

1 The figure captions can still be improved, e.g.

2 Fig.2: the sub-domain in 1 is the study area. Then you don't need to repeat in other figures  
3 caption.

4 We deleted the sentence in the figure captions except for Figure 2.

5 In many figures caption, you stated the same text: "without removing,,", you can write it in the  
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7 We deleted the expression, and added a sentence at the end of the first paragraph in the section  
8 Datasets and methods ("In our analyses, we remain the trends in the data over the 1979-2019  
9 period.").

10 Fig.7: red line is the trend.

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29 **Revisiting the trend in the occurrences of the “warm Arctic-cold Eurasian continent”**

30 **temperature pattern**

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

65

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

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73 **1 Introduction**

74 In recent decades, winter season temperature in the Arctic has been rising at a rate faster than the  
75 warming experienced in any other regions of the world (Stroeve et al., 2007; Screen and Simmonds,  
76 2010; Stroeve, 2012). In contrasts, there has been an increasing trend in colder than normal winters  
77 over the northern mid-latitude continents (Mori et al., 2014; Cohen et al., 2014; 2018). This pattern of  
78 opposite winter temperature trend between the Arctic and high-mid latitude continents, referred to as  
79 the warm Arctic-cold continents pattern (Overland et al., 2011; Cohen et al., 2014; Walsh, 2014), has  
80 received considerable interest in the scientific community especially with regard to dynamical and  
81 physical mechanisms for the development of the phenomenon (Mori et al., 2014; Vihma, 2014; Barnes  
82 and Screen, 2015; Kug et al., 2015; Overland et al., 2015; Chen et al., 2018).

83 Using observational analyses or coupled ocean-atmosphere modeling, a number of studies have  
84 attributed the recent warm Arctic-cold continents pattern to the Arctic sea ice loss in boreal winter  
85 (Inoue et al., 2012; Tang et al., 2013; Mori et al., 2014; Kug et al., 2015; Cohen et al., 2018; Mori et al.,  
86 2019). Sea ice variability in different parts of the Arctic Ocean has been linked to climate variability in  
87 different parts of the world. Specifically, sea ice loss in the Barents and Kara Seas has been linked to  
88 cold winters over East Asia (Kim et al., 2014; Mori et al., 2014; Kug et al., 2015; Overland et al., 2015)  
89 and in central Eurasia (Mori et al., 2014), while a similar connection has been found between cold  
90 winters in North America and sea ice retreat in the East Siberian and Chukchi Seas (Kug et al., 2015).  
91 A most recent study (Matsumura and Kosaka, 2019) attributed the warm Arctic-cold continents pattern  
92 to the combined effect of Arctic sea ice loss and the atmospheric teleconnection induced by tropical  
93 Atlantic sea-surface temperature (SST) anomalies.

94 Other studies, however, found no cause-and-effect relationship between Arctic sea ice loss and

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

105       Despite the recent attention given to the warm Arctic-cold continents pattern, it remains debatable  
106 as to the roles of various dynamical and physical processes play in the formation of this phenomenon.  
107 In this study, we revisit surface temperature variability over the Arctic and Eurasia continent (40-90 °N,  
108 20-130 °E), where the warm Arctic-cold continents pattern is a prominent feature (Cohen et al., 2014;  
109 Mori et al., 2014), by applying the Self-Organizing-Map (SOM) technique to daily surface temperature  
110 over the recent four decades. We will show that while the warm Arctic-cold Eurasian continent pattern  
111 has dominated the recent two decades, its opposite pattern, cold Arctic-warm Eurasia continent,  
112 appeared frequently in the 1980s and the 90s. Using century-long data, we will further show that the  
113 warm Arctic-cold Eurasian continent pattern is an intrinsic climate mode and the recent increasing  
114 trend in its occurrence is a reflection of an interdecadal variability of the pattern. Using linear  
115 regression, we explain the reason for the recent increasing occurrences of the warm Arctic-cold  
116 continents pattern. We also assess the role of the SST anomalies over the North Pacific and Atlantic

117 Oceans in the variability of the warm Arctic-cold Eurasia pattern on the interdecadal time scale.

## 118 **2 Datasets and methods**

### 119 2.1 Datasets

120 Daily surface air temperature and other climate variables used in the current analyses, including  
121 500 hPa geopotential height, 800-hPa wind and mean sea level pressure, all come from the European  
122 Centre for Medium-Range Weather Forecasts Re-Analysis (ERA), the interim version (ERA-Interim;  
123 Dee et al., 2011) with a horizontal resolution of approximately 79 km (T255) and 60 vertical levels in  
124 the atmosphere. Compared to the earlier versions of ERA (e.g., ERA-40, Uppala et al., 2005) and other  
125 global re-analysis products (e.g. the NCEP reanalysis, Kalnay et al., 1996), ERA-Interim has been  
126 found to be more accurate in portraying the Arctic warming trend (Dee et al., 2011; Screen and  
127 Simmonds, 2011) despite its known warm and moist bias in the surface layer (Jakobson et al., 2012).  
128 Daily sea ice data are obtained from the U.S. National Snow and Ice data Center  
129 ([ftp://sidacs.colorado.edu/DATASETS/nsidc0051\\_gsfc\\_nasateam\\_seaice/final-gsfc/north/daily](ftp://sidacs.colorado.edu/DATASETS/nsidc0051_gsfc_nasateam_seaice/final-gsfc/north/daily)).

130 Gridded monthly SST data used in the current analysis are obtained from the U.S. National Oceanic  
131 and Atmospheric Administration (NOAA) data archives  
132 (<ftp://ftp.cdc.noaa.gov/Datasets/noaa.oisst.v2.highres/>) (Reynolds et al. 2007). In our analyses, we  
133 remain the trends in the data over the 1979-2019 period.

134 The results obtained from the data within the recent four decades are put into the context of the  
135 variability over longer time scales using data from the Twentieth Century Reanalysis project, version  
136 2C (20CR) that spans more than a century from 1851 through 2015 (Compo et al., 2011). The 20CR  
137 reanalysis data, which has a horizontal resolution of 2 °latitude by 2 °longitude and temporal resolution  
138 of 6 hours, was produced by a model driven at the lower boundary by observed monthly SST and sea

139 ice conditions and with data assimilation of surface pressure observations. Several indices used to  
140 describe known modes of climate variability including Arctic oscillation (AO), Northern Atlantic  
141 Oscillation (NAO), Atlantic Multidecadal Oscillation (AMO) (Enfield et al., 2001) and PDO (Mantua  
142 et al., 1997), are obtained from NOAA's Climate prediction Center (CPC)  
143 (<https://www.esrl.noaa.gov/psd/data/climateindices/list/>),

## 144 2.2 Methods

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

160 SOM method has been used in atmospheric research at mid and high latitudes of the northern

161 hemisphere (Skific et al., 2009; Johnson and Feldstein, 2010; Horton et al., 2015; Loikith and Broccoli,  
162 2015; Vihma et al., 2019). For example, Johnson and Feldstein (2010) used SOM to identify spatial  
163 patterns of daily wintertime North Pacific sea level pressure and relate the variability of the  
164 occurrences of those patterns to some large-scale circulation indices. Loikith and Broccoli (2015)  
165 compared observed and model-simulated circulation patterns across the North American domain using  
166 an approaching involving SOM. The SOM method was also used to detect circulation pattern trends in  
167 a subset of North America during two different periods (Horton et al., 2015).

168 In this study, the SOM method is applied to ERA-Interim wintertime daily temperature anomalies from  
169 December 1979 through February 2019. The anomalies are calculated by subtracting 40-year averaged  
170 daily temperature from the original daily temperature at each grid point. Prior to SOM analysis, it is  
171 necessary to determine how many SOM nodes are needed to best capture the variability in the data.  
172 According to previous studies (Lee and Feldstein, 2013; Gibson et al., 2017; Schudeboom et al., 2018),  
173 the rule for determining the number of SOM nodes is that the number should be sufficiently large to  
174 capture the variability of the data analyzed, but not too large to introduce unimportant details. Table 1  
175 shows the averaged spatial correlation between all daily surface air temperature anomalies and their  
176 matching nodes. The spatial correlation coefficients increase from 0.26 for a  $3 \times 1$  grid to 0.51 for a  
177  $4 \times 4$  grid, but the gain from a  $3 \times 3$  grid to a  $4 \times 4$  grid is relatively small. Hence, a  $3 \times 3$  grid seems to  
178 meet the above-mentioned rule and will be utilized in this study.

179 The contribution of each SOM node to the trend in wintertime surface temperature anomalies is  
180 calculated by the product of each node pattern and its frequency trend normalized by the total number  
181 (90) of wintertime days (Lee and Feldstein, 2013). The sum of the contributions from all nodes denotes  
182 the SOM-explained trends. Residual trends are equal to the subtraction of SOM-explained trends from



183 the total trends. The anomalous atmospheric circulation pattern corresponding to each of the SOM  
184 pattern is obtained by composite analysis that computes a composite mean of an atmospheric  
185 circulation field (e.g., 500 hPa height) over all occurrences of that SOM node. Regression analysis is  
186 also performed where atmospheric circulation variables are regressed onto the time series of the  
187 occurrence of a SOM node to further elucidate the relationship between the variability of atmospheric  
188 circulations and surface temperatures. The statistical significance of composite and regression analyses  
189 in this study is tested by using the Student's t test.

