Spatial changes in two major modes of atmospheric circulation variability during the 20th century

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ABSTRACT This study presents the time development of two major modes of atmospheric circulation variability in the Northern Hemisphere, the North Atlantic Oscillation (NAO) and the Pacific/North American Pattern (PNA), during the 20th century. We employ 500 hPa winter monthly means of the long-term reanalysis 20CR, which cover the 1871–2011 period. We use a moving Principal Component Analysis calculated for 40-year periods with a one-year step. The spatial structure of NAO is well developed and stable during the whole 20th century using the ensemble mean. However, substantial changes in PNA pattern occur during the late 19th century. Its centres are weaker and smaller, except the centre over the northern Pacific Ocean, which is stronger and larger in the early period. However, these changes are not visible when using ensemble members. Therefore, we suggest that these shifts do not reflect real changes in the atmosphere but are produced by the reanalysis and statistical method itself.

KEY WORDS teleconnections – North Atlantic Oscillation – Pacific/North American Pattern – atmospheric circulation – modes of variability

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1. Introduction

Atmospheric circulation seems to have changed over the Northern Hemisphere (NH) during the 20th century according to recent studies (Frich et al. 2002; He, Soden 2015; Ding et al. 2017). The mid-latitude storm tracks have shifted poleward (Gulev, Grigorieva 2006; Ulbrich, Leckebusch, Pinto 2009; Bender, Ramanathan, Tselioudis 2012; Wang, Kim, Chang 2017), changes are also evident in frequencies of synoptic patterns over Europe (Kyselý, Huth 2006; Kučerová et al. 2017), and the blocking anticyclones have become locally more frequent (Hanna et al. 2016, Kennedy et al. 2016). However, Woolings et al. (2018) noted that trends in atmospheric blocking were not observed in the hemispheric scale. These regional or even local changes in atmospheric circulation could lead, among others, to changes in the occurrence of extreme weather events such as cold spells or heat waves (Vavrus et al. 2006, Horton et al. 2015, Vavrus et al. 2017). However, the long-term trends in changes of NH circulation still remain inconclusive (Barnes, Screen 2015).

A variety of methods and techniques to describe atmospheric circulation are available (Hannachi, Jolliffe, Stephenson 2007; Huth et al. 2008; Wilks, 2011). One of the most extensively used methods is to identify modes of circulation variability (i.e., teleconnections) (Wallace, Gutzler 1981; Barnston, Livezey 1987; Huth 2006). The modes typically represent distant anomalies of atmospheric circulation, which are related to each other, in scale of thousands of kilometres. In NH in winter, the North Atlantic Oscillation (NAO) and the Pacific/North American (PNA) pattern usually emerge as two strongest modes (Wallace, Gutzler 1981; Barnston, Livezey 1987; van den Dool et al. 2000; García-Serrano, Haarsma 2017). The NAO exhibits two prominent centres. One is situated over Iceland and Greenland, while the other forms a belt with an opposite sign along the 35°N parallel. This belt extends from the southeastern United States across the Atlantic Ocean to southwestern Europe, with the core of the centre positioned over the eastern Atlantic. Another, weaker centre forms a belt extending from northern Africa across Egypt and the Middle East to central Asia. The PNA pattern has four centres over (i) the southeast and east of the USA (from the Gulf of Mexico across Florida to the eastern USA), (ii) western Canada and the northwestern USA (from California to the north Canadian coast), (iii) the northern Pacific ocean (an area that covers almost the whole northern part of the Pacific ocean from near the western coast of the USA up to Japan, the highest values being located in the vicinity of the Aleutian Islands), and (iv) central Pacific Ocean over the Hawaiian Islands along 20°N, where the Hawaiian anticyclone is typically located (Fig. 1). Both NAO and PNA are decisive for forming weather and climate anomalies on the continents through the modulation of the strength and direction of air flow, and consequently temperature, humidity, and precipitation (e.g., Leathers, Yarnal, Palecki 1991;

