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ORIGINAL ARTICLE

On the observed relationship between the Pacific Decadal Oscillation and the Atlantic Multi-decadal Oscillation

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Abstract We studied the relationship between the dominant patterns of sea surface temperature (SST) variability in the North Pacific and the North Atlantic. The patterns are known as the Pacific Decadal Oscillation (PDO) and the Atlantic Multi-decadal Oscillation (AMO). In the analysis we used two different observational data sets for SST. Due to the high degree of serial correlation in the PDO and AMO time series, various tests were carried out to assess the significance of the correlations. The results demonstrated that the correlations are significant when the PDO leads the AMO by 1 year and when the AMO leads the PDO by 11–12 years. The possible physical processes involved are discussed, along with their potential implication for decadal prediction.

Keywords Relationship · Pacific Decadal Oscillation · Atlantic Multi-decadal Oscillation · Monte Carlo test · Decadal prediction

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1 Introduction

Interaction between the mid-latitude oceans and their overlying atmosphere is an important aspect to understanding and predicting climate change. On the one hand, mid-latitude sea surface temperature (SST) anomalies are primarily caused by air-sea fluxes that are associated with short-term atmospheric variability (e.g., Frankignoul 1985), and on the other hand, the SST anomalies can also affect the upper level atmospheric variability, although its impact is of modest amplitude compared to internal atmospheric variability (e.g., Kushnir et al. 2002). The mid-latitude oceans can further interact with each other through the overlying atmosphere.

The mid-latitude warm North Pacific SST anomalies most likely favor a warm ridge response of the atmosphere (e.g., Liu and Wu 2004), and the atmospheric anomalies over the North Pacific can propagate across North America in the form of stationary Rossby wave trains and finally trigger atmospheric variation over the North Atlantic (Honda et al. 2001). Eshel (2003) did find that North Pacific surface pressure is a significant and useful predictor for the North Atlantic Oscillation. These results suggest that the North Pacific SST anomalies may lead to the North Atlantic SST anomalies through their modulation of the atmospheric circulation. Likewise, the North Atlantic SST anomalies can also affect the North Pacific SST through their modulation of mid-latitude storm tracks. Both the North Pacific and the North Atlantic are shown to have decadal–multidecadal variability, called the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO), respectively (Mantua et al. 1997; Enfield et al. 2001). Zhang and Delworth (2007) found that the observed AMO index (AMO is defined as the mean of Atlantic SST anomalies north of the equator) leads the observed PDO index (the PDO is defined as the leading principal component of SST anomalies in the North Pacific poleward of 20°N) by 12 years at the maximum correlation, and suggested that a regime shift of the North Pacific climate to a phase of warming over the central and western North Pacific and cooling off the west coast of the North America, opposite to the 1976–1977 shift, might occur in the early twenty-first century, a decade after the switch of the observed AMO to a positive phase in about 1995. The relationship between the North Pacific and the North Atlantic is also visible in the observation analysis of Delworth and Mann (2000). Recent modeling studies (Timmermann et al. 2005; Okumura et al. 2009) found that the slowing down of the Atlantic meridional overturning circulation can affect the North Pacific SST through the Arctic Ocean and Tropical Oceans. The North Atlantic's impact on the North Pacific through the overlying atmosphere is also supported by the paleoclimate modelings. By carrying out a sensitivity experiment with a coupled ocean atmosphere general circulation model, Mikolajewicz et al. (1997) found that a cooling event in the North Pacific synchronous with the Younger Dryas (12,000 calendar years before present) is closely related to a temporary shutdown of North Atlantic Deep Water formation and associated surface cooling over the North Atlantic. Their results demonstrated that the impact of the North Atlantic on the North Pacific is primarily through atmospheric forcing.

Liu et al. (2007) showed that the atmospheric response to SST anomalies becomes more significant at annual and longer time scales because of the faster reduction of the atmospheric internal variability toward longer time scales than that of the response signal. From this perspective the interaction between the PDO and the AMO through the overlying atmosphere may be more significant because of the long duration of the associated SST anomalies. Modeling and observational studies indeed show significant coherent changes between the North Pacific and the North Atlantic oceans on a decadal time scale (Meehl et al. 1998, White and Cayan 1998).

In this paper we focus on a simple but vitally important question of whether we can find significant correlations between the PDO and the AMO from observations. Various tests are carried out to assess the significance of correlations. Our results demonstrate that although the correlation between the PDO and the AMO is modest, it is statistically significant. The possible physical processes involved are also discussed.

The paper is organized as follows: Section 2 introduces the data sets and methods used in this study. Results and analysis are shown in Sect. 3. Possible physical processes are explored in Sect. 4. Discussions and conclusions are given in the last two sections.

