General comments

The description of the SOM and the transition between nodes is good.

Please refer to figures more throughout the results section. I'd cite the figure number each time you change which figure you are discussing. For example, on line 230 you mention Figure 6, but then in the following line you are referring to Figure 5 but you do not give the figure number. It would be easy here (and in other places) for the reader to be looking at the wrong figure. The paragraph starting at line 277 is another instance where figures should be referred to more frequently.

Good suggestion. We have gone through the manuscript carefully and added citations to figures whenever appropriate.

Datasets and methods section – this section provides a good explanation of SOMs, including what SOMs are and how you will apply them to temperature data, but there is no explanation of how you analyse the other variables (i.e. create composites based on the SOM for temperature data), or the use of principal component analysis. Please include this here.

Thanks for pointing out this oversight. We have added more description about the other methods we also used in the analyses, in addition to SOM, in the Method section.

Consider adding analysis to show what portion of the trend in the warm Arctic-cold Eurasia pattern is due to mean warming. What trend is removed from the 20CR data? It seems an oversight to not consider mean warming when so many other variables are being examined.

Trend in wintertime surface air temperature anomalies for the 1854-2014 period for the 20CR data was removed.

In this study, we mainly focused on the role of the interdecadal variability of SST anomalies over northern oceans in trend in the warm Arctic-cold Eurasia pattern. In Conclusions and Discussions section, we increased some discussions of the role of Arctic warming in the trend.

Specific comments

Lines 23-36 – Abstract nicely sums up the major findings of the paper.

Thanks

Line 53 – This line states that the warm Arctic-cold continents pattern has been observed on an interannual timescale. Please state here whether the pattern has been strengthening linearly over time, or whether it's a cyclical pattern, or something else.

We have added a statement here about increasing trend in the occurrence of the warm Arctic-cold continents pattern.

Line 75 – What changes in the Gulf Stream are you referring to here?

Changed the statement to "… the sea surface temperature anomalies over the Gulf Stream."

Line 85 – "Using regression method" should probably read "using regression", or "using linear regression" (if this is correct).

Changed to 'using linear regression'

Lines 90-98 – This first part of the Datasets and methods section seems to be replicating some of what is said in section 2.2. I'd suggest starting the datasets and methods section with section 2.1, and incorporating lines 90-98 into section 2.2.

Removed the replications

Line 94 – Should this say “41 winters”? Or are you only considering complete winters, i.e. December 1979-February 2019 (thus excluding January and February 1979, and December 2019)? Which months do you use for winter? I assume it’s DJF.

Winter is defined by DJF and we only consider complete winters from December 1979 through February 2019.   This is now clarified.

Line 102 – What is the resolution of the ERA-Interim data?

The resolution of the ERA-Interim was added.

Lines 137-138 – What dataset are these lines referring to? Both ERA-Interim and 20CR? If both, which 40-year period do you use? I.e. do you subtract the 1979-2019 mean from both datasets?

These lines refer to ERA-Interim reanalysis. We subtract the 1979-2019 mean from ERA-Interim.

Line 150 – Do the SOM-explained trends mean something physically, i.e. are they the fraction of the total trends that are explained by changes in circulation (or something else)?

The SOM-explained trends are the fraction of the total trends that are explained by the changes in circulations.

Lines 161-162 – This sentence compares the “first node” in each group, however node 9 appears to be the second node in group one, and node 1 is the first node in group two.

Changed

Lines 164-165 – It is not clear from Figure 1 that the maximum anomalies are centered near Svalbard. Please consider adding contour lines to the SOMs, or use a discrete color scale. When you say maximum, are you referring to the greatest departure from zero (i.e. positive or negative values)?

Contour lines are added. Maximum refers to largest values of the anomalies

Line 165 – This line states that nodes 3 and 7 are the second most frequently occurring of their groups, but node 3 occurs most frequently. The comparison of pairs is good, but needs to be worded more carefully. Maybe pick the most frequently occurring node in group 1 then identify its pair.

Good suggestion. Statements rephrased.

Lines 171-172 – Why can’t this SOM consider temperature trends? I think this should say “does not” not “cannot”.

Changed to “does not”

Lines 176-180 – Consider moving these lines to the methods section.

We have added some description on composite method in the Method section, following another reviewer’s comment.

Line 193 – Please add figure reference.

Referred more to figures whenever appropriate.

Line 223 – Nice explanation of turbulent heat flux!

Thanks

Line 229 – Maybe refer back to Figures 2 and 3 if that is where this statement comes from.

Made references back to the figures

Lines 229-230 – Are you sure this is the correct order? I.e. over the Barents Sea in node 1, is it possible that the sea ice melt causes a reduction in the albedo which results in an increased turbulent heat flux?

We believe the cause-effect is correct based on previous studies (Blackport et al., 2019)

Line 231 – When you say “larger” do you mean larger spatially, or a greater magnitude anomaly?

A greatermagnitude anomaly. Clarified

Line 238 – “composted” should probably be “composited”.

Changed

Line 239 – What happens if you do the same lag analysis for sea ice concentration? I think it is important to know that sea ice does not also peak before the day the nodes occur. Similarly, what happens if you do this lag analysis on the geopotential height patterns?

It seems strange to say that circulation leads sea ice cover without mentioning the geopotential height patterns.

The pattern of the composited anomalous 500-hPa geopotential height, turbulent heat flux, and sea ice concentration 2 days prior to the day when the nodes occur (not shown) is similar to the simultaneous pattern in Figures 2, 5, and 6.

Lines 250-251 – How does this differ to the other nodes? I assume they only exhibit interannual variability.

The main difference is the decadal variability.

Line 255 – I think this should refer to Table 3 (not Table 2).

Changed

Line 261 – Figure 8 does not appear to cover a large enough region to determine whether there are positive trends over southern Europe. This might need re-wording.

Rewording done

Line 262 – Maybe point out that negative trends are mostly not significant.

Done

Line 267 – Arctic–cold should be Arctic-cold

Changed

Line 281 – Refer to figure number (Figure 11).

Added reference to Figure 11

Lines 282-285 – Which node are you referring to? I assume node 1 but this should be clear.

Added reference to node 1.

Lines 284-285 – Are you determining the direction of propagation from Figure 11 or Figure 12? From the text it sounds like you are only referring to Figure 11, but I am not sure how you are determining that the Rossby wave moves southeastwards to the Eurasian continent from this figure. Please explain and give figure number.

The direction of wave activity flux points to the Eurasian continent (Figure 12). A reference to Figure 12 is added.

Lines 285-286 – What figure(s) support the claim that “large SST anomalies over the Nordic Ocean augment the wave signal through local air-sea interaction”? This statement needs more support and/or more of a description on how you came to this conclusion.

Added more descriptions with reference to figures

Line 290 – Figure number?

Added

Line 302 – Does “these results” refer to the results in Figures 10-12, or to the results you just mentioned in lines 299-302? If you're referring to Figures 10-12, please state this.

Reference to Figures 10-12 are added

Line 308 – Which figure are you referring to here? If this comparison is not shown, write "(not shown)".

"(not shown)" was added.

Line 321 – Where it states that the magnitude is smaller for the 20 CR data, could this be because the 20 CR data are detrended and the ERA-Interim data are not?

Added detrending of the 20CR as a potential explanation

Lines 321-322 – This sentence says "frequencies of all the nodes (Figure 14)", but Figure 14 only shows data for nodes 1, 4, 6, and 9 – please rectify.

Clarified

Line 322 – Please refer to the corresponding figure that shows node occurrence for ERA-Interim.

Reference to corresponding figures added

Line 325 – The occurrence frequencies at the end of the time series in node 1, Figure 7, appear to be slightly greater than those for node 1 in Figure 14. Could this indicate that mean warming amplifies these trends?

Global warming may be a reason

Lines 335-336 – If these results are not shown, please state this.

Stated

Lines 343-344 – Why isn't the central North Pacific Ocean SST index shown in Figure 15 since it is significantly correlated with EOF modes 1 and 2?

The central North Pacific Ocean SST index is added in Figure 15

Line 347 – And the PDO?

Added

Lines 386-387 – Which figures are you referring to here?

References to corresponding figure added

Lines 388-389 – How does this atmospheric process suggest that the relationship between a warmer Arctic and East Asian cold spells are not as strong? If the atmospheric patterns described by your SOMs show changes in circulation patterns lead to increases in Arctic temperatures and decreases in Eurasian temperatures, then there appears to be a strong link. Or are you saying that temperature increases in the Arctic are not the driver of temperature decreases in Eurasia?

Temperature increases in the Arctic are not the driver of temperature decreases in Eurasia.

Figures

In general - Please add the following to the figure captions: - What years the figure covers (if not shown). E.g. Figure 1 - Whether the data have been detrended or not - Dataset used - Consider making figures more consistent, for example, Figure 10 has the Pacific Ocean in the center, whereas Figure 12 has the Atlantic in the center. It would be easier to compare these figures if they both had the same east/west bounds.

Years and data were added in figure captions. Figure 10 has changed.

Figure 1 - Please consider adding contour lines to the SOM, or use a discrete color scale so it is clearer where the maximum/minimum values are on these plots. – Please mention years and

dataset in the caption.

Figure 1 has been changed into contour lines.

Figure 2 - Please reconsider the use of a rainbow color scale. Reds and greens can look identical to color blind people. - It appears that the stippling/hatching is plotted on top of the contour lines. The plot might be easier to read if the contour lines were on top of the stippling/hatching. - The caption states that this is the “corresponding 500-hPa geopotential height anomalies”, but you do not mention that it corresponds to Figure 1. - The caption states that stippled areas are significant, but what about the hatched areas? I assume they are also significant. - Please mention what contour lines show in caption. - Maybe consider rotating the nodes so they match Figure 1 better, i.e. put Russia at the bottom of the subplots. Alternatively, adding an outline of the region in Figure 1 to the plots like Figure 2 would be helpful.

Rainbow color scale is now used. An outline of the region in Figure 1 is added. We used stippled, not hatched in Figure 2.

Figure 3 - It would be useful to show the contour lines (from Figure 2) on this plot as well (without stippling) so we can see exactly how the contour lines and wind anomalies line up. - What does the gray shading mean?

Adding contour lines made it harder to see vectors. We replaced stipping by shading to denote the above 95% confidence level.

Figure 6 - Node numbers are missing from Figure 6. Please add them.

Added

Figure 7 - Consider adding trend lines and p-values to each subplot (and other similar figures).

Added

Figures 10, 11, and 12 - Consider arranging these plots the same, i.e. all 2x2 or 1x4 for easier comparison between the figures.

Rearranged

Figure 14 - Can the results from Figure 7 be overlaid on Figure 14? Maybe with gray dashed outlines. This would make it clearer to see the similarities/differences between the results.

The time series in Figure 7 is added in Figure 14

Figure 15 - Consider putting r and p values on subplots b and d. Or in caption.

R and P values are added in the caption

Revisiting the trend in the occurrences of the "warm Arctic-cold Eurasian continent" temperature pattern

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Abstract. The recent increasing trend of "warm Arctic, cold continents" has attracted much attention, but it remains debatable as to what forces are behind this phenomenon. Here, we revisited surface-temperature variability over the Arctic and Eurasian continent by applying the Self-Organizing-Map (SOM) technique to gridded daily surface temperature data. Nearly 40% of the surface temperature trends are explained by the nine SOM patterns that depict the switch to the current warm Arctic-cold Eurasia pattern at the beginning of this century from the reversed pattern that dominated the 1980s and the 90s. Further, no cause-effect relationship is found between the Arctic sea-ice loss and the cold spells in high-mid latitude Eurasian continent suggested by earlier studies. Instead, the increasing trend in warm Arctic-cold Eurasia pattern appears to be related to the anomalous atmospheric circulations associated with two Rossby wavetrains triggered by rising sea surface temperature (SST) over the central North Pacific and the North Atlantic Oceans. On interdecadal timescale, the recent increase in the occurrences of the warm Arctic-cold Eurasia pattern is a fragment of the interdecadal variability of SST over the Atlantic Ocean as represented by the Atlantic Multidecadal Oscillations (AMO), and over the central Pacific Ocean.