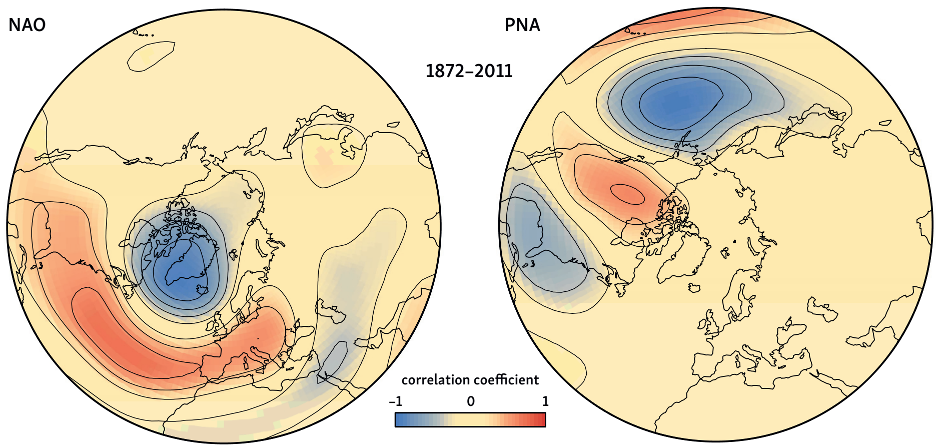

Fig. 1 – NAO and PNA calculated for the whole period 1872–2011. Red colours represent positive values while blue are negative.

Hurrel 1995; Hurrell, van Loon 1997; Trigo, Osborn, Corte-Real 2002; Hertig et al. 2015; Pokorná, Huth 2015).

There is an evidence for spatial changes in NAO and PNA during the 20th century (Jung et al. 2003; Pinto, Raible 2012). A slight eastward shift of the NAO northern centre was described by Jung at al. (2003), Zhang et al. (2008) and Wang et al. (2012). These studies, based on sea level pressure fields, agree that the eastward shift of the northern centre has been most pronounced during the recent decades. Lee et al. (2012) investigated the eastward shift of PNA after the late 1970s. These findings were supported by observations of synoptic eddy feedback and eastward shift of the Pacific storm track. The strong evidence of the eastward shift of large-scale circulation in the North Pacific was provided by Trenberth (1990), he pointed out that the Aleutian low became significantly deeper and extended further east after the late 1970s.

Principal Component Analysis (PCA) is widely used to calculate modes of variability of atmospheric circulation and their spatial patterns (Jolliffe 2002; Huth 2006; Hannachi, Jolliffe, Stephenson 2007). PCA is a statistical tool to reduce the number of variables while preserving as much variability of a data set as possible (Jackson 1991, Jolliffe 2002). Results of PCA are loadings (principal components), which form spatial patterns (maps) in the current setting, and scores, forming time series and describing the intensity of the loadings in every time step. Orthogonal rotation (VARIMAX) is often applied to enhance the interpretability of principal components; its objective is to simplify the structure of loadings by pushing the coefficients towards zero or ±1 (Richman 1986; Hannachi, Jolliffe, Stephenson 2007).

The long-term reanalysis 20CRv2, which covers the period 1871–2011 and is designed for climatological studies (Compo et al. 2011), is used as the data source. Its extent back to the second half of the 19th century allows a comparison of recent periods with the early-industrial era. The reanalysis is based on the assimilation of surface observations from the International Surface Pressure Databank, the rest of atmospheric variables being calculated by a numerical integration of an atmospheric model, equivalent to a model of numerical weather prediction. The 20CRv2 reanalysis is ensemble based, the same model was run 56 times, each run with slightly different settings and slightly different results. At first, we analysed the ensemble mean, which is an average of all 56 ensemble members. However, as Wang et al. (2013) and Woollings et al. (2014) noted, different results can be reached if an ensemble member is used instead of the ensemble mean. Therefore, we employed all 56 independent ensemble members.

The aim of this paper is to demonstrate changes in NAO and PNA modes during the 20th century, and to describe the spatial development of the modes of variability during the last almost one and half century.

2. Data and methods

We used winter (December, January, February) monthly means of 500 hPa geopotential heights of the long-term 20CR reanalysis, version 2 (Compo et al. 2011). This reanalysis is one of the longest data sources on the state of atmosphere. It is based only on observations of sea level pressure reports and it uses monthly sea-surface temperature and sea-ice distribution as boundary conditions. However, during the first approximately 40 years, the state of atmosphere is determined from only less than 200 sea level pressure observations. It introduces a considerable uncertainty into the data (Compo et al. 2011). We employed both, the ensemble mean as well as 56 ensemble members to express the uncertainty. We limit the analysis to the northern extratropics (north of 20°N inclusive) because it is where all the teleconnections in the NH are located. The reanalysis data are available on a regular latitude-longitude grid with a horizontal spacing of 2°×2°.

First, the mean annual cycle was removed from the data by subtracting the long-term mean for each of the three months at all grid points. Then, the resulting anomalies were weighted by the square root of cosine of latitude in order to compensate for the unequal area represented by grid boxes in different latitudes (Jackson 1991). Data were stored in a matrix where columns correspond to spatial location (grid points) and rows correspond to individual months (it constitutes an S-mode in terminology of PCA; see e.g. Richman 1986 and Compagnucci, Richman 2008). PCA was calculated using the covariance matrix. Finally, principal components were orthogonally rotated using the VARIMAX criterion (Richman 1986).

