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Prevalence of Decadal Variability Within the Arctic Climate System

A Thesis Submitted in Partial Fulfillment of the Requirements

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by

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Abstract

This study presents a modern assessment of the spatial and temporal characteristics of decadal climate variability in the Arctic. Using a combination of observational data, reanalysis, and proxy reconstructions, decadal variability of mean annual and seasonal (winter, DJF; summer, JJA) surface air temperature (SAT) and precipitation are investigated from 1901-2013 across the Arctic region. Singular spectrum analysis was used to separate variability into interannual (1-9 years), decadal (10-30 years), and multidecadal (30-60 years) components. In addition to identifying the presence, prominence, and patterns of decadal variability throughout the region, connections to internal modes of atmospheric and oceanic variability are examined and discussed.

Decadal variability is found to be a regionally important and seasonally dependent characteristic of Arctic climate. Overall, decadal variability of temperature displays more coherent and consistent patterns across datasets than precipitation. While increased decadal variability was observed in both temperature and precipitation, a strong seasonal contrast was apparent in temperature patterns. It is reasonable to suggest a link between decadal variability of Arctic temperature and natural modes of variability, although a link to precipitation remains unclear.

Dedication

To the memory of my parents, Katharine and Philip.

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Background and Setting

Arctic Climate

While the Arctic is known for its long, frigid winters and short, mild summers, significant spatial and temporal variations are an innate component of its climate (ACIA 2005). Due to its high-latitude location, the Arctic receives less direct solar radiation than lower latitudes. Surface temperatures generally decrease with increasing latitude from the southern Arctic border towards the central Arctic Ocean, although regional variation can result due to surface cover differences and continentality (ACIA 2005). Temperatures display significant seasonal and interannual variation, which have been linked to seasonal changes in atmospheric and ocean circulation patterns, proximity to water, and variation in regional feedbacks related to sea ice loss (Bintanja and van der Linden 2013).

The Arctic Ocean plays a significant role in Artic climate (Serreze and Barry 2005). Accounting for most of the area above 70º N and largely surrounded by land, this "Mediterranean-type sea" transports large amounts of heat across the Arctic, keeping some high-latitude locations warmer than would be expected (Serreze and Barry 2005; Serreze 2015). Another important control on Arctic temperature is sea ice. Sea ice plays an important role in both the Arctic and global climate systems, as it regulates the amount of insolation absorbed and reflected in the region (ACIA 2005). The Arctic has experienced a significant decline in sea ice over the past 30 years, which has been linked to a rise in Arctic temperatures increasing at twice the global rate (Bintanja and van der Linden 2013). This phenomenon is referred to as Arctic or polar amplification and is especially pronounced over land in the winter (Bintanja and van der Linden 2013).

Precipitation across the Arctic is limited, but spatial and seasonal variation of precipitation is common throughout the region. The largest amounts of annual precipitation typically occur in the North Atlantic and over southern Alaska, while the lowest amounts are often measured over the Canadian Arctic Archipelago (Serreze 2015). Precipitation has been increasing throughout the Arctic, largely seen as a response to increasing temperatures, evaporation, and sea ice decline (Stafford et al. 2000; Frey and Smith 2003; Deser et al. 2009; Wendler et al. 2017). Recent studies suggest Arctic precipitation will significantly increase over the next century as a result of continued sea ice decline (Bintanja and Andry 2017; Pendergrass et al. 2017).

Singular Spectrum Analysis

A popular technique for analyzing climate data is singular spectrum analysis (SSA). SSA is a nonparametric, data-adaptive technique for signal detection in short and noisy time series (Broomhead and King 1986; Vautard and Ghil 1989; Ghil et al. 2002; Golyandina and Korobeynikov 2014). SSA decomposes time series into trends, oscillatory components, and noise, or unexplained variance (Ghil et al. 2002), and is widely applied throughout the physical and life sciences, including to studies of interdecadal variability (Ghil and Vautard 1991; Allen and Smith 1994; Plaut et al. 1995; Robertson and Mechoso 1998). There are two main stages of SSA: decomposition and reconstruction.

The first step of the decomposition stage is to create a covariance matrix (C_x) using one of two approaches: the Trajectory method from Broomhead and King (BK) or the Toeplitz method from Vautard and Ghil (VG). The BK method creates a trajectory matrix (D) by embedding M-lagged copies of the original time series. The VG approach creates the covariance matrix directly from the data as a Toeplitz matrix, which is a matrix with constant diagonals (Ghil et al. 2002). Both methods result in a symmetric C_x (Ghil et al. 2002). Following the methodology of Ault and St. George (2010), this study employed the VG approach to creating a covariance matrix, as it has been shown to perform better at noise reduction, which makes it a preferable choice for time series with only a few hundred data points (Ghil and Taricco 1997; Ghil et al. 2002).

Introduction

There has been increasing demand from scientists, stakeholders, and decision-makers for improved understanding of how the climate will change over the coming decades, which has led to the development of a new field called decadal climate prediction (Meehl et al. 2009; Murphy et al. 2010; Smith et al. 2012). Changes to the climate on this timescale have significant societal relevance, as they influence important decisions made across a wide range of sectors, including agriculture, energy, government, and infrastructure (Murphy et al. 2010; Purcell and Huddleston 2016). While decadal prediction skill is improving, there are a number of obstacles that inhibit our ability to accurately and reliably make climate predictions. Model initialization and bias and internal variability all contribute to the uncertainty surrounding decadal predictions (Meehl et al. 2009; Kirtman et al. 2013; Purcell and Huddleston 2016). The paucity of observation-based studies of past decadal climate variability has been identified as a key limitation to understanding decadal variability and its underlying processes (Vera et al. 2010; Purcell and Huddleston 2016). While the study of decadal variability in the Arctic is far from novel (Polyakov and Johnson 2000; Przybylak 2000; Venegas and Mysak

2000), much of the research was conducted at the beginning of the twenty-first century and had little focus on spatial variation in decadal variability throughout the region.

Decadal and Multidecadal Variability

Climate varies on multiple timescales, ranging from seasonal to interannual to centennial and beyond. Although definitions of these temporal categories vary, decadal variability is variation of the climate on 10 to 30-year timescales (Meehl et al. 2009; Purcell and Huddleston 2016) and multidecadal variability is variation of 30 to 60 years (Poore et al. 2009; Dieppois et al. 2013). Decadal and multidecadal variability appear to be especially pronounced in the Arctic region (Polyakov et al. 2002; Stroeve et al. 2005; Serreze 2015). Evidence of decadal-scale variability has been found in numerous climate variables around the Arctic, including surface temperature (Polyakov et al. 2002; Overland et al. 2004; Semenov et al. 2010), precipitation (Førland et al. 2011), atmospheric pressure (Polyakov and Johnson 2000), and sea ice (Swart et al. 2015; Chen et al. 2016a).

Several studies have identified decadal variability in Arctic surface temperatures throughout the twentieth century (Polyakov et al. 2002; Semenov and Bengtsson 2003; Johannessen et al. 2004; Overland et al. 2004), finding two dominant periods of warming and one of cooling. The first decadal-scale warming period began in the 1920s and lasted until the 1940s, which was followed by a 30-year period of cooling. The second period of warming began in the early 1970s and has continued into the present (Chylek et al. 2009; Beitsch et al. 2014; Bengtsson et al. 2004). While there is little disagreement over the presence of decadal variability in twentieth century Arctic temperatures, there is a large debate over its source (Polyakov and Johnson 2000; Bengtsson et al. 2004; Chylek et al. 2009; Fyfe et al. 2013; Beitsch et al. 2014).

Many studies have linked Arctic climate to modes of ocean-atmosphere variability originating in the Atlantic (Deser 2000; Polyakov and Johnson 2000; Goosse and Holland 2005; Koenigk et al. 2016; Chen et al. 2016b; Guemas et al. 2016; Tokinaga et al. 2017) and to a lesser degree, the Pacific (Deser et al. 2000; Proshutinsky et al. 2002; Sun and Wang 2006; Screen and Francis 2016; Tokinaga et al. 2017). The North Atlantic has been widely suggested as a key region of decadal and multidecadal variability, alluding to a link to internal modes of variability, such as the North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO) (Holland 2003; Hori et al. 2007; Semenov et al. 2010; Andres 2016). For this reason, two oceanic and two atmospheric teleconnections have been selected to investigate the relationship between modes of variability and patterns found within the observational data.

