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A NORTHERN HEMISPHERE ANNULAR MODE AS THE COMBINATION OF THE NAO AND THE PNA

ZHAO Nan (赵　南)[1,2], WANG Ya-fei (王亚非)[1], SHEN Xin-yong (沈新勇)[2,3]

(1. LaSW, Chinese Academy of Meteorological Sciences, Beijing, 100081 China; 2. Key Laboratory of Meteorological Disaster of Ministry of Education, Nanjing University of Information Science and Technology, Nanjing 210044 China; 3. Department of Atmospheric and Oceanic Science, University of Maryland, College Park, Maryland 20742, USA)

Abstract: This paper demonstrates that an annular mode can be constructed from the combination of the North Atlantic Oscillation (NAO) and the Pacific/North American (PNA) patterns. The quasi-annularity, meridional dipole and vertical barotropy of the constructed annular mode resemble those of the Atlantic Oscillation (AO) pattern. It is also a dominant mode in terms of the variance contribution. Moreover, its temporal correlation with the AO is quite strong. This new annular mode has the advantage over the AO in that it incorporates a large portion of the PNA and makes the center of action in the Pacific stronger and more physically relevant than that of the AO. Or, more generally, it may be regarded as a physical mode unlike the AO. The results of this study also indicate the NAO–PNA perspective contains most of the information of the AO, whereas the AO perspective only contains about half of the information of the NAO-PNA. Consequently, the NAO–PNA perspective is regarded by the authors to be more comprehensive than that of the AO.

Key words: annular mode; NAO-PNA perspective; AO

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1 INTRODUCTION

The Arctic Oscillation (AO), the North Atlantic Oscillation (NAO) and the Pacific–North American pattern (PNA) are the three most prominent modes of the winter climate variability of the Northern Hemisphere extra-tropics (Thompson and Wallace[6,7], Wallace[11], Walker and Bliss[9], Wallace and Gutzler[10]). The AO, also known as the Northern Hemisphere Annular Mode (NAM), is usually regarded as a result of wave-zonal interaction on the hemispheric scale. This wave-zonal interaction is particularly characterized by 1) the interaction between the synoptic eddy and the North Atlantic jet in the troposphere, 2) the interaction between the synoptic eddy and the Northern Pacific jet, and 3) the interaction between upward-propagating quasi-stationary waves and the polar vortex in the stratosphere. Point 3) to some extent depends on points 1) and 2), so only the former two points are the most basic. On these issues, one can refer to a review by Thompson, Lee and Baldwin[8]. Generally, the AO, represented by the leading Empirical Orthogonal Function (EOF) of monthly mean sea surface pressure (SLP), does have two centers of action over both of the ocean basins. However, the following facts of 1) weak correlation between the SLP in the two centers of Atlantic and Pacific and 2) that the AO pattern cannot be identified in a physically consistent way in EOF analysis applied to various fields of the whole Northern Hemisphere make people doubt about the meaning of the AO represented by the leading EOF (Deser[2], Ambaum et al.[1], Wallace and Thompson[12]), or rather, the physical relevance of AO's centers of action with the eddy-jet interactions.

On the other hand, the NAO and the PNA, two regional modes, confined to the Euro-Atlantic and the Pacific sectors and found much earlier than the AO,

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Biography: ZHAO Nan, Ph.D., mainly undertaking the research on climate dynamics.

E-mail for correspondence author: zhaon@cams.cma.gov.cn

can reflect well the local eddy-jet interaction in the two basins. Both phases of the NAO/PNA are associated with basin-wide changes in the strength and location of the North Atlantic/Pacific jet stream and storm track. The positive and negative phases of the NAO are found to correspond to the anticyclonic and cyclonic synoptic waves breaking over the Atlantic, respectively (Riviere and Orlanski[5], Benedict[4], Feldstein[3]). The positive phase of the PNA is associated with an enhanced Pacific jet stream and with an eastward shift in the jet exit region, while the negative phase is associated with a westward retraction of that jet stream, which blocks activity over the high latitudes of the North Pacific, and a strong split-flow configuration over the central North Pacific. Thus, unlike the AO, the NAO/PNA pattern can be identified in a physically consistent way in EOF analysis applied to various fields in the Atlantic/ Pacific region (Ambaum et al.[1]), which means that they are physical modes rather than statistic artifacts. All these naturally raise the question as to whether the NAO–PNA or AO perspective is a preferred description of the winter climate variability of the Northern Hemisphere extra-tropics.