Nine principal components were retained for rotation in all analyses, which is the number of modes identified in the winter Northern Hemisphere in most studies (e.g., Barnston, Livezey 1987; O'Lenic, Livezey 1988; Panagiotopoulos, Shahgedanova, Stephenson 2002; Huth et al. 2009). We display spatial patterns of the NAO and PNA modes as correlations between the time series of the corresponding mode and 500 hPa height anomalies.

At first, rotated PCA was calculated for the entire period 1872–2011 of the ensemble mean (winter refers to the year of January). The spatial patterns of the two strongest modes, NAO and PNA, are shown in Figure 1. The spatial structure of both modes, described in Sec. 1, can be clearly seen. Then, separate analyses by rotated PCA were conducted for all sliding periods of 40 years (Thomposn, Wallace 2000; Handorf, Dethloff 2012) shifted by one year; 101 sliding periods were created and analyzed this way. We compared all the modes identified in sliding periods with the NAO and PNA modes calculated for the whole dataset using the coefficient of congruence (uncentered correlation), which is recommended for comparisons of principal components (Richman 1986, Huth 2006). In each sliding period, the mode with the highest congruence coefficient with the full-period NAO (PNA) was identified as NAO (PNA). This procedure allows us to observe even slight changes in the extension, intensity and position of modes during the time. Additionally, we calculated one-point correlation maps for selected gridpoints (Wilks 2011). One-point correlation maps for gridpoints in the action centres of modes are used for verification of the realism of the modes calculated by PCA: a high similarity between the map of the mode as calculated by PCA and the autocorrelation map suggests that the mode is realistic, not a statistical artefact. The procedure was performed for the ensemble mean as well as for all 56 ensemble members separately. The test of equality of correlation coefficients was employed to find out the statistical significance of pattern shifts between two periods. We carried out the Fishers's Z transformation $z_i = 0.5 \ln[(1 + r_i)/(1 - r_i)]$, where r_i are correlation coefficients. The test statistic $u = (z_1 - z_2)\,[1/(n_1 - 3) + 1/(n_2 - 3)]^{-1/2}$ (n_i is the sample size) is normally distributed if the null hypothesis that correlation coefficients are equal is true (Huth et al. 2009, Wilks 2011).

3. Results and discussion

3.1. NAO

The structure of the ensemble mean NAO is well developed in all sliding periods with a centre over Greenland and a belt of positive values across the Atlantic Ocean from the southeastern USA to eastern Europe. The position of centres oscillate around their geographical average position. A slight eastward shift of the northern