The North Atlantic Oscillation is a climate phenomenon described by the difference in sea level pressure between Iceland and the Azores Islands off the coast of Portugal (Walker and Bliss 1932; Hurrell 1995; Jones et al. 1997). Several studies have found links between the NAO and changes in Arctic surface temperatures, precipitation, and storms (Holland 2003; Seitola and Järvinen 2014). The Arctic Oscillation, sometimes referred to as the Northern Hemisphere Annular Mode (NAM), describes the difference in pressure between the Arctic and mid-latitude regions, and is highly correlated with the NAO (Thompson and Wallace 1998; Wallace 2000; Rigor et al. 2002). Changes in sea level pressure associated with the AO have previously been linked to patterns of surface air temperature (SAT) variability in the Arctic, suggesting a positive relationship over the

North Atlantic and Russian Arctic and a negative relationship over the North American Arctic (Broccoli et al. 2001; Thompson and Wallace 2001; Mortiz et al. 2002; van der Linden et al. 2017). However, the link between the AO and Arctic SAT appears to be biased as a result of incomplete spatial coverage, especially in the early twentieth century (Broccoli et al. 2001).

The Atlantic Multidecadal Oscillation is a basin-wide pattern of decadal to multidecadal variability represented by sea surface temperature (SST) anomalies (Enfield et al. 2001). Several studies have implicated the AMO in changes to Arctic sea ice, atmospheric circulation patterns, and surface temperatures (Ruprich-Robert 2017; Tokinaga et al. 2017). Johannessen et al. (2016) used correlation analysis to test the relationship between Arctic SAT and large-scale modes of variability and found a strong link between the AMO and Arctic SAT. Chylek et al. (2009) also found the AMO to be highly correlated with Arctic temperatures and further suggest the AMO as major source of Arctic temperature variability. Similar to the AMO is the Pacific Decadal Oscillation (PDO). The PDO describes the pattern of SST variability in the Pacific north of 20° N (Zhang et al. 1997). Various studies have linked the PDO to increased temperatures and precipitation in Alaska and northwestern Canada (Hartmann and Wendler 2005; Lapointe et al. 2017; Wendler et al. 2017), although the strength and sign of the relationships vary regionally. Others have found the link may not be as stable as once thought (Cassano et al. 2011; McAfee 2014, Wise 2015).

Decadal and Multidecadal Variability in Climate Reconstructions

Due to limited long-term observational data in the Arctic, proxy-based reconstructions may be an important source of evidence of decadal variability.

Temperature-sensitive climate proxies, such as tree rings, ice cores, and lake sediments, have previously been used to identify changes within the Arctic climate system (Overpeck et al. 1997; Serreze et al. 2000; Hinzman et al. 2005; Kaufman 2009; Shi et al. 2013; McKay and Kaufman 2014). Proxies such as tree rings and ice cores are anticipated to be most useful in tracking decadal variability due to their annual resolution, which allows direct comparison to other data used in this study. Lake sediments have a lower-resolution than tree rings and ice cores; however, they can be valuable proxies at latitudes north of the tree line and are widely distributed throughout the Arctic region (Folland et al. 2001; Smol 2005; Smol and Douglas 2007).

Proxies have been widely used to study past climate variability by extending the observational record and increasing data in observation-sparse regions, providing context for modern climatic trends. In addition, paleoclimate proxy records have been used to evaluate both observations (Esper et al. 2002; Frank and Esper 2005; Nicolle et al. 2018) and model simulations (Cook et al. 2004; Smerdon et al. 2017), ultimately reducing uncertainty and improving our understanding of past climate. While proxies are valuable tools, there are many challenges that accompany the use of proxy data. Typically selected for their sensitivity to a specific climatic factor (i.e. temperature or precipitation), other climatic and non-climatic factors can obscure trends in proxy records. Additional challenges include uneven and incomplete spatial coverage, varied response times of different proxy types, and multi-proxy calibration (Jones et al. 2009; Masson-Delmotte et al. 2013; Matsikaris et al. 2016).

The proxy records used in this study are mostly tree-rings, which present unique challenges to the study of past climate variability. For example, the detrending method used to standardizing tree-rings can remove the amount of variability expressed in datasets (Melvin 2008). It is common to standardize tree-ring data by removing the growth trend (the change in ring width as the tree ages), allowing one to average data from trees with different growth rates. However, low-frequency variability is not always distinguishable from the growth trend and can be unintentionally removed from the dataset (Briffa et al. 1996). Standardization techniques have been proposed to preserve low-frequency variability in tree-rings, such as Regional Curve Standardization (RCS: Briffa et al. 1992; Briffa et al. 1996; Cook et al. 2000).

This study has three main objectives. First, we aim to identify the prevalence of decadal variability of temperature and precipitation across the Arctic region. Second, the spatial and seasonal characteristics of decadal variability will be evaluated. Finally, while pinpointing the source of decadal variability is outside the scope of this study, proposed links between Arctic climate and modes of natural variability will be explored.

Data and Methods

Data

Working with datasets from the Arctic can present many challenges. Significant disagreement among observational datasets and reanalyses has been identified in numerous studies (Drobot et al. 2006; Hurley 2009; Alexeev et al. 2012; Lindsay et al. 2014; McAfee 2014; Lader et al. 2016). There are spatial and temporal inconsistencies between the available datasets, in large part due to a sparse and uneven distribution of observational data (Przybylak 2000; Polyakov et al. 2002; Johannessen et al. 2004;

McAfee et al. 2014). Because of these disagreements, we have used multiple datasets to confirm that results are not sensitive to data selection.

Observational Datasets

The Climate Research Unit Time Series v. 4.01 (CRU TS4) temperature dataset (Harris et al. 2014) was downloaded from the University of East Anglia Climate Research Unit's website (http://data.ceda.ac.uk/badc/cru/data/cru_ts/cru_ts_4.01/ data/tmp/, Accessed: 01/10/2018). CRU TS4 uses daily data to calculate monthly average temperatures (ºC, land surface) from 1901 to 2016 on a 0.5º x 0.5º grid. The CRU precipitation dataset was not appropriate for this study due to its use of inverse-distance weighted interpolation, which, in areas of sparse station coverage, can lead to regions with little to no interannual variability (McAfee et al. 2014).

The Global Precipitation Climatology Centre (GPCC) Full Data Reanalysis (V7) provides monthly totals of precipitation (mm) based off of over 60,000 stations with a record length of at least 10 years (Schneider et al. 2015). This dataset was downloaded from NOAA's Earth System Research Laboratory Physical Sciences Division (ESRL/PSD) website (https://www.esrl.noaa.gov/psd/data/gridded/data.gpcc.html). The GPCC dataset provides data coverage for all global land areas from 1901 to 2013 on a 0.5° x 0.5° grid.

The University of Delaware (UDEL) global temperature and precipitation datasets (V4.01) were downloaded from the ESRL/PSD website (https://www.esrl.noaa.gov/psd/ data/gridded/data.UDel_AirT_Precip.html). UDEL provides monthly average temperature (º C, land surface) and monthly precipitation totals (cm) on 0.5° x 0.5 global grids (Willmott and Matsura 2001).

Reanalysis

In addition to the observational datasets, the NOAA/CIRES 20th Century Reanalysis Version 2c (20v2c) was included in the analysis. The 20v2c provides global estimates of a large number of climate variables from 1851 to 2014 (Compo et al. 2011). Global monthly mean 2º x 2º gridded fields of air temperature (K, 2-meter level) and precipitation (mm/s) were obtained from the ESRL/PSD website (https://www.esrl.noaa.gov/psd/data/ gridded/data.20thC_ ReanV2c.html). The 20v2c was selected due to its length of record, which makes it particularly useful when studying decadal variability and climate processes such as the PDO and AMO (Compo et al. 2011). This version, 20v2c, corrects the warm bias found in the previous version (V2) by using the COBE-SST2 sea ice boundary conditions (Hirahara et al. 2014).

Climate Indices

The 20v2c-based AO Index (Thompson and Wallace 2000; Compo et al. 2011), a monthly time series spanning 1851-2014, was downloaded from the ESRL/PSD website (https://www.esrl.noaa.gov/psd/data/20thC_Rean/timeseries/monthly/AO/ao.20crv2c.long.data). The station-based Hurrell NAO Index (Hurrell 1995; Jones et al. 1997), a winter-averaged (DJFM) annual time series that covers 1864-2017, was downloaded from the University Corporation for Atmospheric Research (UCAR) Climate Data Guide website (https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based). The detrended, unsmoothed AMO monthly time series (Enfield et al. 2001), which runs from 1856 to the present, was also obtained from the ESRL/PSD website (https://www.esrl.noaa.gov/psd/data/correlation/amon.us.long.data). NOAA's monthly PDO index was downloaded from the National Centers for Environmental

Information (NCEI) website (https://www.ncdc.noaa.gov/teleconnections/pdo/).

Since climate indices are believed to be particularly important in winter (Hurrell 1995; Thompson and Wallace 1998; Gámiz-Fortis et al. 2002), an annual mean winter (DJF) time series was calculated from the AMO, AO, and PDO monthly indices. The Hurrell NAO index was downloaded as an annual mean winter index and did not need to be further processed. All indices were then cropped to match the same time period as the observational datasets.