### 190 **3 Results**

#### 191 3.1 Surface temperature variability

192 The majority of the 9 SOM nodes depict a dipole pattern characterized by opposite changes in  
193 surface temperatures between the Arctic Ocean and the Eurasian continent, although the sign switch  
194 does not always occur at the continent-ocean boundary (Figure 1). The differences in the position of the  
195 boundary between the warm and cold anomalies reflects the transition between the cold Arctic-warm  
196 Eurasia pattern (denoted, in descent order of the occurrence frequency, by nodes 3, 9, 6), to the warm  
197 Arctic-cold Eurasia pattern (depicted, in descent order of the occurrence frequency, by nodes 1, 7, 4).  
198 The spatial patterns represented by the first group of nodes are almost mirror images of the patterns  
199 denoted by the corresponding nodes in the second group. For example, the second node in group 1  
200 (node 9, 15.4%) and the first node in group 2 (node 1, 17.1%) show a mirror image pattern with cold  
201 (warm) anomalies in the Arctic Ocean extending into northern Eurasia and warm (cold) anomalies in  
202 the rest of the Eurasia continent in the study domain. In both cases, the region of maximum magnitude  
203 anomalies is centered near Svalbard, Norway. The second pair, denoted by node 3 (17.2%) and 7  
204 (13.7%) has the boundary of separation moved northward from northern Eurasia continent toward the

205 shore of the Arctic Ocean. While the maximum anomaly in the Arctic Ocean remains close to Svalbard,  
206 maximum values over the continent are found in central Russia. Nodes 4-6 display a noticeable  
207 transition from node 1 to node 7 and from node 3 to node 9, respectively. Although nodes 2 and 8 show  
208 an approximate monopole spatial pattern, they also represent a transition between nodes 1 and 3, and  
209 between nodes 7 and 9, respectively. Above SOM analysis does not consider the trend in surface air  
210 temperature. The result is similar when the trend is removed (not shown).

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

### 219 3.2 Large-scale circulation patterns

220 For all SOM nodes, the spatial pattern of the composited 500-hPa geopotential height anomalies  
221 (Figure 2) is similar to that of mean sea level pressure anomalies (not shown), indicating an  
222 approximately barotropic structure. For nodes 1, 4 and 7, the 500-hPa height anomalies show a dipole  
223 structure of positive values over Siberia and negative values to its south over the Eurasian continent.  
224 Anomalous southwesterly winds on the western side of the anticyclone over Siberia transport warm  
225 and moist air from northern Europe and the North Atlantic Ocean into the Atlantic sector of the Arctic  
226 Ocean (Figure 3), providing a plausible explanation of the warm surface temperature anomalies in the

227 region (Figure 1). On the eastern side of the anticyclone, anomalous northwesterly winds bring cold  
228 and dry air from the Arctic Ocean into Eurasia continent, which is consistent with the negative surface  
229 temperature anomalies there. The opposite occurs for nodes 3, 6 and 9. A similar explanation involving  
230 anomalous pressure and wind fields can be applied to other nodes. The dipole structure that dominates  
231 the anomalous 500-hPa height fields over the North Atlantic Ocean for most nodes resembles the  
232 spatial pattern of the NAO (Figure 2). In addition, the patterns for several nodes, such as nodes 4 and 7,  
233 have some resemblance to the spatial pattern of the AO over larger geographical region. The possible  
234 connection to NAO and AO is further investigated by averaging the daily index values of NAO or AO  
235 over all occurrence days for each node. The results (Table 2) show that nodes 1, 2, 3 (5, 8, 9)  
236 correspond to a significant positive (negative) phase of the NAO index characterized by negative  
237 (positive) height anomalies over Iceland and positive (negative) values over the central North Atlantic  
238 Ocean. Association is also found between nodes 1, 2, 3, and 6 (5, 7, 8, and 9) and the positive (negative)  
239 phases of the AO index.

### 240 3.3 Downward radiative fluxes

241 Besides the anomalous circulation patterns, anomalous surface radiative fluxes may also play a role in  
242 shaping the spatial pattern of surface temperature variability. In fact, the spatial pattern of the mean  
243 anomalous daily downward longwave radiation for an individual node (Figure 4) is in good agreement  
244 with the spatial pattern of the surface temperature anomalies of that node. In other words, increased  
245 downward longwave radiation is associated with positive surface temperature anomalies, and vice  
246 versa. As expected from previous studies (e.g., Sedlar et al. 2011), there is a significant positive  
247 correlation between downward longwave radiative fluxes and the anomalous total column water vapor  
248 and mid-level cloud cover (not shown). The correlation to low- and high-level cloud cover is, however,

249 not significant (not shown). Most of the water vapor in both the Arctic and Eurasia is derived from the  
250 North Atlantic Ocean, but the water vapor is transported into the Arctic by southwesterly flows and into  
251 Eurasia by northwesterly winds. The anomalous shortwave radiation corresponding to each node (not  
252 shown) is an order of magnitude smaller than that of the longwave radiation anomalies and has a spatial  
253 pattern opposite to that of the mid-level cloud cover and the longwave radiation anomalies.

#### 254 3.4 Sea ice

255 The analyses presented above attempt to explain the spatial pattern of surface temperature  
256 variability for each node from the perspective of anomalous heat advection and surface radiative fluxes.  
257 As mentioned earlier, there has been a debate in the literature about the role played by the sea ice  
258 anomalies in the Barents and Kara Seas in the development of the warm Arctic-cold Eurasia pattern.  
259 Here, we examine the anomalous turbulent heat flux (Figure 5) and sea ice concentration (Figure 6) for  
260 each node. Turbulent heat flux is considered positive when it is directed from the atmosphere  
261 downward to the ocean or land surfaces. Thus, a positive anomaly indicates either an increase in the  
262 atmosphere-to-surface heat transfer or a decrease in the heat transfer from the surface to the atmosphere.  
263 The magnitude of anomalous turbulent heat flux is found to be comparable to that of anomalous  
264 downward longwave radiation (Figure 4). For all nodes, the heat flux anomalies are larger over ocean  
265 than over land (Figure 5). For node 1, positive turbulent heat flux anomalies occur mainly over the  
266 Barents Sea, the western and central North Atlantic Ocean and the eastern North Pacific Ocean,  
267 indicating an increase in heat transport from the air to the ocean due possibly to an increase in vertical  
268 temperature gradient caused by warm air advection associated with anomalous circulation (Figures 2  
269 and 3). The downward heat transfer results in sea ice melt in the Greenland Sea and the Barents Sea  
270 (Figure 6). For node 4, the anomalous southerly winds over the Nordic Sea produce larger positive

271 turbulent heat flux anomalies (Figure 5). For node 7, the anticyclone is located more northwards, which  
272 generates opposite anomalous winds between the Nordic and northern Barents Seas and the southern  
273 Barents Sea and thus opposite turbulent heat flux anomalies that are consistent with the opposite sea ice  
274 concentration anomalies in the two regions (Figure 5). For nodes 3, 6, and 9, the anomalous cold air  
275 from the central Arctic Ocean flows into warm water in the Nordic and Barents Seas, producing  
276 negative turbulent heat flux anomalies and positive sea ice concentration anomalies (Figures 5 and 6).  
277 Sorokina et al. (2016) noted that turbulent heat flux usually peaks 2 days before changes in surface  
278 temperature pattern occur. The pattern of the composited anomalous 500-hPa geopotential height,  
279 turbulent heat flux and sea ice concentration 2 days prior to the day when the nodes occur (not shown)  
280 is similar to the current-day pattern in Figures 2, 5, and 6. Our results support the conclusion of  
281 Sorokina et al. (2016) and Blackport et al. (2019) that the anomalous atmospheric circulations lead to  
282 the anomalous sea ice concentration in the Barents Sea.

### 283 3.5 Trends in wintertime surface temperature

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

289 We first examine the time series of the accumulated number of days for each node in each winter  
290 for the 1979-2019 period (Figure 7). The time series for nodes 1, 4, 6, and 9 exhibit variability on  
291 interannual as well as decadal time scales. The occurrence frequency is noticeably larger after 2003  
292 than prior to 2003 for nodes 1 and 4, and vice versa for nodes 6 and 9, and the difference between the

293 two periods is significant at 95% confidence level. Given the spatial patterns of these four nodes  
294 (Figure 1), this indicates that the warm Arctic-cold Eurasia pattern occurred more frequently after 2003.  
295 A linear trend analysis of the time series for each node (Table 3) reveals significant positive trends in  
296 occurrence frequency for nodes 1 and 4 and significant negative trends for nodes 6 and 9, which agree  
297 with the result from a previous study (Clark and Lee, 2019; Overland et al., 2015) that suggested an  
298 increasing trend of the warm Arctic and cold Eurasia pattern.

299 These trends in the occurrence frequency of the SOM nodes contribute to the trends in the total  
300 wintertime (DJF) surface temperature anomalies (Figure 8, top panel) that have significant positive  
301 trends over the Arctic Ocean and in regions of Northern and Eastern Europe and negative, mostly  
302 insignificant trends in Central Siberia. The contribution, however, varies from node to node (Figure 9).  
303 Node 1 has the largest domain-averaged contribution of 18.7%, followed by its mirror node (node 9) at  
304 10.1%. Nodes 4 and 6 account for 2.8% and 4.3% of the total trend, respectively. None of the  
305 remaining nodes explain more than 2%. All nodes together explain 39.5% of the total trend in  
306 wintertime surface air temperature. The spatial pattern of the SOM-explained trends (Figure 8, middle  
307 panel) is similar to the warm Arctic-cold continent pattern, whereas the residual trend resembles more  
308 the total trend (Figure 8 bottom panel).

### 309 3.6 Mechanisms

310 The results presented above indicate that the SOM patterns explain nearly 40% of the trend in  
311 wintertime surface air temperature anomalies and majority of the contributions (35 out of 40%) come  
312 from the two pairs of the nodes (nodes 1, 9, and 4, 6). The analyses hereafter will focus on these four  
313 nodes. Below we assess the atmospheric and oceanic conditions associated with the occurrences of the  
314 four nodes via regression analysis. Specifically, the anomalous seasonal SST and atmospheric

315 circulation variables are regressed onto the normalized time series of the number of days when each of  
316 the four nodes occurs (Figures 10, 11, and 12).

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

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

337 the amplitude of the wavetrain and SST anomalies. For example, the magnitude of the anomalous SST  
338 and the 500-hPa height over the central North Pacific is larger for node 6 than that for node 4.

