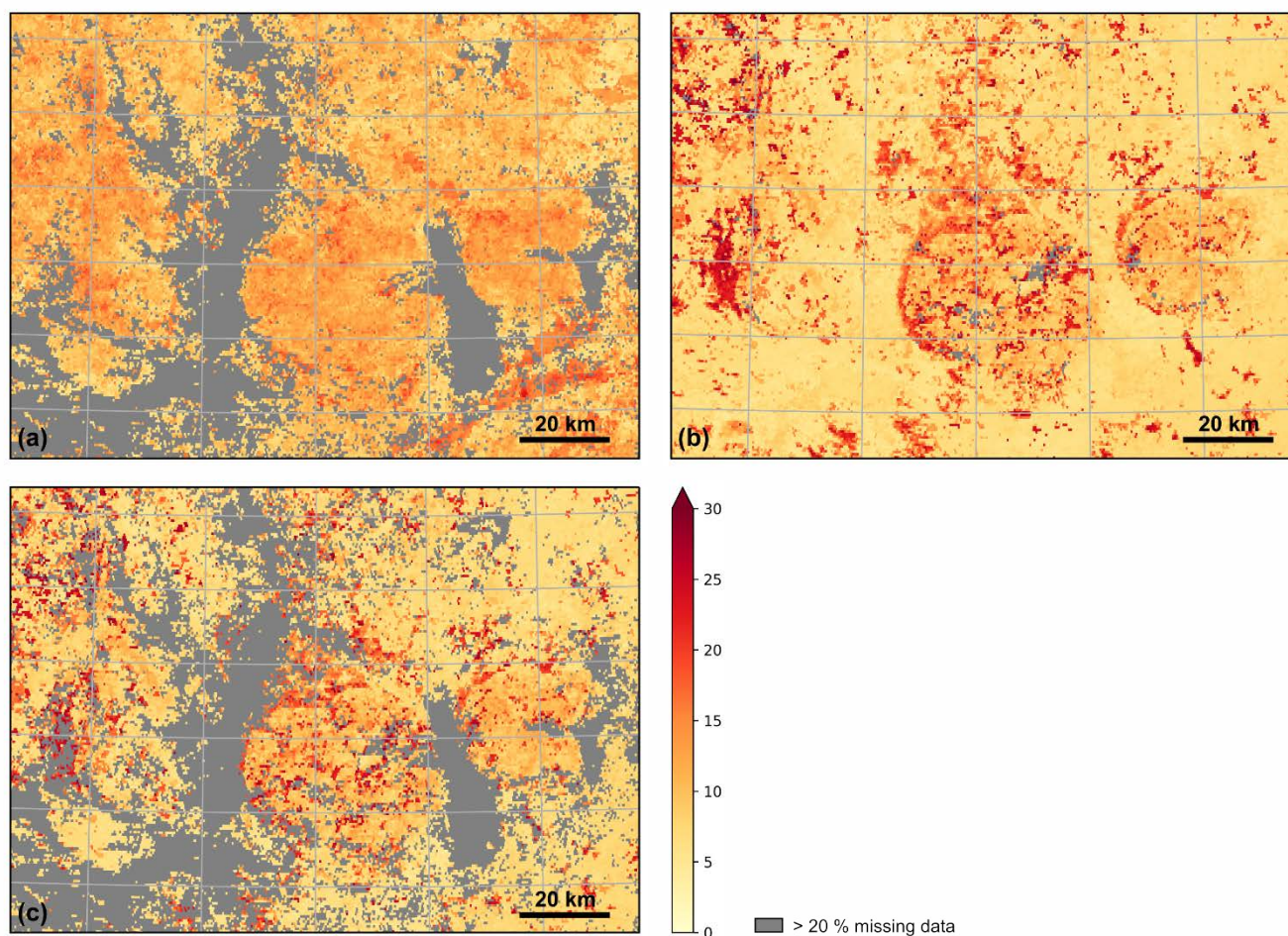
4.2.4 SCS, SCE and SCD inter-annual variability

Figure 7: Standard deviation in days of the a. SCS, b. SCE and c. SCD over the 2000/2001 to 2015/2016 interval in the WMR.

Figure 7 shows the standard deviation from the mean in the SCS, SCE and SCD datasets. The two dark streaks south of the Khibiny Mountains in Fig. 7a are the result of a processing artefact in the original MODIS data in the year 2006 (see Fig. A1g in the Appendix).

