Climate Change in the Kola Peninsula, Arctic Russia, during the Last 50 Years from Meteorological Observations

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ABSTRACT

The authors provide a detailed climatology and evaluation of recent climate change in the Kola Peninsula, Arctic Russia, a region influenced by both the North Atlantic and Arctic Oceans. The analysis is based on 50 years of monthly surface air temperature (SAT), precipitation (PPN), and sea level pressure (SLP) data from 10 meteorological stations for 1966–2015. Regional mean annual SAT is ~0°C: the moderating effect of the ocean is such that coastal (inland) stations have a positive (negative) value. Examined mean annual PPN totals rise from ~430 mm in the northeast of the region to ~600 mm in the west. Annual SAT in the Kola Peninsula has increased by 2.3° ± 1.0°C over the past 50 years. Seasonally, statistically significant warming has taken place in spring and fall, although the largest trend has occurred in winter. Although there has been no significant change in annual PPN, spring has become significantly wetter and fall drier. The former is associated with the only significant seasonal SLP trend (decrease). A positive winter North Atlantic Oscillation (NAO) index is generally associated with a warmer and wetter Kola Peninsula whereas a positive Siberian high (SH) index has the opposite impact. The relationship between both the NAO and SH and the SAT is broadly coherent across the region whereas their relationship with PPN varies markedly, although none of the relationships is temporally invariant. Reduced sea ice in the Barents and White Seas and associated circulation changes are likely to be the principal drivers behind the observed changes.

1. Introduction

The Arctic region has warmed faster than anywhere else on Earth over the past few decades, a process called Arctic amplification (e.g., Serreze et al. 2009; Serreze and Barry 2011), and is believed to be responding to anthropogenic forcing as the observed temperature increase lies outside the range of expected internal climate variability (Gillett et al. 2008; Chylek et al. 2014; Cohen et al. 2014). For the IPCC, Bindoff et al. (2013) concluded that despite uncertainties introduced by limited observational coverage, high internal variability, poorly understood local forcings, and modeling uncertainties, there is sufficient evidence for it to be likely (66%–100% confidence) that there has been an anthropogenic contribution to the warming of Arctic land surface air temperatures (SATs) over the past 50 years.

Arctic amplification above the ''global warming'' signal has resulted from dynamical changes in both the atmosphere and ocean. Several different processes are thought to contribute to the amplification (Cohen et al. 2014, and references therein): they include local drivers, such as changes in the strength of the snow–ice-albedo feedback mechanism due to the reduction in Arctic sea ice extent, and also broad-scale circulation changes, such as increased poleward heat advection from lower latitudes (e.g., Ye et al. 2015).

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The average annual Arctic SAT warmed in the early twentieth century, followed by a significant cooling from 1940 to 1965 after which the current Arctic warming began, at a rate approximately twice the global mean (Chylek et al. 2014). This warming has been relatively widespread across the Arctic, especially from the 1980s, whereas previous Arctic SAT changes were neither spatially or temporally uniform (Overland et al. 2004). Nonetheless, large-scale cooling occurred during boreal winter over much of the Eurasian Arctic in recent decades. Several papers have related this to reduced Arctic sea ice (e.g., Tang et al. 2013; Mori et al. 2014). Cohen et al. (2012) linked this seasonal asymmetry in SAT trends to a dynamical process whereby greater atmospheric moisture during a warmer summer/fall period with less sea ice leads to enhanced Eurasian snow cover. This in turn forces a negative North Atlantic Oscillation (NAO) the following winter, which favors colder temperatures in northern Eurasia (e.g., Hurrell 1995). However, Li et al. (2015) suggested that the cooling arises simply as an extreme event within the range of atmospheric internal variability, although they believed that the reduction in Arctic sea ice has increased Eurasian winter climate variability, and thus enhanced the likelihood of the cooling taking place.

Marked changes in precipitation (PPN) and snow cover across the Arctic have also taken place. Most observation-based datasets suggest an overall increase in Arctic precipitation from 1951 to 2008 (Hartmann et al. 2013), although the relatively sparse data network means that significant uncertainty is attached to the magnitude of this Arctic moistening. Nevertheless, the precipitation increase has been partially ascribed to anthropogenic forcing (Min et al. 2008). Similar to SAT, changes in Arctic snow cover since the 1950s have varied widely both spatially and seasonally. Callaghan et al. (2011) noted the marked contrast between decreases in both snow depth and snow water equivalent in North America and increases in these two parameters across much of Eurasia until after 1980, when they started to decline in this region too. However, fall snow cover has increased across Eurasia since the 1990s (e.g., Cohen et al. 2012), whereas in spring there has been a marked decrease over the Arctic as a whole, which has also been linked to anthropogenic activity (Derksen and Brown 2012; Rupp et al. 2013).

Over the past 50 years Arctic sea level pressure (SLP) has generally decreased and attribution studies have detected an anthropogenic effect here too (e.g., Gillett et al. 2013). This long-term trend, however, has included significant decadal variability in the NAO. There was a significant positive trend in the NAO during the 1970s to early 1990s, which was frequently cited as evidence of anthropogenically forced climate change. However, since then there has been a general decline in the NAO index but with increased interannual variability. This included the lowest value ever recorded across the ~200-yr length record in 2009/10, which resulted in very severe weather across much of the industrialized population centers of the Northern Hemisphere midlatitudes (Cohen et al. 2010; Osborn 2011).

In this paper, we focus on climate change in the Kola Peninsula region of Arctic Russia during the past half century. It forms an initial component of a project that includes fieldwork within the region and that aims to understand recent changes in snow cover across Fennoscandia with the aim of being better able to predict how regional water resources will change in the future. Climatically, the Kola Peninsula is a particularly interesting region to study as it represents a transition from Scandinavia to the west, where the climate is primarily influenced by the North Atlantic Ocean, to northwestern Siberia to the east, where the climate is more affected by the Arctic Ocean. We also note that relatively little has been published on the climate of this region in the scientific literature outside Russia. Thus, the principal aim of this paper is to provide a baseline climatology and, in particular, an analysis of recent trends in SAT, PPN, and SLP derived from meteorological observations across the Kola Peninsula.

We begin by describing the general climate of the study region and summarizing the findings of the small number of previous climate-related studies based there (section 2). Then we identify the meteorological data used in the analysis and outline the statistical methods employed in section 3. We describe the climatology of the Kola Peninsula in section 4 while in section 5 we evaluate linear 50-yr trends in SAT, PPN, and SLP at annual, seasonal, and monthly periods, and in section 6 we examine variability within the 50 years using stacked data from all the Kola Peninsula stations studied. In sections 7 and 8 we analyze the relationship between Kola Peninsula climate and indices of the winter NAO and Siberian high, respectively. In the discussion section (section 9) we qualitatively explore the changes in regional atmospheric circulation associated with some of the seasonal trends and discuss our findings in the context of a longer time frame, both historically and with regard to model projections. Finally, in section 10, we summarize our principal findings.

2. Climate of the study region

The Kola Peninsula comprises the northeastern part of Fennoscandia and lies predominantly north of the Arctic Circle. It encompasses approximately 145 000 km^2, extending for about 400 km north–south and 500 km east–west, and is situated between the Barents Sea to the north and the White Sea to the south and east. The climate is subject to the moderating influence of the ocean, being dominated by the advection of heat and moisture from the North Atlantic, and in particular the North Atlantic Current that flows along its northern shore (e.g., Filatov et al. 2005; Matishov et al. 2012). As a consequence, the regional climate comprises cool, rainy summers and relatively mild winters (Ilyashuk et al. 2013). Moreover, the Kola Peninsula is affected by the passage of a large number of cyclones, making the weather highly changeable. Some of these weather systems, which include vigorous polar lows, are generated in the Norwegian Sea, extending the main North Atlantic storm track farther northeast, while others undergo cyclogenesis farther south in the Baltic Sea (Hoskins and Hodges 2002).

An early climatology of both SAT and PPN for the Kola Peninsula was presented as a series of maps as part of an atlas of the region (Yakovlev and Kozlova 1971; available online at http://kolamap.ru/): it is not apparent over what time period the data for this climatology were obtained. More recently, a figure showing annual SAT for the 1981–2010 period, derived from a gridded dataset of daily SAT values, interpolated from observations, was given in Blinova and Chmielewski (2015); also, annual and seasonal means for 1961–90 and 1990–2010 from several Kola Peninsula stations were presented by Demin (2012).