Key words: Warm Arctic-cold Eurasian continent, Arctic Sea ice, the Kara-Barents Sea, the Self-Organizing-Map (SOM), the Pacific Decadal Oscillation (PDO), the Atlantic Multidecadal Oscillation (AMO)

1 Introduction

In recent decades, winter season temperature in the Arctic has been rising at a rate faster than the warming experienced in any other regions of the world (Stroeve et al., 2007; Screen and Simmonds, 2010; Stroeve, 2012). In contrasts, there has been an increasing trend in colder than normal winters over the northern mid-latitude continents (Mori et al., 2014; Cohen et al., 2014; 2018). This pattern of opposite winter temperature trend between the Arctic and high-mid latitude continents, referred to as the warm Arctic-cold continents pattern (Overland et al., 2011; Cohen et al., 2014; Walsh, 2014), has ~~also been observed on the interannual timescale~~received considerable interest in the scientific community especially with regard to dynamical and physical mechanisms for the development of the phenomenon (Mori et al., 2014;~~ Kug et al., 2015)~~ ~~The question as to what processes are responsible for the opposite change of winter air temperature between the Arctic and mid-latitudes remain open (~~Vihma, 2014; Barnes and Screen, 2015; Kug et al., 2015; Overland et al., 2015; Chen et al., 2018).

Using observational analyses or coupled ocean-atmosphere modeling, ~~A~~a number of studies have attributed the recent warm Arctic-cold continents pattern to the Arctic sea ice loss in boreal winter (Inoue et al., 2012; Tang et al., 2013; Mori et al., 2014; Kug et al., 2015; Cohen et al., 2018; Mori et al., 2019). Sea ice variability in different parts of the Arctic Ocean has been linked to climate variability in different parts of the world. Specifically, sea ice loss in the Barents and Kara Seas has been linked to cold winters over East Asia (~~add a reference~~ Kim et al., 2014; Mori et al., 2014; Kug et al., 2015; Overland et al., 2015) and in central Eurasia (Mori et al., 2014), while a similar connection has been found between cold winters in North America and sea ice retreat in the East Siberian and Chukchi Seas (Kug et al., 2015). A most recent study (Matsumura and Kosaka, 2019) attributed the warm Arctic-cold continents pattern to the combined effect of Arctic sea ice loss and the atmospheric teleconnection induced by tropical Atlantic sea-surface temperature (SST) anomalies. ~~Some recent studies have suggested that the mid-latitude atmospheric circulation anomalies play a role in the formation of the warm Arctic-cold continents pattern (Luo et al., 2016; Peings et al., 2019).~~

Other studies, however, found no cause-and-effect relationship between Arctic sea ice loss and mid-latitude climate anomalies (Blackport et al., 2019; Fyfe, 2019). Numerical modeling studies using coupled ocean and atmospheric models simulated no cold mid-latitude winters when the models were forced with reduced Arctic sea ice cover (McCusker et al., 2016; Sun et al., 2016; Koenigk et al., 2019; Blackport et al., 2019; Fyfe, 2019). Instead, ~~The results from~~ these studies pointed to internal atmospheric variability as the likely cause for cold winters in mid-latitudes. Some studies have also suggested that on the interannual timescale mid-latitude atmospheric circulation anomalies triggered by the Pacific and Atlantic SST oscillations may explain both the Arctic sea ice loss and the cooling of the high-mid latitudes (Lee et al., 2011; Luo et al., 2016; Peings et al., 2019; Matsumura and Kosaka, 2019; Clark and Lee, 2019). The sea surface temperature anomalies over the Gulf Stream have ~~has~~ also been linked to the Barents Sea ice loss and Eurasian cooling (Sato et al., 2014).

Despite the recent attention given to the warm Arctic-cold continents pattern, it remains debatable as to ~~what~~ the roles of various dynamical and physical processes play ~~may be responsible~~in the formation of ~~for~~ this phenomenon. In this study, we revisit surface temperature variability over the Arctic and Eurasia continent (40-90 °N, 20-130 °E), where the warm Arctic-cold continents pattern is a prominent feature (Cohen et al., 2014; Mori et al., 2014), by applying the Self-Organizing-Map (SOM) technique to daily surface temperature over the recent four decades. We will show that while the warm Arctic-cold Eurasian continent pattern has dominated the recent two decades, its opposite pattern, cold Arctic-warm Eurasia continent, appeared frequently in the 1980s and the 90s. Using century-long data, we will further show that the warm Arctic-cold Eurasian continent pattern is an intrinsic climate mode and the recent increasing trend in its occurrence is a reflection of an interdecadal variability of the pattern. Using linear regression ~~method~~, we explain the reason for the recent increasing occurrences of the warm Arctic-cold continents pattern. We also assess the role of the SST anomalies over the North Pacific and Atlantic Oceans in the variability of the warm Arctic-cold Eurasia pattern on the interdecadal time scale.

2 Datasets and methods

~~From the perspective of nonlinear dynamic, a region's climate has its intrinsic modes of variability, but the frequency of occurrence of these internal modes can be modulated by remote forces external to the region (Palmer, 1999l; Hoskins and Woollings, 2015; Shepherd, 2016). In this study we will first obtain the main modes of variability of wintertime surface temperature in a region (40-90 °N, 20-130 °E) by applying the SOM method (Kohonen, 2001) to daily surface temperature data for the 40 winters in the 1979-2019 period. The use of daily data over four decades allows for capturing the variability across two time scales (synoptic and decadal). We will then determine, through regression and composite analyses, the relationships of these modes of climate variability of surface air temperature to known climate variability modes at corresponding time scales.~~

2.1 Datasets

Daily surface air temperature and other climate variables used in the current analyses, including 500 hPa geopotential height, 800-hPa wind and mean sea level pressure, all come from the European Centre for Medium-Range Weather Forecasts –Re-Analysis (ERA), the interim version (ERA-Interim; Dee et al., 2011) with a horizontal resolution of approximately 79 km (T255) and 60 vertical levels in the atmosphere. Compared to the earlier versions of ERA (e.g., ERA-40, Uppala et al., 2005) and other global re-analysis products (e.g. the NCEP reanalysis, Kalnay et al., 1996), ERA-Interim has been found to be more accurate in portraying the Arctic warming trend (Dee et al., 2011; Screen and Simmonds, 2011) despite its known warm and moist bias in the surface layer (Jakobson et al., 2012). Daily sea ice data are obtained from the U.S. National Snow and Ice data Center (ftp://sidads.colorado.edu/DATASETS/nsidc0051_gsfc_nasateam_seaice/final-gsfc/north/daily). Gridded monthly SST data used in the current analysis are obtained from the U.S. National Oceanic and Atmospheric Administration (NOAA) data archives (ftp://ftp.cdc.noaa.gov/Datasets/noaa.oisst.v2.highres/) (Reynolds et al. 2007).

The results obtained from the data within the recent four decades are put into the context of the variability over longer time scales using data from the Twentieth Century Reanalysis project, version 2Cc (20CR) that spans more than a century from 1851 through 2015 (Compo et al., 2011). The 20CR reanalysis data, which has a horizontal resolution of 2 °latitude by 2 °longitude and temporal resolution of 6 hours,. Through the assimilation of surface observational pressure data, the 20CR reanalysis was produced by athe model whose driven at the lower boundary by condition is derived from observed monthly SST and sea ice conditions and with data assimilation of surface pressure observations. Various Several indices used to describe known modes of climate variability are obtained from NOAA's Climate prediction Center (CPC) (https://www.esrl.noaa.gov/psd/data/climateindices/list/), which includinge Arctic oscillation (AO), Northern Atlantic Oscillation (NAO), Atlantic Multidecadal Oscillation (AMO) (Enfield et al., 2001) and PDO (Mantua et al., 1997) indices,. are obtained from NOAA's Climate prediction Center (CPC) (https://www.esrl.noaa.gov/psd/data/climateindices/list/),

2.2 Methods

From the perspective of nonlinear dynamic, a region's climate has its intrinsic modes of variability, but the frequency of occurrence of these internal modes can be modulated by remote forces external to the region (Palmer, 1999l; Hoskins and Woollings, 2015; Shepherd, 2016). In this study we will first obtain the main modes of variability of wintertime surface temperature in a region (40-90 °N, 20-130 °E) by applying the SOM method (Kohonen, 2001) to daily surface temperature data for the 40 winters (December, January, -February) in the 1979-2019 periodfrom December 1979 through February 2019. The use of daily data over four decades allows for capturing the variability across two time scales (synoptic and decadal).The 40-year, daily surface temperature over the study region (40-90 °N, 20-130 °E) is decomposed using the SOM method. SOM is a clustering method based on neural network that can transform multi-dimensional data into a two-dimensional array without supervised learning. The array includes a series of nodes arranged by a Sammon map (Sammon, 1969). Each node in the array has a vector that can represent a spatial pattern of the input data. The distance of any two nodes in the Sammon map represents the level of similarity between the spatial patterns of the two nodes. Because SOM has fewer limitations than most other commonly used clustering methods, (e.g., orthorgonality required by the empirical orthogonal function or EOF method), the SOM method can describe better the main variability patterns of the input data (Reusch et al., 2005).

SOM method has been used in atmospheric research at mid and high latitudes of the northern hemisphere (Skific et al., 2009; Johnson and Feldstein, 2010; Horton et al., 2015; Loikith and Broccoli, 2015; Vihma et al., 2019). For example, Johnson and Feldstein (2010) used SOM to identifyied the spatial patterns of the daily wintertime North Pacific sea level pressure and related the variability of the occurrences of those patterns to some large-scale circulation indices. Loikith and Broccoli (2015) compared observed and model-simulated circulation patterns across the North American domain using an approaching involving SOM. The SOM method was also used to detect circulation pattern trends in a subset of North America during two different periods (Horton et al., 2015).

In this study, the SOM method is applied to ERA-Interim wintertime daily temperature anomalies from December 1979 through February 2019. The anomalies are calculatedobtained by subtracting 40-year averaged daily temperature from the original daily temperature at each grid point. Prior to SOM analysis, it is necessary to determine how many SOM nodes are needed to best capture the variability in the data. According to previous studies (Lee and Feldstein, 2013; Gibson et al., 2017; Schudeboom et al., 2018), the rule for determining the number of SOM nodes is that the number should be sufficiently large to capture the variability of the data analyzed, but not too large to introduce unimportant details. Table 1 shows the averaged spatial correlation between all daily surface air temperature anomalies and their matching nodes. There is an increase in The spatial correlation coefficients increase from 0.26 for a 3×1 grid to 0.51 for a 4×4 grid, but the gain from a 3×3 grid to a 4×4 grid is relatively small. Hence, a 3×3 grid seems to meet the above-mentioned rule and will be utilized in this study.

The contribution of each SOM node to the trend in wintertime surface temperature anomalies is calculated by the product of each node pattern and its frequency trend normalized by the total number (90) of wintertime days (90, Lee and Feldstein, 2013). The sum of the contributions from all nodes denotes the SOM-explained trends. Residual trends are equal to the subtraction of SOM-explained trends from the total trends. The anomalous atmospheric circulation pattern corresponding to each of the SOM pattern is obtained by composite analysis that computes a composite mean of an atmospheric circulation field (e.g., 500 hPa height) over all occurrences of that SOM node. Regression analysis is also performed where atmospheric circulation variables are regressed onto the time series of the occurrence of a SOM node to further elucidate the relationship between the variability of atmospheric circulations and surface temperatures. The statistical significance of composite and regression analyses in this study is tested by using the Student's t test.

3 Results

3.1 Surface temperature variability

The majority of the 9 SOM nodes depict a dipole pattern characterized by opposite changes in surface temperatures between the Arctic Ocean and the Eurasian continent, although the sign switch does not always occur at the continent-ocean boundary (Figure 1). The differences in the position of the boundary between the warm and cold anomalies reflects the transition between the cold Arctic-warm Eurasia pattern (denoted, in descent order of the occurrence frequency, by nodes 3, 9, 6), to the warm Arctic-cold Eurasia pattern (depicted, in descent order of the occurrence frequency, by nodes 1, 7, 4). The spatial patterns represented by the first group of nodes ~~(3, 9, 6)~~ are almost mirror images of the patterns denoted by the corresponding nodes in the second group ~~(1, 7, 4)~~. For example, the ~~first~~ second node in group 1 (node 9, 15.4%) and the first node in group 2 (node 1, 17.1%) show a mirror image pattern with cold (warm) anomalies in the Arctic Ocean extending into northern Eurasia and warm (cold) anomalies in the rest of the Eurasia continent in the study domain. In both cases, the region of maximum ~~anomalies~~ magnitude anomalies is centered near Svalbard, Norway. The second ~~most frequent pattern~~pair, denoted by node 3 (17.2%) and 7 (13.7%) ~~in the two groups, respectively,~~ has the boundary of separation moved northward from northern Eurasia continent toward the shore of the Arctic Ocean. While the maximum anomaly in the Arctic Ocean remains close to Svalbard, maximum values over the continent are found in central Russia. Nodes 4-6 display a noticeable transition from node 1 to node 7 and from node 3 to node 9, respectively. Although nodes 2 and 8 show an approximate monopole spatial pattern, they also represent a transition between nodes 1 and 3, and between nodes 7 and 9, respectively. Above SOM analysis ~~cannot~~ does not consider the trend in surface air temperature. The result is similar ~~while~~ when ~~removing~~ the trend is removed (~~Not~~ not shown).