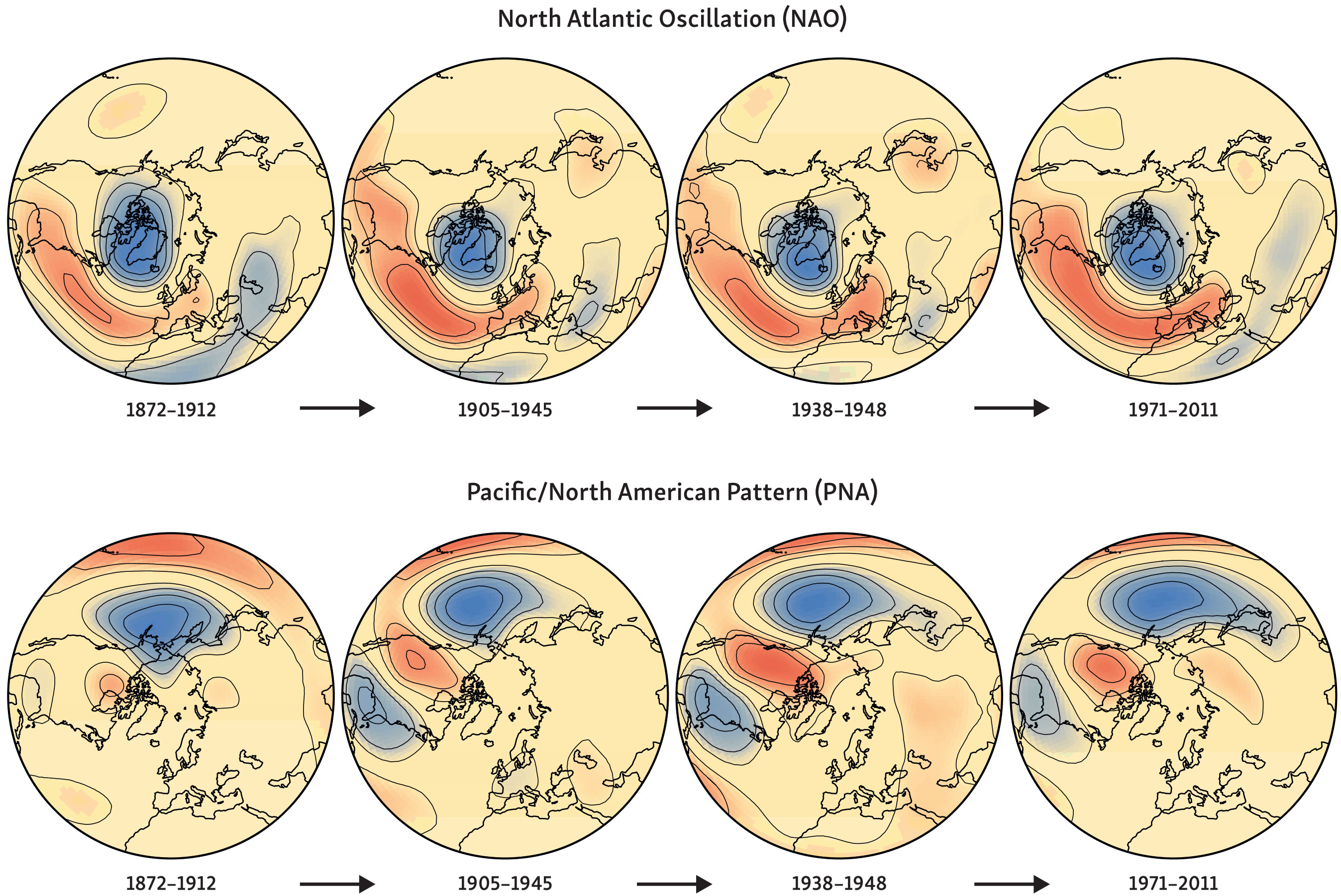

Fig. 2 – Development of NAO and PNA patterns during the 20th century. Red colours represent positive values, while blue are negative.

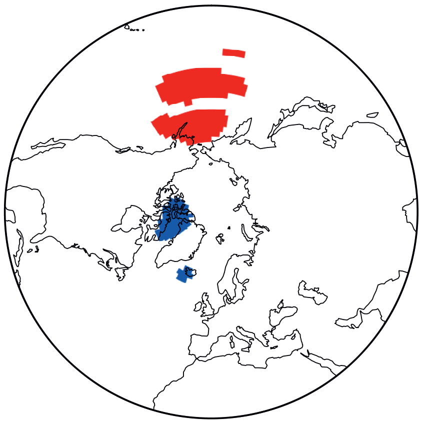

Fig. 3 – Statistically significant differences of correlation coefficients for NAO (blue) and PNA (red) between the first (1872–1912) and last (1971–2011) analysed period.