Proxy-based Datasets

Arctic proxy records were included in our analysis to investigate whether decadal variability identified in proxies is comparable to that seen in the observational record. Temperature-sensitive proxies are more widely available in the Arctic than precipitation and so only temperature-based proxies were selected. Proxy records were chosen for their location within the Arctic region (60-90° N), similar time coverage to the other datasets used in this study, and high resolution (annual to decadal). In total, 12 proxy-based (eight tree-ring and four lake sediment) Arctic temperature reconstructions were retained for analysis (Table 1). All proxy records and associated climate reconstructions were obtained from NOAA's Paleoclimatology Database (https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets). Each reconstruction is a part of the PAGES2k Database (McKay and Kaufman 2014), a collection of proxy-based Arctic temperature datasets from the past 2000 years. Decadal variability in reconstructions was compared to decadal variability in observational datasets and reanalysis (Table 2). Since the majority of proxies used here are summer temperature-sensitive, decadal variability in the proxy data was compared to summer decadal variability in the observational datasets and reanalysis.

Methods

Following the methodology of Ault and St. George (2010), singular spectrum analysis (SSA) was used to investigate the temporal characteristics of temperature and precipitation variability over the period 1901-2013, the longest period of overlap of all gridded data products. Singular spectrum analysis is a widely used method of time series analysis that decomposes a time series into trend, oscillatory components, and noise. Before SSA was applied, the datasets were normalized by removing the mean from each grid cell and diving by the standard deviation (Vautard and Ghil 1989). Annual and seasonal (summer, JJA; winter, DJF) means (totals) were calculated for temperature (precipitation) datasets. With the R programming software and the Rssa package (Korobeynikov et al. 2017; R Core Team 2017), singular spectrum analysis was applied to each dataset using the VG Toeplitz approach and a window length of 20.

The sensitivity of window length (M) was tested from 10 to 40, and results appear to be stable over a window length of 15 to 35. Although no significant discrepancies in decadal variability were found, a small number of grid cells appeared to vary more than others (> 10% decadal variance between different window lengths). The first nine RCs were chosen for the time series reconstructions because they retained on average 60% of the total variance of each grid cell. Higher-order RCs were not included as they each contained less than 5% of variability and are known to contain large amounts of noise (Vautard et al. 1996; Ghil et al. 2002). After SSA was applied, climate variability was parsed into four temporal categories: interannual (1-9 years), decadal (10-30 years), multidecadal (31-60 years), and secular (>60 years). The total retained variance (sum of all variance explained by the 9 retained RCs) was calculated for each grid cell. Finally, time series of decadal variability were reconstructed for each grid point and dataset. A similar analysis was conducted separately on each of the proxy datasets.

In order to investigate decadal variability in observational and proxy-based datasets, SSA was applied to the summer (JJA) temperature time series at the nearest grid cell to each proxy site. The proxy-based decadal variability of summer temperatures was then compared to the decadal variability found in the observational datasets. If a proxy site was located on the border of two grid cells, the results were averaged. The time period over which decadal variability was calculated slightly varied from proxy data to the observation/reanalysis due to the differing temporal coverage of the datasets. For both proxy-based datasets and reanalysis/observational datasets, the longest period of overlap across datasets (proxy: 1901-2000; reanalysis/observational: 1901-2013) was used.

Singular spectrum analysis was applied to the four climate indices used in this study to identify the prominence of decadal variability within each mode and investigate its correspondence with decadal-scale temperature and precipitation variability. After reconstructing the time series of each mode of variability using only its decadal-scale RCs, correlation analysis was applied to the reconstructed decadal-scale time series of each climate index and winter time series in each grid cell of each observational dataset.

Results

Patterns of Variability

Temperature

Decadal variability of mean annual surface temperature appears to be most prominent over the central Arctic Ocean, the North American Arctic, and Fennoscandia (Figure 1d-f). In some areas, it accounts for as much as 60-65% of the retained variance. All datasets showed similar patterns in the prominence of decadal variability across the North Atlantic and North American sectors, although the exact amount of variance explained differed. In other areas, like the Russian Arctic, UDEL and CRU TS4 reflect little decadal variability, while 20v2c portrays it as widespread (Figure 1d). Multidecadal variability appears to be largely absent from the Arctic region, with a few minor exceptions in the North American sector (Figure 1g,1i). Regions with little to no decadal or multidecadal variability (< 20%) are largely dominated by interannual variability (explaining 80-100% of the retained variance).

Seasonally, the strongest decadal variability is observed in winter, accounting for up to 60% of the retained variance. Winter patterns of variability coincide with annual patterns throughout western North America and Fennoscandia. Over the ocean, decadal variability is most significant in winter (Figure 2d). In contrast, decadal variability in the Russian Arctic is most prominent in summer (Figure 3d). Inconsistencies between datasets are largest in summer, especially over Greenland.

Precipitation

Decadal variability in precipitation appears to be less pronounced than in temperature. As with temperature, results from the 20v2c dataset appear to deviate from the two observational datasets, especially over Greenland and the Canadian Arctic Archipelago (Figure 4d). Decadal variability appears to be most prominent in the North

American Arctic, the central Arctic Ocean, and around the Laptev Sea. As with temperature, multidecadal variability of precipitation is limited across the region, with a small presence in the North American Arctic (Figure 4g-i).

Decadal variability of precipitation was more pronounced in winter than summer across the North American and North Atlantic sectors in both the UDEL and GPCC datasets (Figure 5e-f). The 20v2c dataset appears to differ from the two observational datasets, showing more variability in summer than winter, especially across Canada and Alaska (Figure 6d). In both seasons, decadal variability appears relatively important in the northern Kara and Barents seas, accounting for 20-40% of the retained variance. Multidecadal variability was not significant in either season; although it was more apparent in the winter over the eastern North American Arctic.

Relationships with Climate Indices

Of the four climate indices analyzed, decadal variability was found to be a fairly prominent feature of the PDO and AMO (Table 3). Of the 60.1% variance retained in the PDO, decadal variability explained 24.8%. While not as significant, decadal variability explained 15.9% of the 65.8% retained within the AMO. Decadal variability was not found to be a prominent in either the AO (explained 5.3% of 54.8% retained variance) or NAO index (explained 7% of 56.1% retained variance).

Temperature

Correlations between decadal variability of mean winter SAT and decadal variability in the selected climate indices are shown in Figure 7. Decadal variability within the AMO was positively correlated with decadal winter SAT variability over the western North American Arctic (Figure 7j-l) and negatively correlated with winter SAT over the Fennoscandia, the North Atlantic Arctic, and eastern Russian Arctic. Over land, correlations between 20v2c SAT and the AMO were generally weaker than in the gridded observations. The CRU TS4 SAT and UDEL SAT are largely in agreement over most of the Arctic, with the exception of some regional disagreement over the sign and strength of the relationship over Greenland and Iceland.

Decadal variability of winter SAT had the strongest and most consistent relationship with the PDO in the northern Pacific and Alaska, where the correlation was positive, and over Fennoscandia and the western Russian Arctic, where the correlation was negative. The sign of the relationship between 20v2c winter temperature and the PDO appears loosely split across hemispheres, being more negatively correlated to SAT in the eastern hemisphere and more positively correlated to SAT in the western hemisphere (Figure 7g). Disagreement over the relationship between decadal variability in the PDO and temperature in the Canadian Arctic Archipelago was identified between observation-based data and reanalysis (Figure 7g-i). Temperature in the 20v2c SAT and CRU TS4 SAT datasets were positively correlated with the PDO, whereas UDEL SAT was negatively correlated. Maritime 20v2c SAT was negatively correlated to the PDO in the Norwegian, Barents, and Kara seas (Figure 7g).

Strong correlations were identified between decadal variability in the AO and SAT over Fennoscandia and the North American Arctic. Temperatures across all datasets were negatively correlated with the AO throughout the North American Arctic and the surrounding Arctic Ocean (Figure 7a-c). As with the PDO, the relationships between decadal variability in the AO and SAT were largely split, with positive correlations in the eastern hemisphere and negative correlations in the western hemisphere. In addition, 20v2c land SATs have a stronger relationship to the AO in parts of the Russian Arctic the CRU TS4 and UDEL datasets.

Relationships between decadal variability in SAT and in the NAO were similar to those between SAT and the AO, although they were generally weaker and less consistent among the datasets, especially over Alaska and Greenland (Figure 7d-f). Temperatures across all datasets were negatively correlated with the NAO over the northeastern Canadian Arctic Archipelago and northern coast of Greenland, although slightly weaker in UDEL SAT (Figure 7f).

