

What does the APO mean?

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ABSTRACT

The Asian–Pacific Oscillation (APO) is a relatively new teleconnection index and a number of peer-reviewed studies have confirmed its existence. This study reexamines the concept of the APO teleconnection as currently published in the literature. Most results have found that this pattern could be defined as its own teleconnection pattern within the Pacific Ocean Basin. This work demonstrates that the APO is inevitably associated with an additional action centre located over the North Atlantic Ocean, and the index can be extended. Previous studies have used a variety of methods to represent the APO, and a method is proposed here to standardise the formulation. It is argued that the extended index proposed here provides a more robust result. The APO typically is identified using the eddy temperature rather than geopotential height as the source material for its construction, as geopotential could not adequately represent this teleconnection pattern. This leads to a discussion regarding the basic criterion for defining teleconnective activity within the extratropical regions. We also identify other problems in the current understanding of APO theory that need to be addressed.

Keywords: teleconnection, EOF, eddy temperature, Pacific Ocean Basin, Northern Hemisphere, Atlantic Ocean Basin

1. Introduction

In recent years, there is more information available to the public regarding atmospheric teleconnection activity including a recently discovered phenomenon called the Asian–Pacific Oscillation (APO). Published studies describing this teleconnection from different research organisations are on the increase. There are 15 papers alone regarding this topic collected from the proposer as a first or corresponding author (see the reference list). Zhao et al. (2007, hereafter referred to as Z07) in their earliest paper on the subject proposed a seesaw pattern for ‘eddy temperature’ variations in the upper troposphere between Asia and the North Pacific. They called this pattern the APO, and they found that the index based on this teleconnection varies coherently with monsoon activity, subtropical jet movement and location, as well as other important circulation systems (Liu et al., 2011a, 2011b; Wang et al., 2012). They described the APO as an appropriate index for describing the evolution of the circulation over Asia and the North Pacific area. However, there are some issues with the current understanding of APO theory. For example, does the APO index as defined play a role in representing the general circulation locally or more broadly?

The APO index was constructed by using the difference between the mean summer season zonal temperature anomalies in the upper troposphere (500–200 hPa) within the region defined by 15–50°N, 60–120°E and the same variable in the region 15–50°N, 180–120°W. The result was a dipole pattern (Fig. 1). However, the definition of this index may be extended from previously published work. The spatial pattern in the first component of the set of empirical orthogonal functions (EOF1, see Fig. 2) does not support an exclusively Pacific Region Basin seesaw as shown in Fig. 1. The two figures show different information although the correlation between the APO index and the time series of EOF1 was strong (0.93). Many smaller-scale centres distributed throughout Fig. 2 roughly coincide with the characteristic topography of the North Hemisphere. This implies that consideration of the APO as a dipole pattern germane to the Pacific Ocean Basin alone (Fig. 1) is limiting since previous authors used Pacific Region centres of EOF1 (Fig. 2) to confirm the existence of APO. In their analysis, Z07 neglected a large part of the Northern Hemisphere (NH) (0–60°N, 120°W – 30°E in Fig. 1), but which was included here (Fig. 2). The area beyond the Pacific should be considered in order to explore whether an additional action centre exists. Its existence could yield new and useful information about the general circulation. This paper aims to reexamine the APO phenomenon as thoroughly as possible. The investigation begins with a reassessment of

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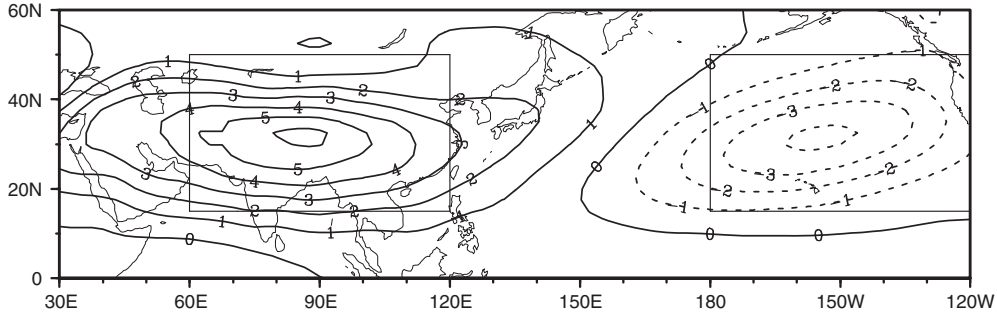


Fig. 1. Climatology of the summer mean upper-tropospheric (500–200 hPa) temperature anomalies from zonal mean (K) for the period 1958–2001 (two boxes represent the regions for Asia and North Pacific, respectively. This was adapted from Fig. 1a of Z07.

the current understanding of APO theory. Note that instead of a complete review of the collected papers themselves, we would rather focus on a detailed discussion of a number of key points regarding the APO phenomenon including a proposal for an improved and expanded index.

In Section 2, the data used here is provided. A statistical analysis regarding the role of the Atlantic Region action centre is carried out in Section 3. A discussion of EOF1 behaviour in different sectors is carried out, and we revisit the use of geopotential height for the APO index in Section 4. A detailed discussion about the limitations of the APO definition is addressed in Section 5, and these issues arise from the analysis from earlier sections. Finally, Section 6 provides a discussion that highlights the main results of this work. We also arranged an appendix table (Table A1) to summarise indices and the domains corresponding to the different acronyms.