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

### 352 3.7 Interdecadal variability

353 The four-decade-long ERA-Interim reanalysis is not adequate for examining interdecadal to  
354 multi-decadal variations represented by the PDO and AMO indices. Further analysis is performed using  
355 the 20CR daily reanalysis data for the 1854-2014 period. Before applying the SOM technique to the  
356 20CR data, we first remove the trend to eliminate the influence from the global warming. No low-pass  
357 filter is applied before SOM analysis in order to test the stability of the SOM results for the different  
358 periods. The spatial SOM patterns from the de-trended century-long 20CR data (Figure 13) are similar



359 to those for the 1979-2019 period (Figure 1). Nodes 1, 4, and 7 correspond to the positive phase of the  
360 warm Arctic-cold Eurasia pattern and the negative phase can be observed in nodes 3, 6, and 9. The  
361 magnitude in Figure 13 is smaller compared to the recent four decades in Figure 1. The occurrence  
362 frequencies of the four nodes, 1, 4, 6, and 9 (Figure 14), are close to those for the recent four decades  
363 (Figure 7). It indicates that the SOM method can obtain stably the main modes of wintertime surface  
364 air temperature variability. For the recent four decades, the time series of the number of days also  
365 displays a noticeable increasing (decreasing) trend for nodes 1 and 4 (6 and 9), suggesting that the  
366 trend in the recent four decades is a reflection of an interdecadal variability of wintertime surface air  
367 temperature.

368       Next, we apply a 40-year low-pass filter to the time series of the occurrence frequencies for nodes  
369 1, 4, 6 and 9 and the AMO and PDO indices and calculate correlations. There is a significant  
370 correlation between the time series and the AMO index, with correlation coefficients of 0.36 for node 1,  
371 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  
372 significant correlations, however, are found between the filtered time series and the PDO index. If we  
373 define a SST index to represent the variability of SST anomalies over the central North Pacific Ocean  
374 (20°N-40°N, 150°E-150°W), the 40-year low-pass filtered central North Pacific Ocean SST index is  
375 now significantly correlated with the filtered time series of occurrence frequencies for nodes 1 and 9  
376 (0.55 for node 1 and -0.46 for node 9). The correlation results are consistent with the SST regression  
377 map for the recent decades (Figure 10).

378       To confirm the effect of SST anomalies on the warm Arctic -cold Eurasia pattern, we also perform  
379 EOF analysis of wintertime detrended seasonal surface air temperature anomalies for the 1854-2014  
380 period (Figure 15). The spatial patterns of the first and second EOF modes show the negative phase of

381 the warm Arctic-cold Eurasia pattern and the 40-year low-pass filtered time series is inversely  
382 correlated with the 40-year low-pass filtered wintertime AMO index (-0.46,  $p < 0.05$  for mode 1 and  
383 -0.44,  $p < 0.05$  for mode 2). The 40-year low-pass filtered time series of the two EOF modes have a  
384 significant negative correlation with the 40-year low-pass filtered central North Pacific Ocean SST  
385 index, with correlation coefficients of -0.19 and -0.26 ( $p < 0.05$ ). Only PC1 has a significant correlation  
386 with the PDO index (0.38,  $p < 0.05$ ). Thus, the increase in the occurrence of the warm Arctic-cold  
387 Eurasia pattern in the recent decades is a part of the interdecadal variability of the pattern, which is  
388 influenced by the AMO index, the PDO index, and the central North Pacific SST.

#### 389 **4 Conclusions and Discussions**

390 In this study, we examine the variability of wintertime surface air temperature in the Arctic and the  
391 Eurasian continent (20°E-130°E) by applying the SOM method to daily temperature from the gridded  
392 ERA-Interim dataset for the period 1979-2019 and from the 20CR reanalysis for the period 1854-2014  
393 and the EOF method to seasonal temperature from the 20CR reanalysis for the period 1854-2014. The  
394 spatial pattern in the surface temperature variations in the study region, as revealed by the nine SOM  
395 nodes, is dominated by concurrent warming in the Arctic and cooling in Eurasia, and vice versa. The  
396 nine SOM patterns explain nearly 40% of the trends in wintertime surface temperature and 88% of that  
397 are accounted for by only four nodes. Two of the four nodes (nodes 1 and 4) represent the warm  
398 Arctic-cold Eurasian pattern and the other two (nodes 6 and 9) depict the opposite cold Arctic-warm  
399 Eurasia pattern. There is a clear shift in the frequency of the occurrence of these patterns near the  
400 beginning of this century, with the warm Arctic – cold Eurasia pattern dominating since 2003, while the  
401 opposite pattern prevailing from the 1980s through the 1990s. The warm Arctic-cold Eurasia pattern is  
402 accompanied by an anomalous high pressure and anticyclonic circulation over the Eurasian continent.

403 The anomalous winds and the associated temperature and moisture advection interact with local  
404 longwave radiative forcing and turbulent fluxes to produce positive (negative) temperature anomalies  
405 in the Arctic (Eurasian continent). The circulation is reversed for the cold Arctic-warm Eurasia pattern.  
406 The warm, moist air mass is advected to the Arctic by the anomalous atmospheric circulations and the  
407 increased downward turbulent heat flux also explain sea ice melt in the Barents and Kara Seas. In other  
408 words, the sea ice loss in the Barents and Kara Seas and the cooling of the Eurasian continent can both  
409 be traced to anomalous atmospheric circulations.

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

420       Using century-long data, we show that the warm Arctic-cold Eurasia pattern is an intrinsic climate  
421 mode, which has been stable since 1854. The recent increasing trend in its occurrence is a reflection of  
422 an interdecadal variability of the pattern resulting from the interdecadal variability of SST anomalies  
423 over the central Pacific Ocean and over the Atlantic Ocean represented by the AMO index. Sung et al.  
424 (2018) investigated interdecadal variability of the warm Arctic and cold Eurasia pattern and considered

425 the variability of the SST over the North Atlantic as its origin. Our results suggest that the variability of  
426 the SST over the North Pacific also plays an important role. However, internal atmospheric variability  
427 remains another potential source. The Rossby wavetrains also lead to deepening of a trough in East  
428 Asia and generate an anomalous low pressure and cold temperature in northern China (Figure 10),  
429 which further suggests that a warmer Arctic, especially warmer Barents and Kara Seas is not the driver  
430 for the increasing occurrence of cold spells in East Asia, as suggested in previous studies (Kim et al.,  
431 2014; Mori et al., 2014; Kug et al., 2015; Overland et al., 2015).

432 Our results suggest that the increasing trend in warm Arctic-cold Eurasia pattern may be related to  
433 the anomalous SST over the central North Pacific and the North Atlantic Oceans. But we cannot rule  
434 out the influence of the Arctic sea ice loss on the trend. The Arctic sea ice loss results from both Arctic  
435 warming due to anthropogenic increasing of greenhouse gas concentrations and natural variability of  
436 climate system such as SST anomalies. This study considers natural variability or internal driver of  
437 climate system. The Arctic warming caused external forcing related to increasing greenhouse gas  
438 emissions can produce an anomalous anticyclone over the Barents and Kara Seas, leading to the warm  
439 Arctic-cold continents pattern.

440 Although the ERA-Interim reanalysis is overall superior in describing the Arctic atmospheric  
441 environment to other similar global reanalysis products, it contains warm and moist biases in the  
442 surface layer (Jakobson et al., 2012; Chaudhuri et al., 2014; Simmons and Poli, 2015; Wang et al.,  
443 2019). However, we believe these biases, as well as the relatively coarse resolution, should have  
444 minimum impact in the results from the current analyses. Further, although the current analyses were  
445 performed on a predetermined SOM grid with 3x3 nodes, an increase in the number of SOM nodes  
446 didn't change the conclusions.

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

#### 452 **Data Availability**

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

#### 461 **Competing interests**

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

#### 463 **Author Contributions**

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

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648 Table 1. Spatial correlations (Corrs) between the daily winter (DJF) surface air  
 649 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

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680 Table 2. Averaged anomalous NAO and AO indices for all occurrences of each SOM  
 681 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*

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721 Table 3. Trends in the frequency of occurrences for each SOM node (day yr<sup>-1</sup>).  
722 Asterisks indicate the above 95% confidence level.

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	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*

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

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793 **Figure Captions**

794 Figure 1. Spatial patterns of SOM nodes for daily wintertime (December, January, and  
795 February) surface air temperature anomalies ( $^{\circ}\text{C}$ ) ~~without removing their linear trends~~  
796 from ERA-Interim reanalysis over the 1979-2019 period. The number in brackets  
797 denotes the frequency of the occurrence for each node.

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

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

806 Figure 4. Corresponding anomalous daily accumulated downward longwave radiation  
807 ( $105 \text{ W m}^{-2}$ ) ~~without removing its linear trend~~ from ERA-Interim reanalysis over the  
808 1979-2019 period for each node in Figure 1. Dotted regions indicate the above 95%  
809 confidence level. ~~The thick black lines denote show the study region.~~

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

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

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

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

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

827 Figure 10. Anomalous SST ( $^{\circ}\text{C}$ ) from the NOAA over the 1979-2019 period regressed  
828 into the normalized time series of occurrence number for nodes 1, 4, 6, and 9 ~~without~~  
829 ~~removing its linear trend from the NOAA over the 1979-2019 period~~.

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

834 Figure 12. The anomalous wave activity flux (vectors) (Takaya and Nakamura, 2001)  
835 and stream function (colors, units:  $10^7 \text{ m}^2 \text{ s}^{-1}$ ) from ERA-Interim reanalysis over the  
836 1979-2019 period regressed onto the normalized time series of occurrence number for

837 nodes 1, 4, 6, and 9 ~~without removing their linear trends from ERA-Interim reanalysis~~  
838 ~~over the 1979-2019 period.~~

839 Figure 13. Spatial patterns of SOM nodes for detrended daily wintertime (December,  
840 January, and February) surface air temperature anomalies ( $^{\circ}\text{C}$ ) from the 20CR  
841 reanalysis for the 1851-2014 period. The number in brackets denotes the frequency of  
842 the occurrence for each node.