Precipitation

Correlations between decadal variability of mean winter precipitation and mean winter climate indices are shown in Figure 8. Relationships between decadal variability in indices and precipitation were weaker and less spatially coherent than temperature. Over the ocean, the AMO was negatively correlated with decadal variability of precipitation, except in Baffin Bay and the Gulf of Alaska where the correlation was positive (Figure 8j-l). Precipitation was negatively correlated with the AMO across the North Atlantic and parts of the eastern Russian Arctic. Decadal-scale precipitation variability in the observational datasets show largely consistent patterns, especially over the North American Arctic and eastern Russian Arctic. The strongest relationships between precipitation and the AMO were found in the 20v2v dataset over Baffin Bay and the Gulf of Mexico (Figure 8j). Our results are similar to those of Gu and Adler (2015), who found the AMO and Pacific Decadal Variability (PDV) to be significantly correlated with high-latitude precipitation patterns (1901-2010) on decadal and multidecadal timescales.

While a more coherent hemispheric pattern was identified between the PDO and decadal SAT variability, the relationships between decadal variability in precipitation and the PDO were much less spatially consistent. As with temperature, the observation-based precipitation datasets and reanalysis were largely inconsistent in terms of sign and strength of the relationships between decadal variability in the PDO and in precipitation.

Decadal variability in the NAO and AO were similarly related to decadal variability in precipitation (Figure 8). The relationships between decadal variability in the NAO/AO and in Arctic precipitation were less spatially coherent than temperature. The NAO/AO were negatively correlated to precipitation over the eastern North American Arctic and positively correlated over the North Atlantic and eastern Russian Arctic. The strongest correlations between decadal variability in precipitation and the NAO/AO were in the 20v2c datasets (Figure 8a, d).

Decadal Variability in Proxy Data

Our results show large discrepancies between decadal variability calculated from proxy-based summer temperature reconstructions and decadal variability calculated from gridded observation-based temperature datasets (Table 2). Decadal variability appears significantly weaker when calculated with a proxy-based temperature reconstruction. While substantial differences are found using both tree-ring and lake varve data, decadal variability is largest when calculated using lake varve reconstructions. Results were not consistent across observational datasets and reanalysis.

Discussion

This study presents one of the first spatially explicit modern analyses of the prevalence of decadal variability in temperature and precipitation across the Arctic region. Our findings show decadal variability is a regionally important and seasonally dependent feature of the Arctic climate system. While not the focus of this study, our analysis suggests interannual variability is the dominant mode of variability across much of the Arctic. Although multidecadal variability appears to be largely insignificant, the short length of the time series used in this analysis (113 years) restricts our ability to extract multidecadal variability (Ghil et al. 2002).

Decadal Variability of Temperature

We found decadal variability to be a regionally important characteristic of Arctic temperature. Most previous studies of decadal and multidecadal variability have conducted their analysis using Arctic-wide, zonal bands, or regionally averaged data. Polyakov et al. (2002) used observational data from across the Arctic to analyze a composite Arctic-wide (northward of 62°N) time series of SAT anomalies over the 20th century. Multidecadal variability was a prominent feature of Arctic temperature; however, periods considered multidecadal in their study (i.e. 30 years) would fall under the category of decadal used in this study (Polyakov et al. 2002). Overland et al. (2004) investigated patterns of decadal variability in Arctic temperature and found results to be especially variable across seasons. In addition, our findings suggest decadal variability is particularly prominent in the North Atlantic region, which is consistent with the literature (Semenov and Bengtsson 2003; Smedsrud et al. 2013; van der Linden et al. 2016).

Winter SAT decadal variability was most prominent over the Arctic Ocean and coastal areas. These findings are similar to those of Vikhamar-Schueler et al. (2016), who found winter decadal temperature variability in the Nordic arctic region to be larger at

Arctic island stations than mainland stations. However, Vikhamar-Schueler et al. (2016) focused on regional trends and used extended winter (October-April) average surface temperatures instead of the December-February averages used here.

Decadal Variability of Precipitation

Very few studies have investigated modern decadal variability of precipitation across the Arctic. In contrast to Arctic-wide temperature studies, most precipitation studies were regionally based. Førland et al. (2011) investigated trends in temperature and precipitation in Svalbard using observational records from the past century. Although not explicitly investigating decadal variability, decadal variability in precipitation was identified by analyzing multiple annual time series from the Svalbard region (Førland et al. 2011). Our results are consistent with Førland et al. (2011), showing decadal variability in precipitation over the Svalbard region. Zhang et al. (2001) investigated the spatial and temporal patterns of precipitation over Canada and identified decadal variability of precipitation events to be a dominant feature of Canadian climate. In agreement with Zhang et al. (2001), our results suggest prominent decadal variability of precipitation across Canada; however, patterns of decadal variability in this region appear weaker in the 20v2c. This could be related to the fact 20v2c is a reanalysis, which have been found to be especially biased in studies of Canadian precipitation (Rapaić et al. 2015). In addition, Lader et al. (2016) evaluated five different reanalyses products in Alaska and found precipitation to be especially variable and problematic when compared to other dataset types.

Relationships Between Temperature, Precipitation, and Climate Indices

To investigate potential drivers of decadal variability, we conducted a correlation analysis between decadal variability of Arctic winter temperature and precipitation and the decadal components of the mean winter AO, NAO, AMO, and PDO indices. Strong relationships were identified between all climate indices and winter surface temperature variability. These results are similar to Johannessen et al. (2016) who found relationships between Arctic surface temperature and the AMO, AO, and PDO, and identified the AMO as having the strongest connection to Arctic temperature. However, Johannessen et al. (2016) correlated each index to detrended Arctic SAT without extracting a specific band of variability (i.e. decadal). Patterns of correlation between decadal variability in Arctic SAT and the PDO were very similar to those of the AMO, although regional differences in the sign of the relationships were identified over parts of the eastern North American Arctic. Our findings corroborate relationships between decadal variability in the AMO/PDO and Arctic SAT.

Many studies have proposed a link between decadal variability in the North Atlantic region and the AO/NAO (Hurrell 1995; Polyakov and Johnson 2000; Dukhovskoy et al. 2004; Frankcombe et al.2010; van der Linden et al. 2016). Polyakov et al. (2003) analyzed variability and trends in maritime Arctic temperatures using observational records and identified strong multidecadal variability, which they proposed originated in the North Atlantic. Using station data from the maritime Arctic, Polyakov et al. (2003) conducted a correlation analysis between the NAO and Arctic SATs, finding results very similar to ours. Our results are also consistent with other studies which have found a nearly identical response between variability in detrended surface temperature and the AO and NAO (Johannessen et al. 2016) and confirm a relationship exists between Arctic SATs and the AO and NAO.

Overall, climate indices more strongly correlated to decadal variability in temperature than precipitation. New et al. (2001) previously found the AO to be the dominant mode of wintertime precipitation variability over land in the Arctic (60-80° N). Our results show spatially varied results, making a relationship between decadal variability in precipitation and any of the climate indices unclear.

Dataset Inconsistencies

Although our results were generally consistent across datasets, there were some spatial and seasonal differences in decadal variability detected both in temperature (20v2c, CRU TS4, UDEL) and precipitation (20v2c, GPCC, UDEL) datasets. Results obtained from the 20v2c reanalysis dataset (both temperature and precipitation) were especially inconsistent from the observational datasets. This finding is unsurprising as reanalyses have been shown to be problematic when studying decadal variations in climate (Purcell and Huddleston 2016; Wunsch 2016). In addition, reanalyses can be less reliable in regions with limited observational records (Bromwich and Wang 2005). This is consistent with findings of Rapaić et al. (2015), who evaluated trends of precipitation and temperature across a range of observational datasets (including UDEL, GPCC, CRU TS3.1) and reanalyses over the Canadian Arctic from 1950-2010. Although the previous version of 20v2c was evaluated (20CR), it was found to exhibit a particularly large winter warm bias over the western Arctic and a widespread year-round wet precipitation bias (Lindsay et al. 2014; Rapaić et al. 2015).

Additional inconsistencies were observed between the observational datasets used in this study. Consistent with the findings of Rapaić et al. (2015), the largest variability across precipitation datasets was found over mountain and coastal areas, or in data-sparse regions like the Canadian Arctic Archipelago. Differences in results found using the UDEL precipitation dataset could be due to substantial changes in station density and/ or data source, which have previously been identified as sources of Inhomogeneities in the UDEL dataset (McAfee et al. 2014). In addition, Rapaić et a. (2015) suggest the incorporation of unadjusted gauge data could account for some of the dataset spread in the GPCC and UDEL precipitation datasets.

Proxy Limitations

Paleoclimate proxies from the PAGES2k database were selected for this study to determine whether we can detect the same degree of decadal variability in proxy data that we do in observations and reanalysis. Our results show substantial disagreement between decadal variability in observational datasets and paleoclimate proxies, especially tree-rings, at the selected PAGES2k proxy sites (Table 2). These results are not particularly surprising, as previous studies have found inconsistencies between paleoclimate and observational data in the Arctic (Jacoby and D'Arrigo 1995; Bird et al. 2009; D'Arrigo et al. 2009; Andreu-Hayles et al. 2011; Gunnarson et al. 2011).