2. Data

We used the European Center for Medium-Range Weather Forecast (ECMWF) reanalysis (ERA) monthly mean data set (ERA-40, see Gibson et al., 1997; Uppala et al., 2005), which was the same data set used by other APO researchers. The primary variables accessed here are the temperature (K) and the geopotential height at the 200–500 hPa levels over the entire NH during the summer period (JJA) from 1958 to

2001. The National Centers for Environmental Prediction/ National Center for Atmospheric Research (NCEP/ NCAR) global atmospheric reanalysis dataset (Kalnay et al., 1996) was used for comparison to the ERA derived results. The monthly mean Arctic oscillation (AO) index was used in this study as well, and the values were provided by Climate Prediction Center (CPC). The North Atlantic Oscillation (NAO) index was derived from the time series of the leading EOF of sea level pressure (SLP) anomalies over the Atlantic sector (Hurrell, 1995).

3. The North Atlantic action centre and its role

Figure 3 shows the same basic information as portrayed in Fig. 1, except including the complementary area included in Fig. 2. Note that there is a warm and cool zonal temperature anomaly over Asia and North Pacific, respectively. There is an additional cool anomaly (30°N, 52.5°W), however, centred over the North Atlantic Ocean, roughly coinciding with the location of the cool region in Fig. 2. This temperature anomaly over the North Atlantic has the same order of magnitude as the Pacific Region centres. In fact, the Atlantic Region anomaly appears to be stronger than the other two when the NCEP/NCAR global reanalysis data were used to produce Fig. 3 (not shown). Note that in this analysis, the warm and cool temperature anomalies are congruent with high and low pressure

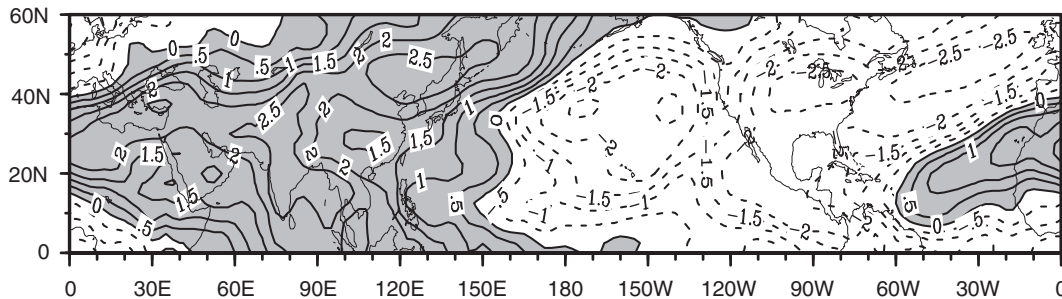


Fig. 2. The spatial pattern ($\times 0.01$) of the EOF1 for T' on the North Hemispheric scale. This was adapted from Fig. 2a of Z07.

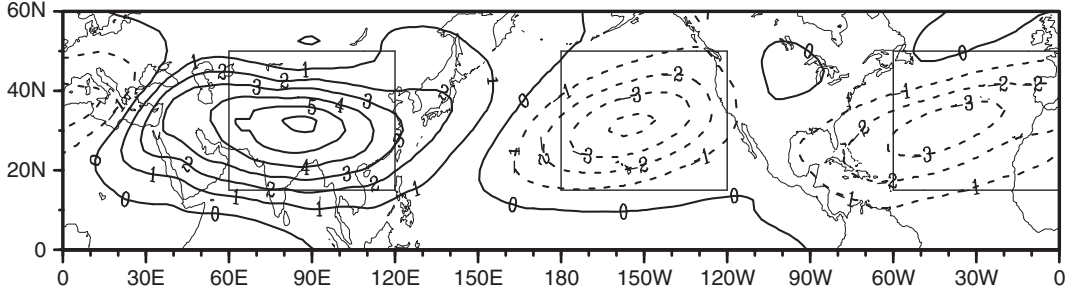


Fig. 3. As in Fig. 1, except for adding the areas for the longitudes of 120°W–0°, in which there was an additional box representing the third action centre area over the North Atlantic Ocean.

regions in the NH general circulation at all levels since, on the time scale used, the upper troposphere is largely equivalent barotropic (Hurrell et al., 1998).

The analysis above implies that the Atlantic Region centre identified above is equally important to the other two centres in order to explain the summer season circulation regime using a hemisphere-wide teleconnection pattern (Figs. 2 and 3). Also, this indicates teleconnectivity between the Atlantic and Pacific Ocean basins especially during the summer season, which cannot be demonstrated using a regional index such as the Pacific North American (PNA) Index. Teleconnection activity during the summer between these two ocean basins has been hinted at in earlier studies of the general circulation over North America (Namias, 1982, 1983). These papers found that the temperature anomalies over the Pacific and Atlantic were often of similar sign during the summer season. Additionally, this extended APO temperature pattern matches what would be expected since the mean upper tropospheric, summer season, NH temperature climatology is more zonal in structure (Hurrell et al., 1998; Fig. 1.5) when compared to the winter pattern. The winter season pattern is opposite to the APO centres, showing a trough over East Asia and ridges over the oceanic region. It is likely that the NH land–ocean distribution may be partially responsible for the APO, and this would argue for an extended APO.