As the separated set of physical processes involved in the NAO and the PNA comprise the wave-jet interactions that are regarded as the key to the mechanism of the AO/NAM, it seems that the NAO, together with the PNA, may be enough to depict the quasi-zonal symmetric variability like the AO as long as this quasi-zonal symmetric variability does exist. If this is true, it can be inferred that an annular mode—which is similar to and more physically relevant than the AO/NAM—can be constructed from an appropriate combination of the NAO and the PNA. The purpose of the present research is to find such a relationship between the NAO–PNA and the AO perspectives, and try to construct an annular mode from the NAO and the PNA.

2 DATA

The most basic data for the analysis is the monthly indices of the NAO and the PNA taken from the Climate Prediction Center (CPC). They are constructed by applying the Rotated Principal Component Analysis (RPCA) technique and the modified point-wise method respectively to monthly mean 500-hPa height anomaly (the definitions in detail can be found at http://www.cpc.noaa.gov/). Other data utilized include the NCEP-NCAR reanalysis data of monthly mean height and the CPC monthly AO index constructed by the normalized time coefficient of the leading EOF of monthly mean 1000-hPa height anomalies. Only the winter (November – March) data of the 58 years from 1950 to 2007 are utilized for the present study.

3 METHODS AND RESULTS

In fact, all possible independent combinations of the NAO and the PNA can be found by an EOF analysis of two random variables X_{NAO} and X_{PNA} representing the NAO and the PNA indices. The covariance matrix is calculated as

$$\mathbf{cov}(X_{\mathrm{NAO}}, X_{\mathrm{PNA}}) = \begin{pmatrix} 0.9612 & -0.0158 \\ -0.0158 & 0.9703 \end{pmatrix}. \quad (1)$$

Its two normalized eigenvectors or EOFs are given by

$$\mathrm{EOF1} = \begin{pmatrix} 0.6009 \\ -0.7993 \end{pmatrix}; \quad \mathrm{EOF2} = \begin{pmatrix} 0.7993 \\ 0.6009 \end{pmatrix}, \quad (2)$$

which can explain 50.85% and 49.15% of the total variance of the two indices, respectively. We name the mode represented by the EOF1 the PNAO1, and that by the EOF2 the PNAO2, attempting to indicate that they are just the independent combinations of the PNA and the NAO, while the two time coefficients of the two EOFs are used to define the indices of the PNAO1 and the PNAO2, i.e.

$$\begin{aligned} X_{\mathrm{PNAO1}} &= 0.6009 X_{\mathrm{NAO}} - 0.7993 X_{\mathrm{PNA}} \\ X_{\mathrm{PNAO2}} &= 0.7993 X_{\mathrm{NAO}} + 0.6009 X_{\mathrm{PNA}} \end{aligned}. \quad (3)$$

One may ask whether the PNAO1 and the PNAO2 are physical modes, or the way in which they are constructed is physically consistent for various fields. The answer seems yes, for both the NAO and the PNA can be obtained in a physically consistent way from various fields and so do their linear combinations. In this context, the PNAO1 and the PNAO2 are more physically relevant than the AO. The pattern of the PNAO1 can be found by the regressions of monthly mean height anomaly or other fields at different levels on the PNAO1 index, and so does the PNAO2. In order to compare with the pattern of the AO that is usually defined by 1000 hPa height anomaly, we choose the regressions of monthly mean 1000 hPa height anomaly on the PNAO1 and PNAO2 indices. These patterns are displayed in Fig. 1, where (a) is the pattern of the AO, (b) and (c) are those of the PNAO1 and the PNAO1, respectively. The most remarkable feature of the PNAO1 pattern is its annular structure similar to that of the AO, except for fact that the center of action in the Pacific is stronger than that in the Atlantic whereas the reverse situation is found in the AO pattern. The PNAO2 pattern has both the basic features of the NAO and PNA in the Euro-Atlantic and the Pacific sectors, but the signs of the centers of action in the two basins are opposite. Hence, the PNAO2 by no means can be viewed as an annular mode and is not the focus of the current discussion until section 4. A further investigation on the similarity of the PNAO1 to the AO is about the vertical and horizontal structure of the zonal wind associated with the PNAO1. Figure 2 is the regression of the monthly zonal mean zonal wind anomaly on the (a) AO and (b) PNAO1 indices. It demonstrates that the PNAO1 has an almost identical barotropic structure as the AO. However, as shown in Fig. 3, their horizontal structures of the zonal wind anomaly are quite different. Unlike the AO, which has only a weak dipole of the zonal wind in the Pacific region, the PNAO1 has a very strong dipole of the zonal wind in situ. This dipole can depict the eddy-jet interaction and the basin-wide changes in the strength and location of the jet stream and storm track in this region just like the PNA. Meanwhile, the PNAO1 retains the capabilities of the AO (and the NAO) in depicting the Atlantic jet. As a matter of fact, this is a natural conclusion because the PNAO1 was argued before to be a physical mode.