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

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

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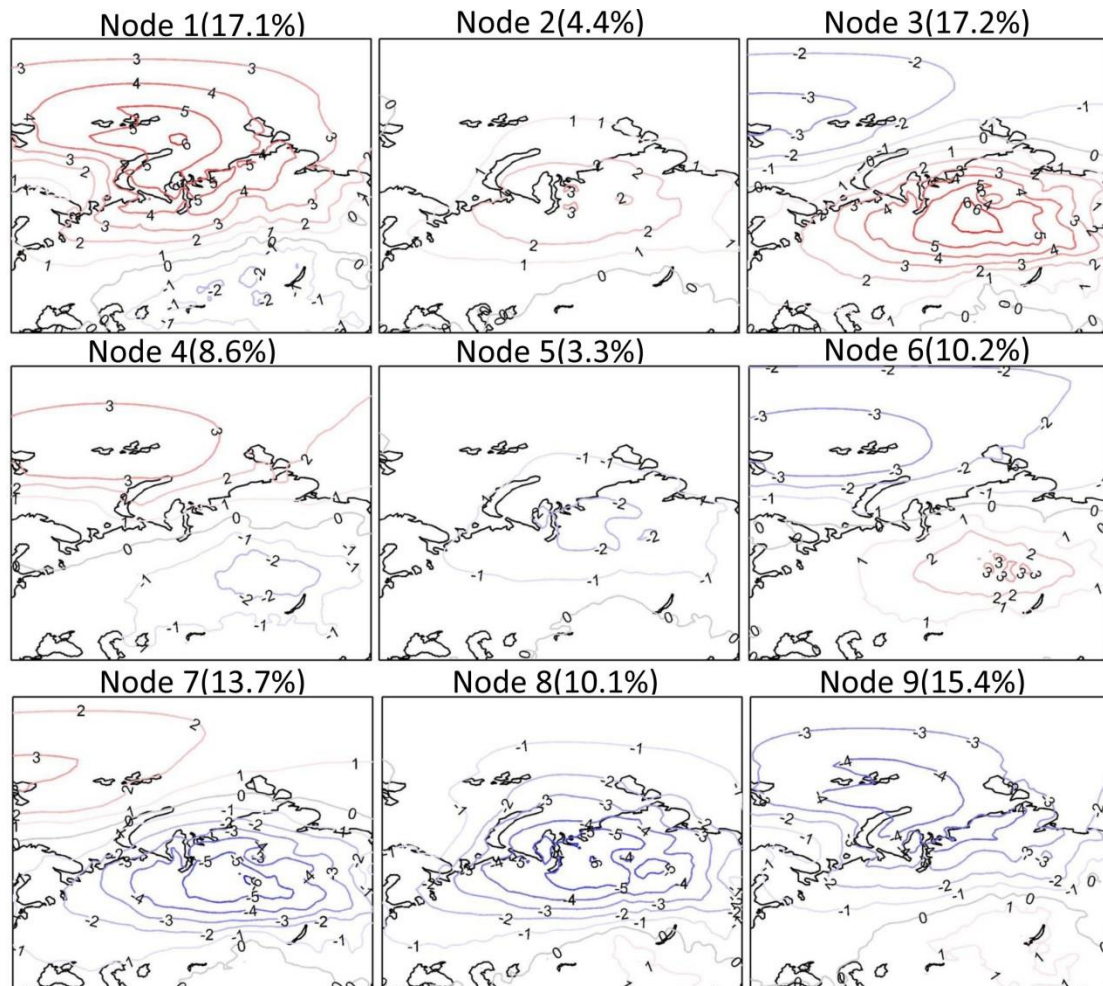
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864 Figure 1. Spatial patterns of SOM nodes for daily wintertime (December, January, and February)  
865 surface air temperature anomalies (°C) ~~without removing their linear trends~~ from ERA-Interim  
866 reanalysis over the 1979-2019 period. The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

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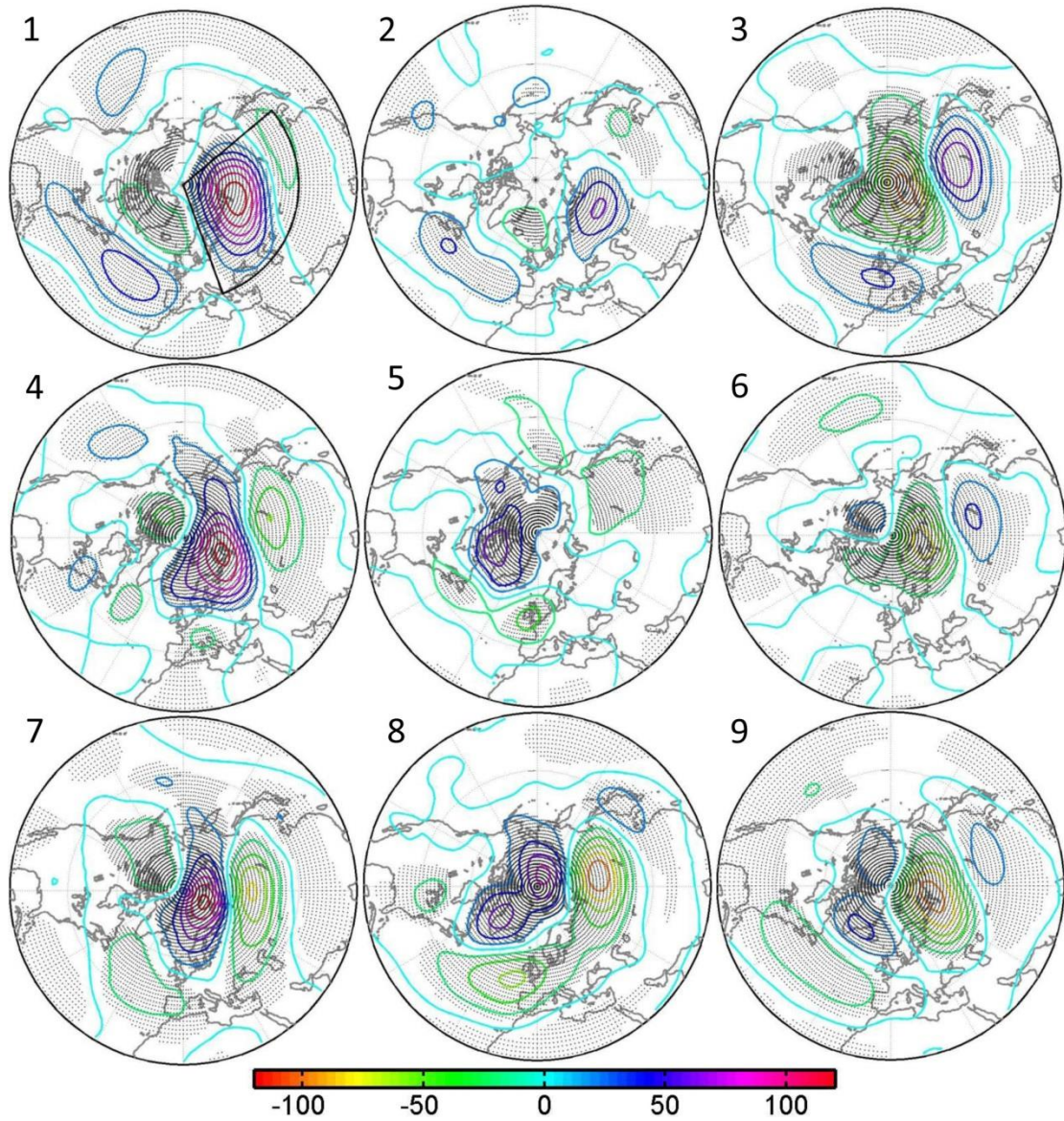
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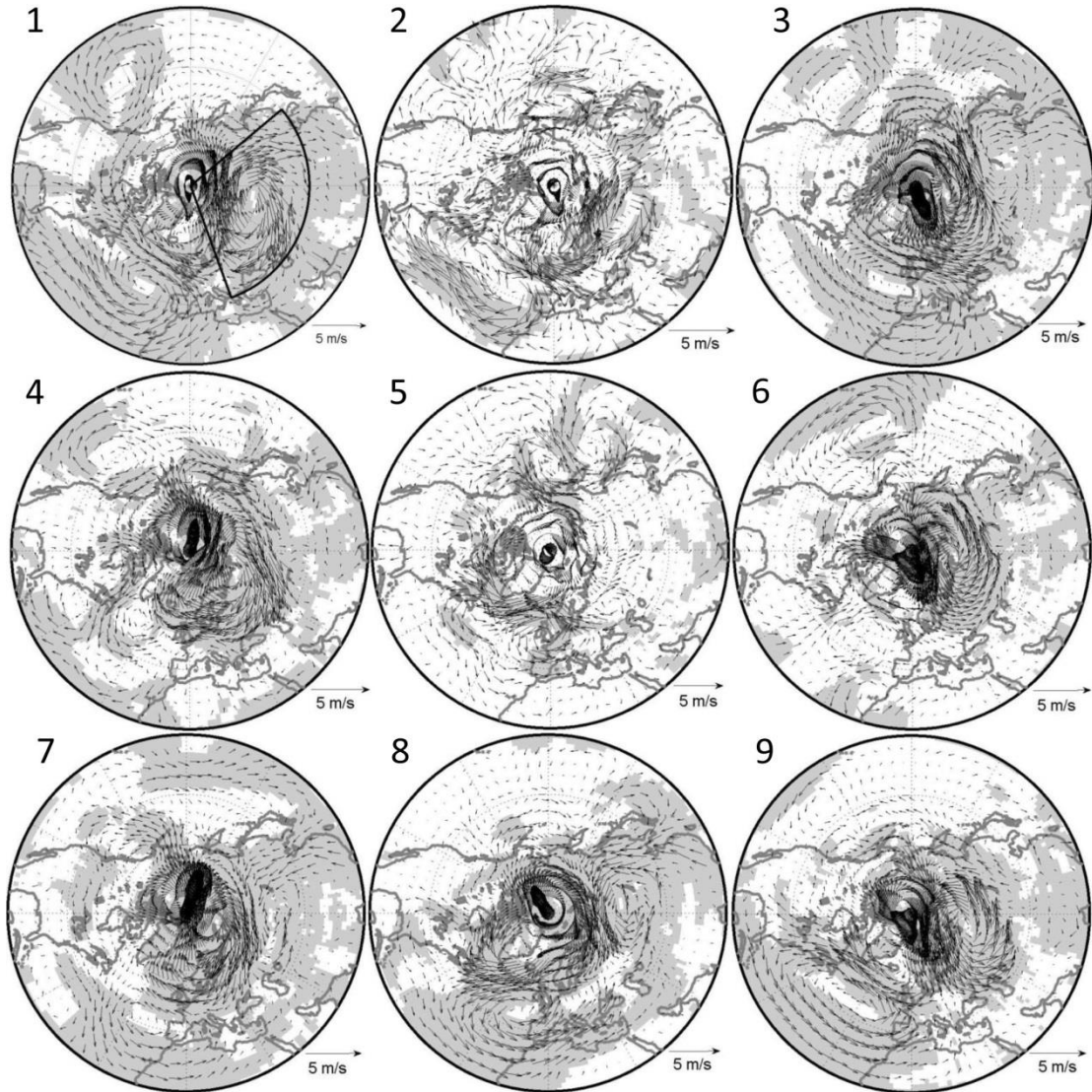
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Figure 2. Corresponding 500-hPa geopotential height anomalies (gpm) ~~without removing their linear trends~~ from ERA-Interim reanalysis over the 1979-2019 period for each node in Figure 1. Dotted regions indicate the above 95% confidence level. The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