In order to investigate whether the Atlantic Region cool anomaly or low centre is closely associated with the other two action centres, we propose a new index as described here. Based on the information displayed in Fig. 3, we chose the region 15–50°N, 0–60°W to define the boundaries for the additional action centre representing the Atlantic Region anomaly. Thus, an Asian–Pacific–Atlantic (APA) index is presented as follows:

$$\text{APA index} = T'_{15-50^{\circ}\text{N}, 60-120^{\circ}\text{E}} - \frac{1}{2}(T'_{15-50^{\circ}\text{N}, 180-120^{\circ}\text{W}} + T'_{15-50^{\circ}\text{N}, 0-60^{\circ}\text{W}})$$

Term 1
Term 2a
Term 2b

(1)

where T' is the zonal temperature anomaly averaged over the 500–200 hPa layer. Here, we call the first and second terms of the right side of eq. (1) the Asian Component (AC) and the Pacific–Atlantic Component (P–AtC), respectively. The latter has two subcomponents, that is, the Pacific Component (PC) and the Atlantic Component (AtC) (terms 2a and 2b, respectively). Note that the AC was assigned as twice the weight of the other two subcomponents in order to make their weighted sum equal to zero following the approach of Wallace and Gutzler (1981). Table 1 shows the relationships among them. Note that all of the correlation coefficients exceeded the 99.9 % confidence level except for that between the PC and AtC. Here we adopt 0.479 as a critical value beyond which a correlation is regarded as highly significant (significance at the 99.9 % confidence level¹). The correlation coefficient between the AC and P–AtC was -0.877 , which is higher than that between AC and PC (-0.78) separately, and the latter are the APO patterns proposed by Z07. The out-of-phase relationship between the AC and AtC was statistically significant as well ($r = -0.61$). The correlation coefficient between the PC and AtC was 0.28, and this approaches statistical significance at the 95 % confidence level (0.297). Table 2 indicates that the NH EOF1 was highly correlated with the APO, APA, and their components. In particular, the correlation coefficient between the NH EOF1 time series and the APA index was 0.905, which is similar to that between NHs EOF1 and APO index (0.93, Table 2). Additionally, the correlation between Asian and Pacific–Atlantic Region teleconnection centres is more significant than those used to construct the APO. The APA index is defined as a tripole pattern, and should be more informative in a statistical and physical sense for circulations covering the entire NH than

¹It is the test for correlation coefficient. In this case, the number of samples was 44 and the degrees of freedom were 42. Thus, if the coefficient is larger than 0.479, we can say that the result is significant at the 99.9 % confidence level.

Table 1. The correlation among the respective components of the APA index

	AC	PC	AtC	P–AtC
AC	<i>1</i>	<i>−0.780</i>	<i>−0.606</i>	<i>−0.877</i>
PC		<i>1</i>	<i>0.280</i>	<i>0.867</i>
AtC			<i>1</i>	<i>0.722</i>
P–AtC				<i>1</i>

Italic values signify significance above the 99.9 % confidence level.

previously published APO formulations. This does not preclude the use of the APO for Pacific Region only general circulation studies.

The action centres in Fig. 2, however, were located at higher latitudes than those in Figs. 1 or 3. This implies that regions which best match with EOF1 centres may not be the same regions indexed by the APO or APA (Fig. 2). In addition, the correlations among the values derived from the respective action centres in Fig. 3 were much lower than those among the area averaged values of the action centres derived at higher latitudes. This suggests that the APO or APA may not be as strong as the teleconnection patterns found in Wallace and Gutzler (1981). In order to find an index that more closely matched with EOF1, we performed many tests by changing the positions or size of the boxed areas on the locations of the three action centres in Fig. 3. Since there are many plausible choices for such a purpose, here we only show one example, that is, a new APA index as follows:

$$\text{nAPA index} = \underbrace{T'_{10-60^{\circ}\text{N}, 70-140^{\circ}\text{E}}}_{\text{Term 1}} - \underbrace{T'_{15-50^{\circ}\text{N}, 170^{\circ}\text{E}-120^{\circ}\text{W}}}_{\text{Term 2}} - \underbrace{T'_{30-60^{\circ}\text{N}, 0-70^{\circ}\text{W}}}_{\text{Term 3}} \quad (2)$$

This new APA index (nAPA) was constructed by covering more area, especially by extending the boxes into higher latitudes than did the APO or APA index. Similarly, the first, second, and the third terms on the right side of the eq. (2) can be defined as a new Asian Component (nAC), new Pacific Component (nPC) and new Atlantic Component (nAtC), respectively. We can give the second and third terms a combined name as in eq. (1), or the new Pacific–Atlantic Component (nP–AtC).

Table 2. The correlations between the time series of EOF1 in NHs and the indexes of APO and APA, nAPA as well as their components

	APO index	P– AtC	AC– AtC	APA index	nAPA index
NHs EOF1	<i>0.930</i>	<i>0.881</i>	<i>0.803</i>	<i>0.905</i>	<i>0.944</i>

Italic values signify significance above the 99.9 % confidence level.

Table 3. As in Table 1, except for the new APA index. An ‘n’ before the name of the terms means the ‘new’ to distinguish from the old one in Table 1

	nAC	nPC	nAtC	nP–AtC
nAC	<i>1</i>	<i>−0.77</i>	<i>−0.86</i>	<i>−0.90</i>
nPC		<i>1</i>	<i>0.642</i>	<i>0.91</i>
nAtC			<i>1</i>	<i>0.90</i>
nP–AtC				<i>1</i>

Italic values signify significance above the 99.9 % confidence level.

The correlation coefficient between the new APA index and the time series of EOF1 in the NH is now 0.944, which is higher than the 0.93 found for the APO index (Z07). The relationship among each term in eq. (2) as shown in Table 3 indicated that the constituent terms for the nAPA index appear to be more closely interdependent than those of the APA or APO. The out-of-phase relationship between nAC and nAtC or between nAC and nP–AtC became much more significant than the corresponding components for the APO or APA indexes, highlighting the role and importance of the Atlantic Region action centre. The relationship between nPC and nAtC is also stronger since the correlation reached 0.642 (significant at greater than 99.9 %). Again, this suggests that upper level temperature over the two oceans tends to vary in phase. If we follow the explanation proposed by Z07, a new Asian–Atlantic oscillation composed of nAC and nAtC ($r = -0.86$) or a new Asian–Pacific–Atlantic oscillation composed of nAC and nP–AtC ($r = -0.90$) would be more acceptable than the APO ($r = -0.78$).