With regard to changes in climate, Shilovtseva and Romanenko (2009) analyzed long-term SAT changes in the White Sea region, including five coastal Kola Peninsula stations. Those on the northern and eastern coasts showed an overall warming in all seasons whereas stations on the southern coast cooled slightly in all seasons except spring. Demin (2012) demonstrated that mean SAT across the region was higher for 1990–2010 compared to 1961–90 in all seasons, while Demin and Zyuzin (2006) showed that annual SAT at a mountain station in the Khibiny Mountains in the central Kola Peninsula increased by more than 1°C between 1962 and 2005. Furthermore, Zvereva et al. (2016) described a warming at Monchegorsk station, also in the Khibiny Mountains region, during the 1993–2014 period, that was especially pronounced during spring and fall. Similarly, phenological data have revealed an increase in the length of the thermal growing season in the Kola Peninsula from 1951 to 2012, due to both an earlier onset and later finish (Blinova and Chmielewski 2015). Although relatively little has been published in the mainstream scientific literature specifically about the Kola Peninsula climate, it has been included in large-scale studies encompassing the whole of Eurasia (e.g., Bulygina et al. 2009; Ye et al. 2015). Franzke (2012) examined the significance of SAT trends of varying length at individual meteorological stations within this broader region using a number of different statistical tests. One of the two stations situated within the Kola Peninsula was among the few studied (17 of 109) that had, according to his exacting criteria, evidence for trends statistically separable from natural climate variability.

Kozlov and Berlina (2002) discovered an increase in the length of the snow-cover period by 15–20 days between 1930 and 1998, at a site on the Kola Peninsula, due to both a delayed spring and advanced fall. This coincides with the findings of Ye (2001), who found statistically significant increases in snow-cover duration based on snow depth measurements. However, more recently there has been a trend toward a shorter snow duration across northern Eurasia as a whole (Bulygina et al. 2009; Callaghan et al. 2011). Ye and Cohen (2013) associated this shorter snowfall season with warmer SATs in both fall and spring across much of this region, including the Kola Peninsula, corroborating the findings of Blinova and Chmielewski (2015) mentioned previously. These various studies suggest clear decadal variability in regional SATs.

While sea ice has been declining markedly across the Arctic Ocean as a whole, the decrease in the Barents Sea, north of the Kola Peninsula, has been especially marked (e.g., Matishov et al. 2012), with predominantly negative anomalies during the twenty-first century. Moreover, the duration of the winter sea ice cover in the White Sea, south of the Kola Peninsula, has declined by about 10 days per decade since 1979 (Parkinson 2014). Anomalously low sea ice extent in the Barents Sea, particularly during winter, leads to higher turbulent heat fluxes that warm the region diabatically (e.g., Serreze et al. 2011) and has led to changes in regional circulation patterns (Zhang et al. 2008) and snow cover (Wegmann et al. 2015). Composite analysis by Inoue et al. (2012) revealed that reduced ice in the Barents Sea is associated with a blocking high (anticyclone) over the Siberian coast, which results in a northward expansion and deepening of the climatological Siberian high (SH) pressure. The SH is an extensive semipermanent anticyclone centered over Asia, largely driven by radiative cooling, and is most prominent during winter, when it extends sufficiently westward to impact the climate of the Kola Peninsula (Panagiotopoulos et al. 2005). Its strength has also been linked to variations in the preceding summer Arctic dipole wind pattern, a couplet of anomalously high/low pressure over the Arctic Ocean/Barents–Kara Seas (Wu et al. 2016), and fall Eurasian snow cover (Cohen et al. 2001). The SH weakened markedly between 1979 and 2001 by 2.5 hPa decade^{-1} (Panagiotopoulos et al. 2005)

TABLE 1. List of stations used in the analysis, their location and the percentage of monthly data available for SAT, PPN, and SLP for the 1966–2015 period.

Station	WMO No.	Latitude (°N)	Longitude (°E)	Proportion of 1966–2015 monthly data available (%)		
				SAT	PPN	SLP
Gremikha Bay	22140	68.13	39.77	94.7	93.0	93.8
Kandalaksa	22217	67.13	32.43	100.0	100.0	99.2
Kanevka	22249	67.13	39.67	98.3	95.2	94.8
Kovdor	22204	67.57	30.38	98.5	98.5	94.2
Krasnoscel'e	22235	67.35	37.05	100.0	99.2	99.2
Lovozero	22127	68.08	34.80	99.3	98.0	62.0
Murmansk	22113	68.97	33.05	100.0	100.0	100.0
Teriberka	22028	69.18	35.08	99.2	97.5	97.3
Umba	22324	66.68	34.35	98.8	99.8	60.3
Vaida Guba Bay	22003	69.93	31.98	96.8	98.0	95.8

although Jeong et al. (2011) reported that it had recovered subsequently.

3. Data and methodology

Seasons are defined using the standard meteorological definitions for the Northern Hemisphere: spring (March–May), summer (June–August), fall (September–November) and winter (December–February). For the station names we use the westernized forms, as employed by the World Meteorological Organization (WMO).

a. Synoptic data

The prime source of SAT and SLP data for this analysis are the archives of synoptic data from the Russian Research Institute of Hydrometeorological Information World Data Centre (RIHMI-WDC). These data begin in 1966 so there are 50 years (1966–2015) available for analysis. Additional SAT and SLP synoptic data were acquired from the UK Met Office Integrated Data System (MIDAS; Met Office 2012), and more recent data from Weather Underground (wunderground.com). These data were quality controlled visually and data with any gross errors removed or altered if it was clear what the error was. For example, a number of the SLP data were 100 hPa out because the original message was incorrectly coded when it was transmitted. Six-hourly data at the standard synoptic hours were used to produce the monthly mean. However, to maximize the number of these data, if a value was missing but adjacent 3-hourly values were available, then an estimate of the 6-hourly value was made by linearly interpolating between these two adjacent values; for example, if a value at 0600 UTC was missing but values existed at 0300 and 0900 UTC, then the mean of those values would be used to estimate a value for 0600 UTC. Any resultant bias will be random and should have a negligible effect on the monthly mean. In addition, a monthly value was produced only if 95% of the 6-hourly data were available.

b. Monthly data

For PPN the primary source of monthly data was the European Climate Assessment and Dataset (ECA&D; available at www.ecad.eu/download/millennium/millennium.php) (Klein Tank et al. 2002). Additional monthly PPN data were taken from the RIHMI-WDC. These data have been corrected for biases due to precipitation measurement deficiencies, principally the result of trying to measure snowfall with traditional rain gauges, and inhomogeneities arising from instrumental changes during the observation period (Groisman et al. 2014). SAT and PPN data for Lovozero station prior to 1985 were kindly supplied by Dr. Valery Demin.

c. Stations chosen

We examined the data availability from a number of stations and eventually chose 10 where there were sufficient data for all three parameters to provide accurate trends and other statistics over the 1966–2015 period (with two exceptions for SLP). These stations and the percentages of the data available for SAT, PPN, and SLP are given in Table 1 and their distribution across the region shown in Fig. 1. We combined data from Svjatoj Nos (in the RIHMI-WDC archives) and Gremikha Bay, which have the same WMO station identifier (22140), to produce a single time series. Additionally, data from Polinjaroe/Severomorsk were not included as this station is located relatively close to Murmansk (22113) and one of the aims of this analysis is to look at climatic spatial variability across the Kola Peninsula region. In some of our analysis we stack data from the 10 stations to produce an approximation of a regional time series. With regard to SAT, given the prevalence of coastal sites there is likely to be a warm bias in winter and a cold bias in

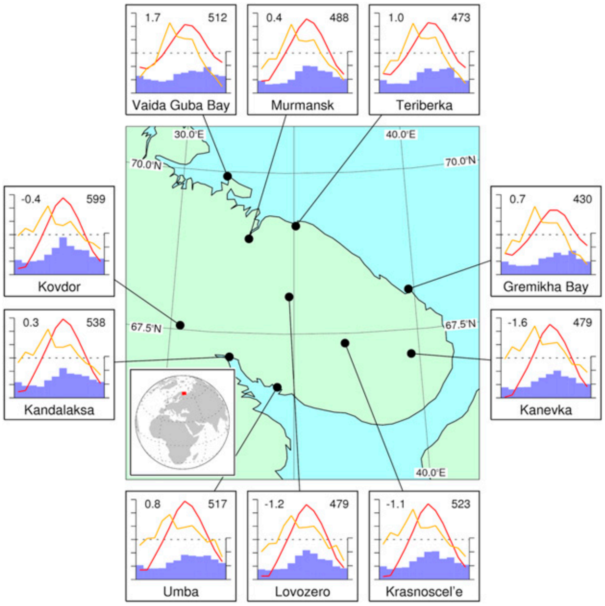

FIG. 1. Mean annual cycle of SAT (red), PPN (blue), and SLP (orange) for data from 1966 to 2015. The left-hand axis scale goes from −15° to 15°C (difference between tick marks is 5°C) and 1002.5 to 1017.5 hPa (difference between tick marks is 3 hPa) for SAT and SLP, respectively, and the right-hand scale from 0 to 90 mm for PPN (difference between tick marks is 30 mm). Mean annual SAT (°C) and mean annual PPN totals (mm) are shown in the top left and right, respectively.

summer. Blinova and Chmielewski (2015) found a mean SAT across the Kola Peninsula of −0.32°C for 1981–2010 whereas the stack of 10 stations has an equivalent figure of +0.06°C, suggesting that the mean of the 10 stations is slightly warmer than the region as a whole across the year. All 10 stations show similar patterns of monthly SAT trends (Fig. 2) so it is unlikely that this bias will significantly affect the magnitude of SAT trends derived from the stack.

d. *Atmospheric circulation indices*

We examine both long-term and decadal variability in the relationship between the climate at three stations with complete or near-complete records (Murmansk, Kandalaksa, and Krasnoscel'e) with boreal winter indices of two of the primary modes of atmospheric circulation variability that impact Arctic European climate during this season, the NAO and SH. As both indices span different calendar years they are available for the 49-yr period from 1966 to 2014 with the year referring to the December.