Most aspects of snow cover in the WMR have been characterised by high inter-annual variability over the past few decades. Figure 8 shows this particularly clearly where the standard deviation from the mean in SCS is consistently over 15 days across the region, and where the standard deviation reaches over 30 days in many pixels in the SCE and SCD datasets.

Overall, the standard deviation is much higher for the SCS than the SCE and SCD. Indeed, the dates of SCS vary considerably
375   from year to year, with a very noticeable difference between the consecutive years 2008 and 2009 for example where the snow
cover in the plains surrounding the mountains starts on average 20 days later in 2009 than it did in 2008 (see Fig. A1i and A1j
in the Appendix). SCD is the most inter-annually uniform snow cover parameter. Station data suggests that this is a result of
SCS and SCE working in the same direction, and thus counter-balancing each other. The SCD standard deviation pattern is
much closer to that of SCE than SCS, as SCE standard deviation is much more spatially variable than SCS. Overall, for all
380   three parameters the standard deviation is larger in the high-altitude areas, reaching over 30 days for SCE and SCD. The
standard deviation is also high on the western edges to all topographical features in both the SCE and SCD, consistently
reaching over 20 days. This is likely due to the strong relationship between westerly winds and orographic precipitation and
thus snow cover. In the SCE and SCD parameters, the plains have very low standard deviations of under 10 days.

4.2.5 Trends in SCS, SCE and SCD

385   It is possible to investigate trends in the snow cover using the SCS, SCE and SCD dates extracted from the MODIS
processed dataset. These can be compared to those recorded at the meteorological stations by calculating the trends over the
common period of 2000-2016. Table 7 shows these trends: the only statistically significant trend is at Monchegorsk, similar
to the observations, where the snow cover season has been ending 11.6 days/decade earlier (14.5 days/decade for the
observations). This result, and the lack of spurious statistically significant trends at the other stations, provides further evidence
390   that MODIS can be used to analyse snow-cover trends in the WMR with a high degree of confidence.

Station	Dates of common period with MODIS	Parameter	Trend Station data (days/decade)	Trend MODIS data (days/decade)
Apatitovaya	2011 - 2016	SCS	-2.9	-80.2
		SCE	-7.7	0.8
		SCD	8.0	7.9
Lovozero	2000 - 2016	SCS	-4.1	-4.8
		SCE	-3.4	-1.4
		SCD	2.7	-2.8
Monchegorsk	2005 - 2016	SCS	-9.9	24.2
		SCE	-14.5***	-11.6*
		SCD	-5.4	-10.7
MSU Khibiny	2000 - 2016	SCS	-3.6	1.9
		SCE	5.3	-1.4
		SCD	8.7	2.6

Table 7: Trends in days per year and their significance of the Snow Cover Start (SCS), Snow Cover End (SCE) and Snow Cover Duration (SCD) at the four WMR stations from both data collected at those stations and from the MODIS processed dataset. Statistically significant trends are marked with asterisks: * = p < 0.1, ** = p < 0.05, ***= p < 0.01.

Figure 8 shows the high spatial variability of trends in snow cover in the WMR, as calculated from the MODIS
395   processed dataset. Figure 9 shows the statistical significance of these trends, with statistically significant trends shown in
colour, matching the direction of the trend.

The SCS trend figure (Fig. 8a) shows a clear orographic influence. The western side of the Khibiny Mountains has a
positive SCS trend, in other words the SCS has been increasingly later in the year over the past 16 years. Conversely, the
eastern side of the mountains has a negative trend of less than 20 days/decade. The snow season in the Lovozero Mountains
400   has also started later by 10 to 20 days/decade, as has the western edge of the VMC Tundras. The proportion of statistically
significant trends in these two high altitude areas however is quite low (Fig. 9a). The plains do not show a consistent trend in
Fig. 8a, but the majority of the statistically significant trends there (Fig. 9a) are negative. These contradicting trends are difficult
to explain, but the delay in the start of the snow season in the high altitudes is probably in part explained by the decrease in
autumn precipitation in the Kola Peninsula (Marshall et al., 2016).