4. Other calculations

Here, we show the results of other tests in this study of the APO phenomenon, and two prominent calculations are introduced in detail below.

4.1. Behaviour of EOF1 in respective sectors

Since previous studies emphasised the importance of EOF1, it is necessary to investigate how different the EOF1 calculations are when the size of the domain changes. Wang et al. (2010) pointed out that changing the domain in a geopotential field could generate quite different responses in EOF analysis especially for a regional teleconnection pattern such as the Okhotsk–Japan teleconnection. The question to be answered here is: how appropriate is the use of the hemisphere-wide EOF1 time series in order to represent the regional-scale APO phenomenon in the temperature field?

Figure 4a–c shows the spatial patterns of EOF1 using the domain as in Fig. 1, including the Pacific–Atlantic Region, and an extended Pacific–Atlantic Region, respectively.

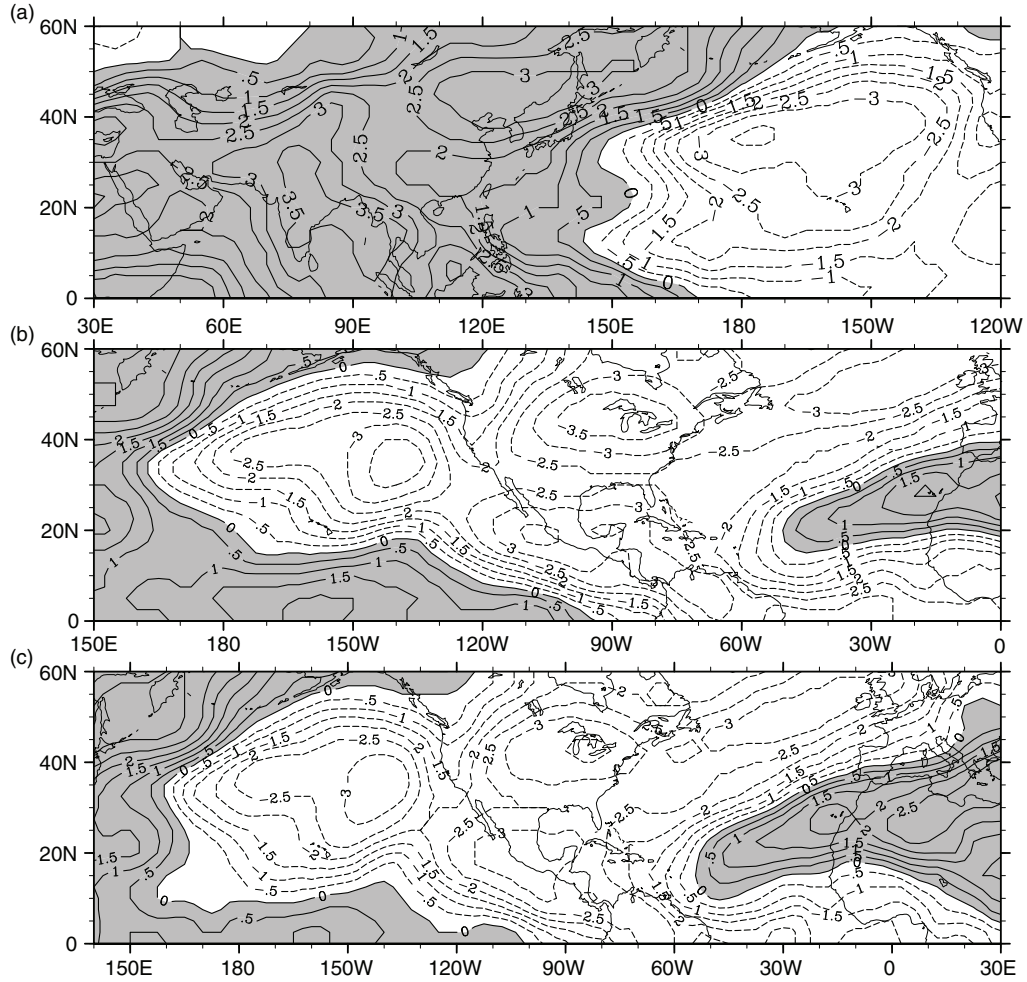


Fig. 4. As in Fig. 2 except for the EOF1 calculated area (a) coinciding with that in Fig. 1, (b) in the Pacific–Atlantic Ocean; (c) extending the Pacific–Atlantic Ocean

Comparing Fig. 4 with Fig. 2 demonstrates that the information displayed in Fig. 4 was almost unchanged in each panel except for some slight drift in the position of the action centres. This implies that the EOF1 distribution basically reflected a NH pattern since the response was not sensitive to the domain change. The correlation coefficients in Tables 4 and 5 provide more evidence supporting this point. The correlations among the time series of EOF1 in

Table 4. The correlation among the time series of EOF1 in the domains of NH, Asian–Pacific, Pacific–Atlantic and extending Pacific–Atlantic

	NH scale	A–P	P–At	e–P–At
NHs	<i>1</i>	<i>0.948</i>	<i>0.861</i>	<i>0.962</i>
A–P		<i>1</i>	<i>0.699</i>	<i>0.842</i>
P–At			<i>1</i>	<i>0.957</i>
e–P–At				<i>1</i>

Italic values signify significance above the 99.9 % confidence level.

their respective regions far exceed the 99.9 % confidence level (Table 4). In other words, any EOF1 analysis in one these domains would show the same result as using one across the entire NH according to previous studies of the APO theory.