1) THE NORTH ATLANTIC OSCILLATION

We utilize the observation-based winter NAO index of the Climate Research Unit (CRU) (Osborn et al. 1999). This comprises the mean of the four monthly NAO values from December to March. Each monthly value is calculated as the difference between the normalized SLP at Gibraltar and that at Reykjavik (Jones et al. 1997). Although the normalization period used to create this NAO index is 1951–80, partly outside the period analyzed here, we are only interested in correlations so this does not affect the results. The data are available online at http://www.cru.uea.ac.uk/~timo/datapages/naoi.htm.

2) THE SIBERIAN HIGH

We use a modified version of an observation-based SH index originally defined by Panagiotopoulos et al. (2005). They used the normalized mean SLP from 11 stations located in the key region between 40°–65°N and 80°–120°E to produce an SLP index. Here, we employ data from the same 11 stations updated to 2015 and, where possible, using the synoptic data from RIHMI-WDC to produce a monthly SLP value. Otherwise, monthly data from the National Center for Atmospheric Research (NCAR) are used (available at http://rda.ucar.edu/datasets/ds570.0/). The SH index is calculated as the mean of the 11 stations across each winter (December to February), normalized for 1966–2014, where the year refers to the December.

e. *Reanalysis data*

As part of the analysis of recent trends in the discussion section, we utilize gridded SLP data from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis (Dee et al. 2011). These data, available for 1979–2015, were obtained on a Gaussian N128 grid, which has a spatial resolution equivalent to ~80 km.

f. *Statistical methods*

Trends are calculated using standard least squares methodology and the effects of autocorrelation are accounted for when calculating the significance of any trend by calculating an effective sample size assuming an autoregressive first-order process (e.g., Santer et al. 2000). Correlations are derived from the residuals of detrended data, which assumes no a priori link between the two parameters.

To examine the broad-scale regional trends and modes of temporal variability of the Kola Peninsula climate, data from the 10 stations are combined into seasonal and annual "stacked" time series of anomalies for each of the three meteorological parameters. For examining time series variability each season or year a normalized anomaly is calculated for each station and then the mean of these is used for the stacked time series so that stations with higher variability are not given

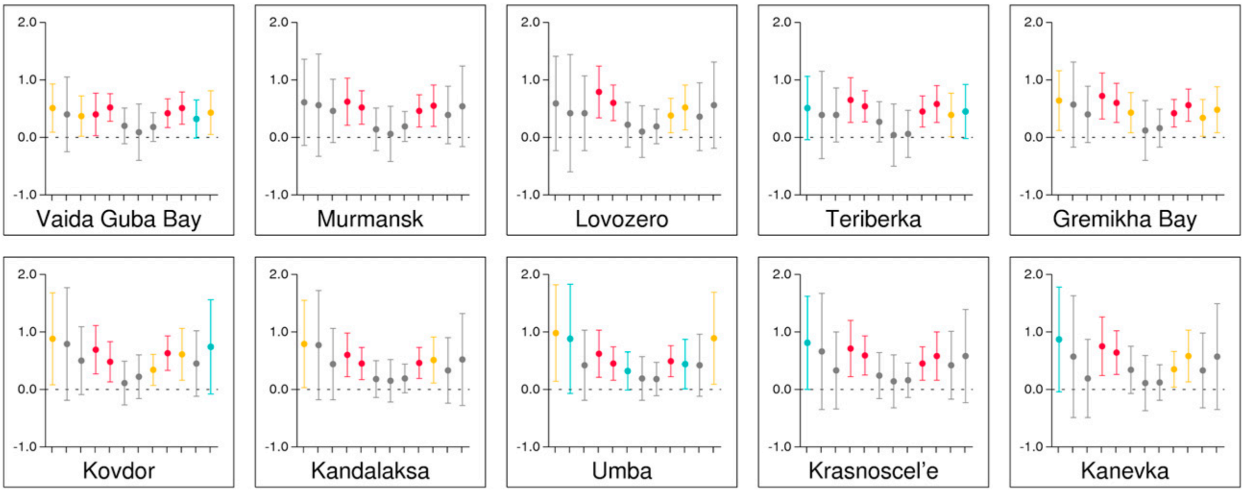

FIG. 2. Monthly SAT trends (°C decade^{-1}) for 1966–2015. Months are from January to December, left to right. The whiskers represent the 95% confidence intervals around the trend. Trends that are statistically significant from zero at $p < 0.10$, $p < 0.05$, and $p < 0.01$ are shown in blue, yellow, and red, respectively.

extra weight and vice versa. Note that Lovozero (22127) and Umba (22324) are not included in the stacked SLP time series as we only have these data available from 1985 onward.

Wavelet analysis (e.g., Torrence and Compo 1998) is used to examine the dominant modes of temporal variability in the stacked normalized time series throughout the 50-yr duration. In this study, we use the Morlet wavelet, which is a complex-valued wavelet often applied for this technique. Standard methodology is employed, such as calculating statistical significance versus a red-noise background spectrum.

4. Climatology

In Fig. 1, we show the mean annual cycle of SAT, PPN, and SLP for the 1966–2015 period derived from monthly data, together with annual mean values of SAT and PPN for the 10 stations analyzed. Interestingly, the mean annual temperature across the Kola Peninsula can be both positive and negative, ranging from −1.6°C at Kanevka to 1.7°C at Vaida Guba Bay, the most northerly station. The gridded data used by Blinova and Chmielewski (2015) suggest that these do actually represent the coldest and warmest parts of the Kola Peninsula, respectively. The four stations examined with negative mean annual temperatures—Kovdor, Kanevka, Krasnoscel'e, and Lovozero—are all located inland, revealing the significant moderating effect of the ocean in the region: however, we note that both the earlier atlas (Yakovlev and Kozlova 1971) and Blinova and Chmielewski (2015) indicate that this effect does not extend to the eastern coast of the Kola Peninsula, where we have no stations. Elsewhere, the moderating influence of the ocean is further shown by differences in the range of mean monthly SATs, which vary from 16.6°C at coastal Vaida Guba Bay to 27.3°C at both Kanevka and Krasnoscel'e inland. Minimum SATs are generally found in January although some of the stations along the northern coast have their minimum in February. All stations have a monthly SAT maximum in July, although at the northern coastal stations August SAT is almost as high. Regional differences in the SAT minimum are much greater than for the maximum.

Mean annual PPN totals at the examined stations vary from 435 mm at Gremikha Bay on the northeast coast of the Kola Peninsula to 600 mm at Kovdor inland in the west of the region. Indeed, in general there is an increase in precipitation from north to south and east to west across the region. However, we note that the greatest regional precipitation is in the Khibny Mountains, west of Lovozero, where annual totals can exceed 1200 mm (e.g., Yakovlev and Kozlova 1971; Demin and Zyuzin 2006). The shape of the PPN annual cycle has broadly similar features across all the stations analyzed. For example, February–April are generally the months with the lowest PPN as the primary storm tracks of the early winter have weakened. Maximum PPN occurs in late summer, sometimes as a distinct peak (e.g., Kovdor) or sometimes as several months of similarly high values (e.g., Teriberka and Umba). The summer PPN maximum is associated with the Arctic frontal zone (Serreze et al. 2001), which appears over northern Eurasia during this season, principally driven by differential heating between the cold Arctic Ocean and warmer snow-free continent. In contrast to SAT, there is significant variation

TABLE 2. Changes in climate parameters in the Kola Peninsula for the 1966–2015 period together with 95% confidence intervals, based on the stack of available stations. Statistical significance at $p < 0.10$, $p < 0.05$ and $p < 0.01$ are shown with one, two, and three asterisks, respectively.

Parameter	Annual/Season				
	Annual	Spring	Summer	Fall	Winter
SAT (°C)	2.31 ± 1.02***	2.71 ± 1.40***	0.90 ± 1.16	2.36 ± 1.07***	2.69 ± 3.29
PPN (mm)	0.56 ± 3.46	5.11 ± 3.20***	3.95 ± 10.88	−7.78 ± 8.15*	1.33 ± 5.24
SLP (hPa)	−0.88 ± 1.46	−3.01 ± 2.61**	−0.29 ± 1.53	1.90 ± 2.94	−1.38 ± 6.19

in interstation correlations of PPN. Analysis of PPN between the different stations reveals negative correlations between stations in the north and south of the western half of the Kola Peninsula during winter, which likely reflect latitudinal shifts in the principal storm tracks.