2 Data and analysis procedures

In this study, we use 1° latitude-longitude yearly mean SST data for 1870–2002, derived from the HADISST dataset [Rayner et al. 2003, UK Meteorological Office, Hadley Centre. HadISST 1.1-Global sea-Ice coverage and SST (1870–present)]. Long-time scale fluctuations, basically the trend, are removed by first fitting a third order polynomial to the original time series at each grid point. A filtered time series is then calculated by subtracting that polynomial from the original time series. The scheme is similar to linear regression, but uses higher order polynomials (Czaja and Frankignoul 2002). Our subsequent analyses use these filtered time series, since the very low frequency changes captured by the third order polynomial are not the subject of the study. The PDO index is defined as the first principal component of the North Pacific (20°N–60°N), and the AMO index is defined as the first principal component of the North Atlantic (0–60°N). To ensure the significance of the results, an updated version of the Kaplan et al. (1998) monthly reanalysis of global SST anomalies is also analyzed for comparison, although the two SST data sets are not completely independent. We chose the same time interval (1870–2002) as the Kaplan SST for analysis.

The simple lagged correlation analysis is the main method used in this study. Due to the high degree of serial correlation in the PDO and AMO indices, three different kinds of significance tests are carried out to assess the significance of the results.

The first significance test method uses the two-tailed Student's t-test with the effective degree of freedom (DOF) calculated as

$$N = N_o \times \frac{1 - R_1 R_2}{1 + R_1 R_2},$$

where N_o is the length of the time series, and R_1 and R_2 are the lag1 correlation coefficients of each time series (e.g., Bretherton et al. 1999).

The second and third methods are carefully designed Monte Carlo tests based on the bootstrap approach (von Storch and Zwiers 1999) and nth-order autoregressive (ARn) models (Katz 1982), respectively. The significance levels of Monta Carlo tests are estimated based on 1000 times calculations of the designed time series.

To be more specific, for the second method we used randomly scrambled PDO and AMO indices (e.g., Czaja and Frankignoul 2002) to calculate the correlation coefficients 1000 times. First, we randomly scrambled the original PDO and AMO index and obtained a new pair of time series. Then we calculated the lead-lag correlation based on these new time series. We repeated this process for 1000 times and finally got a distribution of correlation values for each lag. The quoted significance levels indicate the percentage of randomized correlation coefficients that exceed the value being tested. The third method is similar to the second, except that the random time series are composed by a first-order autoregressive process with the lag1 correlation coefficients and variance maintained the same as the original indices. We also tested higher order autoregressive models, for example, the AR2 process, and the results are qualitatively the same as that of the AR1 models. Hence, we will only show results estimated based on the AR1 model in this article.

3 Lead-lag relationship between the PDO and the AMO

Figure 1 shows the first EOF modes and their principle components (PCs, hereafter) for the North Pacific (Fig. 1a, c, e) and the North Atlantic (Fig. 1b, d, e) calculated based on HADISST (Fig. 1a, b) and the Kaplan SST data set (Fig. 1c, d). The two SST data sets give quantitatively similar results. EOF1 of the North Pacific (Fig. 1a, c), much like the results of previous studies (e.g., Zhang et al. 1997), displays a horseshoe-like pattern. SST anomalies extending from the Japan Sea to the Kuroshio/Oyashio extension region show different signs from the remaining region of the North Pacific. In contrast, EOF1 for the North Atlantic (Fig. 1b, d) shows a basin-wide warming with two warming centers located at northeast subtropics and south of Greenland, respectively. This is similar to the previous results. Deser and Blackmon (1993) also found that the first EOF mode of the North Atlantic has uniform polarity over the entire basin. Both PCs (Fig. 1e) of the North Pacific and North Atlantic show multiple time scales of interannual and interdecadal variability. We will refer to these two PCs as the PDO and AMO indices, respectively, in the context of this article. The explained variances of these two