The temporal variability on this time scale is typically related to synoptic processes and hence the questions are what synoptic patterns are responsible for the occurrence of the spatial patterns depicted by each of the 9 SOM nodes and how these patterns are related to those of the Arctic sea ice anomalies? These questions can be answered by using the composite method. Specifically, for each SOM node, composite maps are made respectively for the anomalous 500-hPa geopotential height, mean sea level pressure, 850-hPa wind, downward longwave radiation, surface turbulent heat flux, and sea ice concentration over all the days when the spatial variability of the surface temperature anomalies is best matched by the spatial pattern of that node.

3.2 Large-scale circulation patterns

For all SOM nodes, the spatial pattern of the composited 500 hPa-geopotential height anomalies (Figure 2) is similar to that of mean sea level pressure anomalies (~~Not~~ not shown), indicating an approximately barotropic structure. For nodes 1, 4 and 7, the 500-hPa height anomalies show a dipole structure of positive values over Siberia and negative values to its south over the Eurasian continent. Anomalous southwesterly winds on the western side of the anticyclone over Siberia transport warm and moist air from northern Europe and the North Atlantic Ocean into the Atlantic sector of the Arctic Ocean (Figure 3), providing a plausible explanation of the warm surface temperature anomalies in the region (Figure 1). On the eastern side of the anticyclone, anomalous northwesterly winds bring cold and dry air from the Arctic Ocean into Eurasia continent, which is consistent with the negative surface temperature anomalies there. The opposite occurs for nodes 3, 6 and 9. A similar explanation involving anomalous pressure and wind fields can be applied to other nodes. The dipole structure that dominates the anomalous 500-hPa height fields over the North Atlantic Ocean for most nodes resembles the spatial pattern of the NAO (Figure 2). In addition, the patterns for several~~a few~~ nodes, such as nodes 4 and 7, have some resemblance to the spatial pattern of the AO over larger geographical region. The possible connection to NAO and AO is further investigated by averaging the daily index values of NAO or AO over all occurrence days for each node. The results (Table 2) show that nodes 1, 2, 3 (5, 8, 9) correspond to a significant positive (negative) phase of the NAO index characterized by negative (positive) height anomalies over Iceland and positive (negative) values over the central North Atlantic Ocean. Association is also found between nodes 1, 2, 3, and 6 (5, 7, 8, and 9) and the positive (negative) phases of the AO index.

3.3 Downward radiative fluxes

Besides the anomalous circulation patterns, anomalous surface radiative fluxes may also play a role in shaping the spatial pattern of surface temperature variability. In fact, the spatial pattern of the mean anomalous daily downward longwave radiation for an individual node (Figure 4) is in good agreement with the spatial pattern of the surface temperature anomalies of that node. In other words, increased downward longwave radiation is associated with positive surface temperature anomalies, and vice versa. As expected from previous studies (e.g., Sedlar et al. 2011), there is a significant positive correlation between downward longwave radiative fluxes and the anomalous total column water vapor and mid-level cloud cover (not shown). The correlation to low- and high-level cloud cover is, however, not significant (~~Not~~ not shown). Most of the water vapor in both the Arctic and Eurasia is derived from the North Atlantic Ocean, but the water vapor is transported into the Arctic by southwesterly flows and into Eurasia by northwesterly winds. The anomalous shortwave radiation corresponding to each node (not shown) is an order of magnitude smaller that of the longwave radiation anomalies and has a spatial pattern opposite to that of the mid-level cloud cover and the longwave radiation anomalies.

3.4 Sea ice

The analyses presented above attempt to explain the spatial pattern of surface temperature variability for each node from the perspective of anomalous heat advection and surface radiative fluxes. As mentioned earlier, there has been a debate in the literature about the role played by the sea ice anomalies in the Barents and Kara Seas in the development of the warm Arctic-cold Eurasia pattern. Here, we examine the anomalous turbulent heat flux (Figure 5) and sea ice concentration (Figure 6) for each node. Turbulent heat flux is considered positive when it is directed from the atmosphere downward to the ocean or land surfaces. Thus, a positive anomaly indicates either an increase in the atmosphere-to-surface heat transfer or a decrease in the heat transfer from the surface to the atmosphere. The magnitude of anomalous turbulent heat flux is found to be comparable to that of anomalous downward longwave radiation (Figure 4). For all nodes, the heat flux anomalies are larger over ocean than over land (Figure 5). For node 1, positive turbulent heat flux anomalies occur mainly over the Barents Sea, the western and central North Atlantic Ocean and the eastern North Pacific Ocean, indicating an increase in heat transport from the air to the ocean due possibly to an increase in vertical temperature gradient caused by warm air advection associated with anomalous circulation (Figures 2 and 3). The downward heat transfer results in sea ice melt in the Greenland Sea and the Barents Sea (Figure 6). For node 4, the anomalous southerly winds over the Nordic Sea produce larger positive turbulent heat flux anomalies (Figure 5). For node 7, the anticyclone is located more northwards, which generates opposite anomalous winds between the Nordic and northern Barents Seas and the southern Barents Sea and thus opposite turbulent heat flux anomalies that are consistent with the opposite sea ice concentration anomalies in the two regions (Figure 5). For nodes 3, 6, and 9, the anomalous cold air from the central Arctic Ocean flows into warm water in the Nordic and Barents Seas, producing negative turbulent heat flux anomalies and positive sea ice concentration anomalies (Figures 5 and 6). Sorokina et al. (2016) noted that turbulent heat flux usually peaks 2 days before changes in surface temperature pattern occur. The pattern of the composited anomalous 500-hPa geopotential height, turbulent heat flux and sea ice concentration 2 days prior to the day when the nodes occur (not shown) is similar to the current-day pattern in Figures 2, ~~6~~5, and 6. Our results support the conclusion of Sorokina et al. (2016) and Blackport et al. (2019) that the anomalous atmospheric circulations lead to the anomalous sea ice concentration in the Barents Sea.

3.5 ~~Contributions of SOM nodes to the t~~Trends in wintertime surface temperature

The results above suggest that both the surface temperature anomaly patterns over the Arctic Ocean and Eurasian continent and the sea ice concentration anomalies in the Nordic and Barents Seas can be explained largely by changes in atmospheric circulations and the associated vertical and horizontal heat and moisture transfer by mean and turbulent flows. Next, we assess the trends of wintertime surface temperature and the contributions of the~~se~~ SOM nodes to the trend~~s in wintertime surface temperature~~.

We first examine the time series of the accumulated number of days for each node in each winter for the 1979-2019 period (Figure 7). The time series for nodes 1, 4, 6, and 9 exhibit variability on interannual as well as decadal time scales. The occurrence frequency is noticeably larger after 2003 than prior to 2003 for nodes 1 and 4, and vice versa for nodes 6 and 9, and the difference between the two periods is significant at 95% confidence level. Given the spatial patterns of these four nodes (Figure 1), this indicates that the warm Arctic-cold Eurasia pattern occurred more frequently after 2003. A linear trend analysis of the time series for each node (Table ~~2~~3) reveals significant positive trends in occurrence frequency for nodes 1 and 4 and significant negative trends for nodes 6 and 9, which agree with the result from a previous study (Clark and Lee, 2019; Overland et al., 2015) that suggested an increasing trend of the warm Arctic and cold Eurasia pattern.

These trends in the occurrence frequency of the SOM nodes contribute to the trends in the total wintertime (DJF) surface temperature anomalies (Figure 8, top panel) that have significant positive trends over the Arctic Ocean and in regions of Northern and ~~Southern~~ Eastern Europe and negative, mostly insignificant trends in Central Siberia. The contribution, however, varies from node to node (Figure 9). Node 1 has the largest domain-averaged contribution of 18.7%, followed by its mirror node (node 9) at 10.1%. Nodes 4 and 6 account for 2.8% and 4.3% of the total trend, respectively. None of the remaining nodes explain more than 2%. All nodes together explain 39.5% of the total trend in wintertime surface air temperature. The spatial pattern of the SOM-explained trends (Figure 8, middle panel) is similar to the warm Arctic--cold continent pattern, whereas the residual trend resembles more the total trend (Figure 8 bottom panel).

3.6 Mechanisms

The results presented above indicate that the SOM patterns explain nearly 40% of the trend in wintertime surface air temperature anomalies and majority of the contributions (35 out of 40%) come from the two pairs of the nodes (nodes 1, 9, and 4, 6). –The analyses hereafter will focus on these four nodes. Below we assess the atmospheric and oceanic conditions associated with the occurrences of the four nodes via regression analysis. Specifically, the anomalous seasonal SST and atmospheric circulation variables are regressed onto the normalized time series of the number of days when each of the four nodes occurs (Figures 10, 11, and 12).

For node 1, the SST regression pattern in the Pacific Ocean shows significant positive anomalies over the tropical western Pacific Ocean and central North Pacific Ocean (Figure 10). The positive SST anomalies also occur over most of the North Atlantic. Negative SST anomalies occur over the central tropical Pacific Ocean, though they are not significant at 95% confidence level. The SST regression pattern is reversed for node 9. The direction of wave activity flux indicates the direction of group speed of stationary planetary wave. Here we calculate the wave activity flux defined by Takaya and Nakamura (2001), which considers the influence of mid-latitude zonal wind (Figure 12). For node 1, ~~The~~ the corresponding anomalous 500-hPa height regression (Figure 11) shows two Rossby wavetrains: one is excited over the central Pacific Ocean and propagates northeastwards into North America and North Atlantic Ocean, and the other, which displays a~~the~~ stronger signal, originates from central North Atlantic and propagates northeastwards to the Arctic Ocean and southeastwards to the Eurasian continent ~~and the western Pacific Ocean~~ (Figure 11 and 12). ~~The large SST anomalies over the Nordic Ocean augment the wave signal through local air-sea interaction. The wave activity flux and streamfunction exhibit well the horizontal propagating direction of the planetary wave.~~ For node 9, the corresponding anomalous 500-hPa height and streamfunction show an opposite pattern, but the wave activity flux is similar to that of node 1.

For node 4, the SST anomalies over the tropical Pacific Ocean appear to be in a La Niña state, which shows stronger negative SST anomalies over the eastern tropical Pacific Ocean than those for node 1 (Figure 10). The positive SST anomalies over the North Pacific shift more northwards relative to that of node 1. The positive SST anomalies over the North Atlantic are weaker than those for node 1. The corresponding wavetrain over the Pacific Ocean is stronger than that over the Atlantic Ocean (Figure 11), which is~~can~~ also be observed in the pattern of wave activity and streamfunction (Figure 12). The corresponding pattern for node 6 is nearly reversed, but there are some noticeable differences in the amplitude of the wavetrain and SST anomalies. For example, the magnitude of the anomalous

SST and the 500-hPa height over the central North Pacific is larger for node 6 than that for node 4.

Besides the above-mentioned variables, similar regression analysis is also performed for the anomalous 850-hPa wind field and anomalous downward longwave radiation (~~Not~~ not shown). Their regression patterns, which are similar to those in Figures 3 and 4, explain well the decadal variability of the number of days for nodes 1, 4, 6, and 9. Together, these results in Figures 10-12 indicate that the decadal variability of the occurrence frequency of the four nodes in recent decades is related to two wavetrains induced by SST anomalies over the central North Pacific Ocean and the North Atlantic Ocean (Figures 10 and 11). The aforementioned SST regression patterns over the Atlantic and Pacific Oceans also show features of the AMO and PDO (Figure 10). Since both the AMO and PDO exhibited a phase change in the late 1990s (Yu et al., 2017), the question is whether a similar change in the SOM frequency also appear in the late 1990s. A comparison of the averaged frequency before and after 1998 shows a significant drop in frequency for nodes 6 and 9 and an increase in frequency for node 1 (not shown). This result suggests that the change in the AMO and PDO indices may contribute to the change in the frequencies of the warm Arctic-cold Eurasia continent pattern.