There is little variability in the annual cycle of SLP across the region and the mean annual SLP at the 10 stations examined lie within 1.8 hPa of each other (not shown). Maximum SLP occurs in May with the minimum in December, the latter related to the much greater frequency of cyclonic weather systems that occur in the region in winter as compared to other seasons (e.g., Serreze and Barry 2005). There are a number of features in the SLP annual cycle that make it deviate from a sine wave more than that for SAT. Foremost of these are the very similar SLP values throughout summer (June–August). Cullather and Lynch (2003) suggested that this may reflect the interaction between annual and semiannual cycles in pressure. However, analysis of the stacked station data indicates that the amplitudes of the first and second harmonics are about 3.5 and 0.1 hPa, respectively, with the former explaining ~88% of the total variance and the latter essentially zero. Thus, the importance of the semiannual cycle in SLP in the Kola Peninsula observations across 1966–2015 appears much reduced from that in the study of reanalysis data for 1979–2001 by Cullather and Lynch (2003), although these authors did state that its impact was temporally highly variable.

5. 50-yr trends

a. Surface air temperature

Annual and seasonal SAT trends for the Kola Peninsula (based on the stacked time series) are given in Table 2 while monthly SAT trends for these individual stations are shown in Fig. 2. The former indicates that there has been a statistically significant warming of 2.3° ± 1.0°C (95% confidence intervals) in the Kola Peninsula over the 1966–2015 period. Using the software tools at the website for the Goddard Institute for Space Studies (GISS) SAT analysis (GISTEMP Team 2015; Hansen et al. 2010) suggests that this is among the highest regional rates of warming observed globally in this particular 50-yr period. Further evidence for a regional warming can be seen by the much greater proportion of the Kola Peninsula having an annual SAT greater than 0°C during 1981–2010 (Blinova and Chmielewski 2015) as compared to a period prior to the 1970s (Yakovlev and Kozlova 1971).

On a seasonal basis, significant warming is limited to the equinoctial seasons (both at the $p < 0.01$ level). The rate of SAT increase is actually greater in winter than fall, as also seen in a comparison between 1961–90 and 1990–2010 SATs (Demin 2012), but the higher SAT variability in this season means that the warming is not statistically significant. Summer warming in the Kola Peninsula is much less than in the other three seasons (Table 2). Similar seasonal variation in SAT trends has been found in neighboring Finland for the 1959–2008 50-yr period (Tietäväinen et al. 2010). It has been linked to the loss of Arctic sea ice: during the summer "excess heat" is used to melt ice or is absorbed by the open ocean rather than to warm the atmosphere (e.g., Kumar et al. 2010).

In contrast, Cohen et al. (2012) described a widespread winter cooling across Eurasia for 1988–2010, suggesting that this may be a dynamical response to warmer summers rather than internal climate variability. We note that the winter trend for this period from the stacked Kola Peninsula SAT data was −0.22° ± 1.77°C decade^{-1} but when this time period is extended five years to 1988–2015 the cooling trend is reduced to −0.08 ± 1.32°C decade^{-1}. Therefore, given the shortness of the cooling period and the longer 50-yr warming trend, we conclude that it is likely the cooling was simply indicative of the region's marked natural climate variability, in agreement with Li et al. (2015).

The annual cycle of monthly 50-yr SAT trends is broadly similar across the 10 Kola Peninsula stations (Fig. 2). There are no cooling trends at any station in any month, although, of course, negative trends are possible within the 95% uncertainty intervals shown for some station/month combinations. The spring trend is clearly dominated by warming in April and May: all 10 stations have a statistically significant warming in these two months at the $p < 0.01$ level. The majority of the stations have no significant SAT trend in any of the summer months. Similar to the spring warming, the fall warming is predominantly confined to two months, September and October. All 10 stations have a significant warming in these two months, the majority at $p < 0.01$, with only the three north coast stations, Vaida Guba Bay, Teriberka, and Gremikha Bay, also having a significant warming in November. In winter most of the warming has occurred in January: Murmansk and Lovozero are the only stations not to have a significant SAT trend in this month.

b. Precipitation

There is no significant change in the annual mean Kola Peninsula PPN during the past 50 years (cf. Table 2). However, seasonally, there is a significant moistening of 6.2 ± 3.1 mm in spring ($p < 0.01$) and a drying of 8.2 ± 8.4 mm in fall ($p < 0.10$). Fall is the only season when there is a reduction in the observed PPN. The positive trend in spring PPN is contrary to the reported decreases in spring snow cover extent reported for the Arctic as a whole during the first part of the twenty-first century (e.g., Derksen and Brown 2012; Rupp et al. 2013) although, as discussed below, statistically significant trends of opposite sign do occur across the Kola Peninsula in this season.

The raw monthly PPN trends indicate there is relatively little coherence between the stations compared to the monthly SAT trends, suggesting a strong influence from local factors such as orography. Gremikha Bay, the station farthest east, has the most significant monthly trends (seven) while Kovdor, the most westerly station, does not have any. Gremikha Bay, which has the lowest average annual precipitation of the 10 stations studied (cf. Fig. 1), is also the only station where all the monthly trends are of the same sign (negative), which is due primarily to strongly positive (negative) PPN anomalies in the 1960s and 1970s (first decade of the twenty-first century) (not shown). Thus, it appears that the driest part of the Kola Peninsula has become even drier. Demin and Zyuzin (2006) showed that a decline in PPN also occurred across much of the year in the Khibiny Mountains. Despite the marked moistening trend in the stacked data in spring, Murmansk is the only station with significantly positive PPN trends in all three months of this season (cf. Fig. 3). Other stations where there is a similar coherent seasonal PPN trend are Gremikha Bay (negative in fall and winter) and Umba (positive in winter). The latter is unique in having significant wetting in this season, perhaps indicative of an increased frequency of weather systems in the White Sea at this time.

c. Sea level pressure

Table 2 also reveals that there has been no significant 50-yr trend in annual SLP across the Kola Peninsula from 1966 to 2015. The only significant seasonal trend over this period has been in spring, when there has been a pressure decrease of 2.9 ± 2.6 hPa, significant at $p < 0.05$. Other seasonal SLP trends are also negative except for fall so the overall annual trend has been toward slightly lower pressure.

The monthly SLP trends from eight individual stations are shown in Fig. 4. Note that we have only been able to obtain SLP data for Lovozero and Umba from 1985 onward and so have not produced any trends for these stations. Given that SLP varies at much larger spatial scales than SAT or PPN, it is unsurprising that the monthly trends at the other eight stations are all broadly similar. May is the only month with a statistically significant (negative) trend in SLP. This trend is significant at all eight stations (six at $p < 0.01$ and two at $p < 0.05$). Figure 4 demonstrates that the uncertainty attached to the trends is much smaller for the May–August period than in other months of the year. So, for example, the positive SLP trend observed in November is of similar magnitude to the May trend at many stations but is not statistically significant.

6. Time series variability

a. Surface air temperature

The seasonal anomalies for the stacked Kola Peninsula SAT time series are shown in Fig. 5a. Within the 50 years of positive SAT trend there are distinct periods when either positive or negative anomalies are dominant, indicating marked decadal-scale SAT variability within the region. For example, cold periods occurred in the late 1960s, late 1970s and early 1980s, and another short period centered on 1998. During this latter period Kola Bay/Murmansk Fjord became frozen for only the fourth time during the twentieth century (Matishov et al. 2012). Periods of several consecutive positive seasonal SAT anomalies are relatively scarce in the first part of the time series, with the early 1970s and late 1980s being exceptions. However, what Fig. 5a demonstrates clearly is that since the turn of the twenty-first century almost all the Kola Peninsula seasonal SAT anomalies have been positive.

The wavelet analysis results from the normalized SAT stack are displayed in Fig. 5b for periods greater than a year. This figure reveals that there are low frequencies of variability that are particularly distinct in the Kola Peninsula SAT, such as between 2–4 years, which is observed up to about the year 2000; since then positive anomalies

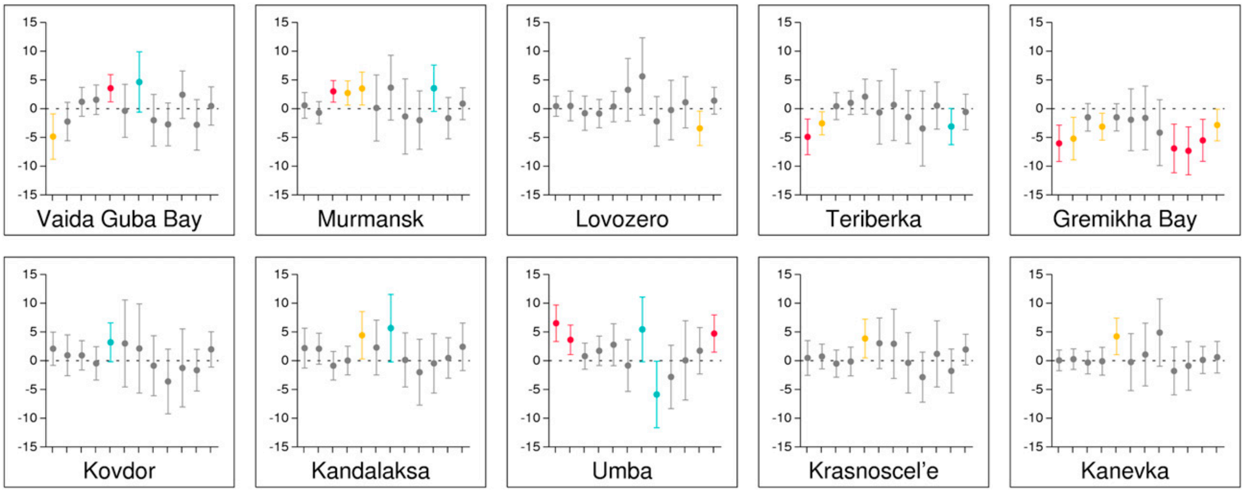

FIG. 3. As in Fig. 2, but for PPN (mm decade^{-1}).