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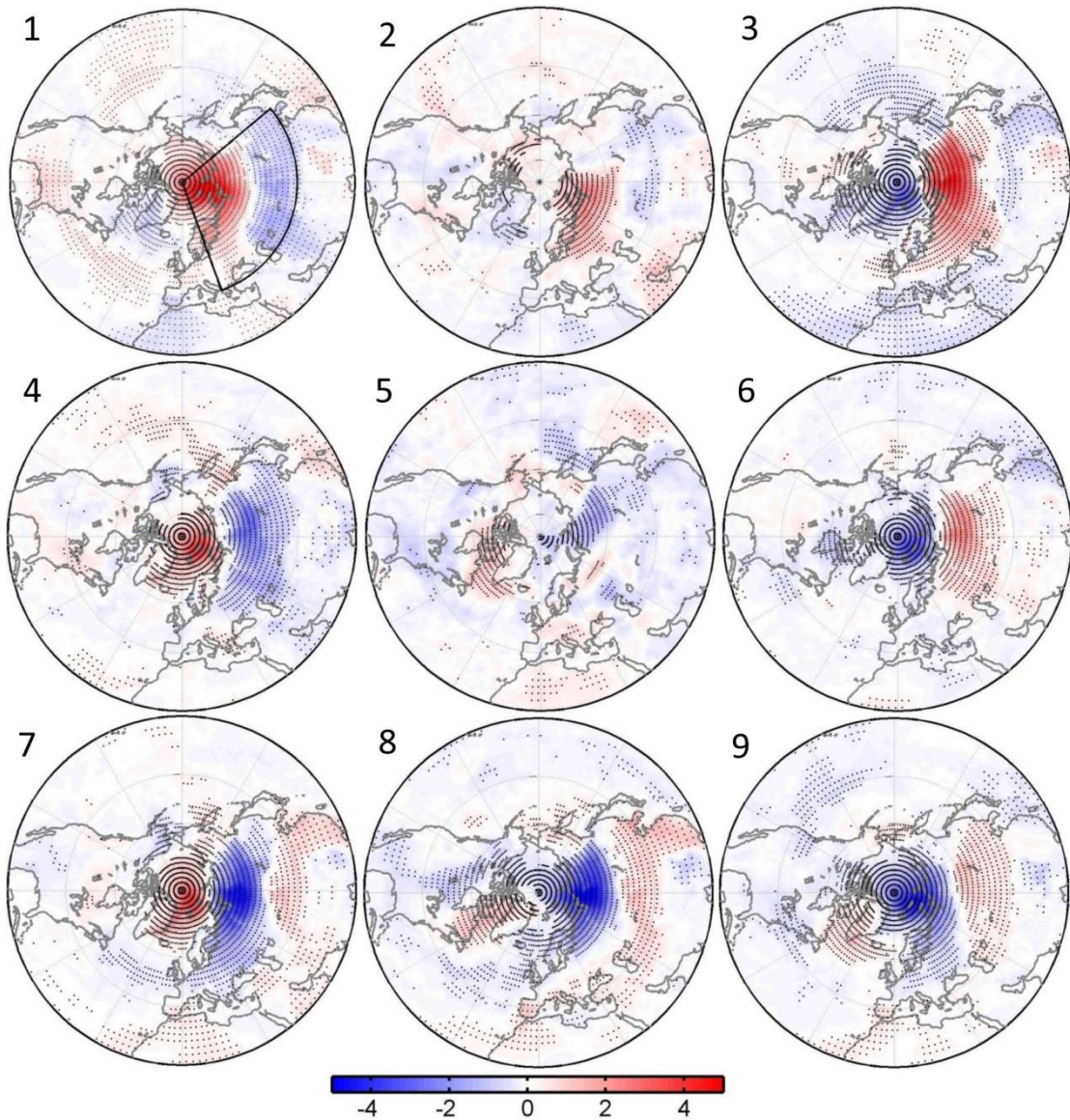


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900 | Figure 3. Corresponding anomalous 850-hPa wind field ~~without removing its linear trend~~ from  
901 | ERA-Interim reanalysis over the 1979-2019 period for each node in Figure 1. Shaded regions  
902 | indicate the above 95% confidence level.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

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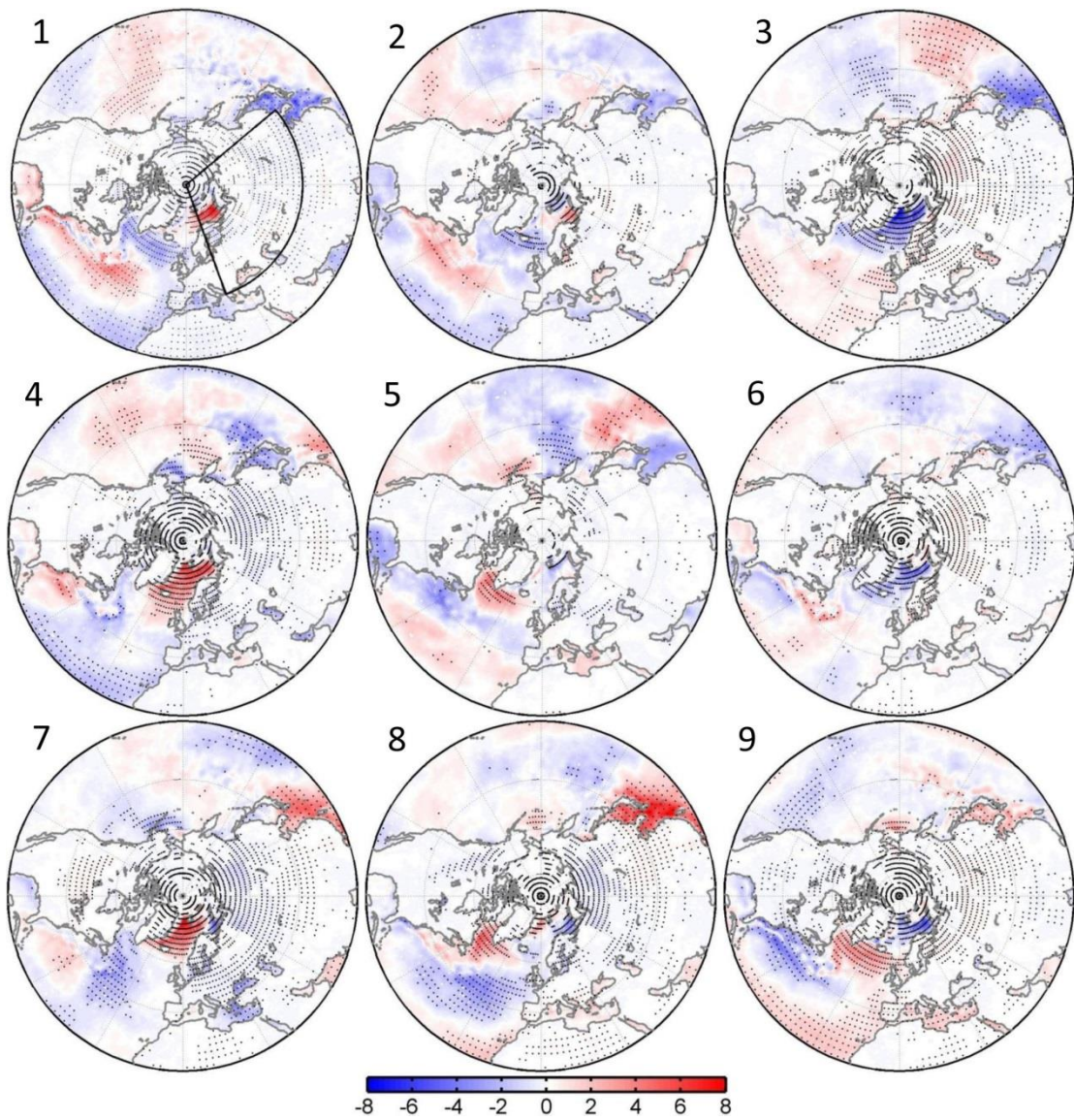


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920 Figure 4. Corresponding anomalous daily accumulated downward longwave radiation ( $10^5 \text{ W m}^{-2}$ )  
921 **without removing its linear trend** from ERA-Interim reanalysis over the 1979-2019 period for each  
922 node in Figure 1. Dotted regions indicate the above 95% confidence level. **The thick black lines**  
923 **show the study region.**