One possible explanation for discrepancies between observational data and Arctic proxy records, tree-rings in particular, is called the divergence problem. Discovered by Jacoby and D'Arrigo (1995), the divergence problem refers to the phenomenon of high-latitude temperature-sensitive trees becoming less responsive to warmth. This decoupling from temperature, particularly throughout Alaska and the Yukon, has been suggested to be a stress response resulting from increasing temperatures (Jacoby and D'Arrigo 1995; Wiles et al. 2014). Of the eight tree-ring proxies included in our analysis, three (Seward Peninsula, Yukon, and Coppermine River) could be impacted by divergence (D'Arrigo et al. 2005, 2007, 2009). Our results found substantial disagreement of decadal variability between these three proxies (Seward Peninsula, Yukon, and Coppermine River) and their corresponding observations (Table 2). Since disagreement was not restricted to these proxy records, however, divergence is unlikely to affect our results.

As previously discussed, traditional methods of tree-ring standardization have been found to obscure or remove low-frequency variability from datasets (Briffa et al. 1996). It is unlikely that the choice of standardization method significantly influenced results in this study. Seven out of the eight tree-ring datasets used in this study were standardized using RCS. A conventional standardization technique was used by D'Arrigo et al. (2009) as previous studies from that particular location (Coppermine River, Canada) showed no additional low-frequency variability was preserved when RCS was used.

Conclusion

This study provides a spatially explicit 113-year analysis of decadal variability of temperature and precipitation across the Arctic region. Results show decadal variability, although not particularly prominent Arctic-wide, is a regionally important and seasonally dependent feature of the Arctic climate system. As a whole, decadal variability of temperature is more prevalent throughout the region than precipitation. On a seasonal scale, decadal variability of both temperature and precipitation are elevated in winter. Decadal variability of precipitation appears to be more important on a smaller, localized scale, leaving its role in the Arctic unclear. Although identifying the drivers of variability is outside the scope of this study, our analysis suggests it is reasonable to link the AMO, AO, NAO, and/or PDO and decadal variability of Arctic surface temperature. This assessment highlights spatial and seasonal patterns of decadal variability throughout the Arctic and underscores the need for more extensive studies of past variability.

Table 1. Characteristics of the proxy-based summer temperature reconstructions used in our analysis. A total of 12 datasets were selected, four lake sediment (LS) and eight tree ring (TR) reconstructions, based on their location, time coverage, and resolution.

Site	Region	Lat (°N)	Long (°E)	Archive Type	Study Period (C.E.)	Reference
Blue Lake	Alaska	68.1	-150.5	LS	730 – 2005	Bird et al. 2009
Avam-Taimyr	Central Russia	72	101	TR	-100 – 2003	Briffa et al. 2008
Lower Lake Murray	Canada	81.4	-69.5	LS	-3236 – 2004	Cook et al. 2009
Seward Peninsula	Alaska	65.2	-162.2	TR	1288 – 2002	D'Arrigo et al. 2005
Gulf of Alaska	Alaska	61	-146.6	TR	724 – 2002	Wiles et al. 2014
Yukon	Canada	67.9	-140.7	TR	1177 – 2002	D'Arrigo et al. 2007
Coppermine River	Canada	67.1	-115.9	TR	1288 – 2003	D'Arrigo et al. 2009
Torneträsk	Scandinavia	68.3	19.6	TR	-39 – 2010	Melvin et al. 2013
Jämtland	Scandinavia	63.5	15.5	TR	1107 – 2007	Gunnarson et al. 2011
Lapland	Scandinavia	69	25	TR	0 – 2005	Helama et al. 2009
Big Round Lake	Arctic Canada	69.9	-68.8	LS	971 – 2003	Thomas and Briner 2009
Lone Spruce Pond	Alaska	60	-159.1	LS	-1252 – 2005	Kaufman et al. 2012

Table 2. Decadal variability, expressed as a percentage of the total retained variance, compared across datasets. An asterisk (*) signifies the proxy site was located on the border of two grid cells in the observational datasets.

Site	**Seasonality**	**Proxy Data (%)**	**20v2c (%)**	**UDEL (%)**	**CRU TS4 (%)**
Blue lake	Summer (JJA)	17	24	29*	24*
Avam-Taimyr	June and July	9	25	23*	16*
Lower Lake Murray	Melt Season (July)	11	16	30	0
Seward Peninsula	Mean summer (JJA)	4	27	27	29
Gulf of Alaska	Feb – Aug	6	10	22	26
Yukon	Annual	6	21	21	10
Coppermine River	June – July	2	30	9	10
Torneträsk	April – Aug	3	10	13	0
Jämtland	Apr - Sep	0	13	21*	9*
Lapland	Summer (July)	1	31	22*	21*
Big Round Lake	July -Sep	2	14	10	25
Lone Spruce Pond	Growing Season (July)	7	36	13	35

Table 3. Variance totals (percent) for each climate index, both of decadal variance and total overall variance, contained within the nine reconstructed components (RCs) used in our analysis.

Index	**Decadal Variance (%)**	**Total Retained Variance (%)**
Arctic Oscillation (AO)	5.3	54.8
Atlantic Multidecadal Oscillation (AMO)	15.9	65.8
North Atlantic Oscillation (NAO)	7.0	56.1
Pacific Decadal Oscillation (PDO)	24.8	60.1

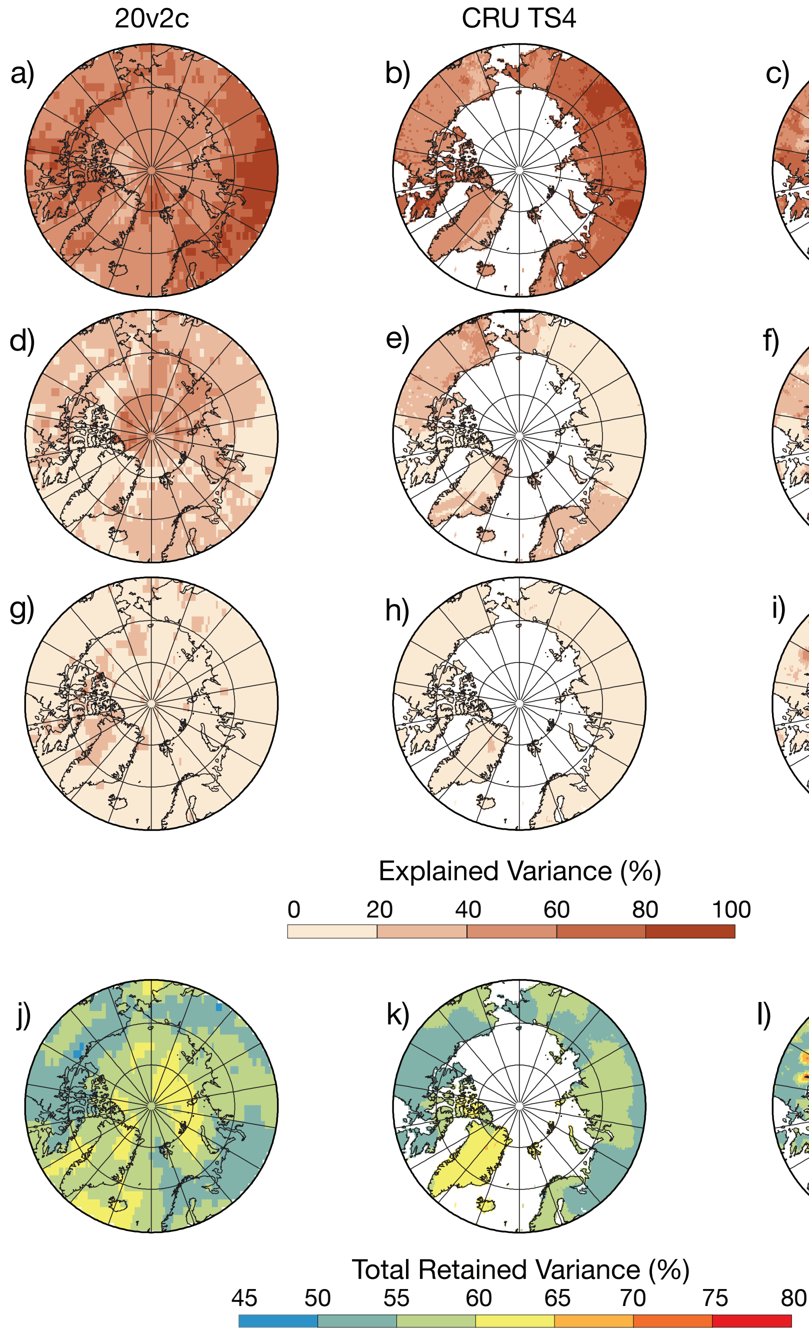

Figure 1. Interannual (a-c), decadal (d-f), and multidecadal (g-i) variability (expressed as percentage of retained variance) of mean annual surface temperature in the 20v2c (left column), CRU TS4 (middle column), and UDEL (right column) datasets. The total retained variance in the 9 RCs at each grid cell is shown in the bottom row (j-l).