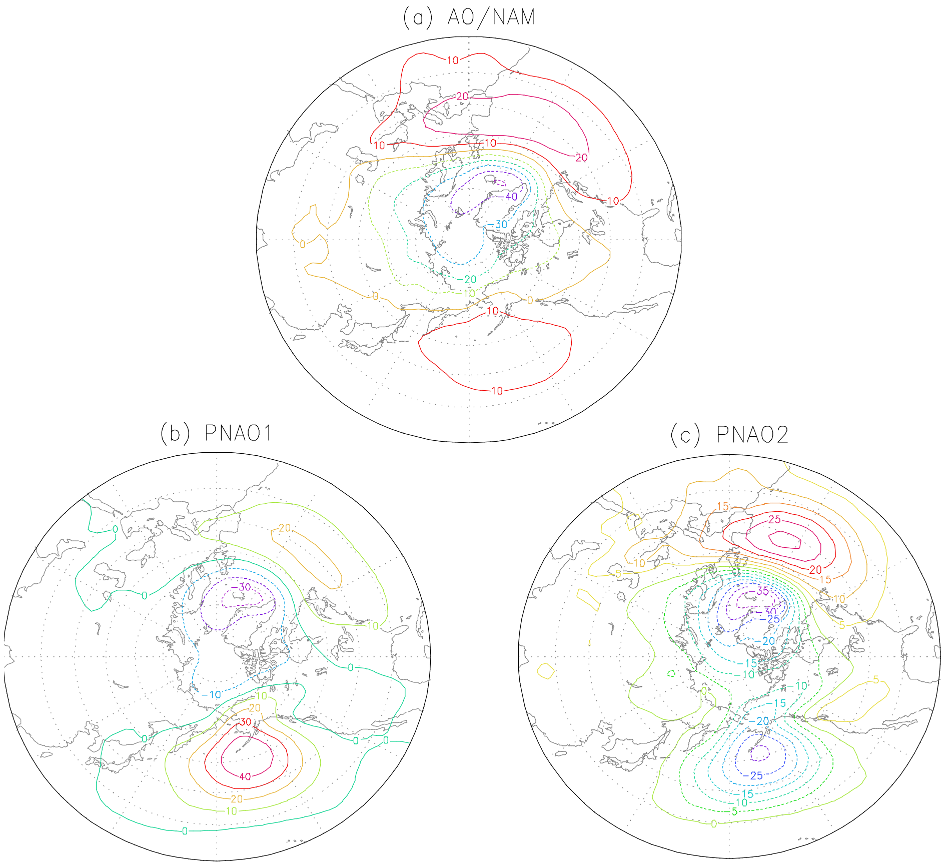

Fig.1 The regression of monthly mean 1000 hPa height anomaly on (a) AO, (b) PNAO1 and (c) PNAO2 index. Contour intervals are 10 m^2/s^2 for (a) and (b), and 5 m^2/s^2 for (c).