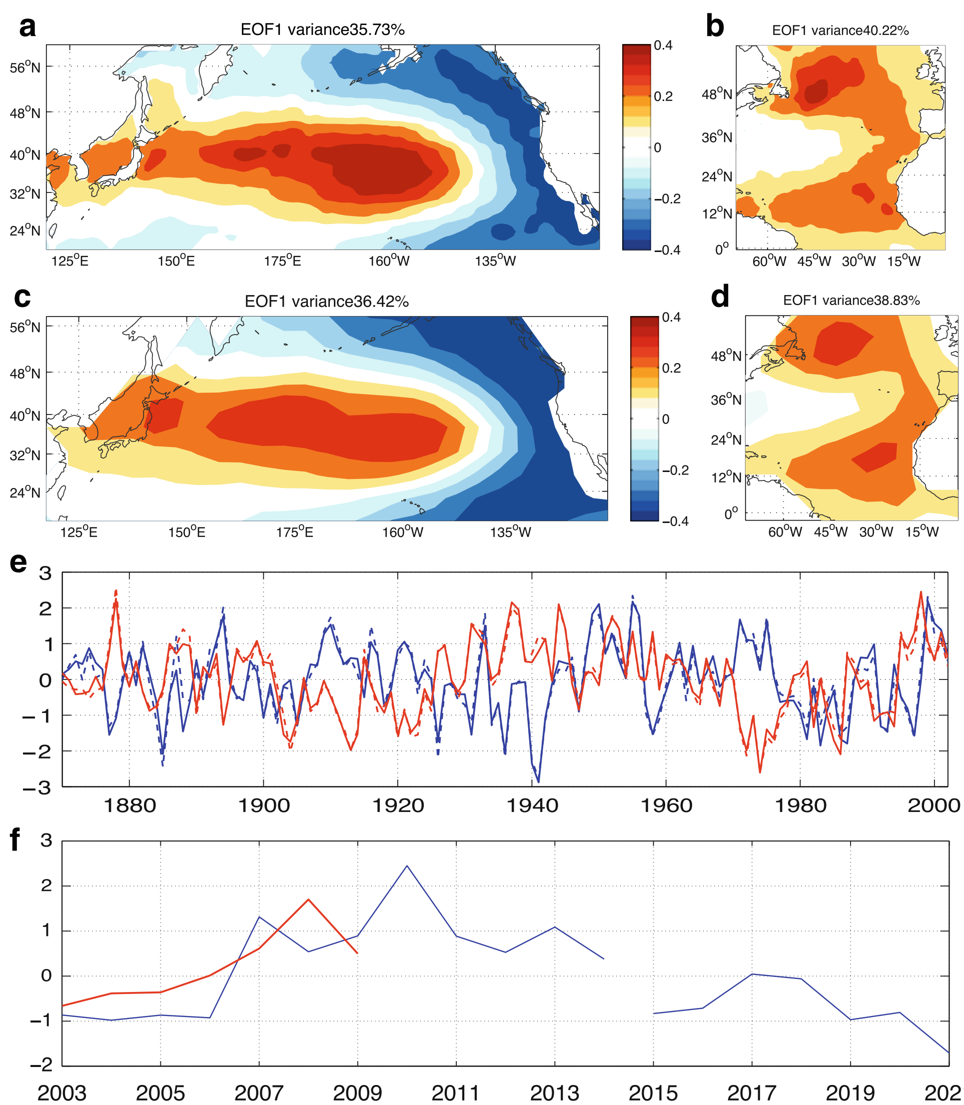

Fig. 1 Leading EOF patterns of yearly mean SST anomalies in the North Pacific (20°N–60°N, **a**, **c**) and in the North Atlantic (0–60°N, **b**, **d**), and the related principal components (**e**, *blue lines* for NP; *red lines* for NA) for HadISST (**a**, **b**, *solid lines* in **e**) and Kaplan SST (**c**, **d**, *dashed lines* in **e**). **f** The predicted PDO index (*blue*) estimated by shifting the AMO index afterward by 12 years and observed PDO index (*red*)