405

Figure 8: Trends in days per decade in the a. SCS, b. SCE and c. SCD over the 2000/2001 to 2015/2016 interval in the WMR.
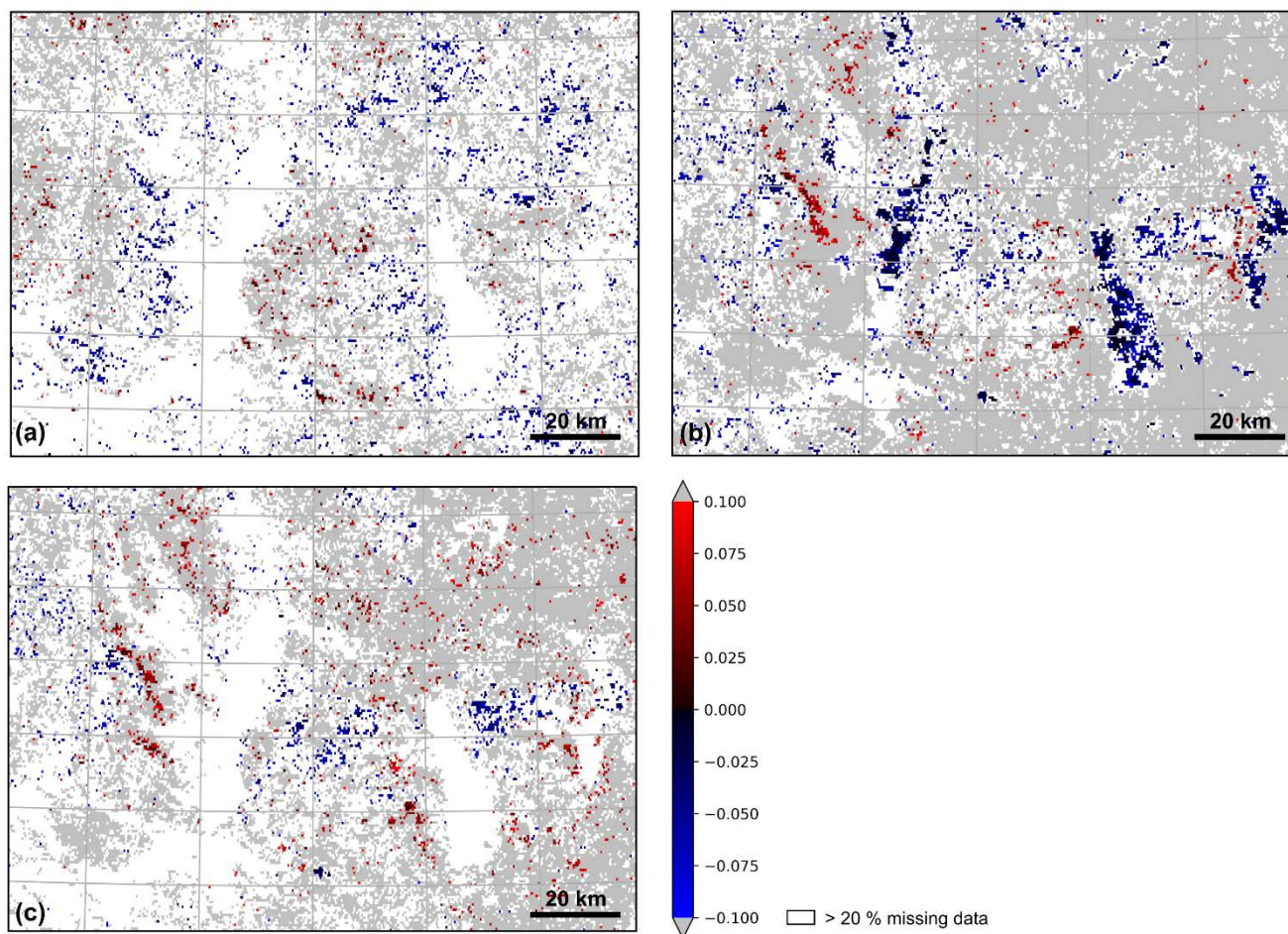
Figure 9: Statistical significance of positive (red) and negative (blue) trends in the a. SCS, b. SCE and c. SCD over the 2000/2001 to 2015/2016 interval in the WMR. Grey pixels show trends that are not statistically significant.