Interestingly, the time series correlation between e–P–At (extended area in the Pacific and Atlantic) and P–At regions was 0.957, whereas that between NH and e–P–At regions was slightly higher at 0.962. This suggests that including a

Table 5. The correlation between the time series of EOF1 in respective domains and the respective indexes

	APO	P–AtC	A–AtC	APA index	nAPA index
A–P EOF1	<i>0.940</i>	<i>0.887</i>	<i>0.757</i>	<i>0.889</i>	<i>0.925</i>
P–At EOF1	<i>0.797</i>	<i>0.737</i>	<i>0.719</i>	<i>0.79</i>	<i>0.834</i>
At–A EOF1	<i>0.888</i>	<i>0.843</i>	<i>0.812</i>	<i>0.886</i>	<i>0.918</i>

Italic values signify significance above the 99.9 % confidence level.

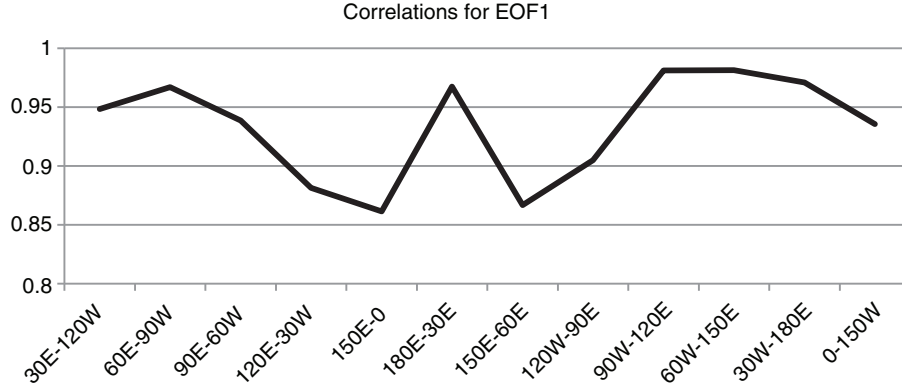


Fig. 5. The evolution of the correlations between time series of the NHs EOF1 and the ones of the respective regional EOF1.

larger domain (approaching that of the entire NH) would be key in strengthening the regional calculations. The values in Table 5 show that the EOF1 in every domain were highly correlated with every index we produced here. In order to investigate the correlation between the regional EOF1 and NH EOF1 in detail, we produced correlations in bands of 30 degrees longitude over the domain of 60° latitude $\times$ 180° longitude as shown in Fig. 5. All of correlation coefficients exceeded 0.85, far above the value needed for confidence at the 99.9 % level. Three peaks in the correlation coefficient greater than 0.95 were found in the bands bordered by 60°E – 90°W , 180° – 30°E and 60°W – 150°E , respectively. The highest correlation was 0.981 in the 60°W – 150°E band. Thus, Fig. 5 and Table 5 suggest that an index for the Atlantic–Asian region may best be reflected by the NH APA, although the patterns in the Asian–Pacific and Pacific–Atlantic regions were also equally robust.

4.2. Situation in the geopotential field

There have been only brief comparisons between temperature and other important meteorological variables in the previously published APO literature. These comparisons are necessary in order to determine if the APO corresponds to teleconnectivity as derived by Wallace and Gutzler (1981). Wallace and Gutzler (1981) used the 500 hPa geopotential height in their teleconnection indexes. Also Z07 suggested that geopotential height could be used to represent the APO, but they only looked at the Pacific Region and did not construct the EOF1 time series based on this data.

The geopotential height is used here instead of temperature as shown in Fig. 6a and b. There were large differences between Fig. 3 and 6a, although a weak high and two weak low centres were located in Asia, Pacific and Atlantic oceans, respectively. However, other strong centres appeared (e.g. North America – high; Fig. 6a). An APO or APA-like structure was nearly non-existent when compared with the pattern appearing in Fig. 3. Additionally, no APO

or APA-like signal can be found in Fig. 6b, which is very different from that shown in Fig. 2. It is especially evident that there was a dipole-like pattern occurring in the Atlantic Region in Fig. 6a, which might imply a different dynamic mechanism from the eddy-temperature-based APA.

The correlation coefficient between the eddy height in 60° – 120°E , 15° – 50°N and in 180° – 120°W was 0.378, which does exceed the 95 % confidence level. The correlation between the NH EOF1 time series and the eddy height anomaly for the two regions (H-APO), however, was not statistically significant (0.127) at all. The NH EOF1 height fields demonstrate a relatively good relationship with the eddy temperature APO index and the NH EOF1 temperature (Table 6). However, the AO was significantly correlated negatively with APO ($r = -0.318$) although the AO has no significant correlation with EOF1 (Table 7).

Zhou and Wang (2015) showed a significant correlation between the NAO index and an APO index they constructed. However, there was no significant correlation between NAO index and the APO indexes as shown in Z07 and here. The strength of the relationship between APO and indexes such as NAO or AO could be adjusted subjectively as needed. However, researchers have argued that while the NAO is limited to the North Atlantic, it is closely linked to the broader hemispheric AO pattern. This does not imply that a study based on the NAO alone necessarily leads to less valuable or useful results than one using the AO alone. However, the relationship between AO and NAO is very different from that of the APO and APA. Both of the former indexes can be expressed in terms of the SLP or geopotential height (Thompson and Wallace, 2000), whereas both the latter indexes can be explained in the upper tropospheric and hemispheric-wide eddy temperature EOF1. However, note that NAO does not belong to an EOF 1 in the NH scale, which is different from AO and APO-like indices.