In the above discussion, we just touch upon the spatial structure of the PNAO1; another important aspect is its temporal correlation with those of the NAO, the PNA and the AO. Table 1 gives the correlation coefficients among different indices. Just like the AO, the PNAO1 has a positive correlation with the NAO and a negative correlation with the PNA. Compared with the AO, the correlation between the PNAO1 and the PNA is largely promoted from –0.2309 to –0.8042, at the cost of a slight reduction of the correlation between the PNAO1 and the NAO from 0.7129 to 0.6074. This newly constructed mode or the PNAO1 still has a reasonable correlation (0.6073) with the AO, which shows some similarity of time variability between the PNAO1 and the AO. Therefore, the PNAO1 can be regarded as such a mode that it incorporates both the NAO and the PNA into one physical mode that basically retains the spatio-temporal characters of the AO.

Table 1 Correlation coefficients among different indices.

Correlation	AO	NAO	PNA
AO	1.0000	0.7129	–0.2309
PNAO1	0.6073	0.6074	–0.8042
PNAO2	0.4331	0.7944	0.5944

As also shown in the calculation, the PNAO1 can explain nearly 10% of the variance of the monthly mean 1000 hPa height, while the AO explains 19%.

This is a natural result, for the latter is defined by the leading EOF, an optimal one in explaining the maximum variance.

4 SUMMARY AND DISCUSSIONS

We have demonstrated that an annular mode can be constructed from the NAO and the PNA. The validity of this construction can be checked by the possibility and necessity in doing this. First, the quasi-annularity, meridional dipole and the vertical barotropic structure of the PNAO1 resemble those of the AO. It remains also a dominant mode in terms of the variance contribution. Moreover, the temporal correlation between the PNAO1 and the AO is quite strong. These spatio-temporal similarities to the AO indicate clearly that the construction is possible. Second, the PNAO1 is different from the AO in that it incorporates a large portion of the PNA and enhances the center of action in the Pacific, which makes it more physically relevant than the AO. This advantage over the AO indicates that the construction is necessary.

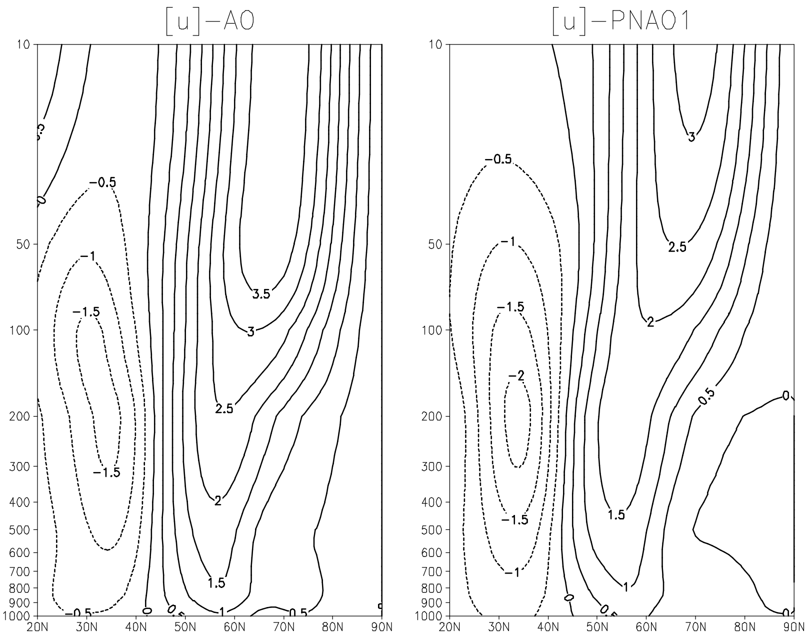

Fig.2 The regression of zonal mean zonal wind anomaly on (a) AO and (b) PNAO1 index (contour interval: 0.5 m/s).