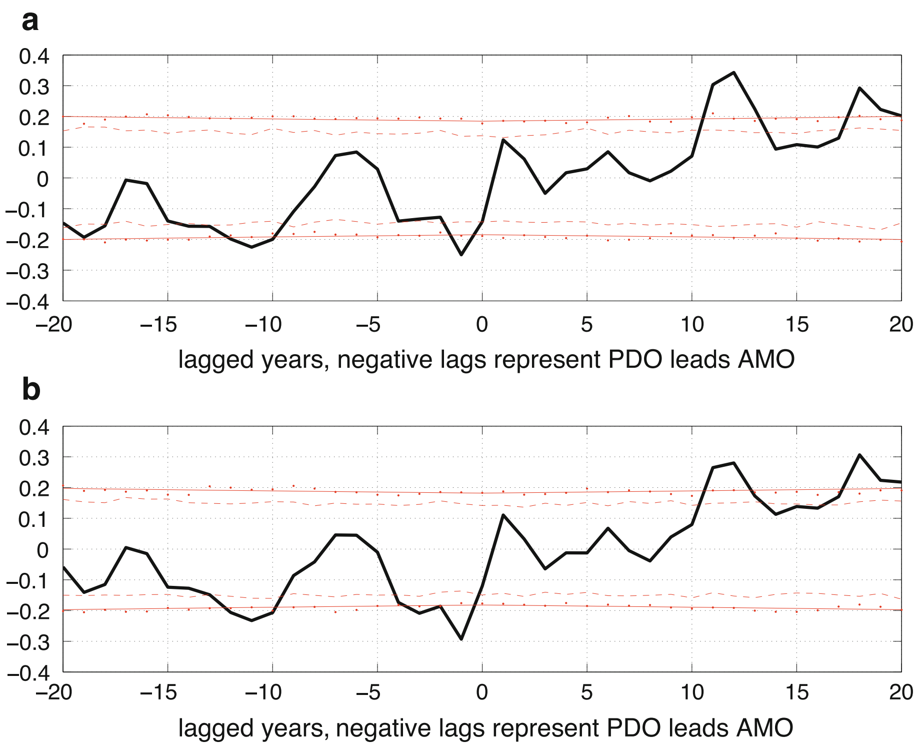

Fig. 2 Lagged correlation (*black thick solid lines*) between the PDO and the AMO index calculated based on HADISST (**a**) and Kaplan SST (**b**). The 95% confidence levels are estimated using the effective DOF method (*red thin solid lines*), bootstrap approach (*red dashed lines*) and AR1 models (*red dotted lines*)

modes for each basin are about 35 and 40%, respectively. It should be noted that the AMO index is originally defined as the mean of Atlantic SSTA north of the equator (Enfield et al. 2001). However, since the correlation coefficient between the basin averaged AMO index and the AMO index used here is +0.98, results obtained using that alternative index are not substantially different from those presented here.

To quantify the relationship between the PDO and the AMO, the two indices were correlated with each other for lead-lag times ranging from minus 20 years to plus 20 years. The lead-lag correlation coefficients are shown in Fig. 2. As mentioned above, we used three different methods to test the significance levels for the correlation coefficients. The AR1 models and effective DOF methods give quantitatively similar results, while the bootstrap method gives less strict results. Against all these testing methods, the most significant correlation happens when the AMO leads the PDO by about 11–12 years and when the PDO leads the AMO by 1 year. The Kaplan SST data show similar results (Fig. 2). There are some other correlations, which are relatively small but still significant. We will talk about these correlations later in the discussion part.

From the above analysis, we show that there are significant correlations between the PDO and the AMO indices in the observations. Possible physical processes involved will be discussed in the next section.

4 Possible physical processes involved

As is seen in Fig. 1e, the PDO and AMO indices include both interannual and decadal variability. It is helpful to separate the indices into interannual (<10a) and decadal (>10a) parts before exploring the possible physical processes. Figure 3 shows the lag-correlation results for the high (<10a) and low (>10a) frequency parts. The lag-correlation results for the high frequency part (Fig. 3a) show several significant peaks when the PDO leads the AMO by 1 year, and when the AMO leads the PDO by 1, 11–12 and 17 years. In contrast, the results for the low frequency part (Fig. 3b) show significant correlations when the PDO leads AMO by 1–3 and 12–13 years, and when the AMO leads the PDO by 12–14 years. Comparing the results of Figs. 2 and 3 indicates that the significant lag-correlation results between the PDO and the AMO mainly arise from the in-phase relationship between the interannual and decadal parts with the interannual part dominating the short lag relation (1 year lead of the AMO by the PDO) and decadal part dominating the long lag relation (11–12 years lead of the PDO by the AMO).

4.1 The PDO's impact on the AMO

The mid-latitude atmosphere-ocean interaction process is dominated by the forcing of the ocean by the atmosphere.