Thus, it is difficult to sufficiently compare the two pairs of indexes. Using eddy temperature might have limitations in expressing teleconnection patterns when compared with

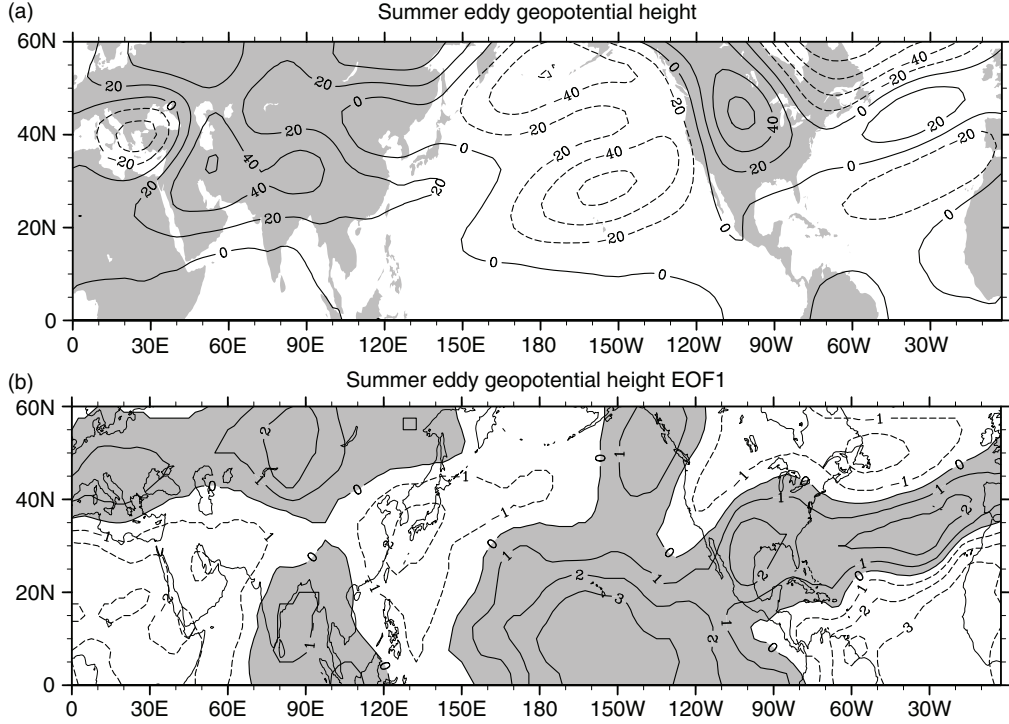


Fig. 6. (a) As in Fig. 3 except for the geopotential height (m); (b) as in Fig. 2 except for the geopotential height (500–200 hPa).

geopotential height as discussed here. Note also that, unlike in the temperature field, higher correlations between the values obtained by using a large enough domain for the NH EOF1 time series does not occur in the geopotential field. A weaker result here might be expected since the geopotential height is a function of both temperature and pressure although the atmospheric state appeared to be quasi-barotropic (see Section 2). Lastly, note that the difference between the Zhou and Wang (2015) study and this study here is that we included a discussion using the AO index for comparison. Also, in this study we investigated the relationship between the AO and APO indexes in detail. This analysis indicates that the AO potentially has a stronger connection to the APO since both phenomena can be explained via the first principle component of the respective meteorological elements in the NH scale. More studies regarding this issue are desirable in future.

5. Major problems with the definition of the APO

In this analysis, an anomalous low centre over the North Atlantic Region with same order of magnitude was shown to be as important as the other two centres (Fig. 3). This low centre coincides with a coherent low over the North Atlantic in the spatial pattern of EOF1 (Fig. 2) based on which Z07 documented the APO (Fig. 1). However, the APO index as proposed formerly is a more regional index or phenomenon

(Fig. 1), whereas our analysis includes the Atlantic Ocean Basin (Fig. 2). Previous research did not consider the linkage to the Atlantic Region, but Figs. 2 and 3 show that this linkage is an important part of the teleconnection phenomenon. As discussed in Section 4, our analysis proposes an extension of the previously published methodologies for expressing the APO.

Additionally, here we obtained higher correlations among the terms of an APA index constructed by changing the calculation to include three action centres of greater area (Fig. 3) than those using a more regional APO index.

The larger geographical areas included here for the index components produced even higher correlations between the indexes and the EOF1 time series. Since EOF1 accounted for only 0.21 of the contribution to the total NH variance, this result suggests that the APO cannot act as a teleconnection pattern significantly independent of any other pattern constructed using random selection and EOF1 alone. Thus, it is demonstrated in previous sections that an approach used which includes more centres of action is more physically meaningful.

Although Z07 did not originally include the Atlantic Region low, it was a surprise that this low centre was included in a later publication without any reasonable explanation (see Fig. 3a in Zhao et al., 2010). Additionally, their study only used data within the 300–200 hPa layer, which is inconsistent with the original formulation of

Table 6. Correlation between the time series of EOF1 for eddy geopotential height from 200 to 500 hPa (NHs H-EOF1) and NHs EOF1, APO index as well as APO index in the geopotential field (H-APO)

	NHs EOF1	APO	H-APO
NHs H-EOF1	<i>0.495</i>	0.414**	0.127

Italic value (or double asterisk) signifies significance above the 99.9 % (99 %) confidence level.

the APO (500–200 hPa layer). Instead, APO studies that followed (e.g. Zhao et al., 2009, 2010, 2011a, 2012a) did not assign great importance to, or use, the Atlantic Region lows. Rather, we consider this feature as an important accessory that needs further research.