Since the centers of action of the PNAO1 and the PNAO2 over the Pacific have almost equal strengths, coinciding location and opposite signs, they may cancel each other greatly. However, this is not the case over the Atlantic, where their centers of action have different strengths, separated location and the same signs. Such configurations of the PNAO1 and the PNAO2 can give a reasonable explanation of the lack of correlation between the SLP at the centers of action of the two oceans, just like that given by Wallace et al[12], where evidence of the coexistence of patterns (EOF1 and EOF2) in which fluctuations over the North Atlantic and North Pacific are inversely related is presented. Anyway, the lack of correlation between the centers of action in the Pacific and Atlantic Oceans is a fact no one can change just by constructing some new modes. However, as pointed by Wallace et al[12], such mutual canceling of the EOF1 and EOF2 in the Pacific sector does not necessitate the denial of the existence of the EOF1(AO). For the PNAO1 and the PNAO2, this is also the case. Nevertheless, the difference is that the PNAO1 and PNAO2 are physical modes, whereas the EOF1 and EOF2 cannot be explained as physical modes. In stead of giving a general definition of physical modes, we just explain this issue in a more intuitive way as below. The PNA and the NAO are regarded as physical modes because 1) they can be simply explained as the pulsation or meandering of the jets over the two oceans and 2) corresponding fields of height and wind satisfy the quasi-geostrophic relation. As a result, the linear combinations of them, the PNAO1 and the PNAO1, can be also regarded as physical modes because 1) they can be explained as the in-phase and out-of-phase states of the jets over the two oceans, respectively, and 2) since the quasi-geostrophic relation is a linear one, any linear combination of two quasi-geostrophic flows remains also a quasi-geostrophic flow. At present, what is unexplained is the almost zonally symmetric structure of the AO, and our results may be significant for this issue.

At last, we would like to address the question as to whether the NAO–PNA or AO perspective is preferred (Ambaum et al[1]). As argued above, the roles of the

NAO and the PNA in depicting the winter variability of the Northern Hemisphere can be equivalently replaced by two hemispheric scale modes constructed from them. The first one is an annular mode similar to but more physically relevant than the AO, while the second one has opposite signs for their two centers of action at the midlatitudes. This means that the NAO–PNA perspective contains most of the information of the AO, whereas the AO perspective only contains about half of the information of the NAO-PNA. By "most of the information" we just mean that the basic features of the spatial structures of the PNAO1 and the AO are very much similar and they also have quite good temporal correlation. Thus the "information" here is just about the qualitative basic spatiotemporal features rather than the variances explained by them. This idea is illustrated in Fig. 4. Consequently, the NAO–PNA perspective seems to be more comprehensive than that of the AO.

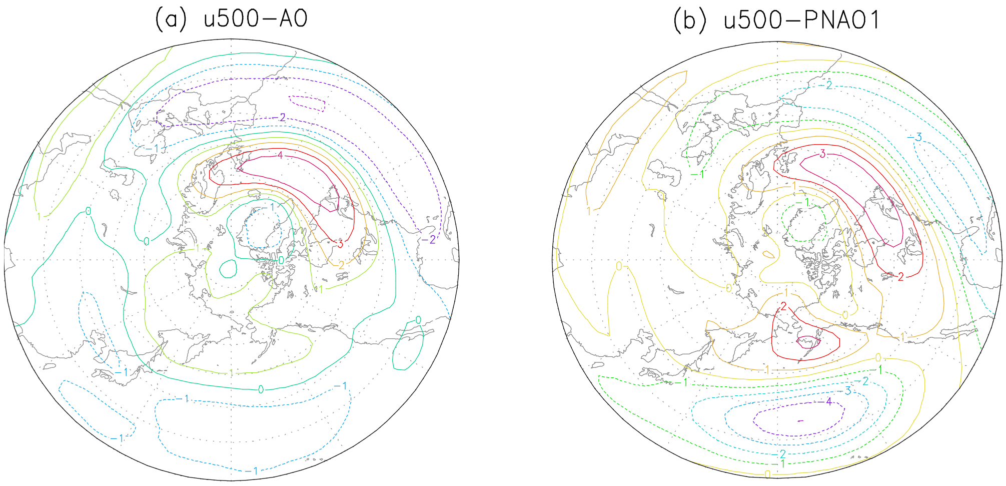

Fig.3 The regression of monthly mean 500 hPa zonal wind anomaly on (a) AO and (b) PNAO1 index (contour interval: 1 m/s).

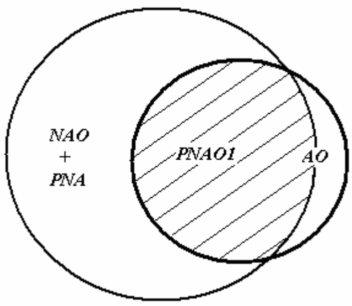

Fig.4 The large circle represents the union of the NAO and the PNA, while the small circle represents the AO. The intersection of the two circles (shadow part) then represents the PNAO1.

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