410   In Fig. 8b, the plains have a consistent positive trend in SCE (of less than 10 days/decade). These positive trends are not so dominant in Fig. 9b, as the majority of the trends in the plain are not statistically significant. However, the main clusters of significant trends in the low attitude zones are negative over water bodies and are positive along the eastern edges of the mountain ranges. These positive trends in the plains may be explained by the fact that spring has become increasingly wet (Marshall et al., 2016), so increased snowfall would delay the end of the snow season. Trends in the SCE in the higher altitude

415   areas are not so clear in Fig. 8b. Some of the high-altitude zones have had a delay in the end of the snow cover (positive trend) and others, such as the northern Khibiny and Lovozero Mountains, have had an increasingly early SCE (negative trend). The picture becomes clearer in Fig. 9b, where it is possible to see that parts of the northern Khibiny and Lovozero Mountains as well as the VMC Tundras are characterised by statistically significant negative trends, and that the only statistically significant positive trends in SCE at high elevations are in the southern and eastern Khibiny and Lovozero Mountains. The increasingly

420   early to end to the snow cover in the higher altitudes may be due, in part, to increased blowing snow (Demin, personal
communication) as a result of the overall trend towards stronger winds in the Kola Peninsula (Roshydromet, 2005).

The SCD has shortened statistically significantly by 10 to 20 days/decade within the mountains at the higher altitudes
in the northern Khibiny, northern Lovozero Mountains as well as the lower elevation topography of the VMC Tundras. The
very south-eastern areas of the Khibiny and Lovozero Mountains are the only regions of high elevation that have undergone

425   statistically significant positive trends. Contrastingly, the SCD has undergone small, positive and statistically significant trends
(less than 10 days/decade extension) in mountain valleys and widespread areas of the plains in the WMR. The plains to the
north-west corner of the Khibiny Mountains is the only low elevation zone with an increasingly short snow cover season, due
to an earlier end of the snow season by approximately 20 days/decade.

5 Conclusions

430   In this paper, we have used a combination of remote sensing data and meteorological observations to analyse past changes in
snow cover in the WMR of the Kola Peninsula, Arctic Russia. MODIS snow products were processed in order to create SCS,
SCE and SCD datasets. Although for some areas and some years, the start and end of the snow season could not be detected
due to long overcast periods (Fig. 4), this MODIS post-processing reduced the number of missing pixels by more than half.

- MODIS is able to provide a highly reliable snow parameter dataset in the WMR of Arctic Russia. We have validated
435   it through a comparison of the timing and trends of the snow cover season with station data. The average difference
between the station data and MODIS processed dataset-derived SCS and SCE dates is 8.6 and 10.4 days respectively,
both relatively low errors. In this analysis, we find that for 85.8 % of pixels investigated (SCS and SCE combined)
the deviation in the MODIS-derived dates is less than 20 days.

- It is possible to extract realistic trends from the MODIS processed dataset. Indeed, MODIS-extracted trends are
440   identical to observed trends in that MODIS was able to identify the only statistically significant trend while not giving
spuriously significant trends elsewhere.

- There is high inter-annual and spatial variability in the long-term snow cover trends in the WMR of the Kola
Peninsula. Overall, between 2000 and 2016, the snow cover duration has been decreasing at higher altitudes and
increasing at lower altitudes. The end of the snow cover season has become increasingly later in the plains that
445   surround the WMR, but there is not such a clear trend in SCE in the higher altitude areas. Snow depth was also found
to be highly spatially variable and the difference in maximum yearly snow depth was found to be over 50 cm between
two stations (PABGI Khibiny and MSU Khibiny) only 2 km apart at very similar altitudes in valleys within the
Khibiny Mountains. These differences in snow depth as well as some of the trends in the snow cover season are
probably explained by wind scouring that occurs in the WMR.

450   • Three of four meteorological stations in the WMR were found to have recorded an increasingly long snow cover season across their differing length but the only statistically significant trend was negative. This spatial variability is also found to exist on larger scales over longer periods.

• Overall, six of the eight stations with daily snow data examined across the western Murmansk region over 2000-2016 recorded a lengthening of the snow cover season over their records, but only two positive trends and the two negative 455   trends were statistically significant.

• A uniform, statistically significant, regional decrease in the duration of the snow cover season between 1992 and 2016 has occurred across the lower altitudes of the western Murmansk Region.

The next step in this work will be to link the regional snow cover variability to changes in atmospheric circulation 460   through regional coupled model runs and, subsequently, to make predictions of future snow cover based on projected circulation changes in the main IPCC emission scenarios.