have been predominant so this frequency of variability disappears. However, we note that none of these frequencies are statistically significant for more than a few years at a time. The most notable periods of significance are for ~2-yr variability in the early 1970s and for ~4-yr variability centered on the year 2000. The latter clearly relates to the successive approximately 2-yr periods of negative seasonal anomalies (1998/99) followed by s period of positive seasonal anomalies of similar length (2000/01) (cf. Fig. 5a).

b. *Precipitation*

The stacked time series of normalized seasonal Kola Peninsula PPN anomalies is shown in Fig. 5c. In addition to there being no long-term trend, it is apparent from the relatively small amplitude of the significant majority of the seasonal anomalies that the amplitude of any low-frequency variability is likely to be small, as demonstrated by the black line that approximates decadal variability. Wavelet analysis of the data (Fig. 5d) indicates that, similar to SAT, there are no long periods when low-frequency variability is statistically significant. Short periods of significance exist for ~6-yr variability in the early 1980s, 2–3-yr variability in the late 1980s, and 1–2-yr variability in the late 1990s. There is no evidence of the very low-frequency variability (greater than 10 yr) seen in the SAT data.

c. *Sea level pressure*

Although there is also no long-term trend in the SLP seasonal anomaly time series (Fig. 5e), the range of anomalies is much greater than for PPN and indeed the

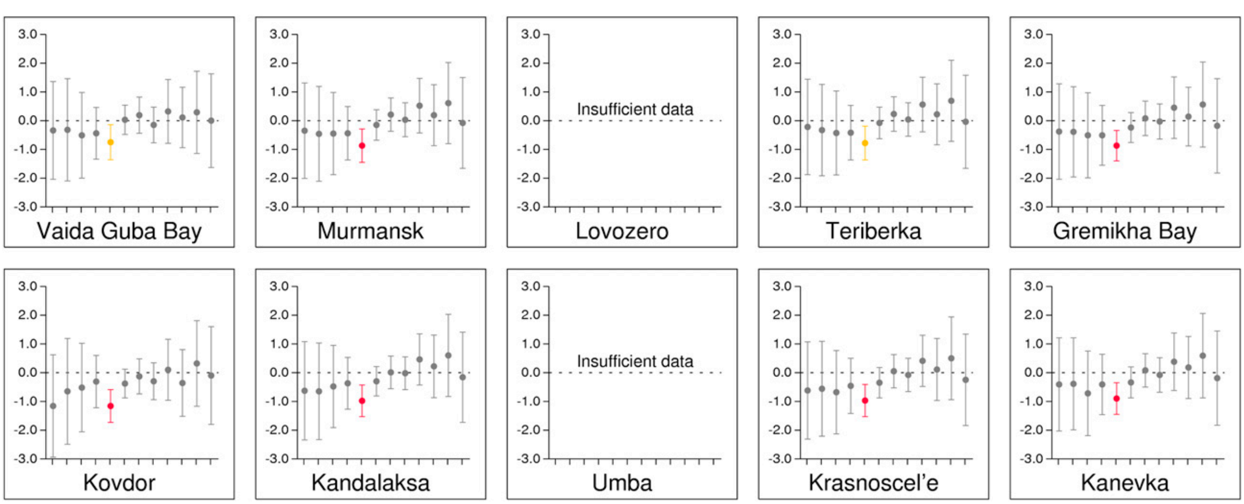

FIG. 4. As in Fig. 2, but for SLP (hPa decade^{-1}).

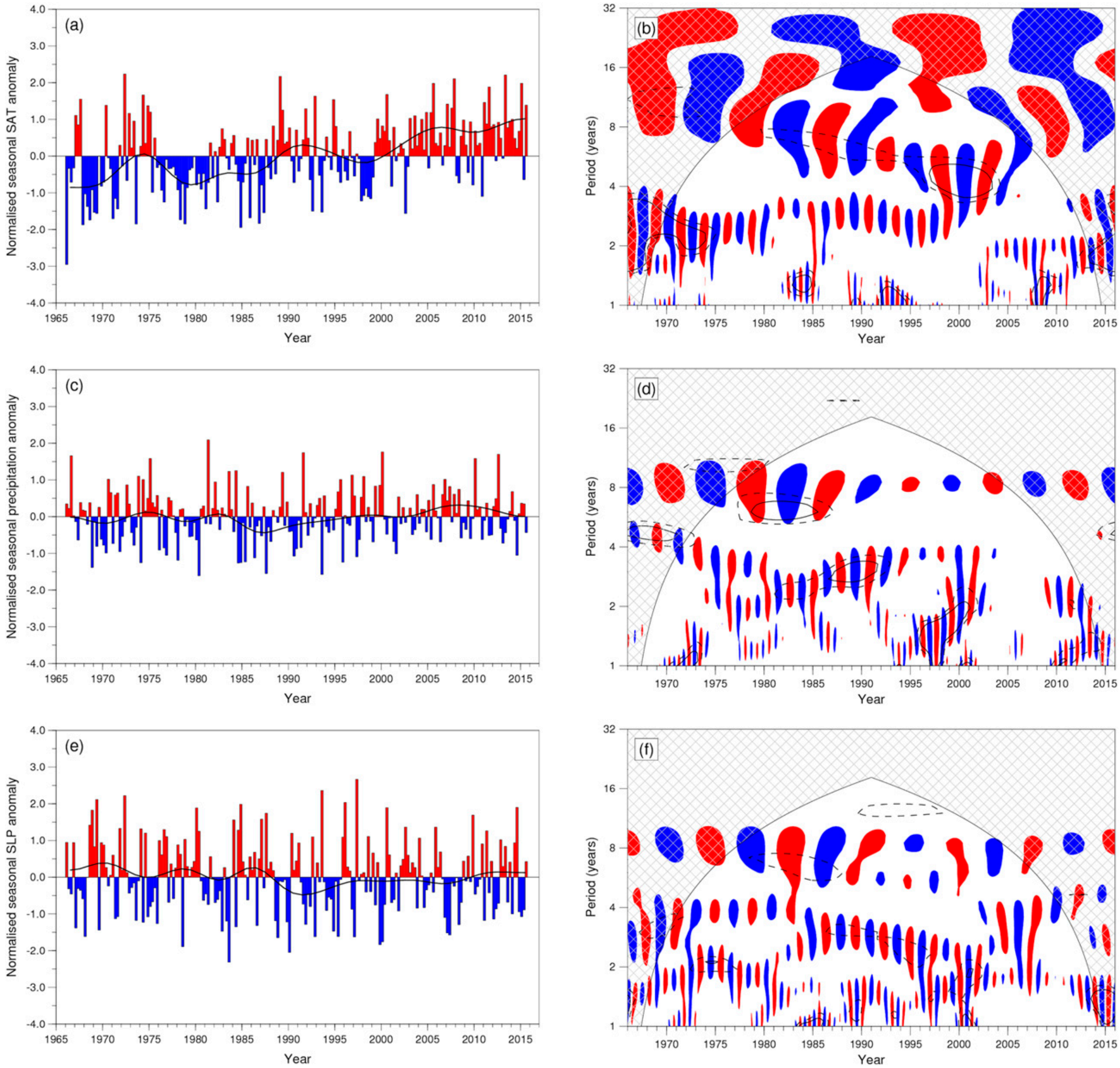

FIG. 5. Seasonal stacked (left) normalized time series and (right) wavelet decomposition results for Kola Peninsula (a),(b) SAT, (c),(d) PPN, and (e),(f) SLP. The black line in (a),(c), and (e) represents decadal variability and is calculated following the methodology in Mann (2004). In (b),(d), and (f) the real part of the wavelet is shaded and significance levels above the background spectrum are drawn at the $p < 0.10$ (dashed line) and $p < 0.05$ (solid line), respectively. Cross-hatched areas indicate regions where the variance is reduced by edge effects from zero padding and the results are unreliable (e.g., Torrence and Compo 1998).

magnitude of the largest are bigger than the equivalent for SAT. There appear to be three principal modes of low-frequency variability, at 1–2, 3–4, and ~8 years, although the first two appear to switch to a 3-yr variability between 1983 and 2002 (Fig. 5f). Like the two other parameters studied, there are relatively few periods when any frequencies are statistically significant; the longest is an approximately 3-yr frequency from 1986 to 1997, significant at $p < 0.10$. Similar to PPN, there is no signal of variability greater than 10 years in the SLP time series.