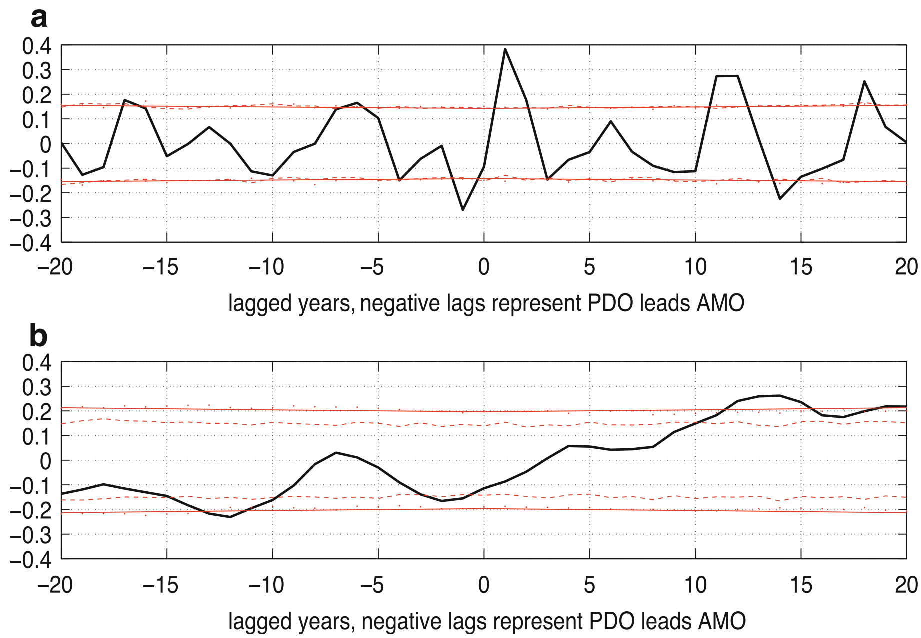

Fig. 3 The same as Fig. 2, but for lagged correlation for the high (**a**, <10a) and low (**b**, >10a) frequency part of the PDO and the AMO index calculated based on HADISST. The results of Kaplan SST are quantitatively the same

Nevertheless, the ocean can also have modest feedback to the atmosphere. The most likely occurring season for the feedback in the North Pacific reflected by observational data is the late fall and early winter (Frankignoul and Sennechael 2007). The late fall ocean temperature's impact on the later atmospheric variability is also demonstrated by the coupled model experiment (Liu et al. 2007), which showed that late fall's warm ocean temperature anomaly leads to a warm ridge response in the atmosphere in the subsequent early winter over the North Pacific.

It is also well known that a seasaw-like oscillation exists between the Aleutian-Icelandic low from one winter to another (Kutzbach 1970; van Loon and Madden 1983). Honda et al. (2001) showed that the formation of this seasaw pattern is not simultaneous over the North Pacific and the North Atlantic; instead, the wave energy accumulates over the North Pacific first, then propagates through North America and triggers the atmospheric variability over the North Atlantic later. This wave activity bridge over North America is most active in the mid-winter.

These studies point out a possible way for the early winter atmospheric anomalies that are caused by the late fall SST anomalies to propagate through North America and trigger atmospheric variation over the North Atlantic later. This atmospheric variation can further lead to the spring North Atlantic SST anomalies.

To check if these processes exist and how they contribute to the 1-year leading correlation of the AMO by the PDO shown by the above analysis, we calculated the seasonal lagged correlation coefficient with the monthly indices binned into 3 months (e.g., Czaja and Frankignoul 2002). The monthly indices are calculated by projecting the

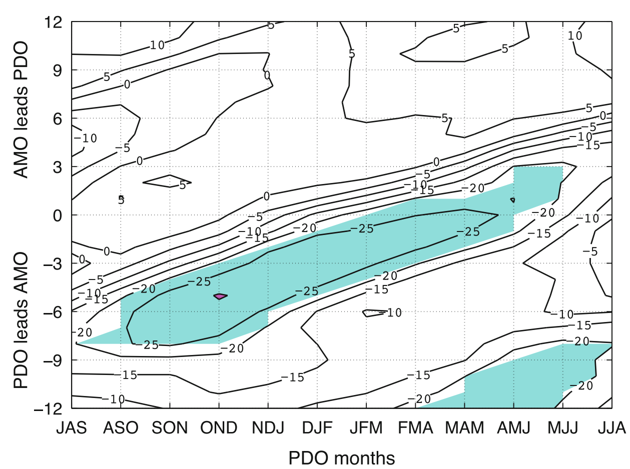

Fig. 4 Seasonal lagged correlation between the PDO and the AMO index. Calculations are based on 3-month binned data (e.g., Czaja and Frankignoul 2002). The *shaded area* is significant at a 95% confidence level

de-trended (here we also used third order polynomial to remove the trend) monthly SST onto SST EOF patterns in Fig. 1. The seasonal correlation results (Fig. 4) show that the maximum correlation happens when OND (OND represents October-November-December; other abbreviations also follow this rule) North Pacific leads MAM North Atlantic by 5 months. There are large significant regions centering around this lag. These correlations may arise from the long persistence of SST anomalies of the SON North Pacific and MAM North Atlantic.