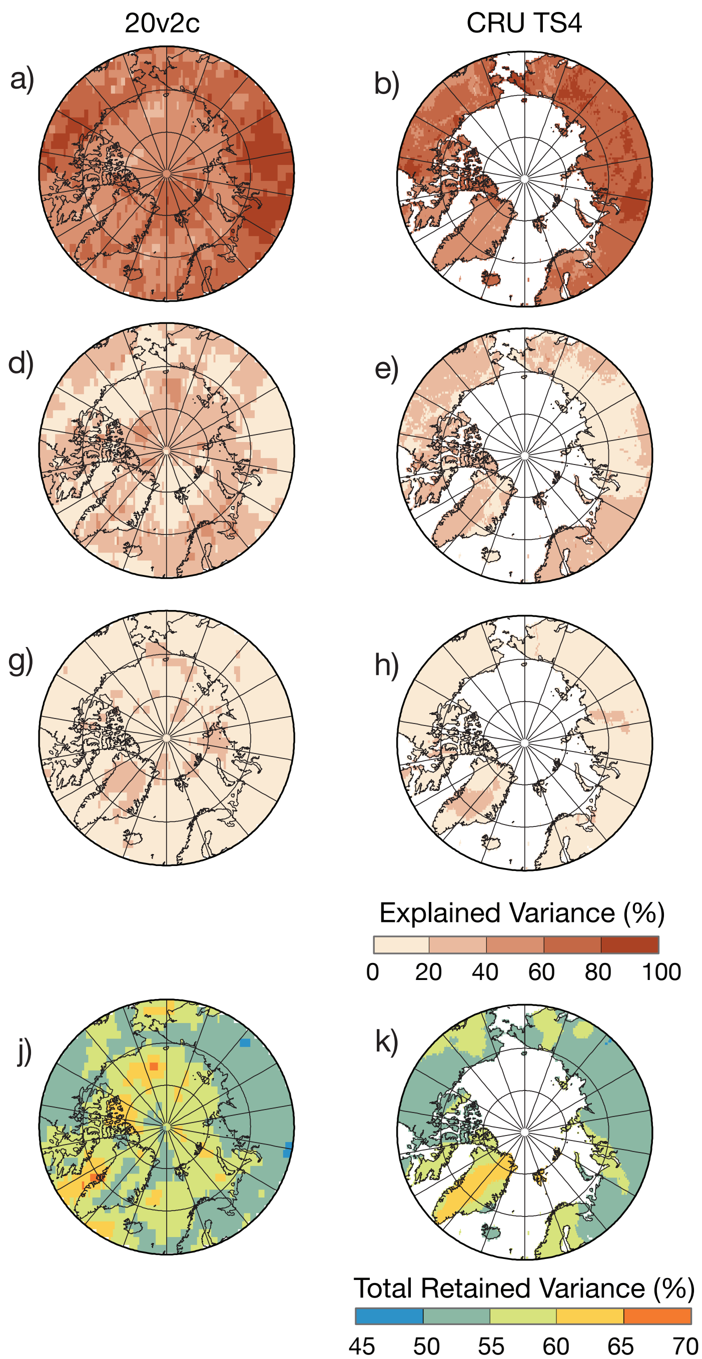

Figure 2. Interannual (a-c), decadal (d-f), and multidecadal (g-i) variability (expressed as percentage of retained variance) of mean winter (DJF) surface temperature in the 20v2c (left column), CRU TS4 (middle column), and UDEL (right column) datasets. The total retained variance in the 9 RCs at each grid cell is shown in the bottom row (j-l).

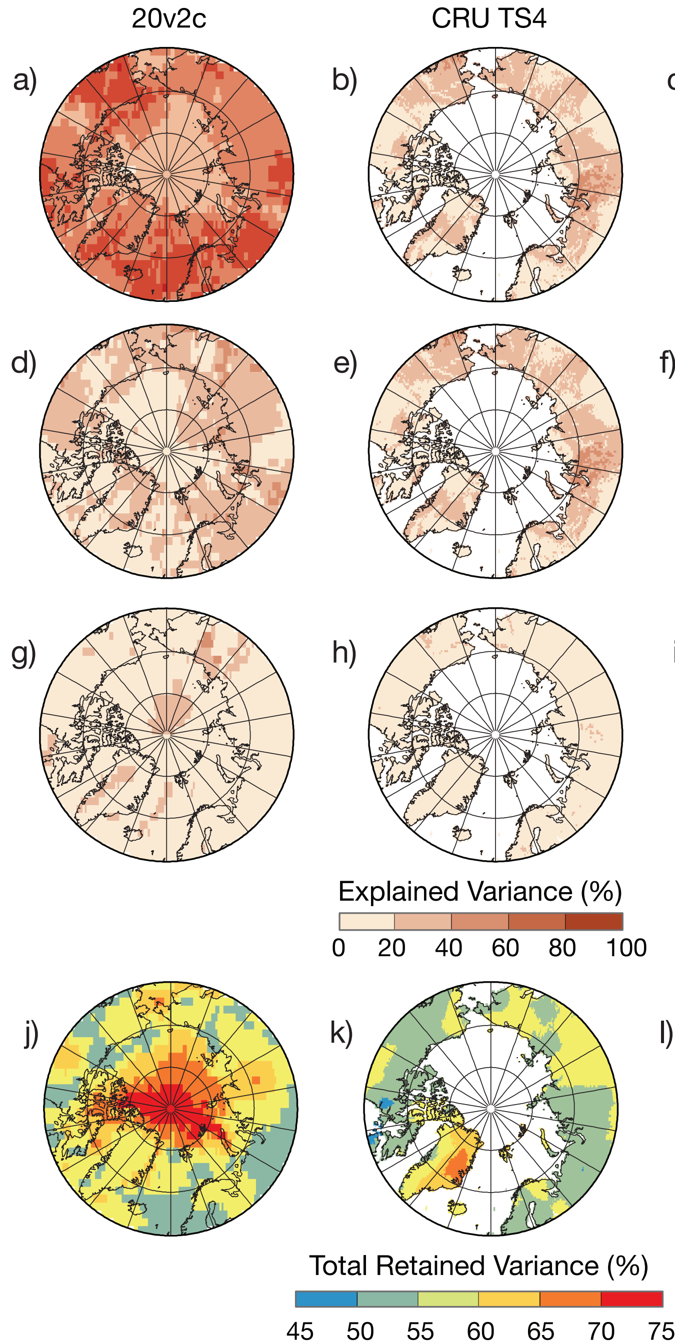

Figure 3. Interannual (a-c), decadal (d-f), and multidecadal (g-i) variability (expressed as percentage of retained variance) of mean summer (JJA) surface temperature in the 20v2c (left column), CRU TS4 (middle column), and UDEL (right column) datasets. The total retained variance in the 9 RCs at each grid cell is shown in the bottom row (j-l).