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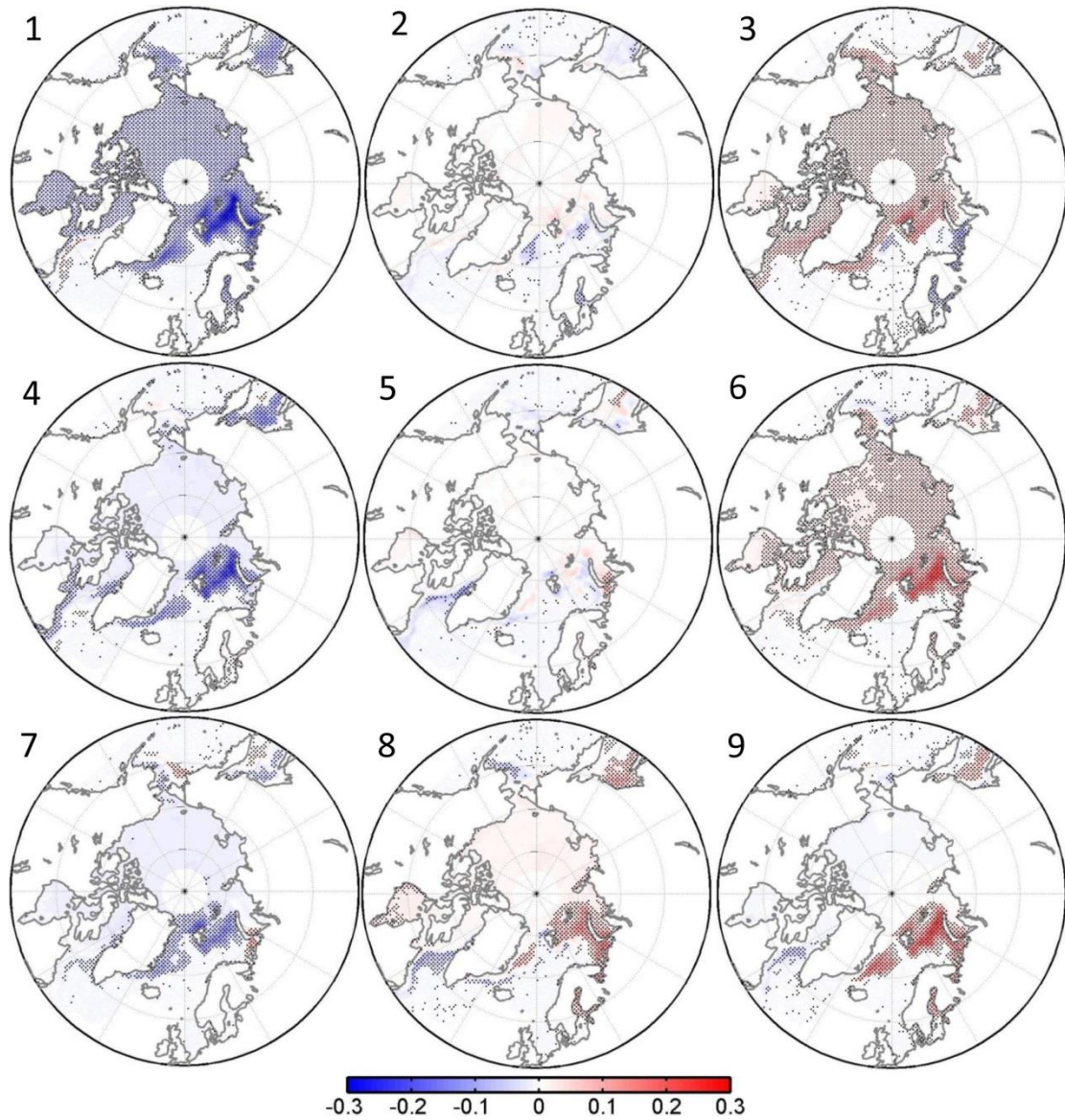
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Figure 5. Corresponding anomalous daily accumulated turbulent heat flux (sensible and latent heat) ( $10^5 \text{W m}^{-2}$ ) ~~without removing their linear trends~~ from ERA-Interim reanalysis over the 1979-2019 period for each node in Figure 1.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

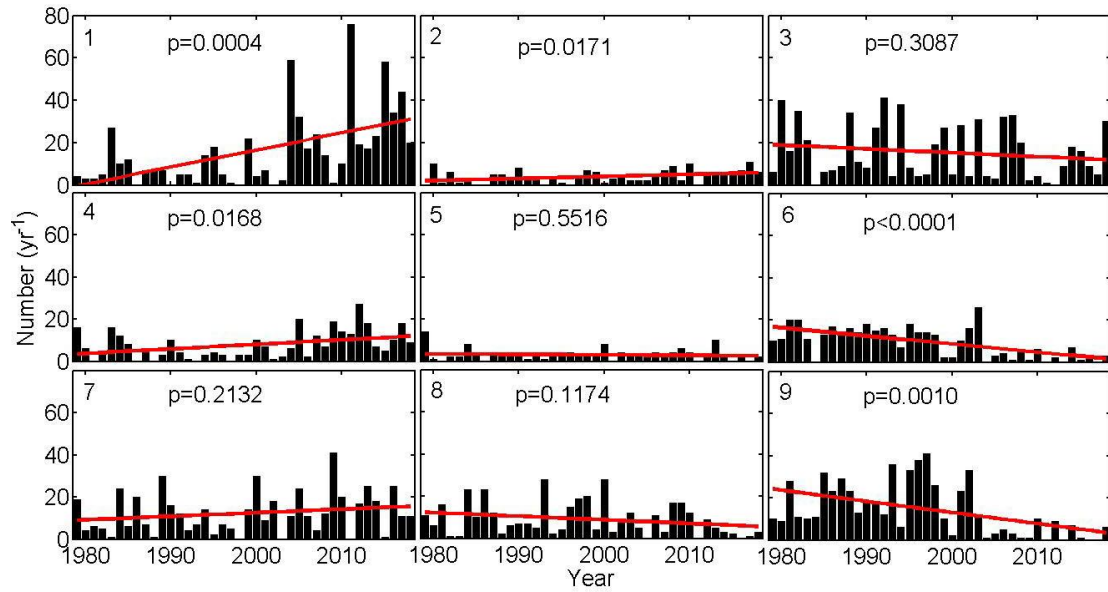
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Figure 6. Corresponding anomalous wintertime sea ice concentration ~~without removing its linear trend~~ from the NSIDC over the 1979-2019 period for each node in Figure 1. Dotted regions indicate the above 95% confidence level.

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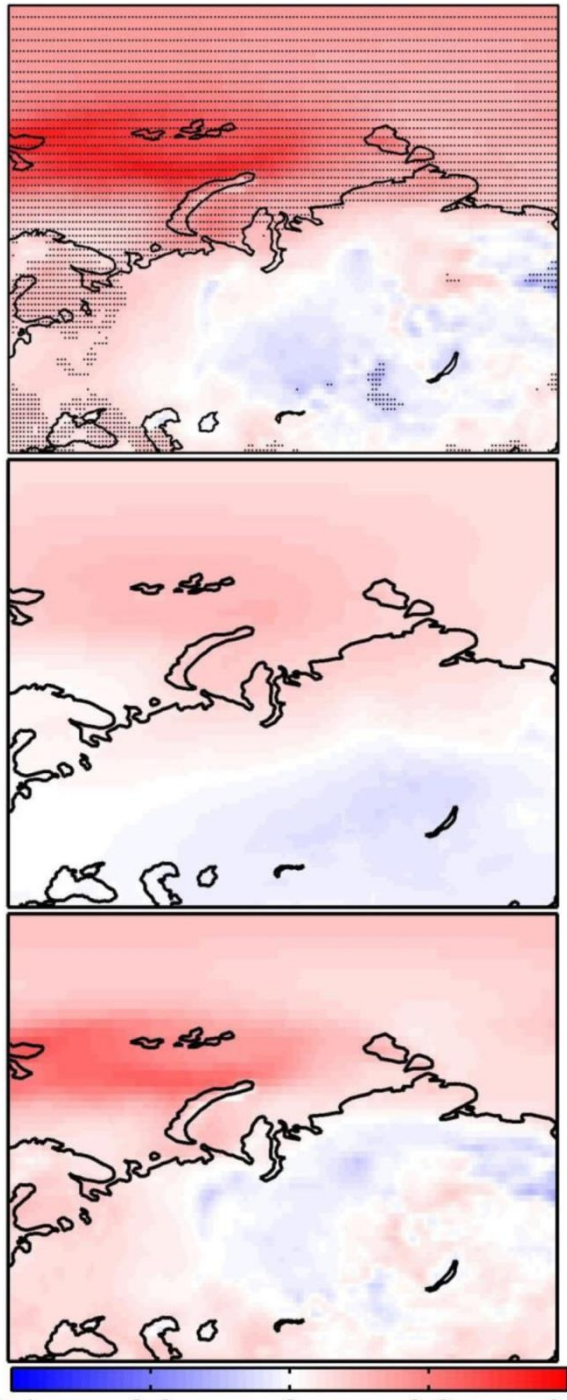


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973 Figure 7. Time series of the number of days for occurrence of each SOM node in Figure 1 over the  
974 | 1979-2019 period. The ~~thick-red~~ lines denote the trend in time series.