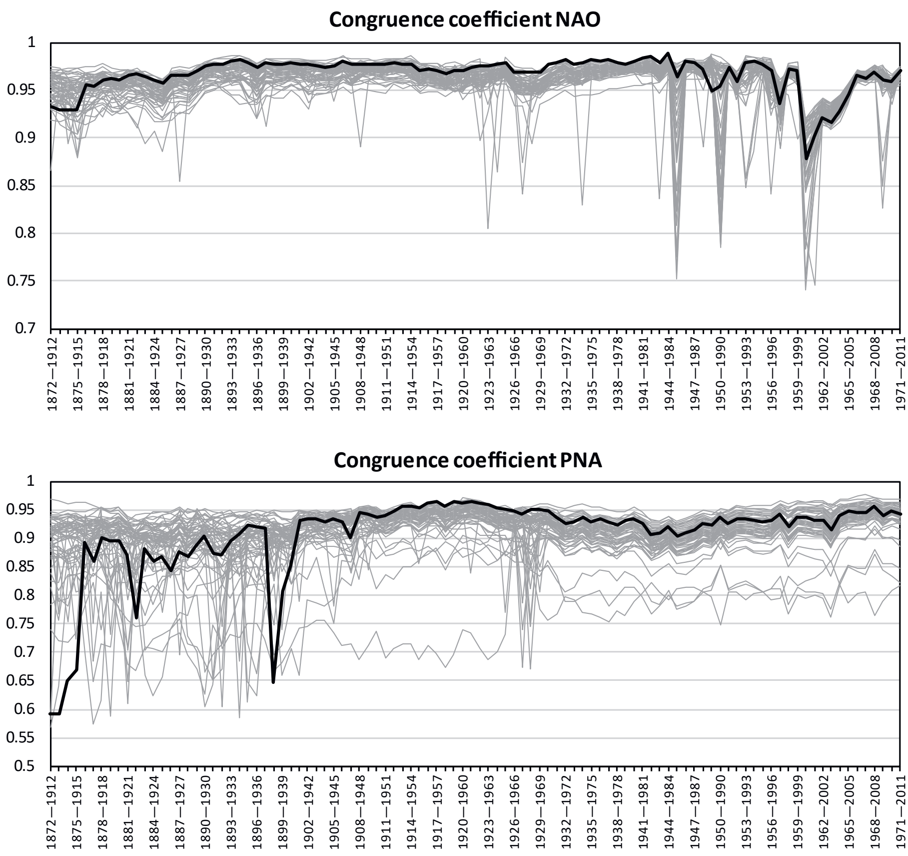

Fig. 4 – Congruence coefficient calculated between the PNA pattern (1872–2011) and all 40-years long periods. The bold line represents the ensemble mean, while the grey lines are the ensemble members; NAO (top) and PNA (bottom).

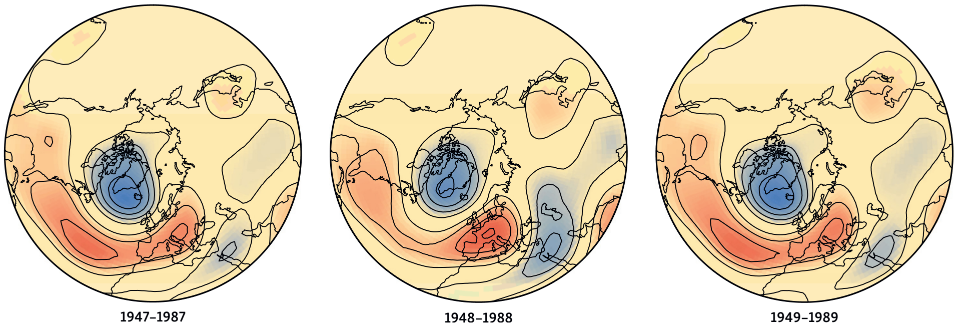

Fig. 5 – Spatial patterns of NAO for periods (a) 1947–1987, (b) 1948–1988 and (c) 1949–1989. Red colours represent positive values while blue are negative.

centre of NAO can be seen during the 20th century (Fig. 2). Moreover, this eastward shift between the first (1872–1912) and the last (1971–2011) period is statistically significant using the Fishers's Z transformation, that indicates that the difference is unlikely to have occurred by chance. In Figure 3, the areas of statistical significance are indicated by the blue highlighting, specifically over northern Canada and Iceland. Presented results are in accordance with previous studies (Jung et al. 2003, Zhang et al. 2008, Wang et al. 2012).

The congruence coefficient, however, shows sudden drops and rises from period to period (Fig. 4). The coefficient expresses the degree of similarity, therefore, sudden changes can be interpreted as indicating a substantial shift or change in the pattern. These changes also occur in two consecutive periods. One of them is the sudden drop in the similarity degree in the period 1960–2000, which occurs both for the ensemble mean and for all ensemble members. During this period, the northern and southern centers of the NAO shift slightly to the south, and in subsequent periods they shift slowly to the north again (not shown). However, it is interesting to focus on the period 1948–1988. While there is no sudden change observed in the congruence coefficient, it is noteworthy that the NAO pattern noticeably differs from those identified as NAO in the previous and subsequent periods: The belt of positive values is weaker in the region around the Azores while in the eastern part over Europe is stronger (Fig. 5).

To verify whether the changed shape of NAO in the 1948–1988 period is realistic, correlation maps were calculated for the grid points with the highest and the lowest correlation coefficients. The structure of the correlation with the centre of negative correlations (Fig. 6a) is close to a common appearance of NAO. However, the correlation with the centre of positive correlations (Fig. 6b) is fragmented into several isolated centres and the belt across the Atlantic Ocean is missing. Therefore, we assume that the mode identified as NAO for 1948–1988 does not describe the real connectivity between distant areas and does not correspond