Now the question is how SON North Pacific SST anomalies are related to the later MAM North Atlantic SST anomalies. Figure 5 (left column) shows the regression

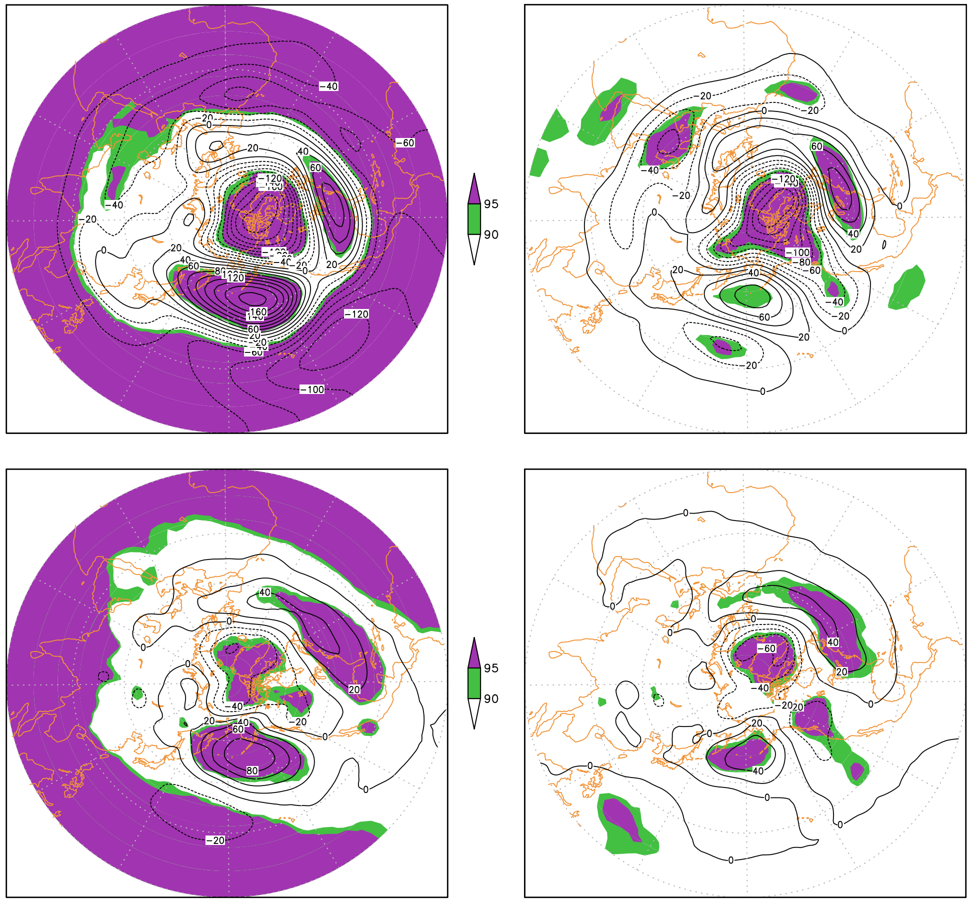

Fig. 5 Regression maps of northern hemisphere HGT (DJF) on the PDO (OND) index, *top panel* for 200 GPH and *bottom panel* for 850 GPH. ENSO impacts are removed for the *right panel* by regressing out the 2 months leading the NINO3.4 index. *Shaded areas* represent 90 and 95% confidence levels

maps of DJF HGT (geopotential height) anomalies on the OND PDO index. The structure of the middle latitude region is much like the famous PNA pattern (a little east) with dipole HGT anomalies located over the North Atlantic. In the meantime, the whole tropical region also shows significant regressions. Since the PDO's impact on the AMO is mainly on an interannual time scale, and ENSO dominates the global interannual variability, there is a possibility that the significant correlation we just mentioned may arise from the forcing of the PDO and the AMO by the same ENSO. Reflected by Figs. 4 and 5 (left column), together with the previous studies (Alexander et al. 2002; Lau and Nath 2001), the ENSO impact on the correlation between the PDO and the AMO can be described as follows: ENSO can cause both the SON North Pacific cooling (Alexander et al. 2002) and the PNA HGT anomalies in DJF, which further leads to the MAM North Atlantic warming (Lau and Nath 2001). Therefore, the forcing of SON North Pacific SST anomalies and MAM North Atlantic SST anomalies by the same ENSO can result in a significant lag correlation between these two SST anomalies.

Besides ENSO impact, is there any other physical processes that may also contribute to the correlation? To answer this question, like many other studies, we removed the ENSO impact by linearly regressing out the 2 months leading the NINO3.4 index from both the SST and HGT anomalies first, and then we repeated the regression analysis (Fig. 5, right column). It can be seen that although the amplitudes decreases a great deal, the response pattern of HGT to the PDO is still qualitatively similar, and reminiscent of the atmospheric response to the North Pacific SST anomalies reflected by modeling (Liu and Wu 2004) and by observational studies using another approach (Wen et al. 2010).