It is likely that the importance of the Atlantic Region centre is the result of Rossby Wave propagation. Wallace and Gutzler (1981) pointed out that connections between the flow regime over the Pacific and North America have been quantified for a long time in the literature going back at least (now) 75 years when Allen et al. (1940) noted a negative correlation between SLP in the Aleutian region and the western USA. Later, Lorenz (1951) and Namias (1951) noted that there were strong correlations between the North Pacific and Eastern USA flow regimes. Additionally, Jiang and Lau (2008) demonstrated a summer season Pacific Region wave train showing centres of action between the Bering Sea region and North America. Rossby Wave propagation may explain the higher correlations shown here when the calculation domains were extended poleward (Section 3). In fact, there was strong wave activity flux crossing the North American continent, which was linked to strong positive/negative phases of the APA (not shown).

Zhao et al. (2010) then postulated that the APO index could be formulated using data obtained from 300 to 200 hPa layer only, which was then demonstrated subsequently in Zhao et al. (2011a). This does provide for a more consistent definition of the APO index. This change in definition may not be convincing as it now does not include a large portion of the upper and middle troposphere. Here, it is recommended that examining the 500–200 hPa level for all three centres produces a better statistical result and it includes a significant portion of the upper airflow. Also, the

Table 7. Correlation between AO in the summer and NHs EOF1, NHs H-EOF1 as well as APO index

	NHs EOF1	NHs H-EOF1	APO
AO	0.135	−0.234	−0.318*

Single asterisk signifies significance above the 95 % confidence level.

300–200 hPa layer could be located largely within the stratosphere in regions of low pressure during the winter season (Hurrell et al., 1998). The revised APO index using the proposed new equation should be renamed, however, since the action centres now include an Atlantic centre of action within NH (Fig. 2). The APA name has been proposed here. Additionally, using the definition proposed in this work, one can more readily identify an anomalous hemisphere-wide general circulation change that might be related to teleconnections between the Pacific and Atlantic Ocean basins.

The new index that was constructed is better correlated with EOF1 as well and provides for a better physical explanation in describing hemispheric-scale patterns than previous APO formulations. Small differences in highly significant correlations, however, may not be a sufficient reason for generating a new index. Additionally, we have pointed out that the eddy temperature has weaknesses in identifying teleconnection patterns compared with using geopotential height or pressure.

6. Concluding remarks

Some uncertainty and inconsistency in published APO theory is summarised here:

- (1) This phenomenon is not, as of yet, a widely used teleconnection pattern that is generally expressed by using geopotential height. This variable is convenient for explaining the evolution of atmospheric circulation over the extratropical regions (e.g. Wallace and Gutzler, 1981). Previous studies discussed the APO phenomenon in order to explain variations in the Pacific Region general circulation, although these same studies have not proposed a satisfactory explanation for the exclusive use of temperature variations to define this index rather than the geopotential height (Wallace and Gutzler, 1981). Since the H-APO phenomenon was much weaker than APO, geopotential height may not reflect this teleconnection pattern adequately. This implies that it is more difficult to use a temperature-based APO to explain atmospheric circulations since the geopotential height may only partly explain three dimensional circulations. The poor correlation between NH H-EOF1 and H-APO suggested that the hemispheric-scale EOF1 could not represent an APO-like phenomenon well. A better correlation would be desired since variations in the geopotential field more faithfully indicate the presence and location of the jet stream and atmospheric waves (e.g. Rossby or Kelvin) than temperature. This is the reason why most teleconnection

research tended to use the geopotential height when expressing teleconnection phenomenon².

- (2) Since EOF1 analysis was applied to determine whether the APO should be considered a teleconnection pattern on the hemispheric scale, the APO might have similar features to those in some other widely recognised teleconnection patterns. For example, the AO was identified using EOF1 analysis as well (Higgins et al., 2002). Unfortunately, a pertinent comparison between the APO and other teleconnections as performed here is rare in previous studies. Since the AO was well correlated with the APO as shown in our analysis here, we could not ignore the influence of the AO on the APO.
- (3) There have been many investigations showing the relationship between the APO and other atmospheric phenomena (Zhou et al., 2009; Liu et al., 2011a; Wang et al., 2012; Zhou and Zhao, 2013, etc.). These simultaneous correlations or composite analyses were used to demonstrate that APO phases could be associated with variations in other indexes, for example, the monsoon index (Z07; Zhao et al., 2011a, 2011b, 2011c, 2012a, 2012b, etc.). However, these analyses may be unnecessary since the APO cannot replace any other index that specialised in describing a specific phenomenon due to the weak correlations.
- (4) The time series of the NH EOF1 is not the best tool for describing the APO teleconnection since the strongest match was in the area of 90°W–150°E (Fig. 5). In addition, the NH EOF1 must include a robust signal from the Atlantic Region low, which improves and extends the representativeness of the APO as a hemispheric-wide teleconnection, as shown here.
- (5) Unlike those in geopotential field, highly significant correlations between the indexes using the eddy temperature tended to appear almost everywhere as long as the construction of index involved large enough geographical areas (see Tables 1–5). This feature significantly reduces the existence and value of temperature-based teleconnection pattern because one cannot define a teleconnection pattern precisely using simple correlation as Wallace and Gutzler (1981) did. Thus, the APO pattern would lack uniqueness, which does not coincide with the rationale for the existence of a teleconnection.