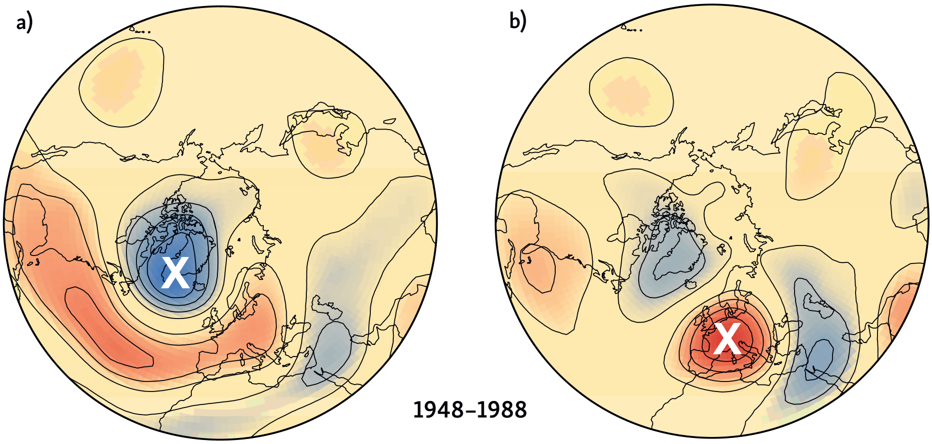

Fig. 6 – Correlation maps calculated for the point a) with the lowest value and b) with the highest value of correlation coefficient in period 1948–1988. The position of the points is highlighted by white crosses. Red colours represent positive values while blue are negative.

to the North Atlantic Oscillation. The fact that the "missing" part of NAO over the Azores appears in another mode for the period 1948–1988 suggests that the NAO is split into two separate modes in 1948–1988. The spatial structure of NAO in period 1948–1988 is, therefore, an artefact of PCA rather than a real feature. Similar pattern splitting may sometimes occur in any ensemble member as well (not shown), but not necessarily during the same period.

As we have shown, the mode pattern can be modified and thus shifted as a result of PCA. However, this remains hidden if we compare just two (Hilmer, Jung 2000; Jung et al. 2003) or three periods (Zhang et al. 2008). Therefore we advocate to use moving PCA to detect these sudden changes.

3.2. PNA

For most periods in the 20th century, the ensemble mean PNA pattern is the strongest mode with its typical position of centres over Hawaii, over the Aleutian Islands in northern Pacific, over Canada and the northwestern USA, and over the southeastern USA. Despite the changes in sea-level pressure observations and simulations over the northern Pacific, as described by Gan et al. (2017) or Choi et al. (2020), the structure of PNA pattern remains relatively stable throughout most of the 20th century. However, there is a slight northward shift observed in the centre over Canada and the northwestern USA during this period. In the early 20th and late 19th century, the centres over North America are getting smaller, weaker, and even almost disappear (Fig. 2). Modes identified as PNA in very early periods have typically one strong and extensive centre over the northern Pacific Ocean (Fig. 7). The other centres are considerably smaller, weaker, and unstable using the ensemble mean. The northward shift of the Pacific centre during the 20th century was found to be statistically significant (Fig. 3), unlike changes in the intensity of other centres.

These changes of ensemble mean PNA would indicate a substantial change in circulation over North America at the turn of the century, for which there is no support in available literature and which is unlikely to represent a real shift in the atmospheric circulation. Therefore, we suppose that the changes reflect mainly the lack of observations from remote areas such as Alaska and Siberia during the late 19th century that were available for assimilation into the 20CR reanalysis. In those times, historical observations from less than 100 land stations were assimilated, mainly from Europe (Compo et al. 2011); as a result, the description of atmospheric circulation over North America and the North Pacific Ocean by the 20CR reanalysis is not sufficiently constrained by observations and its description could, therefore, be only very crude. Variability of atmospheric circulation over the North Pacific is strongly underestimated in the 20CR reanalysis as a result. This is why the Atlantic and European modes dominate in the early periods over the North American and Pacific modes. During the century, we identified statistically significant northward shift of the northern centre (Fig. 3). However, we suspect that even this shift is driven by the lack of observations entering the reanalysis mentioned above. Therefore, results differ from findings of Lee et al. (2012) and Trenberth (1990) who presented the eastward shift.

The congruence coefficient can vary considerably from period to period (Fig. 4). As in the case of the NAO, these fluctuations are related with spatial shifts. However, they are more frequent during the first third of the analysed period. This increases the likelihood that if we were comparing slightly different periods, and looking for statistical significance, we would get different results.