These results point to a possible mid-latitude origin for the inter-basin interaction.

Collectively, the physical processes involved can be explained as follows: the OND warm North Pacific SST anomalies (positive horseshoe pattern) first cause a local atmospheric ridge response over the North Pacific. The North Pacific atmospheric anomalies then propagate through North America in the form of stationary Rossby waves (Honda et al. 2001) and lead to HGT dipole anomalies over the North Atlantic later in DJF. The HGT dipole anomalies are related to reductions of surface winds (figure not shown), and hence the decrease of heat release out of the ocean, and they finally lead to warm SST anomalies. Although the HGT dipole structures are mainly confined to the extra-tropical regions, the resulting SST anomalies can still propagate to the tropics through the Wind-Evaporation-SST feedback mechanism (Xie and Tanimoto 1998; Chiang and Vimont 2004) and finally lead to basin-wide warming in the North Atlantic.

In reality, the ENSO impact and mid-latitude process may work together in causing the relationship.

We explained how the SON PDO is related to the MAM AMO. Then how do the above physical processes contribute to the 1-year leading correlation of the AMO by the PDO? We have a simple argument. Note that we calculated the correlation coefficients based on annual mean data, which is the mean from January to December. Hence the North Pacific OND and the subsequent North Atlantic MAM are counted into the different year, which leads to a 1-year leading correlation. In addition to the above reason, the correlation of OND North Pacific (MAM North Atlantic) with the previous (lately) season's SST anomalies due to the persistence of SST and the re-emergence. Mechanism (e.g. Alexander and Deser 1995; Alexander et al. 1999; Timlin et al. 2002) may also contribute to the 1-year correlation.

4.2 The AMO's impact on the PDO

The AMO can exert a profound impact on the northern hemisphere (e.g., Zhang et al. 2007). The possible physical processes involved in the impact of the AMO on the PDO can be through three possible paths: the mid-latitude atmosphere (Zhang and Delworth 2007), the Arctic Ocean (Okumura et al. 2009) and tropical oceans (Timmermann et al. 2005; Dong et al. 2006; Xie et al. 2008).

The mechanism through the mid-latitude atmosphere process can be explained as follows (Zhang and Delworth 2007): let us start with the AMO warm phase. A warm AMO event reduces the meridional SST gradients in the mid-latitude, which further reduces the surface atmosphere eddy heat transport and upper level vorticity flux. These cause northward shifts of mid-latitude westerlies both over the North Atlantic and North Pacific. The northward shift of westerlies over the North Pacific leads to weakness of the Aleutian low, which further causes the warm SST anomalies in the north Pacific. The anomalous warm SST signal then propagates to the west through oceanic Rossby waves. When the anomalous SST signal reaches the Kuroshio/Oyashio Extension region, it further causes the atmospheric anomalies whose sign is the same with the initial atmospheric anomalies. Hence, there is a positive feedback between the Aleutian high (weakness of the Aleutian low) and warm SST anomalies around the Kuroshio/Oyashio Extension. The leading time of 11–12 years between the AMO and the PDO is mainly caused by oceanic Rossby wave propagation and the strength of positive feedback.

The above process was demonstrated in a coupled model experiment (Zhang and Delworth 2007), where the simulated time lead between the AMO and the PDO (3 years) is much shorter than that observed (12 years), probably because of the relatively weak positive feedback in the model. Observations show a 10-year time scale for advecting SST anomalies just off Japan eastward to the dateline to affect the atmosphere (Pierce et al. 2001). This decadal advection time scale introduces an additional time lead, which is missing in the coarse resolution model and might contribute to the much longer lead between the observed AMO and PDO.

Beside the middle latitude atmosphere, the Arctic Ocean may also serve as a bridge for the AMO to affect the PDO. Okumura et al. (2009) analyzed four different ocean-atmosphere coupled general circulation models. They found that, in all four models, the cooling of the North Pacific is related to the slowing down of the Atlantic meridional overturning circulation (AMOC), which is represented as a cooling of the North Atlantic SST. The sign of the correlation between the AMO and the PDO is consistent with the result we showed here. Detailed analysis of one coupled GCM showed that the North Pacific cooling is mainly caused by the outflow of cold water from the Arctic Ocean to the North Pacific. This might be the dominant mechanism for the last deglacial period. However, given that our analysis period is 1870–2002, during which time the flow across the Bering Strait has always been from the North Pacific to the Arctic Ocean, this "Arctic bridge" cannot be the cause for the correlation.