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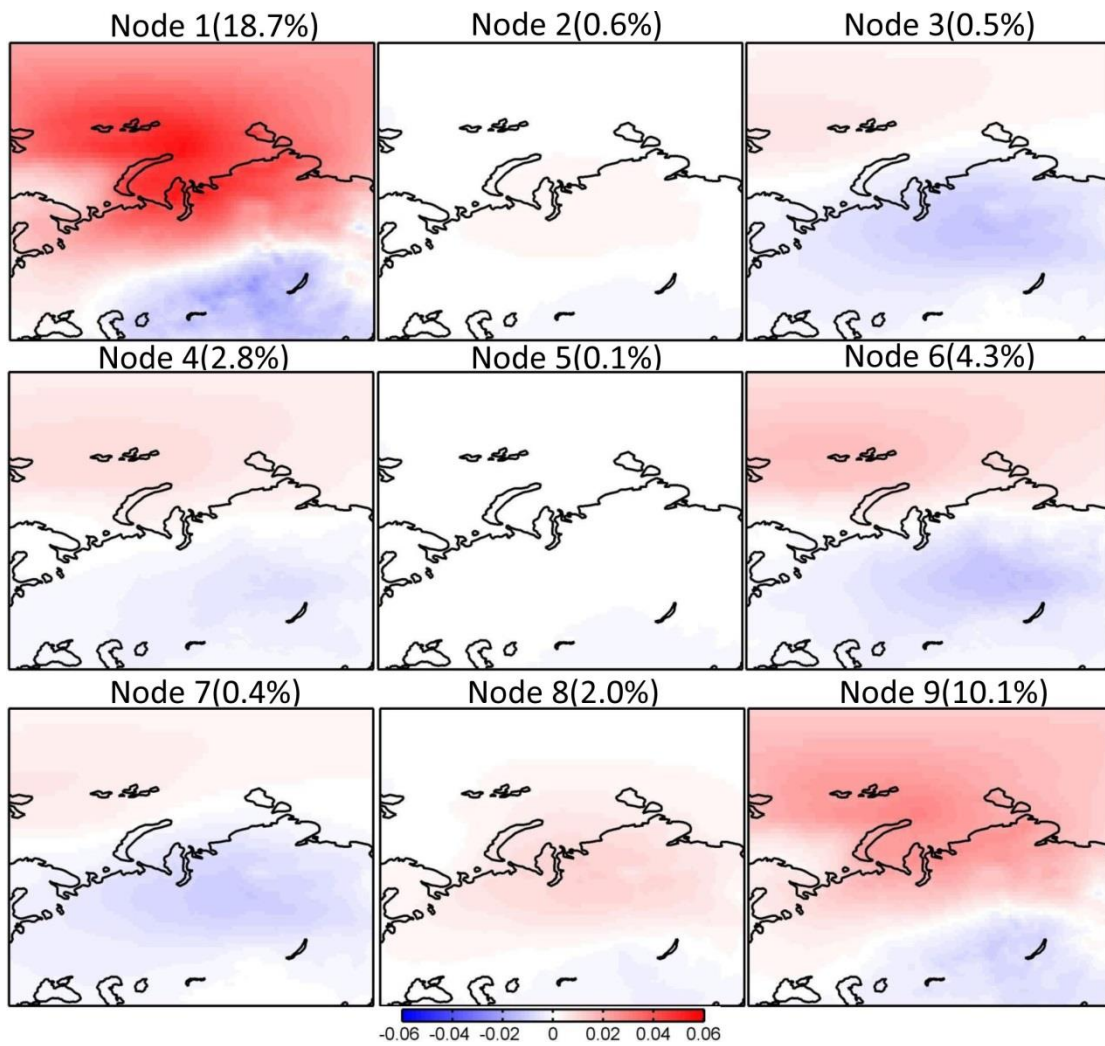




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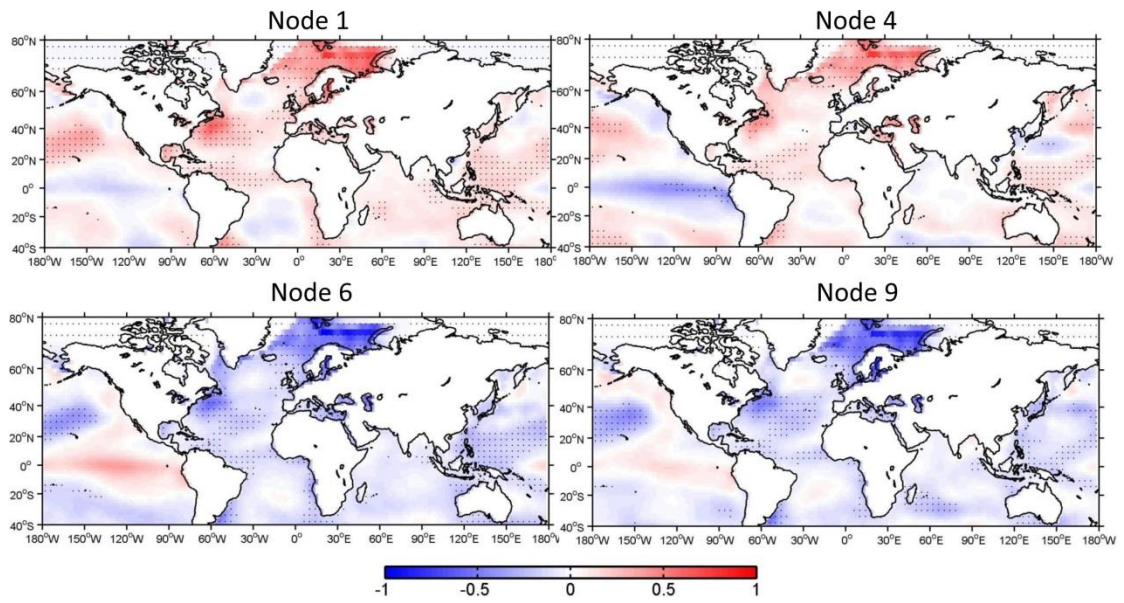
Figure 8. Total (top), SOM-explained (middle), and residual (bottom) trend in wintertime (DJF) surface air temperature ( $^{\circ}\text{C yr}^{-1}$ ) over the 1979-2019 period. Dots in the top panel indicate above 95% confidence level.



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

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1018 Figure 10. Anomalous SST (°C) from the NOAA over the 1979-2019 period regressed into the  
1019 normalized time series of occurrence number for nodes 1, 4, 6, and 9 ~~without removing its linear~~  
1020 ~~trend from the NOAA over the 1979-2019 period.~~

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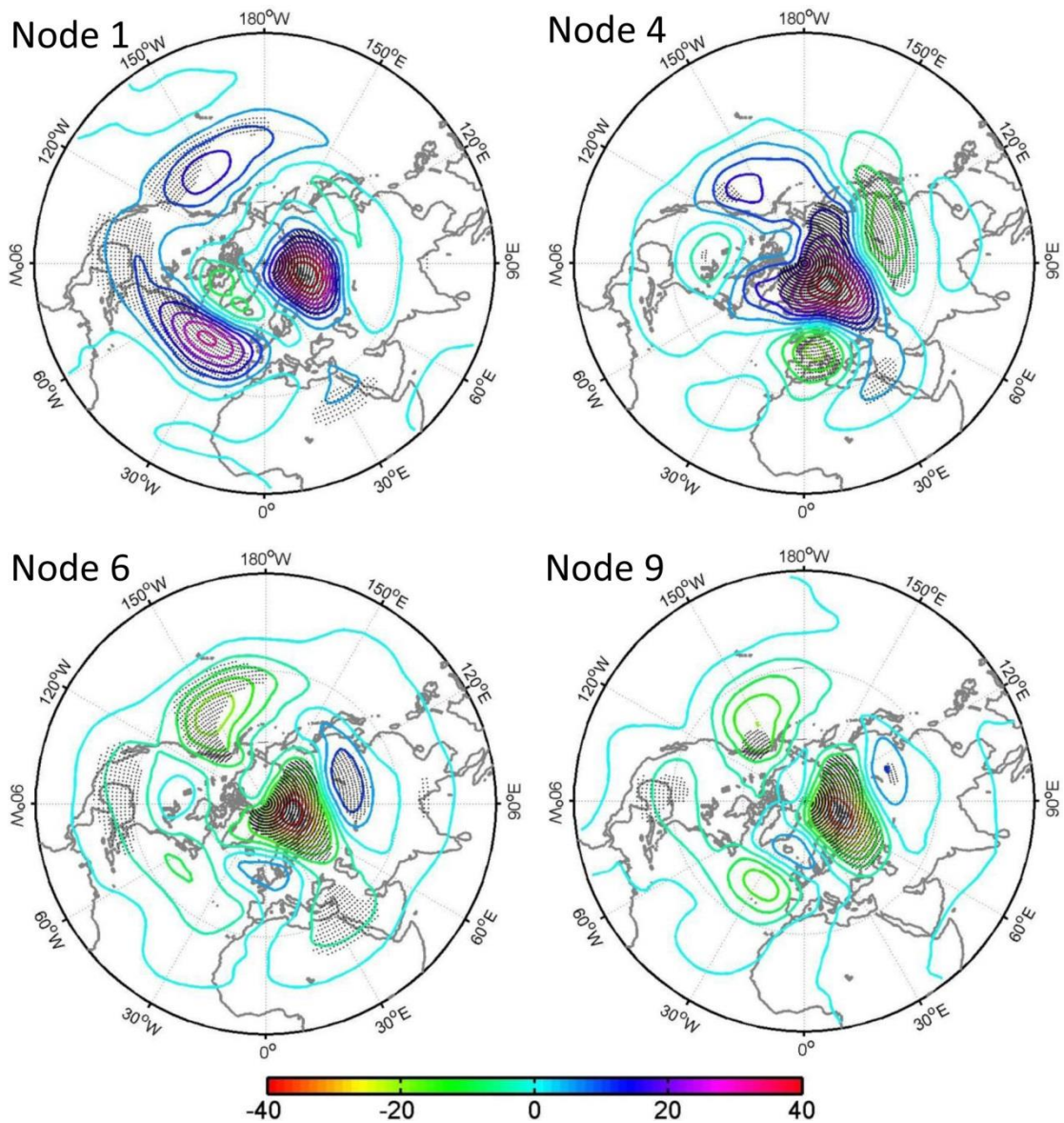
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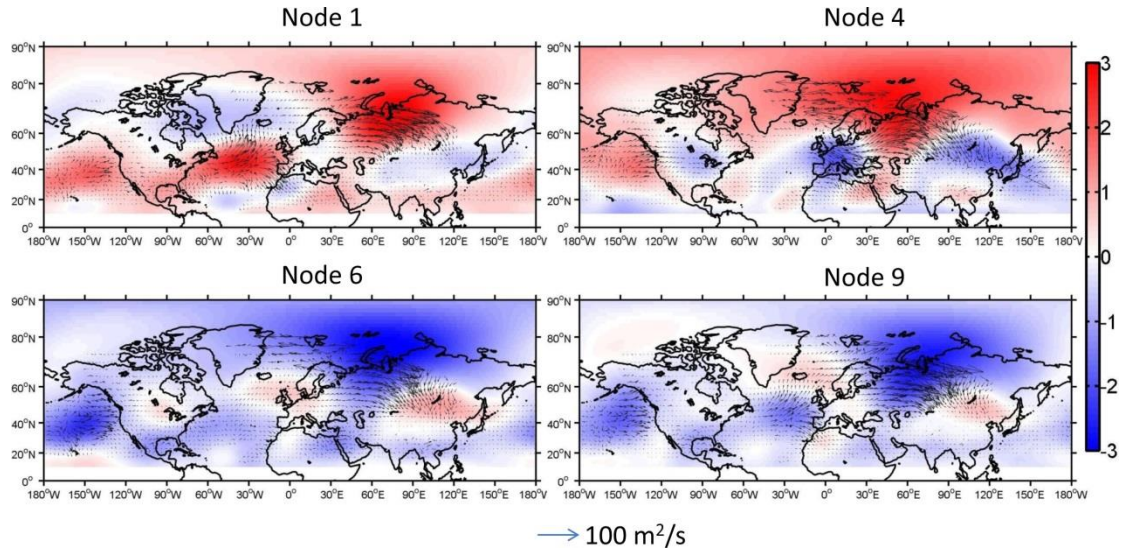
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Figure 11. Anomalous 500-hPa geopotential height (gpm) from ERA-Interim reanalysis over the 1979-2019 period regressed into the normalized time series of occurrence number for nodes 1, 4, 6, and 9 without removing its linear trend from ERA-Interim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