3.3. Ensemble members

The changes presented so far were detected in the ensemble mean. The analysis of individual ensemble members provides a somewhat different picture, however. Figure 8 shows the explained variance of all PCs identified as NAO (a) and PNA (b) during all 40-years periods for each ensemble member. The agreement between ensemble members is decreasing towards the past and the greatest differences occur during the early periods. However, one would expect that ensemble mean will represent average value of explained variance during the time. Surprisingly, this is not true. The explained variance of NAO is lower in all ensemble members

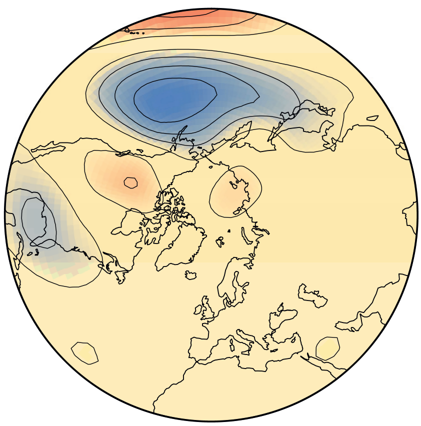

Fig. 7 – The structure of PNA in the ensemble mean for period 1877–1917

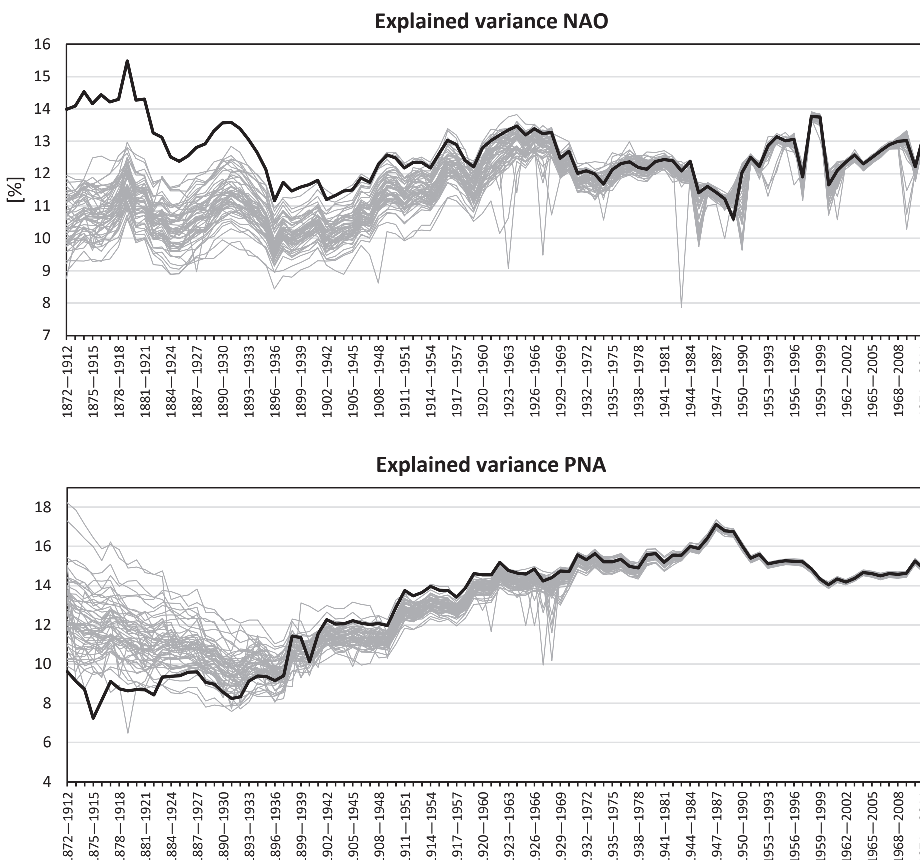

Fig. 8 – Variance explained by the ensemble mean (black) and by each ensemble member (grey) during for all analysed periods; NAO (top) and PNA (bottom)

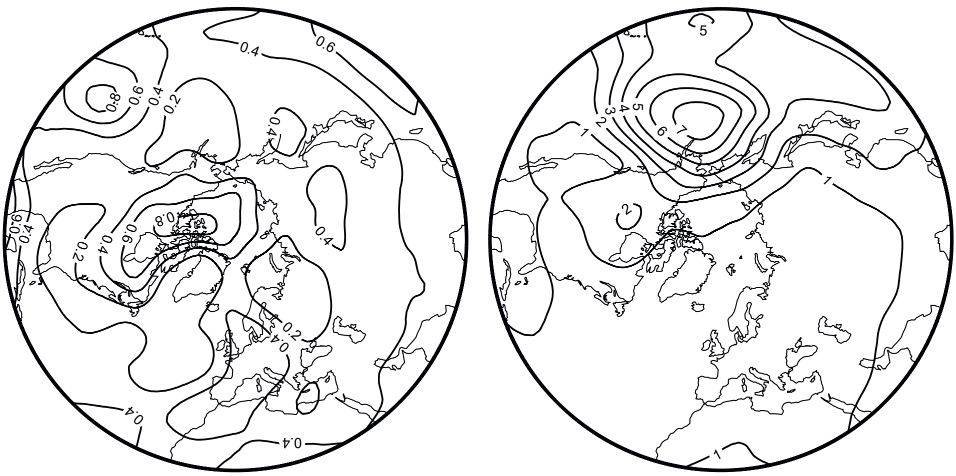

Fig. 9 – The variance of all PCs identified as NAO (a) and PNA (b) of all 56 ensemble members in the period 1872–1912

than in the ensemble mean during the early periods. Contrariwise, the variance related to PNA is smaller in the ensemble mean than in the ensemble members.