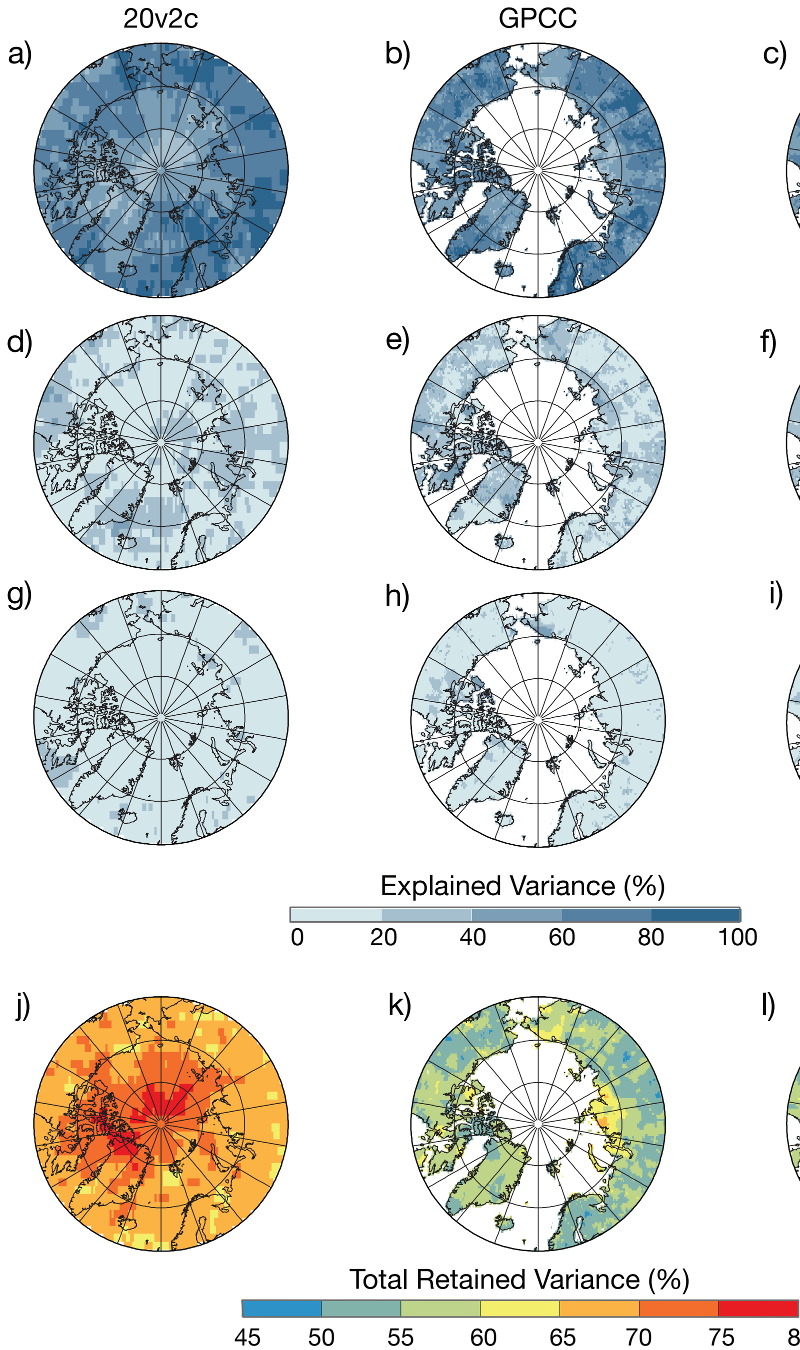

Figure 4. Interannual (a-c), decadal (d-f), and multidecadal (g-i) variability (expressed as percentage of retained variance) of mean annual precipitation in the 20v2c (left column), GPCC (middle column), and UDEL (right column) datasets. The total retained variance in the 9 RCs at each grid cell is shown in the bottom row (j-l).

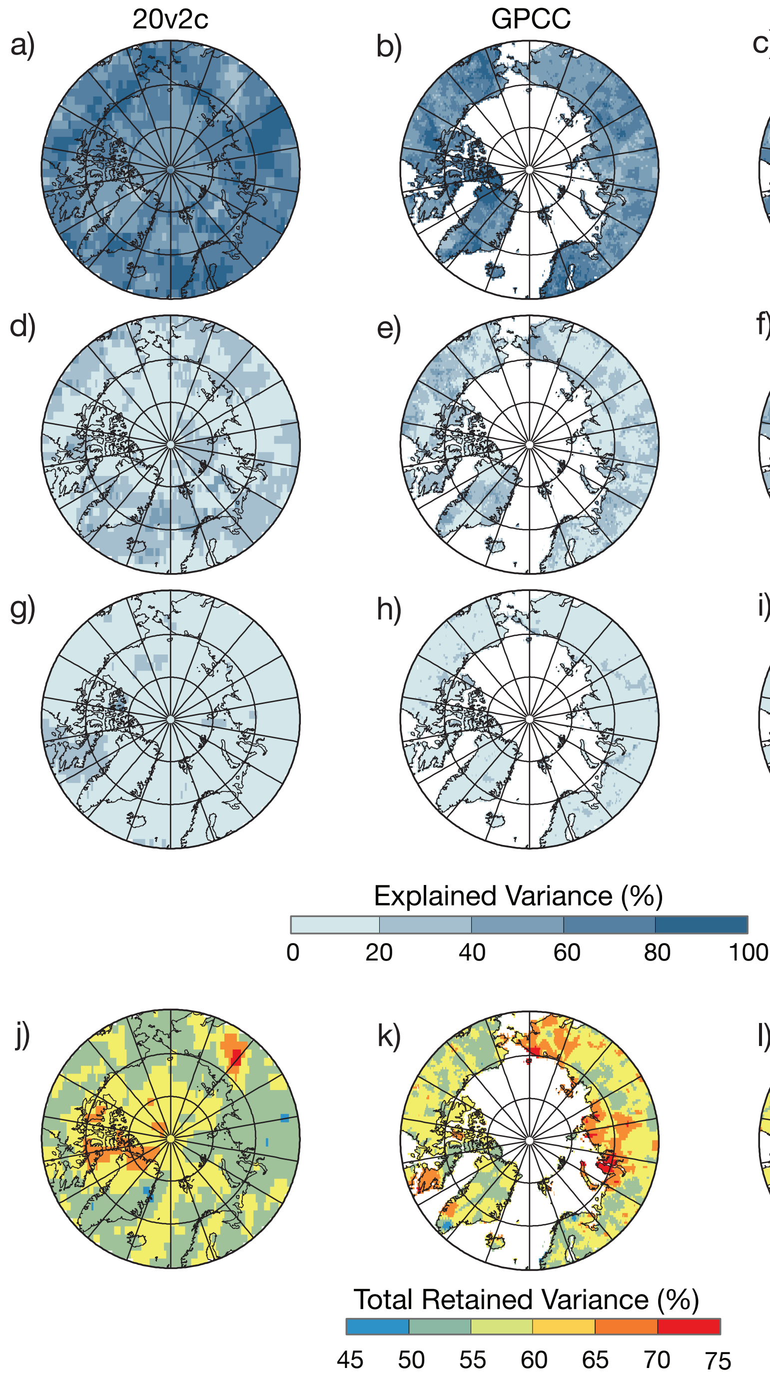

Figure 5. Interannual (a-c), decadal (d-f), and multidecadal (g-i) variability (expressed as percentage of retained variance) of mean winter (DJF) precipitation in the 20v2c (left column), GPCC (middle column), and UDEL (right column) datasets. The total retained variance in the 9 RCs at each grid cell is shown in the bottom row (j-l).

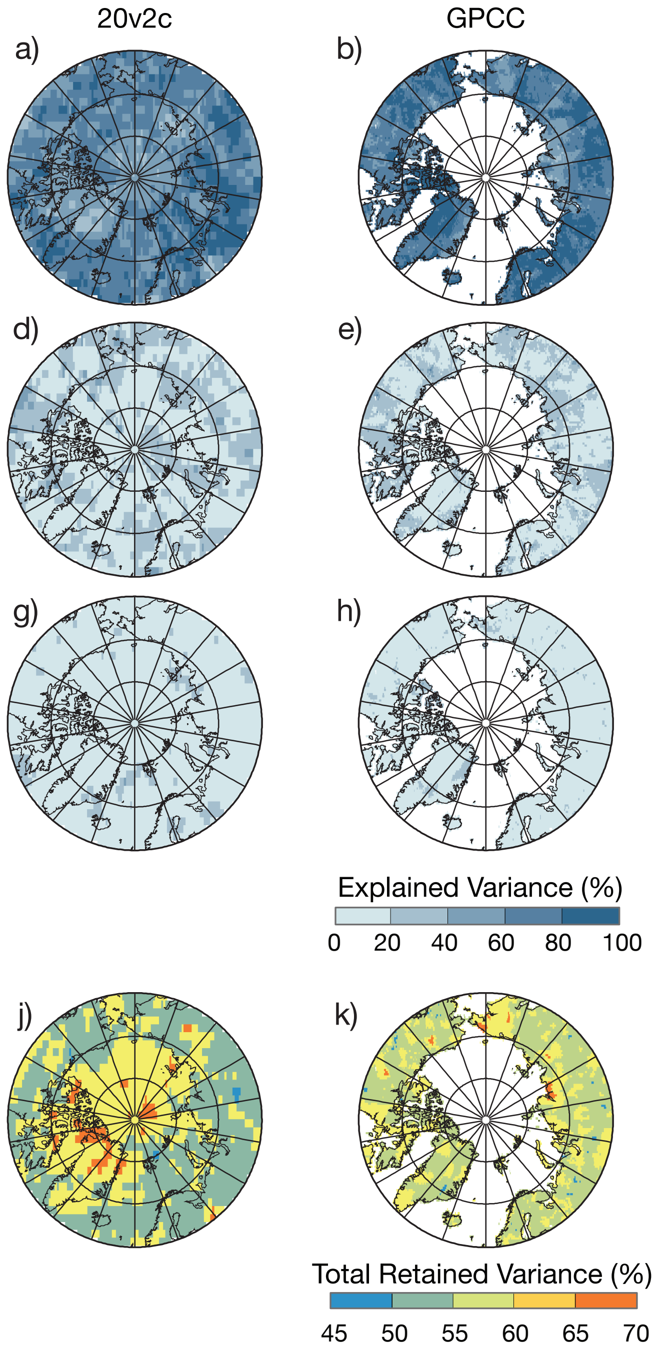

Figure 6. Interannual (a-c), decadal (d-f), and multidecadal (g-i) variability (expressed as percentage of retained variance) of mean summer (JJA) surface temperature in the 20v2c (left column), GPCC (middle column), and UDEL (right column) datasets. The total retained variance in the 9 RCs at each grid cell is shown in the bottom row (j-l).