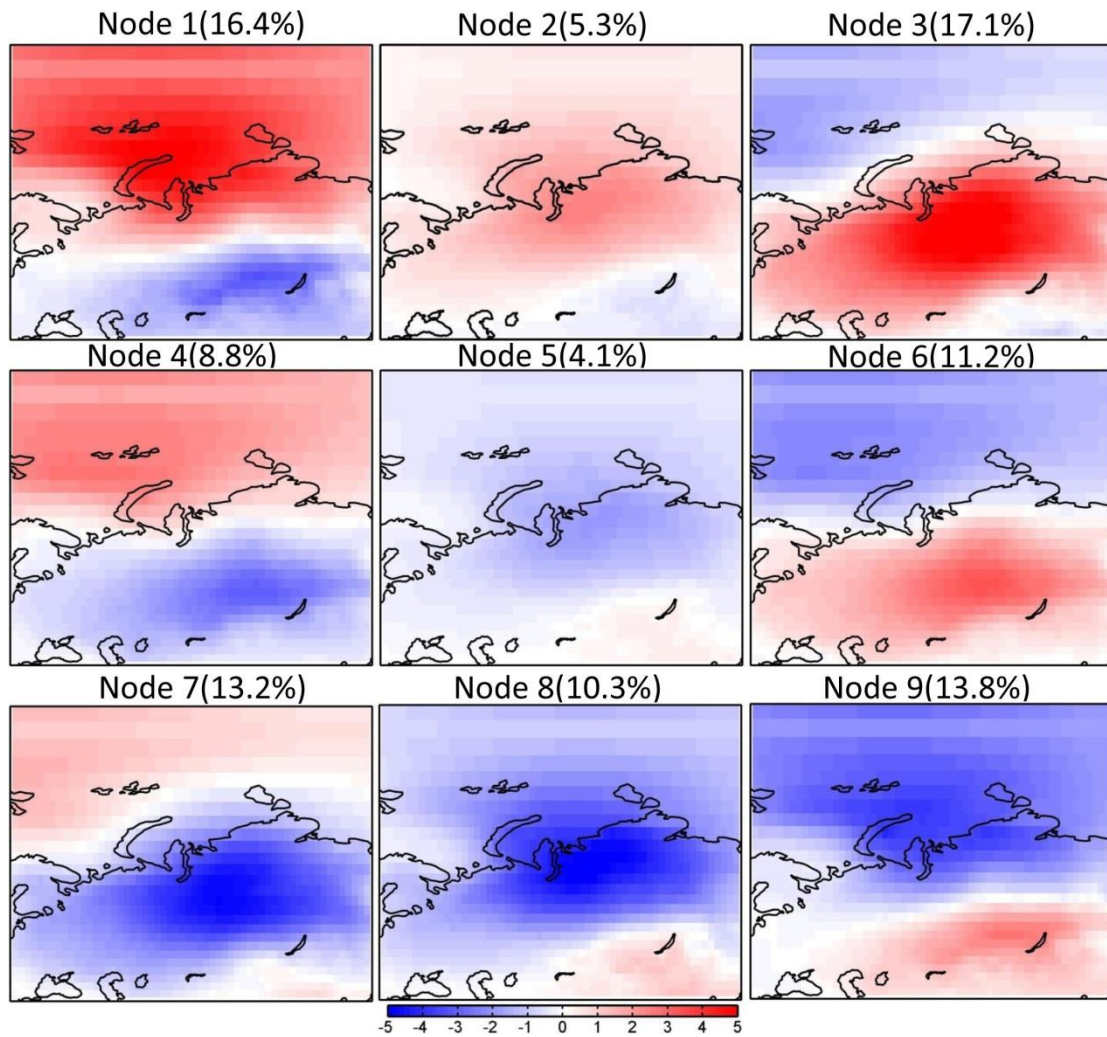
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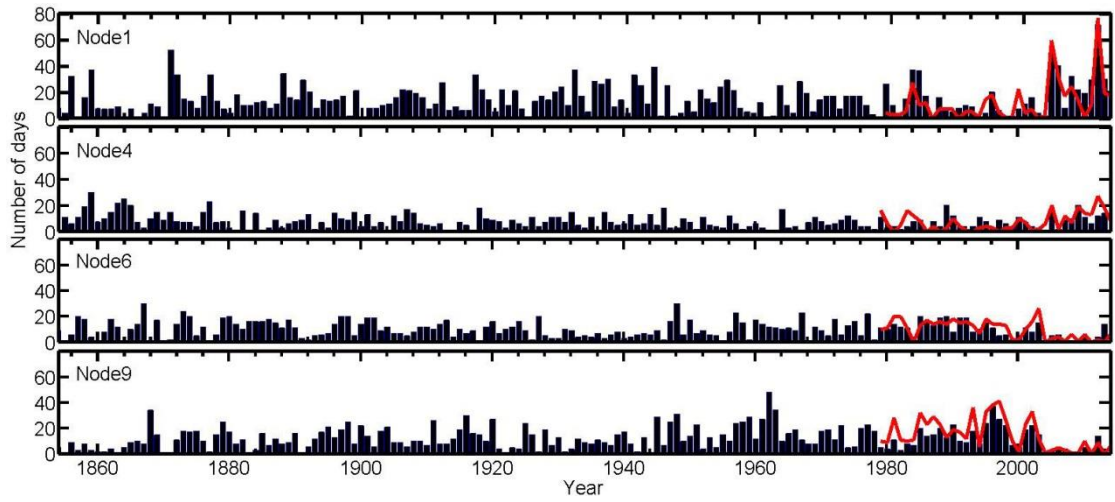
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Figure 13. Spatial patterns of SOM nodes for detrended daily wintertime (December, January, and February) surface air temperature anomalies ( $^{\circ}\text{C}$ ) from the 20CR reanalysis for the 1851-2014 period. The number in brackets denotes the frequency of the occurrence for each node.

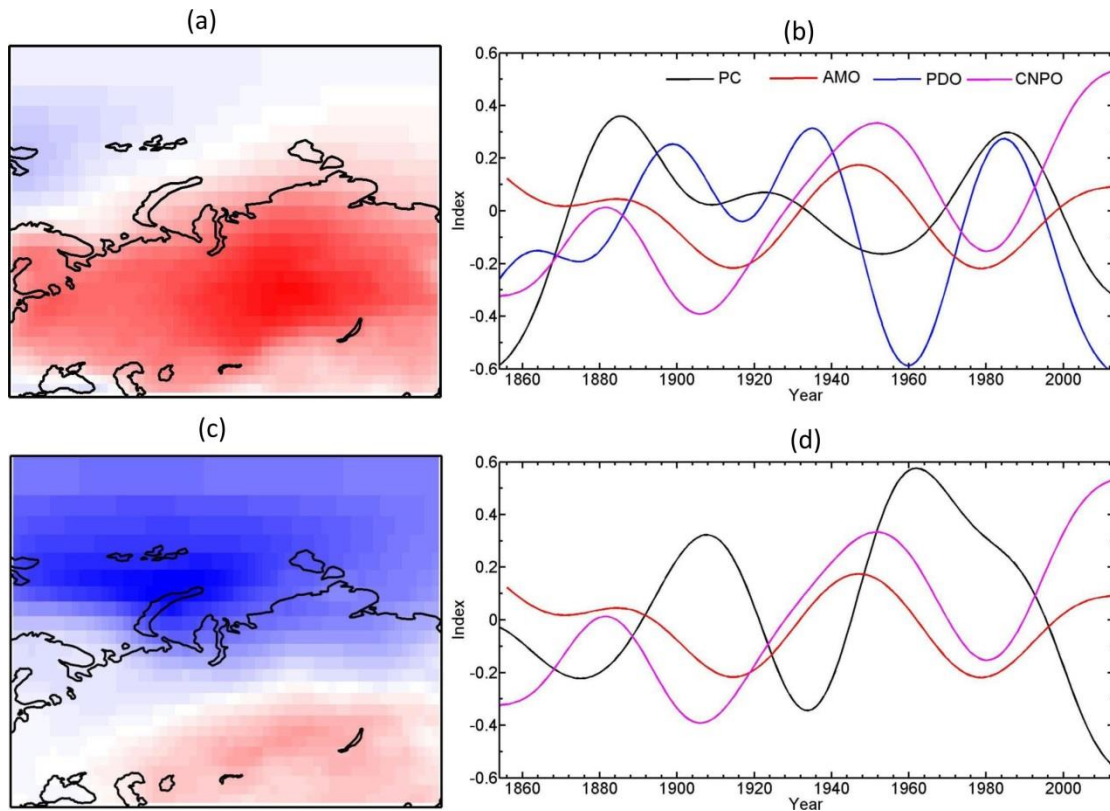


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Figure 14. Time series of the number of days for occurrence of each SOM node in Figure 13 from the 20CR reanalysis for the 1851-2014 period. The thick red lines denote the result in Figure 7 from the ERA-Interim reanalysis for the 1979-2019 period.

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