7. The impact of the NAO

In Fig. 6, we examine the decadal-scale relationship between the winter NAO and SAT at three Kola Peninsula stations: Murmansk in the northwest of the region, Kandalaksa in the southwest, and Krasnoscel'e farther

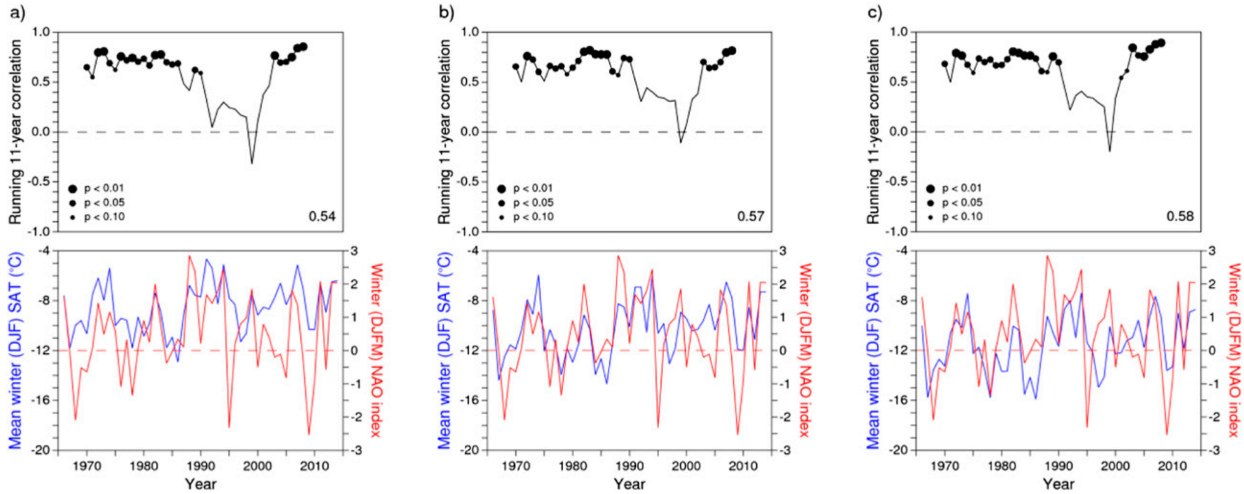

FIG. 6. Running 11-yr correlations between a winter NAO index and winter SAT at (a) Murmansk, (b) Kandalaksa, and (c) Krasnoscel'e. Statistical significance, if any, is shown by the size of the black dot in the center of the 11-yr period. The lower panels show time series of the winter NAO index (red) and station SAT (blue).

east (cf. Fig. 1). The 49-yr correlation between the NAO and SAT is essentially the same at all three stations, ranging from 0.54 to 0.58 and thus explaining ~31% of the winter SAT variability. However, the regression coefficients in Table 2 reveal less consistency, with Krasnoscel'e having the largest value of the three (1.03°C) (cf. Table 3). Analysis of the decadal variability in the relationship, calculated using running 11-yr periods, between the NAO and SAT, reveals that the stations show remarkably similar patterns, typically with statistically significant correlation coefficients of ~0.7–0.8 but with a period of reduced correlations, which actually turn negative in 1995–2005. This period of nonsignificance lasts from 1987–97 to 1998–2008, indicating that a reversal in the ''normal'' positive relationship in the winters of 1997/98 and 1998/99 is the principal cause for this shift.

A similar analysis was undertaken for PPN and the results are shown in Fig. 7. Here, we note a different relationship between the NAO and PPN at Murmansk than at the other two stations examined (cf. Figs. 7a–c). The key difference is the reversal in the sign of the relationship following the winter of 2009/10. In this year the strongly negative NAO coincided with the greatest winter PPN recorded at Murmansk in the last 50 years, and this reversal in the relationship with winter PPN appears to have continued since (cf. Fig. 7a). However, the decadal-scale NAO–PPN relationship at the other two stations analyzed has remained positive with correlations again typically about ~0.7. Regression coefficients calculated over the 49 years are 12–13 mm for Kandalaksa and Krasnoscel'e but only ~2 mm for Murmansk (cf. Table 3).

8. The impact of the SH

Analysis of the relationship between SAT at the three stations and the SH for the full period examined reveals a very low negative correlation across the full 49-yr period in all cases (Fig. 8). The plots of running decadal correlations show distinct reversals in the sign of the relationship that are essentially identical at the three stations and that include different 11-yr periods with statistically significant positive and negative correlations. Although the length of the period examined is too short to say with any certainty, there is the suggestion of an approximately 20-yr periodicity to this relationship. Although the magnitude of the slightly negative 49-yr average correlations are broadly similar at the three stations, the impact of the SH on SAT is much greater for the two stations in the west Kola Peninsula (regression coefficient of −0.27°C) compared to Krasnoscel'e in the east (regression coefficient of −0.09°C) (cf. Table 3). The low average correlation values are in agreement with previous studies that examined the spatial relationship between the SH and SAT across Eurasia (Panagiotopoulos et al. 2005; Park et al. 2015).

In contrast, the relationship between the SH and PPN shows differences between all three stations throughout the

TABLE 3. Regression coefficients vs NAO and SH.

Station	NAO		SH	
	SAT (°C)	PPN (mm)	SAT (°C)	PPN (mm)
Murmansk	0.82	1.87	−0.27	−5.77
Kandalaksa	0.69	12.11	−0.27	−1.61
Krasnoscel'e	1.03	12.65	−0.09	−5.05

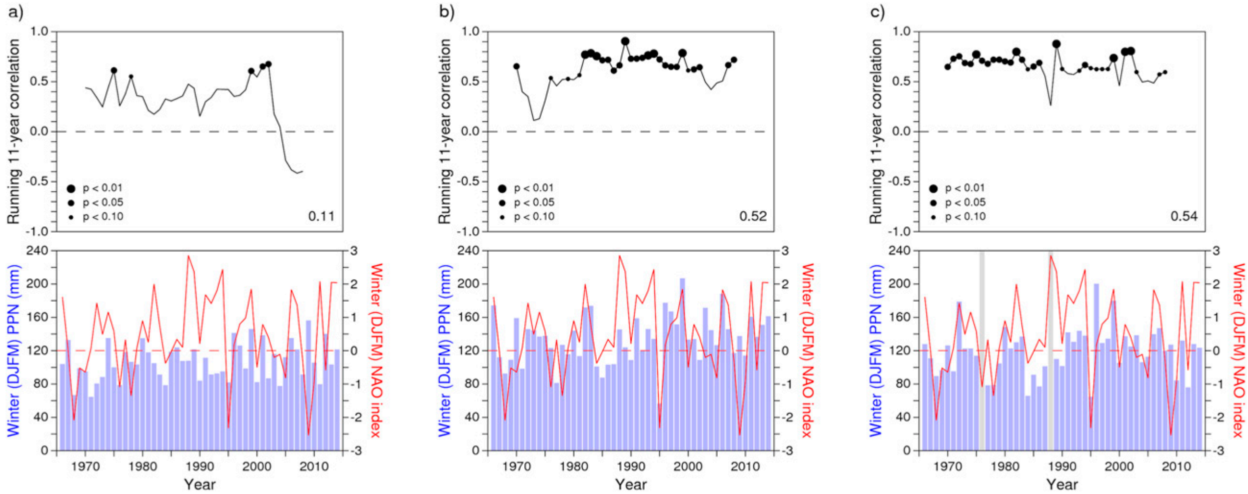

FIG. 7. As in Fig. 6, but for winter PPN.

49 years examined, although overall they all have a negative relationship (Fig. 9). At Murmansk the decadal correlations are primarily negative and sometimes statistically significant, particularly in the most recent decade (Fig. 9a). At Kandalaksa, farther south, there are no periods when there is a significant relationship between winter PPN and the SH, with correlations never exceeding 0.5 in magnitude (Fig. 9b). To the east, at Krasnoscel'e, there are decades with both significant positive and negative correlations (Fig. 9c). The significant negative correlations are centered on the 1990s and have become nonsignificant since then, in contrast to the PPN-SH relationship at Murmansk. Overall regression coefficients vary from −5.77 mm at Murmnask to −1.61 mm at Kandalaksa.

Comparing the relative average impacts of the NAO and SH on Kola Peninsula winter climate over the past half century, as they are defined here (with the caveats that they are calculated over slightly different ''winter'' periods and we only examine the relationship at three stations), reveals that they have opposite effects, with a more positive NAO generally giving warmer SATs and greater PPN and vice versa for a positive SH. The magnitude of the regression coefficients (cf. Table 3) indicates that for SAT the NAO has a bigger influence per unit change than the SH at all three stations, whereas for PPN the SH has a bigger effect at Murmansk.