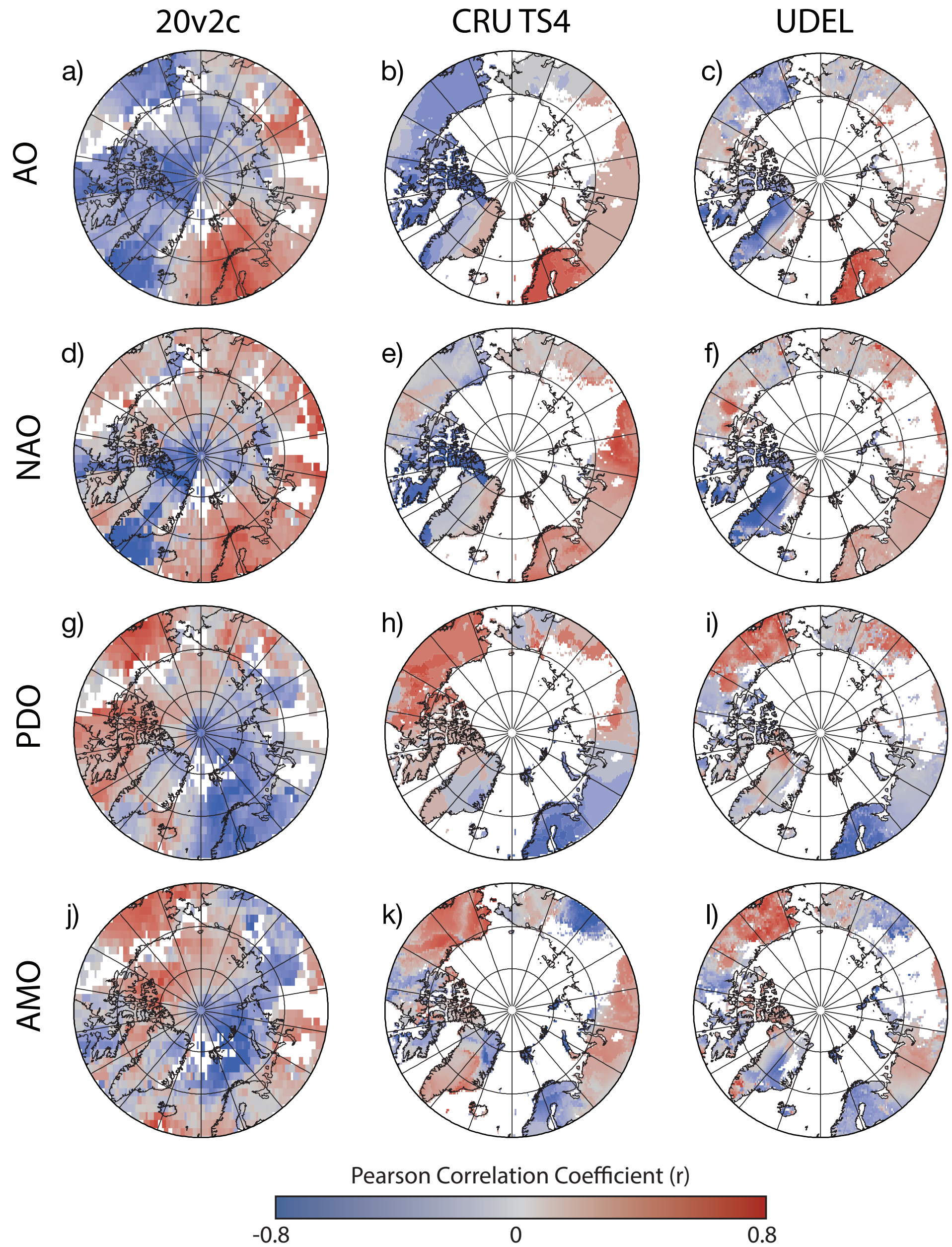

Figure 7. Correlations between decadal components of mean winter Arctic SAT and of mean winter AO (a-c), NAO (d-f), PDO (g-i), and AMO (j-l) indices using the 20v2c (left column), CRU TS4 (middle column), and UDEL (right column) datasets.

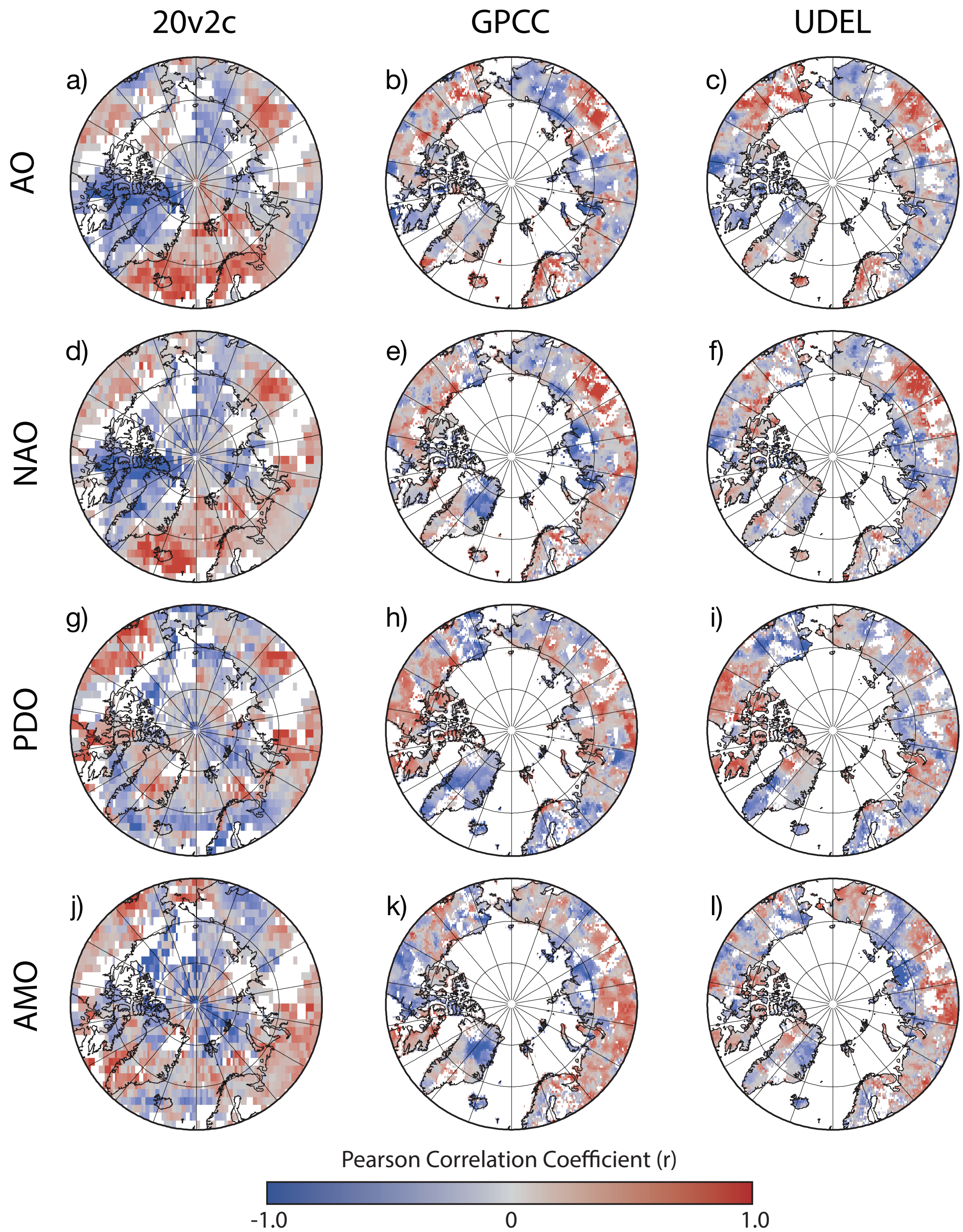

Figure 8. Correlations between decadal components of mean winter Arctic precipitation and of mean winter AO (a-c), NAO (d-f), PDO (g-i), and AMO (j-l) indices using the 20v2c (left column), GPCC (middle column), and UDEL (right column) datasets.

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