3.7 Interdecadal variability

The four-decade-long ERA-Interim reanalysis is not adequate for examining interdecadal to multi-decadal variations represented by the PDO and AMO indices. Further analysis is performed using the 20CR daily reanalysis data for the 1854-2014 period. Before applying the SOM technique to the 20CR data, we first remove the trend to eliminate the influence from the global warming. No low-pass filter is applied before SOM analysis in order to test the stability of the SOM results for the different periods. The spatial SOM patterns from the de-trended century-long 20CR data (Figure 13) are similar to those for the 1979-2019 period (Figure 1). Nodes 1, 4, and 7 correspond to the positive phase of the warm Arctic-cold Eurasia pattern and the negative phase can be observed in nodes 3, 6, and 9. The magnitude in Figure 13 is smaller compared to the recent four decades in Figure 1. The occurrence frequencies of ~~all~~ the four nodes, 1, 4, 6, and 9 (Figure 14), are close to those for the recent four decades (Figure 7). It indicates that the SOM method can obtain stably the main modes of wintertime surface air temperature variability. For the recent four decades, the time series of the number of days also displays a noticeable increasing (decreasing) trend for nodes 1 and 4 (6 and 9), suggesting that the trend in the recent four decades is a reflection of an interdecadal variability of wintertime surface air temperature.

Next, we apply a 40-year low-pass filter to the time series of the occurrence frequencies for nodes 1, 4, 6 and 9 and the AMO and PDO indices and calculate correlations. There is a significant correlation between the time series and the AMO index, with correlation coefficients of 0.36 for node 1, 0.27 for node 4, -0.37 for node 6, and -0.20 for node 9, all of which are at the 95% confidence level. No significant correlations, however, are found between the filtered time series and the PDO index. If we define a~~n~~ SST index to represent the variability of SST anomalies over the central North Pacific Ocean (20°N-40°N, 150°E-150°W), the 40-year low-pass filtered central North Pacific Ocean SST index is now significantly correlated with the filtered time series of occurrence frequencies for nodes 1 and 9 (0.55 for node 1 and -0.46 for node 9). The correlation results are consistent with the SST regression map for the recent decades (Figure 10).

To confirm the effect of SST anomalies on the warm Arctic -cold Eurasia pattern, we also perform EOF analysis of wintertime detrended seasonal surface air temperature anomalies for the 1854-2014 period (Figure 15). The spatial patterns of the first and second EOF modes show the negative phase of the warm Arctic-cold Eurasia pattern and the 40-year low-pass filtered time series is inversely correlated with the 40-year low-pass filtered wintertime AMO index (-0.46, p<0.05 for mode 1 and -0.44, p<0.05 for mode 2). The 40-year low-pass filtered time series of the two EOF modes haves a significant negative correlation with the 40-year low-pass filtered central North Pacific Ocean SST index, with correlation coefficients of -0.19 and -0.26 (p<0.05). Only PC1 has a significant correlation with the PDO index (0.38, p<0.05). Thus, the increase in the occurrence of the warm Arctic-cold Eurasia pattern in the recent decades is a part of the interdecadal variability of the pattern, which is influenced by the AMO index, the PDO index, and the central North Pacific SST.

4 Conclusions and Discussions

In this study, we examine the variability of wintertime surface air temperature in the Arctic and the Eurasian continent (20 °E-130 °E) by applying the SOM method to daily temperature from the gridded ERA-Interim dataset for the period 1979-2019 and from the 20CR reanalysis for the period 1854-2014 and the EOF method to seasonal temperature from the 20CR reanalysis for the period 1854-2014. The spatial pattern in the surface temperature variations in the study region, as revealed by the nine SOM nodes, is dominated by concurrent warming in the Arctic and cooling in Eurasia, and vice versa. The nine SOM patterns explain nearly 40% of the trends in wintertime surface temperature and 88% of that are accounted for by only four nodes. Two of the four nodes (nodes 1 and 4) represent the warm Arctic-cold Eurasian pattern and the other two (nodes 6 and 9) depict the opposite cold Arctic-warm Eurasia pattern. There is a clear shift in the frequency of the occurrence of these patterns near the beginning of this century, with the warm Arctic – cold Eurasia pattern dominating since 2003, while the opposite pattern prevailing from the 1980s through the 1990s. The warm Arctic-cold Eurasia pattern is accompanied by an anomalous high pressure and anticyclonic circulation over the Eurasian continent. The anomalous winds and the associated temperature and moisture advection interact with local longwave radiative forcing and turbulent~~ce~~ fluxes to produce positive (negative) temperature anomalies in the Arctic (Eurasian continent). The circulation is reversed for the cold Arctic-warm Eurasia pattern. The warm, moist air mass advected to the Arctic by the anomalous atmospheric circulations and the increased downward turbulent heat flux also explain sea ice melt in the Barents and Kara Seas. In other words, the sea ice loss in the Barents and Kara Seas and the cooling of the Eurasian continent can both be traced to anomalous atmospheric circulations.

Increasing occurrences of the warm Arctic-cold Eurasian continent pattern appear to relate to rising SST over the central North Pacific and North Atlantic Oceans (positive AMO phase). The SST anomalies trigger two Rossby wavetrains spanning from the North Pacific Ocean, North America, and the North Atlantic Ocean to the Eurasian continent. The two wavetrains are strengthened through local sea-atmosphere-ice interactions in mid-high latitudes, which influence the change in the occurrence frequency of the warm Arctic-cold Eurasian continent pattern. Our results agree with those of previous studies (Lee et al., 2011; Sato et al., 2014; Clark and Lee, 2019). But previous studies only focus on the effects of SST anomalies over either North Pacific or North Atlantic Oceans. We also note that the two wavetrains excited by SST anomalies over different oceans differ in amplitudes, leading to somewhat different warm Arctic-cold Eurasia patterns.

Using century-long data, we show that the warm Arctic-cold Eurasia pattern is an intrinsic climate mode, which has been stable since 1854. The recent increasing trend in its occurrence is a reflection of an interdecadal variability of the pattern resulting from the interdecadal variability of SST anomalies over the central Pacific Ocean and over the Atlantic Ocean represented by the AMO index. Sung et al. (2018) investigated interdecadal variability of the warm Arctic and cold Eurasia pattern and considered the variability of the SST over the North Atlantic as its origin. Our results suggest that the variability of the SST over the North Pacific also plays an important role. However, internal atmospheric variability remains another potential source. The Rossby wavetrains also lead to deepening of a trough in East Asia and generate an anomalous low pressure and cold temperature in northern China (Figure 10), which further suggests that ~~the relationship between~~ a warmer Arctic, especially warmer Barents and Kara Seas ~~, and~~ is not the driver for~~of~~ the increasing occurrence of cold spells in East Asia, as suggested in ~~may not be as strong as~~ previous~~ly thought~~ studies (Kim et al., 2014; Mori et al., 2014; Kug et al., 2015; Overland et al., 2015).

Our results suggest that the increasing trend in warm Arctic-cold Eurasia pattern may be related to the anomalous SST over the central North Pacific and the North Atlantic Oceans. But we cannot rule out the influence of the Arctic sea ice loss on the trend. ~~Because the~~ The Arctic sea ice loss results from ~~two main drivers: external and internal forcings. The former refers to the~~ both Arctic warming due to anthropogenic increasing of greenhouse gas concentrations and natural variability of ~~; the latter comes from the~~ climate system ~~internal variability,~~ such as ~~anomalous~~ SST anomalies. This study considers natural variability or ~~only the~~ internal driver of climate system. The Arctic warming caused external forcing related to increasing greenhouse gas emissions can produce an anomalous anticyclone over the Barents and Kara Seas, leading to the warm Arctic-cold continents pattern.

Although the ERA-Interim reanalysis is overall superior in describing ~~has the best performance in overall depiction of~~ the Arctic atmospheric environment to other similar global reanalysis products, it contains ~~includes~~ warm and moist biases in the surface layer (Jakobson et al., 2012; Chaudhuri et al., 2014; Simmons and Poli, 2015; Wang et al., 2019). However, we believe these biases, as well as the relatively coarse resolution, should have minimum impact in the results from the current analyses. Further, although the current analyses were performed on a predetermined SOM grid with 3x3 nodes, an increase in the number of SOM nodes didn't change the conclusions.

Our results help broaden the current understanding of the formation mechanisms for the warm Arctic-cold Eurasia pattern. The SST anomalies over Northern Hemisphere oceans may offer a potential for predicting its occurrence. The statistical relationship between SST anomalies and the occurrences of the warm Arctic-cold continents pattern may help improve the predictability of wintertime surface air temperature over Eurasian continent on interdecadal time scales.

Data Availability

All data used in the current analyses are publicly available. The monthly sea ice concentration data are available from the National Snow and Ice Data Center (NSIDC) (http://nsidc.org/data/NSIDC-0051), the ERA-Interim reanalysis data are available from the European Center for Mid-Range Weather Forecasting (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim) and the sea surface temperature data are available from the Hadley Centre for Climate Prediction and Research (ftp://ftp.cdc.noaa.gov/Datasets/noaa.oisst.v2.highres/). The long-term SST data are derived from from the Twentieth Century Reanalysis project, version 2c (20CR) (https://climatedataguide.ucar.edu/climate-data/noaa-20th-century-reanalysis-version-2-and-2c).

Competing interests

The authors declare that they have no conflict of interest.

Author Contributions

L. Yu designed the study, with input from S. Zhong, and carried out the analyses. L. Yu and S. Zhong prepared the manuscript. C. Sui plotted a part of Figures. –B. Sun revised the manuscript.

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Table 1. Spatial correlations (Corrs) between the daily winter (DJF) surface air temperature and the corresponding SOM pattern for each day from 1979 to 2018.

	3×1	2×2	3×2	4×2	3×3	5×2	4×3	5×3	4×4
Corr	0.26	0.43	0.48	0.48	0.50	0.49	0.50	0.51	0.51

Table 2. Averaged anomalous NAO and AO indices for all occurrences of each SOM node. Asterisks indicate the above 95% confidence level.

	Node1	Node2	Node3	Node4	Node5	Node6	Node7	Node8	Node9
NAO	0.38*	0.22*	0.12*	0.05	-0.22*	-0.02	-0.07	-0.31*	-0.32*
AO	0.44*	0.38*	1.03*	-0.42	-0.62*	0.22*	-0.44*	-1.11*	-0.41*

Table 3. Trends in the frequency of occurrences for each SOM node (day yr^{-1}). Asterisks indicate the above 95% confidence level.

	Node1	Node2	Node3	Node4	Node5	Node6	Node7	Node8	Node9
Trend	0.80*	0.10	-0.18	0.22*	-0.02	-0.39*	0.17	-0.17	-0.50*

Table 4. Frequencies of occurrence (%) of wintertime surface air temperature patterns in Figure 1 for all winters before 1998 and after 1998 for the period 1979-2019. Values with Asterisks are significantly different from climatology above the 95% confidence level.

	Frequencies of occurrence		
SOM patterns	All winters	Winters before 1998	Winters after 1998
Node 1	17.1	7.4*	26.8
Node 2	4.4	3.3	5.4
Node 3	17.2	18.8	15.6
Node 4	8.6	5.4	11.7
Node 5	3.4	3.4	3.5
Node 6	10.2	15.2*	2.1*
Node 7	13.7	10.6	16.8
Node 8	10.1	12.1	8.0
Node 9	15.4	23.7*	7.1*

Figure Captions

Figure 1. Spatial patterns of SOM nodes for daily wintertime (December, January, and February) surface air temperature anomalies (℃) without removing their linear trends from ERA-Interim reanalysis over the 1979-2019 period. The number in brackets denotes the frequency of the occurrence for each node.

Figure 2. Corresponding 500-hPa geopotential height anomalies (gpm) without removing their linear trends from ERA-Interim reanalysis over the 1979-2019 period for each node in Figure 1. Dotted regions indicate the above 95% confidence level. The thick black lines show the study region.

Figure 3. Corresponding anomalous 850-hPa wind field (ms^{-1}) without removing ~~the~~ its linear trend from ERA-Interim reanalysis over the 1979-2019 period for each node in Figure 1. Shaded regions indicate the above 95% confidence level. The thick black lines show the study region.

Figure 4. Corresponding anomalous daily accumulated downward longwave radiation (105 W m-2) without removing ~~the~~ its linear trend from ERA-Interim reanalysis over the 1979-2019 period for each node in Figure 1. Dotted regions indicate the above 95% confidence level. The thick black lines denote show the study region.

Figure 5. Corresponding anomalous daily accumulated turbulent heat flux (sensible and latent heat) (10^{5}W m^{-2}) without removing their linear trends from ERA-Interim reanalysis over the 1979-2019 period for each node in Figure 1. Positive values denote heat flux from atmosphere to ocean and vice versa. Dotted regions indicate the above 95% confidence level. The thick black lines denote show the study region.

Figure 6. Corresponding anomalous wintertime sea ice concentration without removing ~~the~~ its linear trend from the NSIDC over the 1979-2019 period for each node in Figure 1. Dotted regions indicate the above 95% confidence level.