9. Discussion

Table 2 shows that statistically significant increases in both Kola Peninsula SAT and PPN ($p < 0.01$) occurred during the boreal spring from 1966 to 2015. Here we

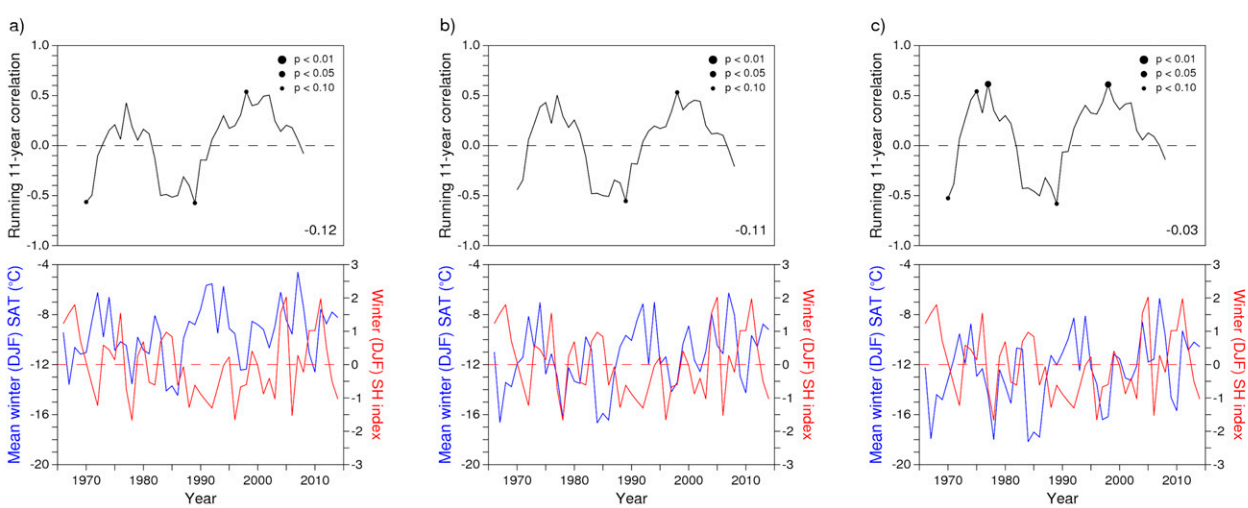

FIG. 8. As in Fig. 6, but for winter SH index.

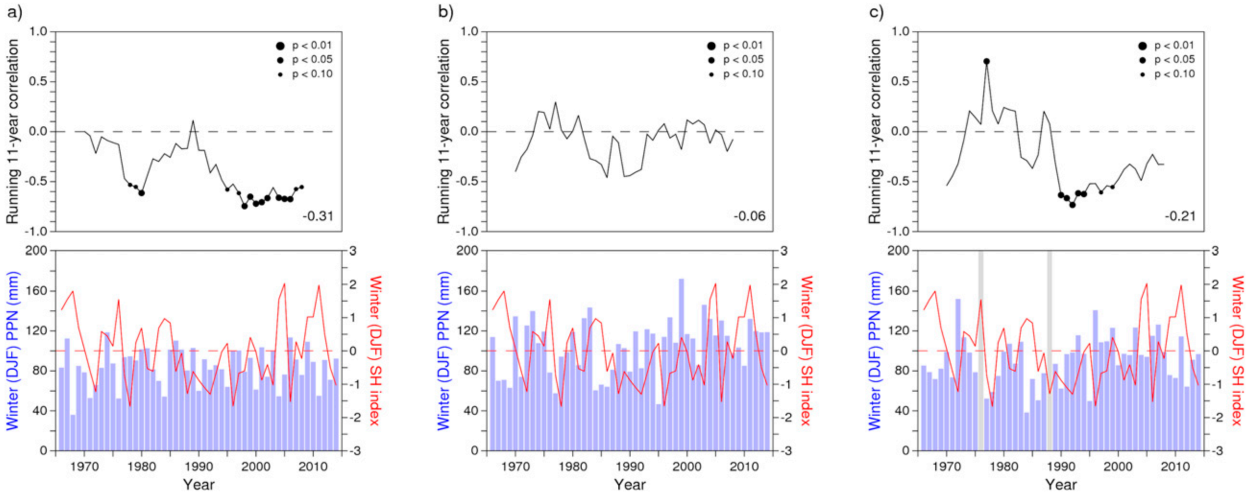

FIG. 9. As in Fig. 8, but for winter PPN.

investigate qualitatively the associated atmospheric circulation changes using gridded ERA-Interim reanalysis SLP data for the 1979–2015 period. Over this shorter period the spring trends for SAT and PPN are significant at $p < 0.05$ and $p < 0.10$, respectively. Figures 10a and 10b show spatial SLP correlation patterns against the stacked Kola Peninsula SAT and PPN, respectively. In spring, SAT has a strong negative correlation with SLP to the east of Greenland between Iceland and Svalbard, such that warmer SATs are associated with southwesterly winds (Fig. 10a). PPN is negatively correlated with SLP over the Kola Peninsula itself, unsurprisingly indicating that PPN is associated primarily with the passage of depressions. This SLP pattern is essentially the same as the negative phase of the Scandinavian (or Eurasian, type 1) low-frequency circulation pattern defined by Barnston and Livezey (1987).

The trend in spring SLP is shown in Fig. 10c, and is dominated by a statistically significant lowering of pressure over northwest Russia, including the Kola Peninsula, and much of the Barents Sea. This pattern is similar to that associated with cold springs at Barrow, Alaska, by Overland et al. (2002), who linked it to the positive phase of the Arctic Oscillation (AO), which, while having some similarities to the NAO, has its main center of action over the central Arctic basin (e.g., Thompson and Wallace 1998). The attendant Kola Peninsula wind anomalies from the observed SLP change will be increased northwesterlies, in contrast to the circulation pattern of Fig. 10a. Thus, this suggests that the warmer spring SATs may not be simply due to regional atmospheric circulation changes. Using a coupled climate model, Koenigk et al. (2009) demonstrated that an increase in regional SLP and decreases in SAT and PPN followed a positive sea ice anomaly in the Barents Sea. Thus, with the marked decline in observed Barents Sea ice from 1979 (e.g., Matishov et al. 2012), we might expect the opposite effects, which is what is indeed shown in Fig. 10c and in the Kola Peninsula SAT and PPN observations. The reduction in sea ice cover means greater oceanic release of sensible and latent heat, which will contribute to the regional reduction in SLP and increased SAT. Although Koenigk et al. (2009) found that Barents Sea sea ice anomalies had little effect on PPN over land, as much of the area of significant SLP correlation with Kola Peninsula PPN overlaps with the area of significantly reduced SLP (cf. Figs. 10b and 10c), then the observed PPN increase can be linked directly to the trend toward a greater number and/or deeper depressions associated with the lower regional SLP.

To set the 50-yr changes in a longer context, we show normalized SAT and PPN for Teriberka station in Figs. 11a and 11b, respectively. We use this particular station because it is one of the earliest available in the Kola Peninsula, beginning in 1900, and the observations are mostly complete throughout the two 116-yr time series. Figure 11a demonstrates that there have been periods in the longer record other than the twenty-first century with consistently strong positive SAT anomalies, particularly during the 1930s, as also observed at Arkhangelsk to the south of the White Sea (Shilovtseva and Romanenko 2009) and indeed across much of the Arctic (Overland et al. 2004). However, it is clear that the last 15 years does represent the period with the longest predominantly positive SAT anomalies within the Teriberka record. We also note that the late 1960s had the coldest SATs, apart from the beginning of the twentieth century, which has enhanced the 50-yr SAT

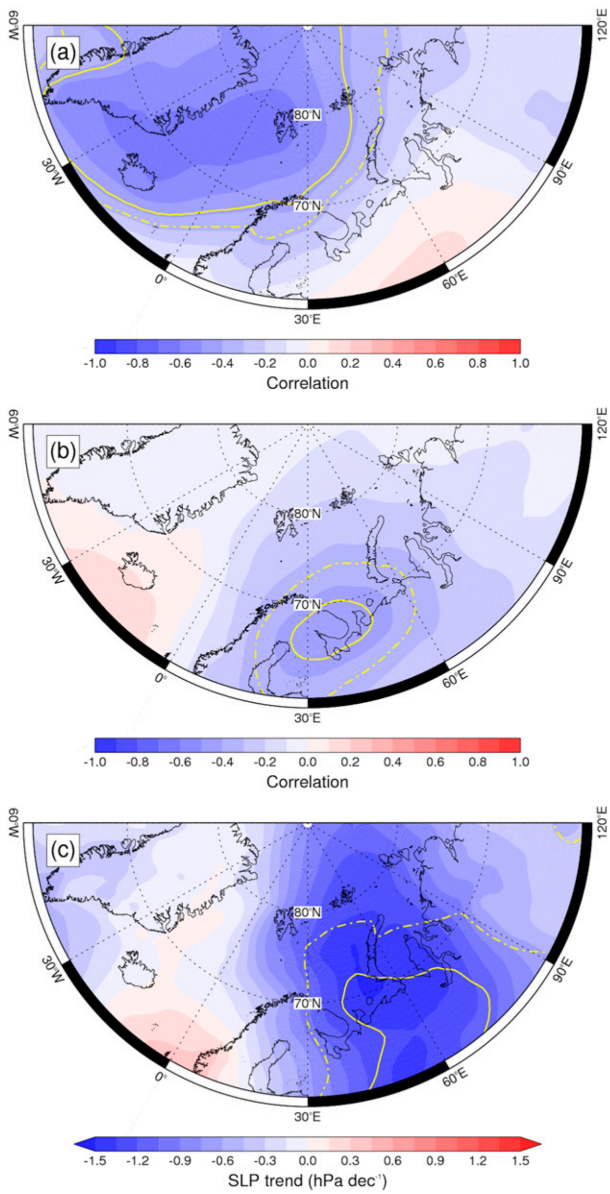

FIG. 10. Correlation of the spring Kola Peninsula (a) stacked SAT and (b) stacked PPN against SLP for 1979–2015. (c) The trend in spring SLP for this period. Regions where there are statistically significant correlations or trends are shown enclosed by a dashed line for $p < 0.05$ and a full line for $p < 0.01$.