There is also the possibility that the AMO may affect the PDO through the tropical oceans (Wu et al. 2005; Timmermann et al. 2005; Dong et al. 2006; Wu et al. 2007; Xie et al. 2008; Okumura et al. 2009). We will just temporally call this the "tropical oceanic bridge" hereafter. The processes can be described as follows: the Atlantic SST anomalies can lead to tradewind anomalies over the eastern tropical Pacific, which can further lead to a meridionally symmetrical thermal background state in the eastern tropical Pacific through evaporative fluxes, mixing and changes in the Ekman divergence, and finally cause a substantial variation of the annual cycle and subsequent variation of ENSO. According to Alexander et al. (2002), the variation of ENSO will further lead to SST variations in the North Pacific. Model experiment results of Dong et al. (2006) directly show that a warming of the North Atlantic will lead to a warming of the North Pacific through the modification of the ENSO intensity. It can be also speculated from Wu et al. (2005, 2007) and Alexander et al.'s (2002) results that the warming of the North Atlantic will lead to the warming of the North Pacific. Using a coupled GCM, Wu et al. (2005, 2007) demonstrated that a warming of the north tropical Atlantic could lead to a La Niña SST anomaly pattern in the tropical Pacific. According to Alexander et al. (2002), the La Niña SST anomaly pattern will further lead to a warming North Pacific. Collectively, the "tropical oceanic bridge" for the North Atlantic and the North Pacific seems to be a possible candidate to explain the positive correlation between the AMO and the PDO. However, noting that lag time for the significant correlation is as long as 11–12 years, while these tropical processes are all fast processes, this "tropical oceanic bridge" also may not contribute very much to the correlation we are studying here.

5 Discussion

One of the interesting results of this study is the 11–12 years of the leading of the PDO by the AMO. This correlation coefficient ($\sim$0.35) is not large, although it is indeed significant, implying that the AMO is not the sole determining factor for the PDO anomalies. Actually, the correlation coefficient has increased a little to about 0.45 in the last 30 years. This suggests that the correlation has become bigger recently. Nevertheless, this lagged correlation offers the simplest way to predict future PDO anomalies. From this perspective, the AMO index after being shifted by 12 years can serve to predict PDO 12 years later (Fig. 1f). We checked the validation of the predicted results using the latest SST data from Kaplan SST (January 2003–November 2009). Note that when we carried out the correlation analysis we never used the information after 2002. Hence, using the latest data for validation is reasonable. The red line in Fig. 1f is the latest PDO index estimated based on Kaplan SST. We can see that the predicted results and actual values are roughly consistent. Especially the shift of cooling to warming that occurred around 2006 is well predicted. These results imply that although the correlation between AMO and PDO is not very large, this relationship may still be useful for decadal prediction. If we further consider the latest AMO index, another shift is seen to occur around 2014 (Fig. 1f).

In addition to the two most significant correlations mentioned, there are some slightly significant lags. The correlation is close to the 95% confidence level when the PDO leads the AMO by about 11–12 years. Previous studies indicate that the AMO and PDO can be further decomposed into two modes with the time scale around bidecadal and multidecadal ranges, respectively (Minobe 1999; Wu et al. 2003). Hence, the leading of the AMO by the PDO by about 11–12 years may arise from the bidecadal signal of either PDO or AMO. However, further exploration of the mechanism is beyond the scope of this study. There are also other lags; for example, when the AMO leads the PDO by about 18 years, the correlation is also significant. Whether this relationship reflects a real physical process is still unclear.

There may be another issue concerning the significance of our results since the main thrust of our paper is the statistical analysis and we used lagged correlation. We calculated a total of 41 (−20a–20a) correlation coefficients. It is possible that several correlation coefficients (out of 41) may have become significant by chance. To test this, we counted the number of significant correlations for each random pair of time series. Then we built a distribution of the numbers. Based on this distribution and a given significance level, we can find the value of numbers that should not arise from a random process. The results (not shown) demonstrated that the number of significant correlations revealed in our study is significant at the 95% confidence level.

6 Conclusion

In this article we used three different kinds of significant tests to assess the significance of correlations between the PDO and AMO. The lagged correlation analysis suggests that significant correlation occurs when the PDO leads the AMO by 1 year and the AMO leads the PDO by 11–12 years. Further analysis suggests that the correlation may arise from the ENSO forcing and the interaction between the Atlantic and Pacific Ocean through the overlying atmosphere.

The leading of the PDO by the AMO by 11–12 years offers a simple way of predicting future PDO changes. Although the correlation is only modest, the correlation coefficient has increased in the last 30 years. Validation of the latest data also supports the relationship. The simple model suggests that the PDO is in its cooling phase now and that another region shift may take place around 2014.

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