6 Data availability

MODIS/Terra Snow Cover Daily L3 Global 500m Grid, Version 6 and MODIS/Aqua Snow Cover Daily L3 Global 500m Grid, Version 6, available for download from http://reverb.echo.nasa.gov/reverb. Other data available by contacting the 465   corresponding author.

7 Author contributions

RMV undertook the research described in this paper and prepared the manuscript with contributions from all co-authors. GJM made figure 2, RMV prepared all other figures.

8 Competing interests

470   The authors declare that they have no conflict of interest.

9 Acknowledgements

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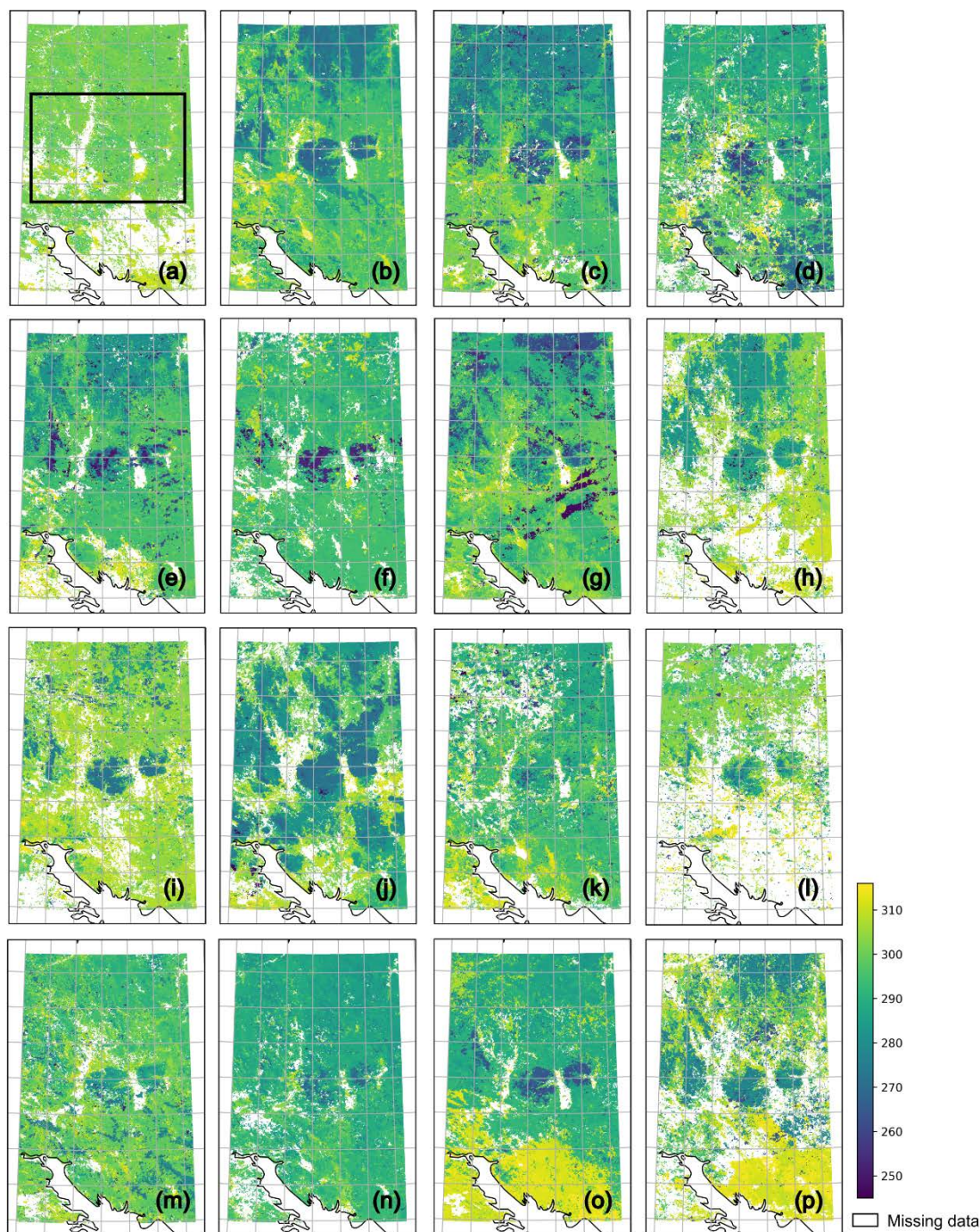
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11 Appendix