Figure 7. Time series of the number of days for occurrence of each SOM node in Figure 1 over the 1979-2019 period. The thick lines denote the trend in time series.

Figure 8. Total (top), SOM-explained (middle), and residual (bottom) trend in wintertime (DJF) surface air temperature (^{o} C yr^{-1}) over the 1979-2019 period. Dots in the top panel indicate above 95% confidence level.

Figure 9. Trends in surface air temperature explained by each SOM node (℃ yr^{-1}) over the 1979-2019 period. The percentage in the upper of each panel indicates the fraction of the total trend represented by each node.

Figure 10. Anomalous SST (℃) regressed into the normalized time series of occurrence number for nodes 1, 4, 6, and 9 without removing ~~the~~ its linear trend from the NOAA over the 1979-2019 period.

Figure 11. Anomalous 500-hPa geopotential height (gpm) regressed into the normalized time series of occurrence number for nodes 1, 4, 6, and 9 without removing ~~the~~ its linear trend from ERA-Interim reanalysis over the 1979-2019 period.

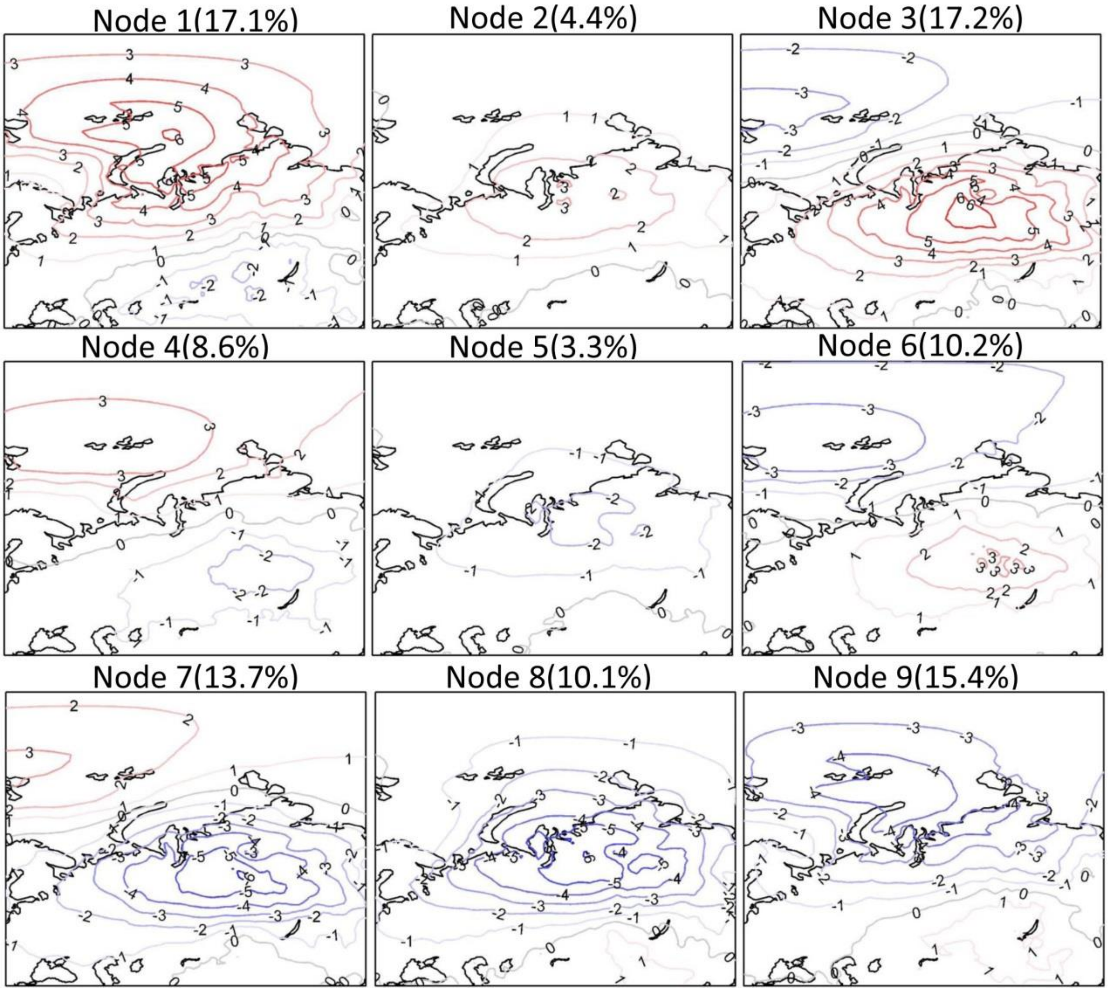
Figure 12. The anomalous wave activity flux (vectors) (Takaya and Nakamura, 2001) and stream function (colors, units: 10^{7} m^{2} s^{-1}) regressed onto the normalized time series of occurrence number for nodes 1, 4, 6, and 9 without removing ~~the~~ their linear trends from ERA-Interim reanalysis over the 1979-2019 period.

Figure 13. Spatial patterns of SOM nodes for detrended daily wintertime (December,

January, and February) surface air temperature anomalies (℃) from the 20CR reanalysis for the 1851-2014 period. The number in brackets denotes the frequency of the occurrence for each node.

Figure 14. Time series of the number of days for occurrence of each SOM node in Figure 13 from the 20CR reanalysis for the 1851-2014 period. The thick red lines denote the result in Figure 7 from the ERA-Interim reanalysis for the 1979-2019 period.

Figure 15. The (a) leading pattern and (b) its time series (PC1 and PC2) of EOF analysis of wintertime surface air temperature anomalies from the 20CR reanalysis for the 1851-2014 period. Prior to EOF analysis, surface sir temperature data are detrended. A 40-yr low-pass filtered is applied to the time series of PC1, PC2, AMO, PDO, and central North Pacific Ocean (CNPO) indices. The correlation coefficients between PC1 and AMO, PDO and CNPO indices are -0.46 ($p<0.0001$), 0.38 ($p<0.0001$), and -0.19 ($p=0.019$); those between PC2 and and AMO, PDO and CNPO indices are -0.44 ($p<0.0001$), 0.38 ($p<0.0001$), and -0.26 ($p=0.0009$).



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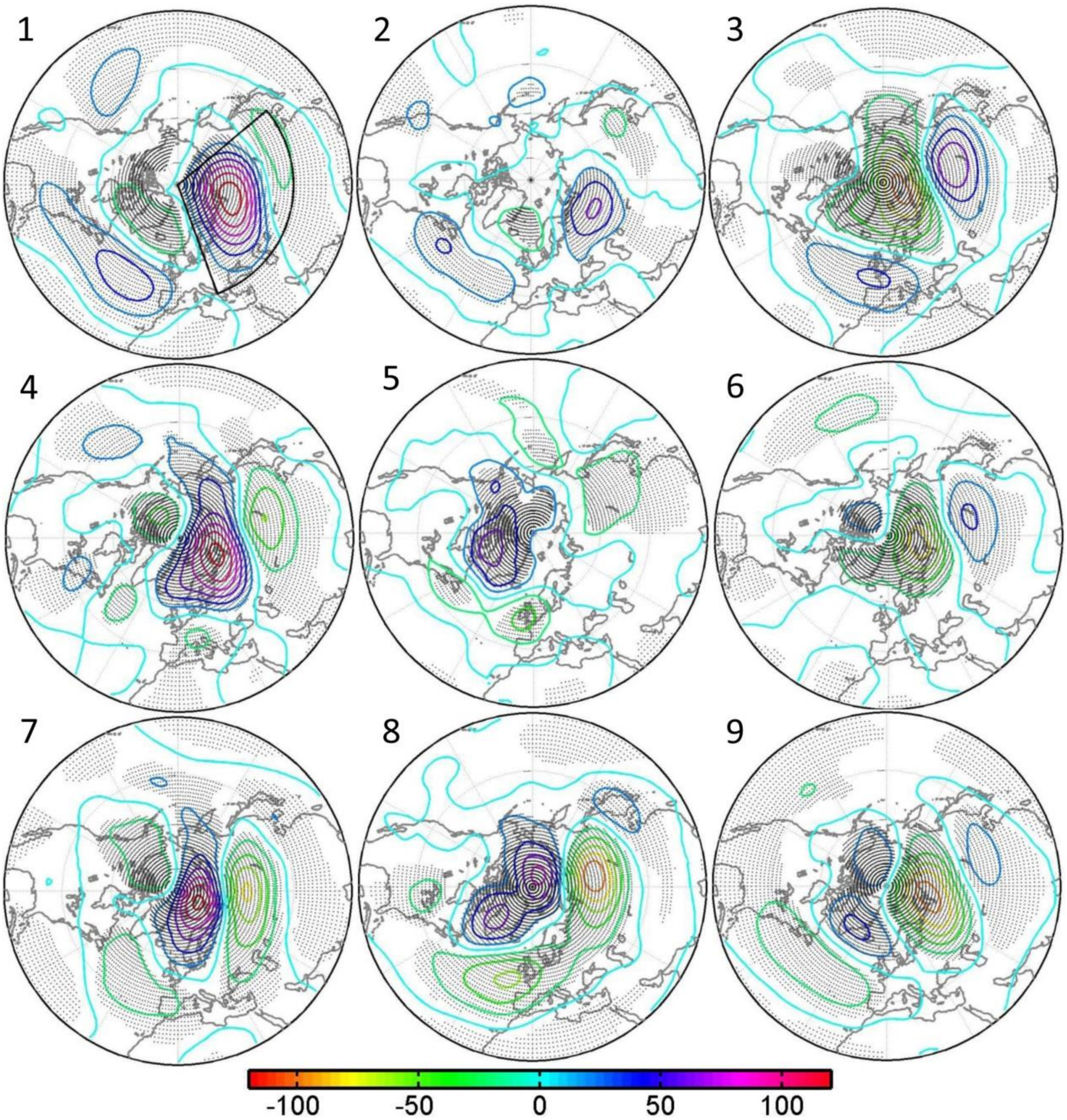

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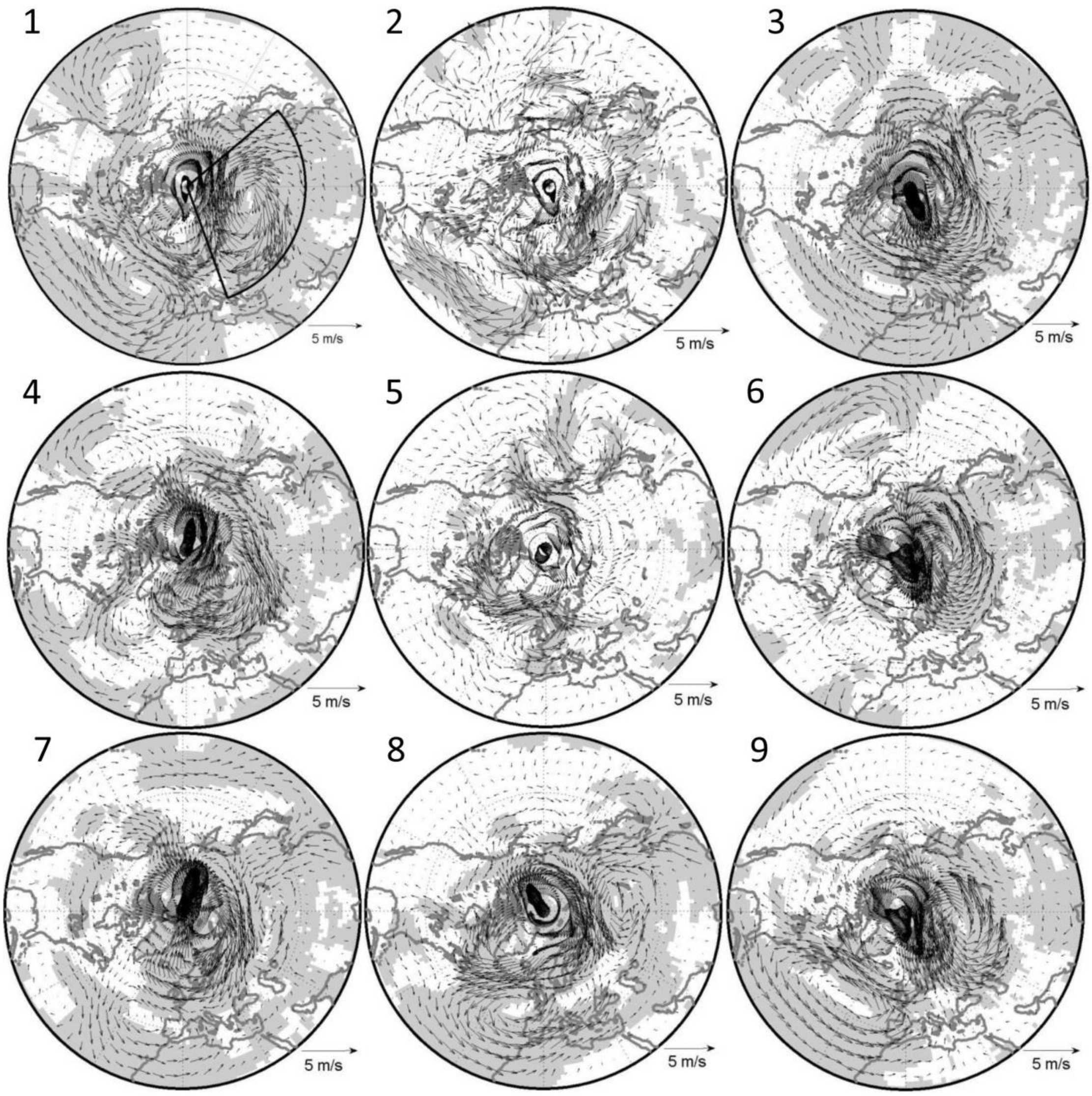