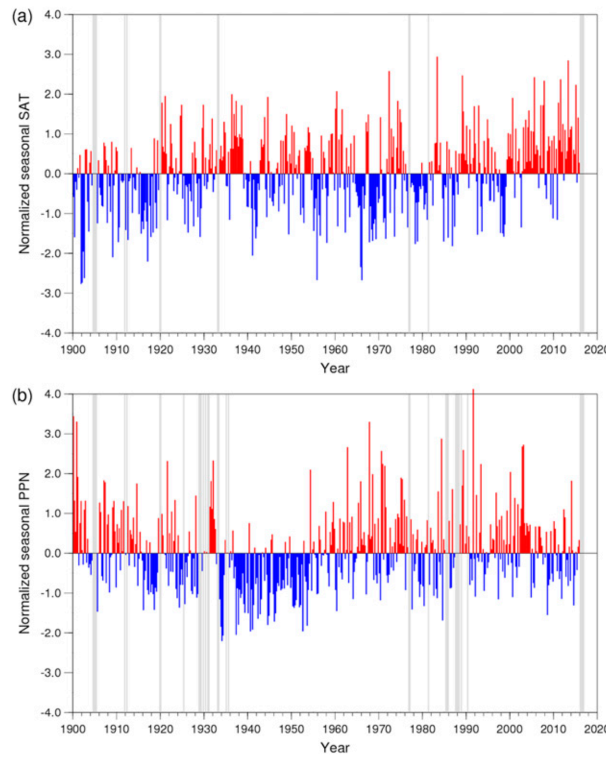

FIG. 11. Normalized seasonal (a) SAT and (b) PPN at Teriberka station. The data are normalized for the entire period (1900–2015). Gray shading represents missing data.

trends from 1966 to 2015. Regarding PPN, Fig. 11b reveals that Teriberka had above average PPN for the 1966–2015 period when compared to the entire station record, although similarly high PPN was observed during the first few decades of the twentieth century. A distinct period of lower than average PPN then occurred during the two decades from the mid-1930s to the mid-1950s. Other Kola Peninsula stations indicate broadly similar long-term climate variability to Teriberka. Unsurprisingly, given a comparison of Figs. 2 and 3, the spatial variability of temporal PPN changes varies more than for SAT, although the 1966–2015 period has had above average PPN compared to the earlier twentieth century across most of the region.

It is interesting to compare the climate change observed in the Kola Peninsula over the past 50 years with model projections of future changes to ascertain to what extent signals of anthropogenically forced changes may already be apparent in the region. Results from the Coupled Model Intercomparison Project phase 5 (CMIP5) projections suggest that Arctic amplification and the warming of the Kola Peninsula are likely to continue through the twenty-first century (Collins et al. 2013). The mean model difference in the regional annual SAT for 2081–2100 relative to 1986–2005 ranges from 1°–7°C, dependent on the projected representative concentration pathway (RCP) used (Taylor et al. 2012). Seasonal differences in SAT trends are also likely to continue as already observed, with summer warming at a much smaller rate than other seasons (e.g., Koenigk et al. 2013). The CMIP5 models also indicate that there will be enhanced regional PPN as a warmer atmosphere can hold more moisture. These increases will occur primarily in winter, the season predicted to warm the most. Given that higher SAT in fall and spring is associated with a shorter snowfall season in Eurasia (Ye and Cohen 2013), it is not apparent without analyzing the model output in detail whether there will be an overall reduction in snowfall or whether a similar or even greater amount will fall over a shorter period. We note, however, that this projected variation in seasonal PPN trends is not yet apparent in the 1966–2015 observations. There appears to be less certainty regarding the CMIP5 model projections of SLP change over the Kola Peninsula, with the region being at the southern edge of a general SLP decrease over the Arctic basin and north of an increase over mainland Europe (Collins et al. 2013; Koenigk et al. 2013). We have demonstrated that the relationship between two of the principal modes of Northern Hemisphere extratropical variability and regional SAT and PPN during the last 50 years is far from being temporally invariant: therefore, even if the models agree on how these modes are likely to behave in the future (e.g., Gillett and Fyfe 2013), considerable uncertainty must be attached to climate projections for the Kola Peninsula because of the marked internal climate variability of the region.

10. Conclusions

In this paper, we have undertaken a detailed analysis of the climatology and recent climate change of the Kola Peninsula region in Arctic Russia based on observations from 10 meteorological stations from the 50-yr period from 1966 to 2015.

The region has a mean annual SAT close to 0°C, with coastal stations having a positive value and those inland, away from the moderating effect of the ocean, having a negative value. Mean annual PPN totals increase from ~430 mm in the east of the region to ~600 mm in the west, with higher values in the central mountains. Maximum PPN occurs in late summer, likely related to the presence of the Arctic frontal zone over northern Eurasia in this season. Negative correlations between the winter PPN time series of stations in the north and south of the Kola Peninsula reflect latitudinal shifts in the principal storm track. The greater frequency of cyclones at this time of year is also manifested in the minimum monthly SLP being in December.

We demonstrate that there has been a mean warming in the Kola Peninsula of 2.3° ± 1.0°C over the past 50 years, significant at the $p < 0.01$ level. Seasonally, statistically significant warming has taken place in spring and fall, although a trend of similar magnitude has occurred in winter, a seasonal distribution similar to that observed in Finland (Tietäväinen et al. 2010). At the stations examined, all the estimated monthly SAT trends are positive, with the majority being statistically significant at the $p < 0.10$ level or higher. All 10 stations have a significant warming in September and October (Fig. 2). A stacked time series of seasonal SAT anomalies for the region reveals distinct periods when either positive or negative anomalies were dominant, indicating marked decadal-scale variability. However, since the turn of the twenty-first century almost all the Kola Peninsula seasonal SAT anomalies have been positive (cf. Fig. 5a).

In contrast to SAT, we establish that there has been no significant change in the annual mean Kola Peninsula PPN although, seasonally, there has been a significant moistening in spring and a drying in fall, the latter the only season when there has been a reduction in PPN. There is relatively little coherence between the stations, suggesting a local orographic influence. The northeast of the region, which has the lowest average annual PPN, has negative trends in all months so that the driest part of the Kola Peninsula is getting drier still. The PPN data may be indicative of more weather systems in the White Sea during winter, in response to changes in the principal regional SLP patterns and storm tracks (Zhang et al. 2008). However, May is the only month with a statistically significant (negative) trend in SLP. Part of the reason for the lack of significant trends is the high interannual variability in SLP, reflecting similar properties in the principal modes of circulation variability that influence the Kola Peninsula climate.

Of these, we show that a positive winter NAO is most often associated with a warmer and wetter Kola Peninsula with a positive SH having the opposite effect. The temporal relationship between the winter NAO and SAT appears broadly coherent across the region (Fig. 6), typically explaining about two-thirds of interannual winter SAT variability, although this relationship can disappear in individual years. In contrast, varying relationships exist between the NAO and PPN in different parts of the region (Fig. 7). Similar to the NAO, the temporal relationship between the winter SH and Kola Peninsula SAT appears to be consistent throughout the region (Fig. 8) but includes occasional decades with both statistically significant positive and negative correlations. However, the temporal relationship between the SH and PPN is quite variable spatially, although negative across the 50 years as a whole (Fig. 9).

We have demonstrated that the Kola Peninsula region of the Arctic has warmed significantly over the past half century while also undergoing marked changes in the seasonal cycle of PPN. Many different processes are likely to be contributing to this observed climate change (e.g., Cohen et al. 2014). Given the prevalence of coastal stations in our analysis, the declining sea ice in the Barents Sea is likely to be a principal driver; moreover, the modeling results of Koenigk et al. (2009) are in accord with the observed changes in SAT and SLP. It is also clear that the Kola Peninsula is a region of pronounced atmospheric circulation variability from interannual through to decadal time scales. Future work will examine the physical mechanisms behind the temporal variability in the links between the major modes of broad-scale circulation and the region's climate, as has occurred in the relationship between the NAO and PPN at Murmansk following the strongly negative NAO in the winter of 2009/10.

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