655 **Figure A1: SCS maps for the WMR showing the last day of the snow-free season from the year 2000 (a) to 2015 (p). The colourbar shows the day of the year. The WMR is outlined in (a) for scale.**
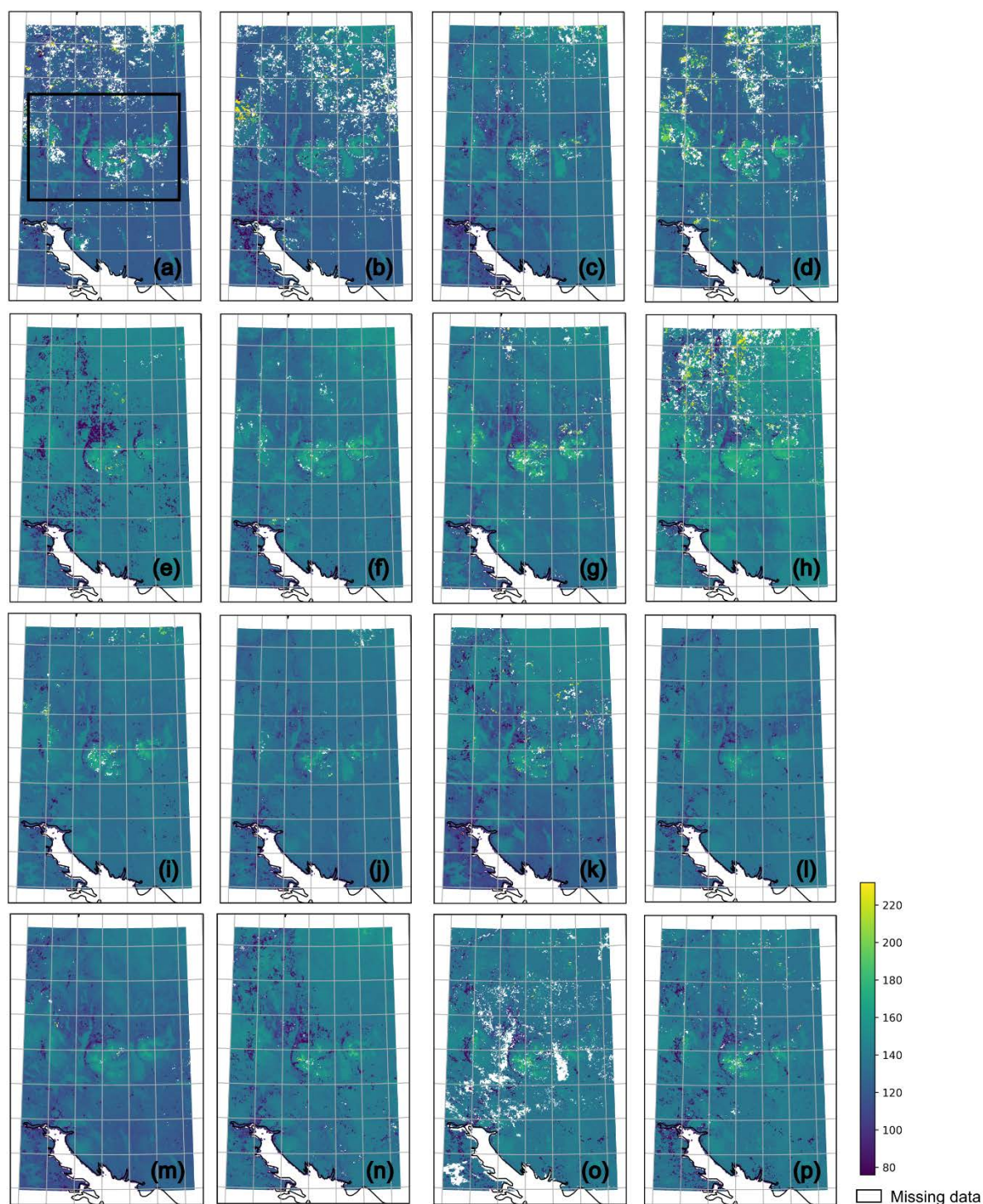
Figure A2: SCE maps for the WMR showing the first day of the snow-free season from the year 2001 (a) to 2016 (p). The colourbar shows the day of the year. The WMR is outlined in (a) for scale.
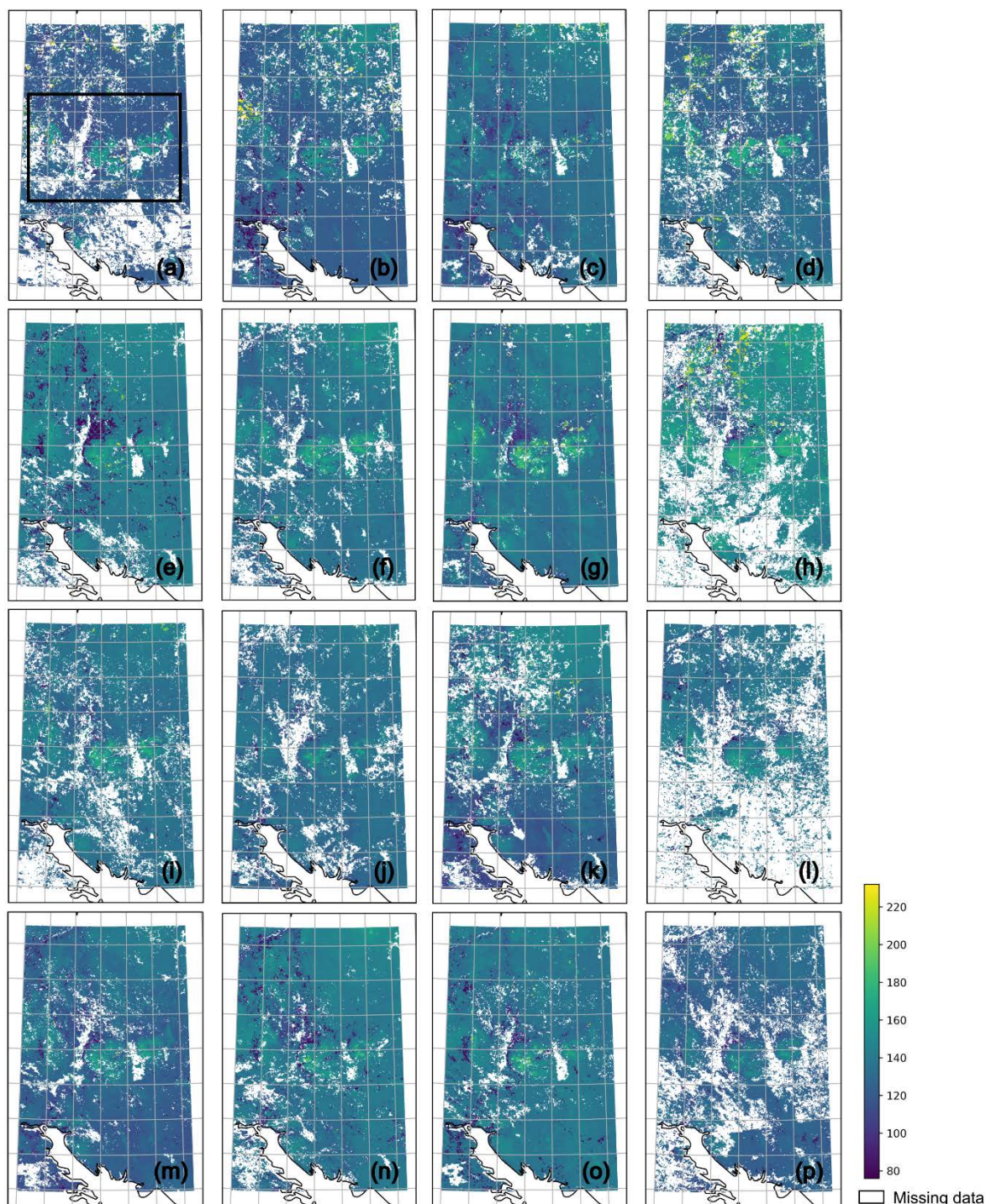
Figure A3: SCD maps for the WMR showing the duration of the snow season from the snow year 2000/2001 (a) to 2015/2016 (p). The colourbar shows the number of days. The WMR is outlined in (a) for scale.