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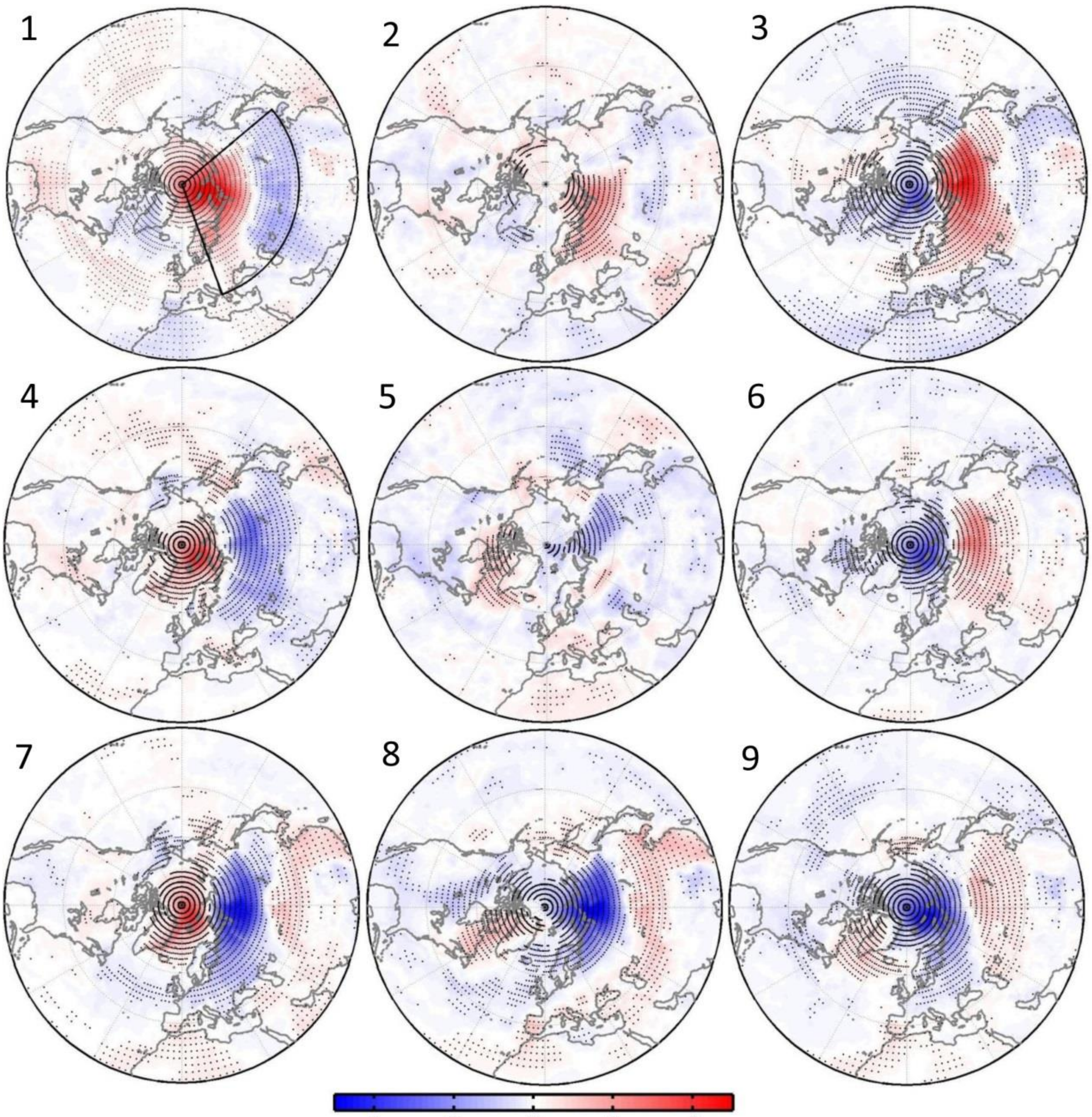

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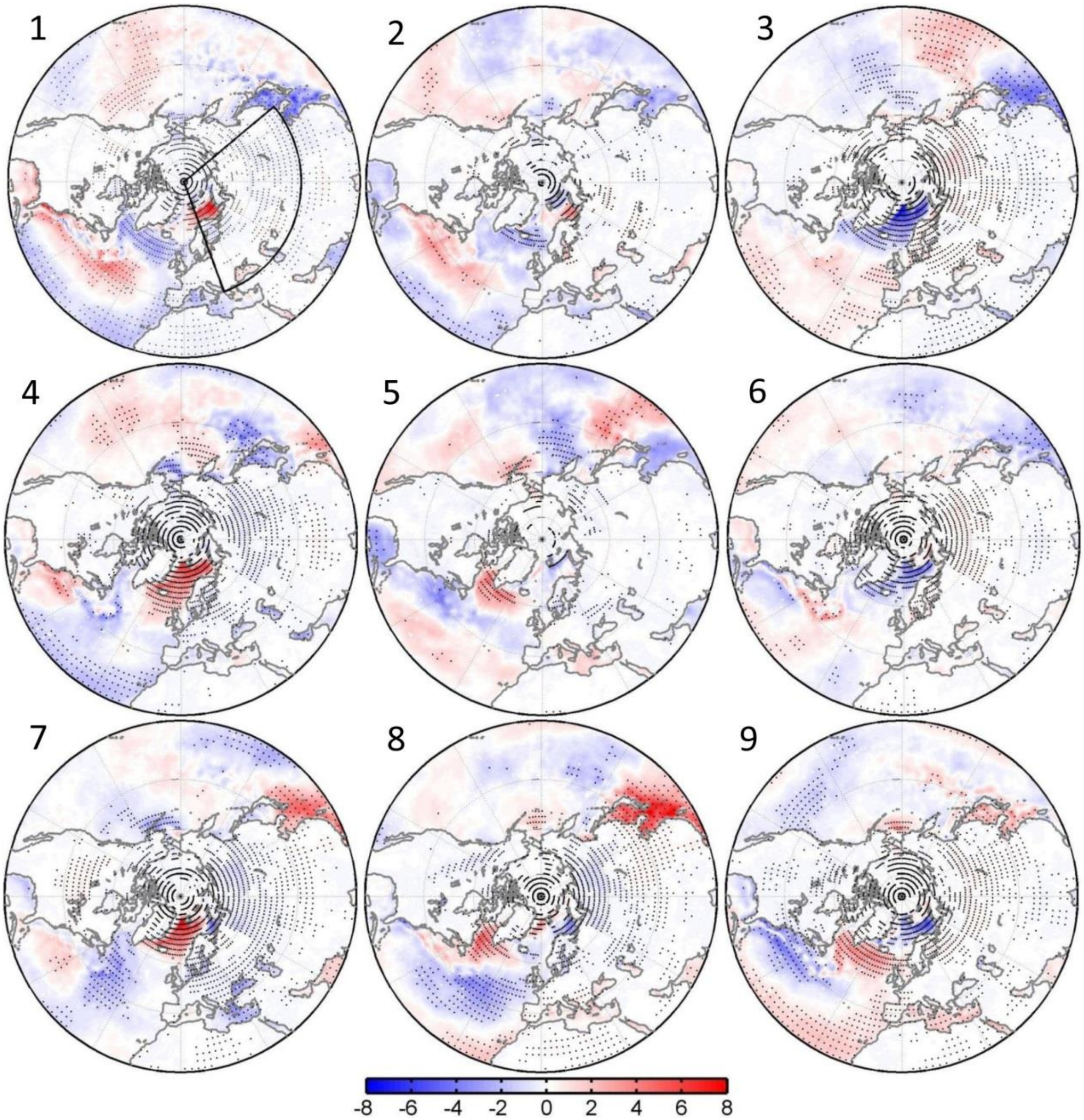

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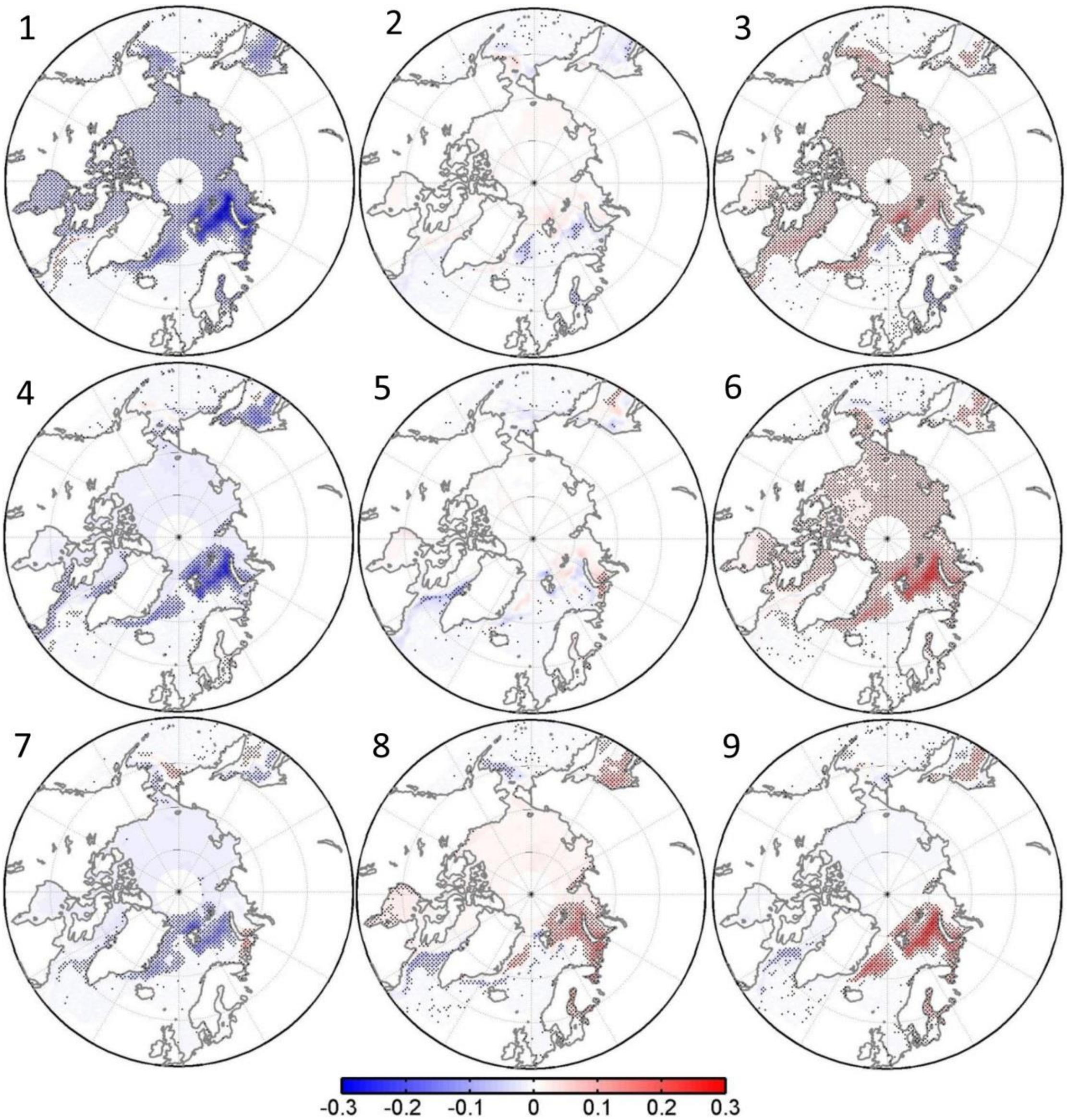