The possible cause is shown in Figure 9 which displays the variance of loadings of NAO (a) and PNA (b) across all ensemble members during the first period 1872–1912. For NAO, a good agreement between all ensemble members is shown for the north Atlantic (where NAO is placed), north Pacific, and northeastern Europe, while the highest variation is located in northern Canada and eastern and western Pacific (Fig. 9a), which are the areas suffering from the lack of observations in the early period. Therefore, we suppose that the difference between the ensemble mean and ensemble members is caused by the lack of measurements assimilated to the reanalysis mainly in remote areas.

The variance of loadings of PNA during the earliest period (Fig. 9b) shows that the area with the highest uncertainty is situated in the northern Pacific where the north Pacific centre of PNA is located. It means that PNA differs considerably between ensemble members in this area. We suppose that the atmospheric circulation in individual ensemble members is not constrained by the real circulation because of the lack of assimilated data. However, it is noteworthy that the circulation in each ensemble member appears to be realistic, and the structure of the PNA is relatively well developed across all members. This is supported by the high congruence coefficient values observed in the majority of ensemble members during the early periods (Fig. 4). The main difference is the position of PNA centres, which varies a lot during the early periods (especially over the northern Pacific) due to the observational uncertainty. The ensemble mean is a result of averaging of all ensemble members, which leads to the loss of variability where ensemble members differ from each other.

Additionally, the process of averaging not only affects the distribution of total variance across the entire Northern Hemisphere but also impacts the ensemble mean PNA's ability to explain variability compared to the individual PNAs within the ensemble members. This is evident from the lower amount of variance explained by the ensemble mean PNA during the early periods, as illustrated in Figure 8. The divergence of variance related to PNA between the ensemble mean and individual members is in accordance with Wang et al. (2013) who noted that ensemble mean fields are not suitable for cyclone statistics during the early periods especially in areas with few observations, while they advocate using ensemble members. As demonstrated, the ensemble means are not suitable for detecting modes of low-level variability as well due to the loss of variability during the averaging process.

4. Summary

We have presented spatial changes of NAO and PNA in the ensemble mean of the 20CR reanalysis during the 20th century. We used Principle Component Analysis, which is widely used statistical technique to detect modes of low level variability. However, we have described several situations where comparisons of PCA results for different periods do not describe real changes in the atmospheric circulation. The main findings are following:

- The modes produced by the PCA method can vary considerably even between two consecutive periods. The explained variance and degree of similarity may suggest significant changes from period to period, despite the data in two consecutive periods being nearly identical. This behaviour of PCA has not yet been described in the literature before. We strongly advocate to use moving PCA to detect these sudden fluctuations, when comparing two or more periods and looking for the statistical significance of the shift.
- The changes in the structure of the PNA pattern are substantial when analysing the ensemble mean during the early periods, which is not consistent with any previous study. However, it is worth noting that the weakening and disappearance of the PNA pattern in earlier periods are not captured by the individual ensemble members.
- We identified statistically significant eastward shift of the NAO northern centre between the first and the last analysed period (1872–1912 versus 1971–2011). This finding is in accordance with other studies (Jung at al. 2003, Zhang et al. 2008). However, we did not observed the eastward shift of PNA described by Lee at al. (2012) and Trenberth (1990) using the long term reanalysis 20CRv2.

- The differences observed in the PNA among the ensemble members suggest a loss of information in the ensemble mean during the early periods. Although the model can reproduce the PNA mode, the lack of assimilated observations results in the variance not being adequately modeled in that specific area.
- The lack of assimilated data is causing the underestimation of explained variance by the ensemble mean PNA. The low-frequency variability is captured by ensemble members, however, the strength of the signal is weakened by averaging members to the ensemble mean.
- We recommend using ensemble members rather than the ensemble mean fields to describe changes in modes of low-frequency variability.
- The comparison with other reanalyses is needed in the further studies.

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Data availability statement

The data that support the findings of this study are openly available in the NOAA Physical Sciences Laboratory (PSL) at https://psl.noaa.gov/data/gridded/data.20thC_ReanV2.html (Compo et al. 2011).

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