Therefore, the conclusion that two subregions belong to one pattern by using correlation would be unreliable especially in the temperature field. It is apparent that two patterns with qualitative differences (see Figs. 1 and 2) might represent the same atmospheric processes physically as long as there is a high correlation between them. Additionally, there was no reasonable explanation in previously published work justifying the use of the eddy temperature as the variable for the analysis of the APO. This technique was used typically to express wave train propagation in the atmosphere (Wang et al., 2010). However, it is difficult to find APO-related temperature wave propagation in previous studies and our results. In fact, the temperature anomalies alone from the time mean field can also produce a similar picture to Fig. 1. The eddy technique should not be necessary.

We have found some fundamental differences between the previously published APO work and our analysis here based on physical properties. For example, Fig. 7b in Zhao et al. (2012b) could be interpreted to show that there was westward-propagating wave activity over Eurasian continent. However, the westward wave propagation does not occur in a location where a westerly jet is climatically located over the continent, according to the wave theory proposed by Hoskins and Karoly (1981). The simulation and prediction of the APO pattern using models (Zhao et al., 2010; Chen et al., 2013; Zhou and Zhao, 2013; Liu et al., 2015) could be difficult because there may be so many problems in the APO definition, the APO meaning, and the impacts of the APO as shown in our analysis here. Similarly, some composite analyses presented in previous work cannot be explained readily through a physical mechanism.

Also, Zhao et al. (2010) indicated that their Fig. 12b shows a structure associated with zonal wave number two. However, their work only shows the Pacific Ocean Basin, and one might find five or more irregular centres when examining the NH flow regime. This does not necessarily indicate a wave train structure. Additionally, previous studies have provided no explanation of the mechanism for driving the APO.

Thus, we believe that a complete reexamination of the current theory regarding the physical mechanism of APO-caused climate anomalies would be necessary because of the mentioned problems above. The new index that included the Atlantic Region cool anomaly definitely expresses a more hemispheric-scale teleconnection than the old index. Although the use of the eddy temperature may largely limit the practical application of all the indexes, the first step for the further study of the APO-like phenomenon should be to construct an index with a rigorous or standard definition. An ideal reexamination would include information based on (1) including the Atlantic low, and (2) overcoming

²Sir Gilbert Walker was one of the few researchers who made numbers of attempts in using temperature to describe extratropical variability (e.g. Walker, 1923).

the limitation of using eddy temperature. A large-scale dynamics-based analysis that supports our claim would be beyond the scope of this study.

Using the results presented here, the out-of-phase between the AC and PC or AtC, might be a by-product of the large-scale scope of thermodynamic equilibrium among continents and oceans in the NH. However, any APO index does not describe accurately the land–sea equilibrium because the temperature centres in Fig. 2 did not precisely coincide with the NH land–sea distribution. Since there are so many possible problems in defining the APO, we would like to suggest new avenues for APO study:

- (1) Avoid the use of NH EOF1 eddy temperature time series to explain the APO pattern since it could not precisely describe this pattern as shown in Fig. 5 and Tables 6 and 7. Although there is high correlation between the NH EOF1 and APO, it only reflects the fact that a strong signal in a large enough region has been included in the NH EOF1 produced by grid point data. This phenomenon is particularly prominent in the temperature field. Although many time series including the regional EOF1 as shown in Fig. 5 could be regarded as APO indexes that are fit for use as the standard in APO papers, we cannot use all of them. A careful comparison of the details for the correlation analysis procedures is necessary. In this case, the EOF1 in the band of 60°E–90°W with higher correlation as shown in Fig. 5 would be a better choice though not perfect.
- (2) Since using temperature cannot elucidate atmospheric waves well, describing how to use geopotential height to represent the APO effectively would be an important issue for future study. An attempt to find more connections with the AO would be a good option for further studies since the AO was significantly correlated with one of the APO indexes as shown in this analysis,
- (3) It is necessary to include the Atlantic Region low, extending the APO index into the Atlantic Basin in order to study hemispheric-scale phenomena. We should seek to understand the physical meaning for the difference between a Pacific Basin only APO and that with the Atlantic low incorporated (APA).

We must acknowledge that the previous studies proposed a thought-provoking question, that is, how can we explain a teleconnection in the temperature field for so many indexes that were highly correlated with each other. In order to improve our understanding of this phenomenon, further research must develop a more rigorous research plan in overcoming the defects mentioned here. If these are overcome, this will be beneficial to climate research.

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8. Appendix

Table A1. The acronyms for the pattern names and their associated areas were summarised as follows:

Acronym	Name	Covering area
APO	Asian–Pacific Oscillation	15–50°N, 60–120°E; 15–50°N, 180–120°W
APA	Asian–Pacific–Atlantic	15–50°N, 60–120°E; 15–50°N, 180–120°W; 15–50°N, 0–60°W
AC	Asian centre	15–50°N, 60–120°E
PC	Pacific centre	15–50°N, 180–120°W
AtC	Atlantic centre	15–50°N, 0–60°W
P–AtC	Pacific–Atlantic centre	15–50°N, 180–120°W; 15–50°N, 0–60°W
nAPA	New APA	10–60°N, 70–140°E; 15–50°N, 170°E – 120°W; 30–60°N, 0–70°W
nAC	New Asian centre	10–60°N, 70–140°E
nPC	New Pacific centre	15–50°N, 170°E – 120°W
nAtC	New Atlantic centre	30–60°N, 0–70°W
nP–AtC	New Pacific–Atlantic centre	15–50°N, 170°E – 120°W; 30–60°N, 0–70°W
NHs	North Hemisphere scale	0–60°N, 0°E – 0°W
A–P	Area from Asia to Pacific	0–60°N, 30°E – 120°W
P–At	Area from Pacific to Atlantic	0–60°N, 150°E – 0°W
e-P–At	Extended area in Pacific and Atlantic	0–60°N, 150°E – 30°E
H-APO	APO in geopotential height field	Same as in APO

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