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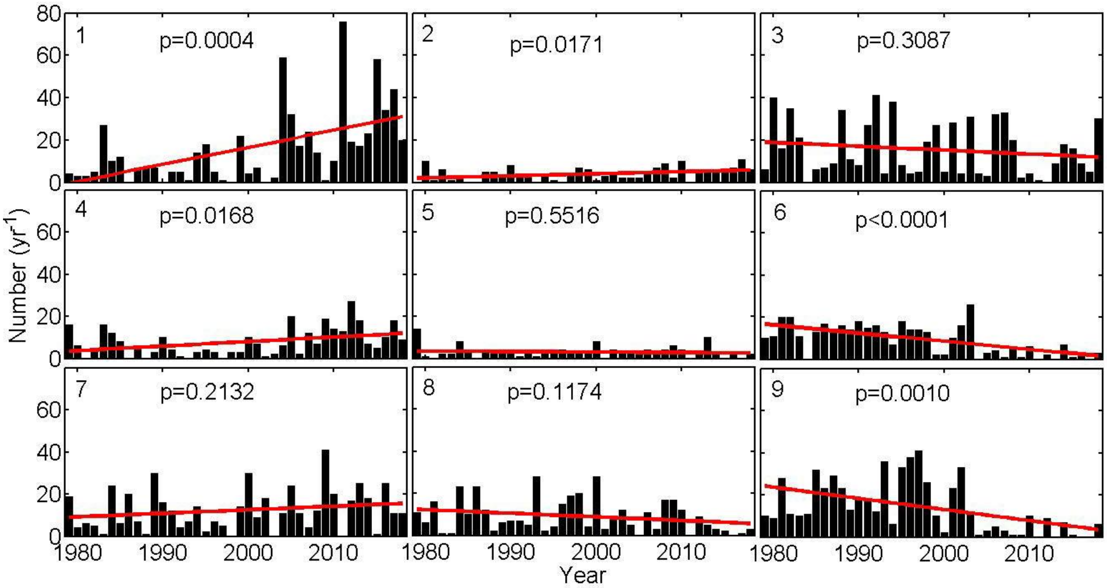

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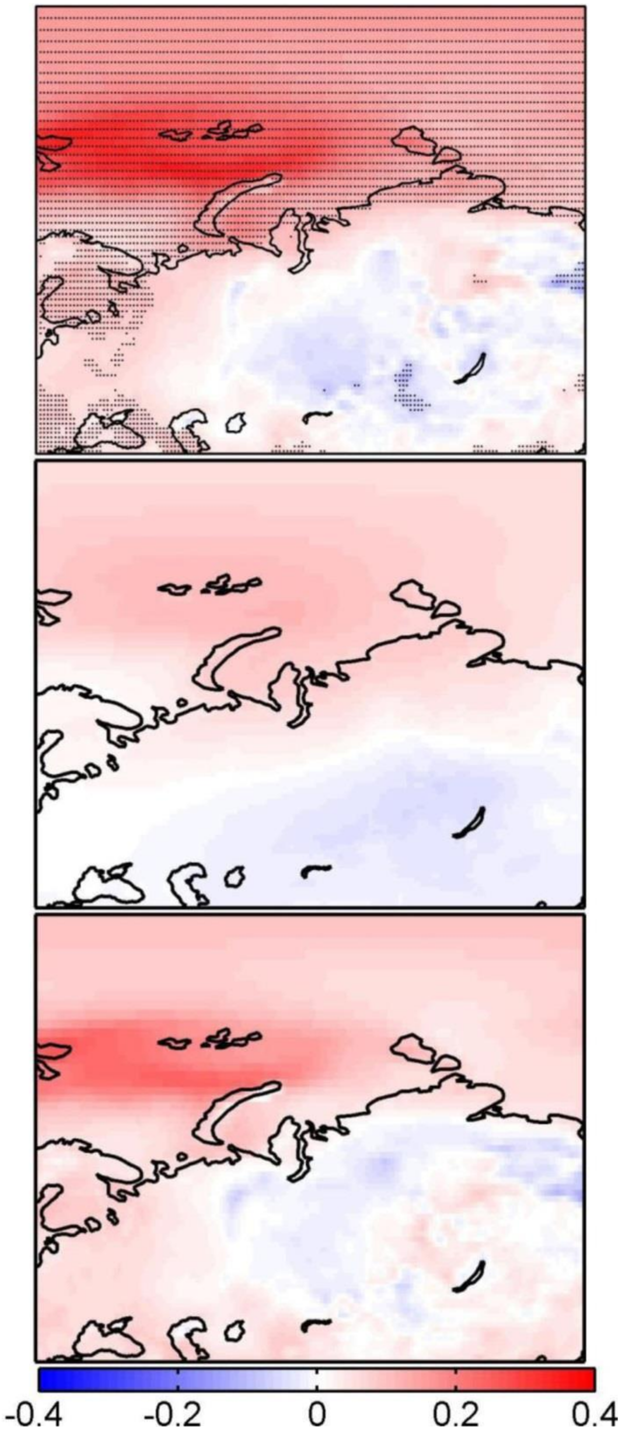

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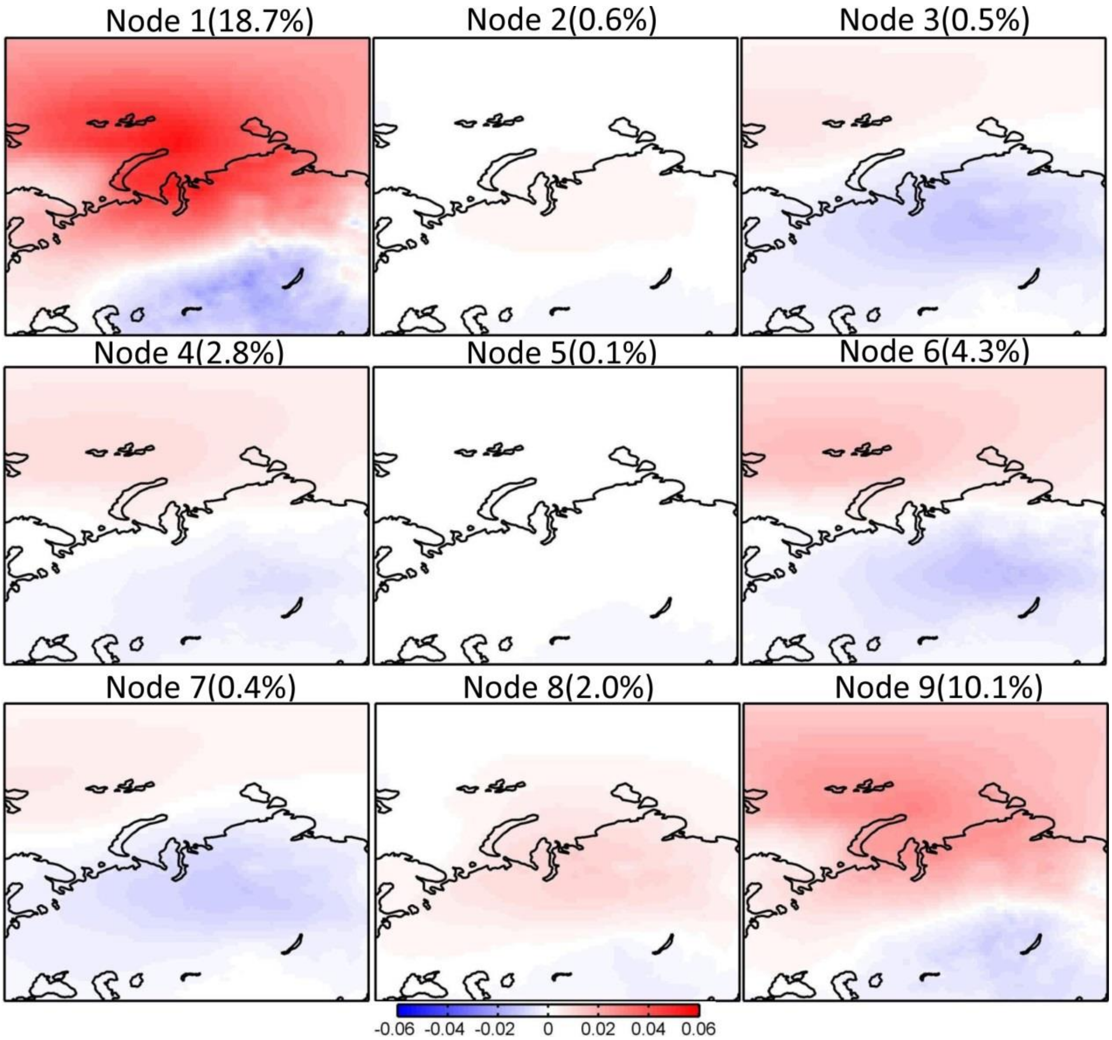

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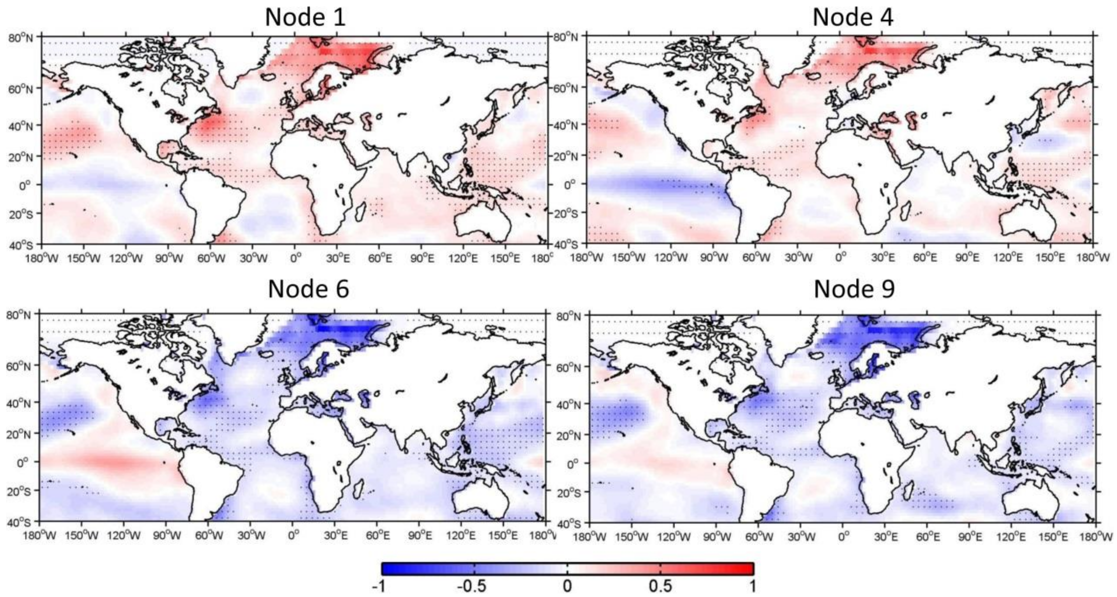

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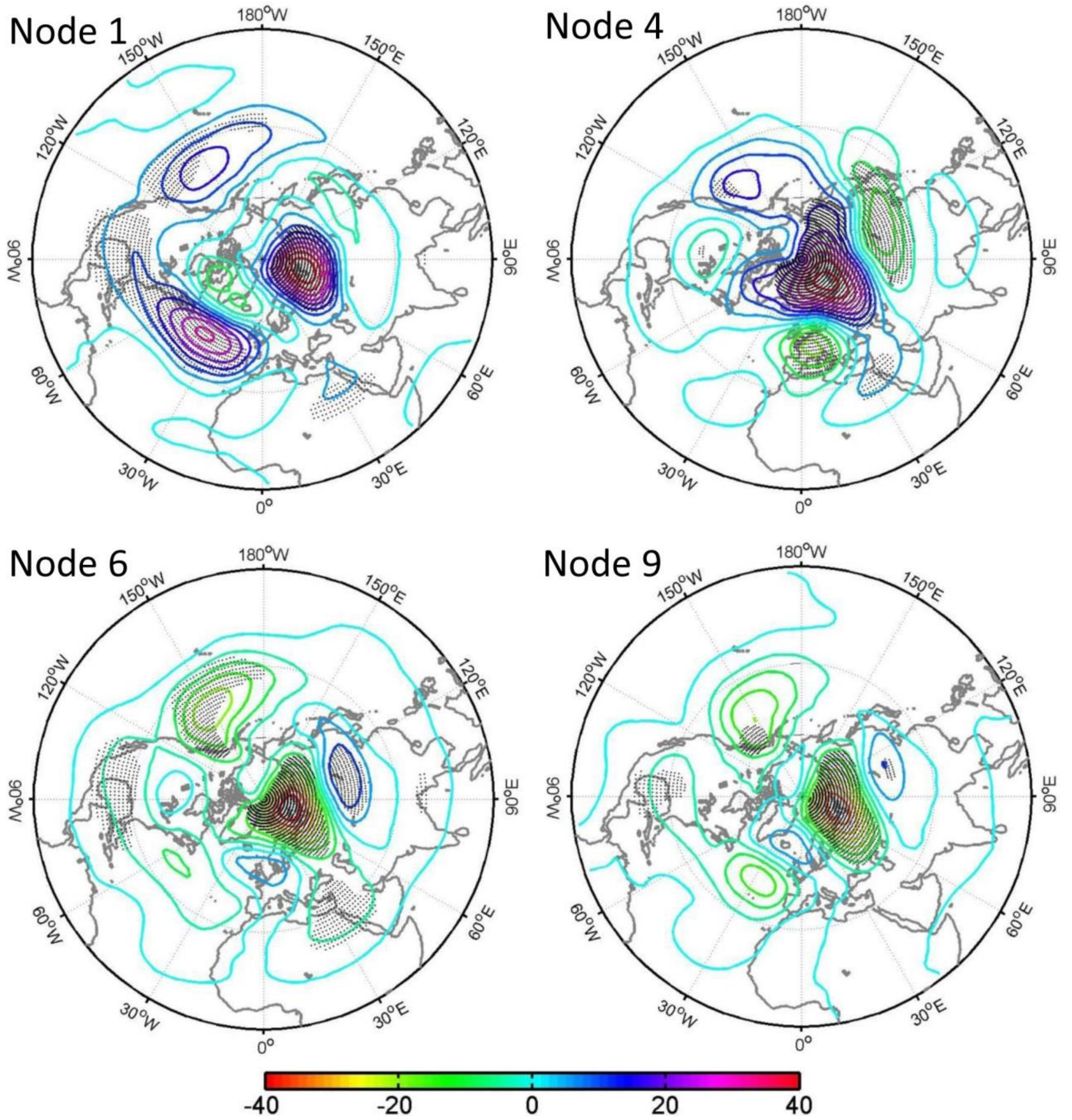

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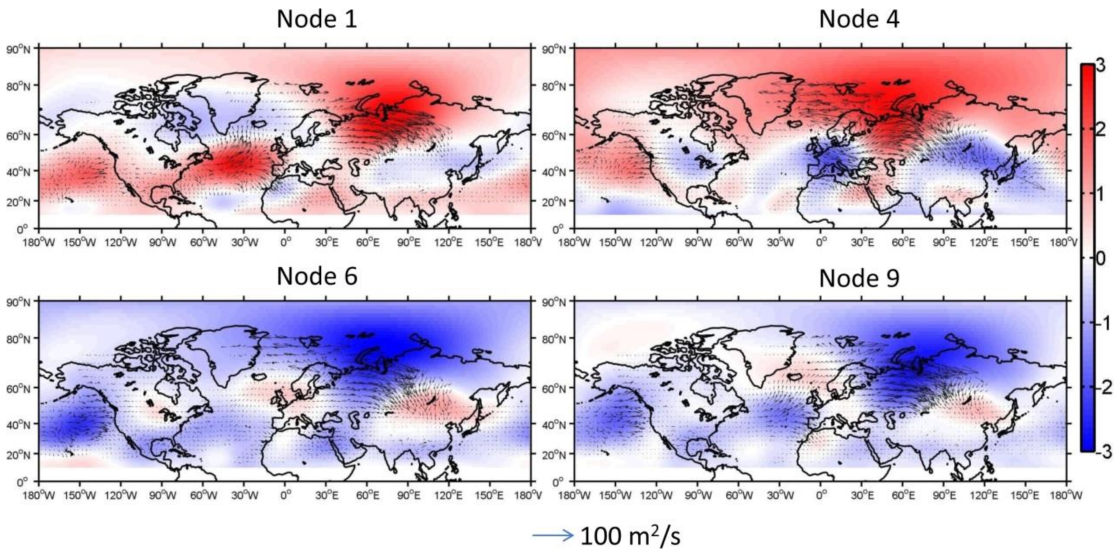

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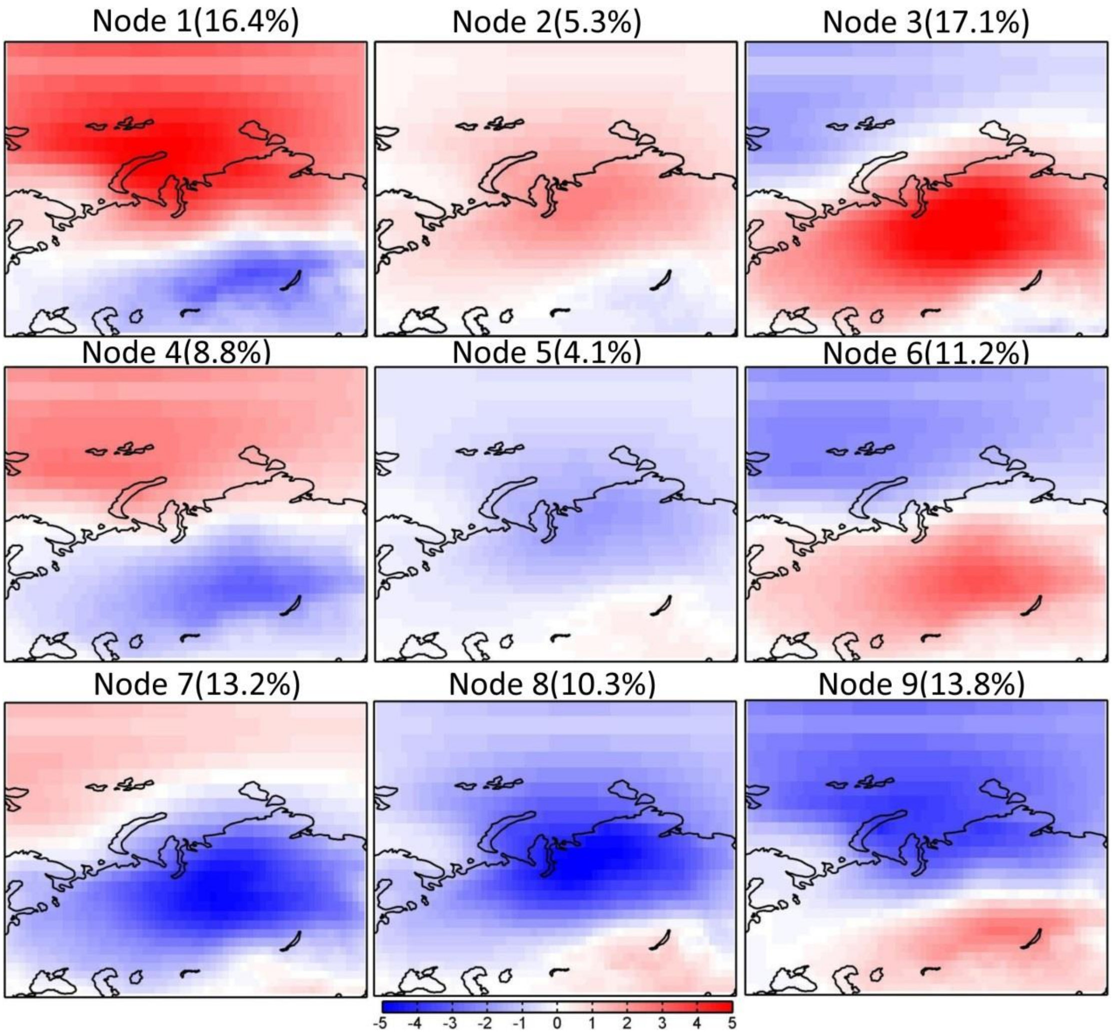

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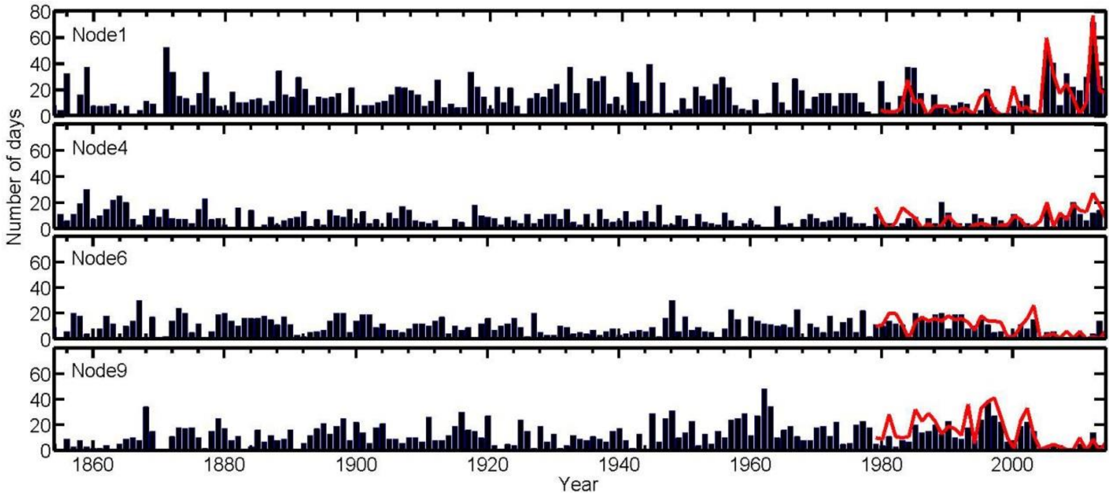

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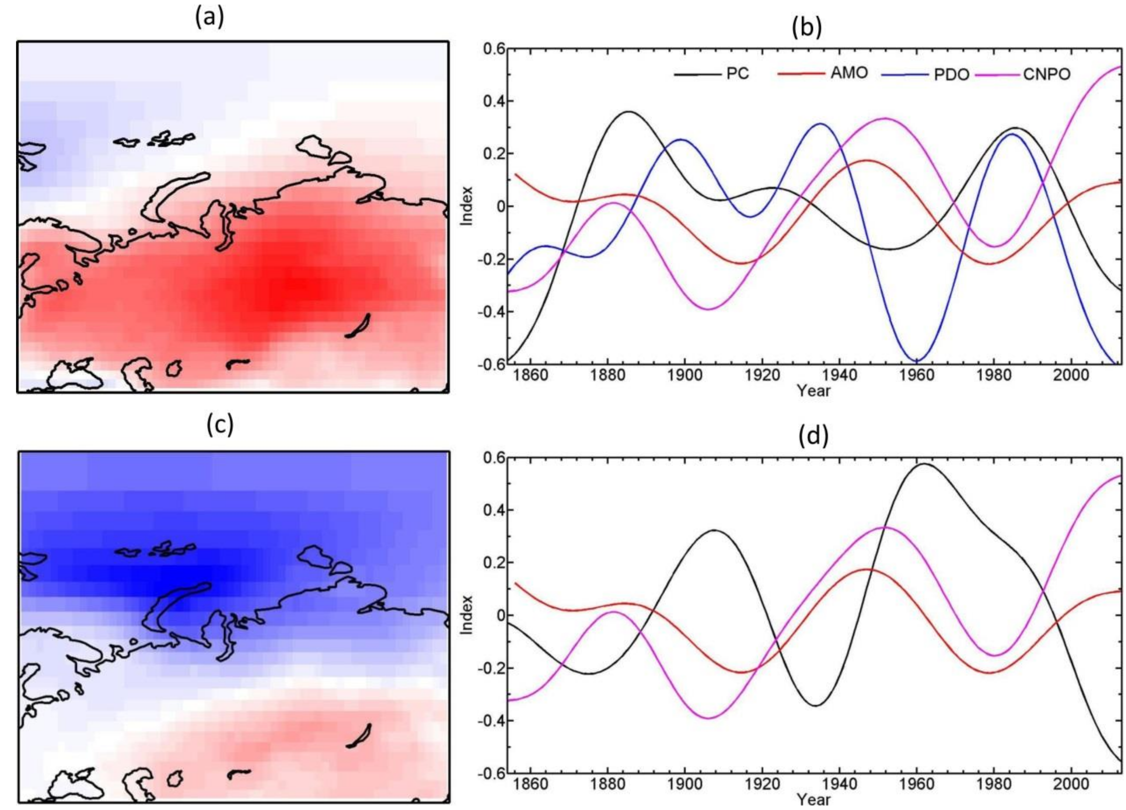

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