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Sea Ice Area Inter-annual Variability in the Pacific Sector of the Arctic and its Correlations with Oceanographic and Atmospheric Main Patterns

Jie Su, Jianfen Wei, Xiang Li, and Dong Xu
Key Laboratory of Physical Oceanography of State Education Ministry, Ocean University of China,
Qingdao, Shandong, China

ABSTRACT

Data sets of SSM/I (Special Sensor Microwave Imager) were used to study the inter-annual variability of sea ice area (SIA) in Pacific sector of the Arctic. The results show that SIA in this region has the most significant inter-annual variability in summer and experiences a frequency shift during 1979-2008. The main atmospheric patterns were studied using sea level pressure (SLP) grid data from NCEP/NCAR. The three leading EOF modes of SLP behave as north/south SLP anomaly seesaw, Aleutian Low pressure, and west/east SLP anomaly seesaw in the Arctic. The time series of the first two modes are similar to AO (Arctic Oscillation) and NPI (North Pacific Index) respectively. While the AO had a high correlation with the SIA in Pacific sector of the Arctic during 1992-1997, the NPI performed much better than the AO after 2001 in the correlation with SIA. An index called WED which represents the SLP difference between west and east Arctic in Pacific sector has a high correlation with the SIA in our study region after 2004. These large scale atmospheric patterns contribute to SIA variability for different time periods. If its low frequency fluctuation is not taken into account, the oceanographic index, PDO (Pacific Decadal Oscillation), is a relatively stable factor which has a negative correlation with the SIA.

KEY WORDS: sea ice area; inter-annual variability; Pacific sector of the Arctic; oceanographic and atmospheric patterns

INTRODUCTION

Under global warming conditions, sea ice in the Arctic Ocean has changed rapidly over the last 30 years. Because of its unique properties such as high albedo and heat insulation, sea ice plays an important role in coupled air-ice-sea system. As a result, Arctic sea ice variability and its controlling mechanism, as well as its effects on the climate of the northern hemisphere and the whole earth, have become an important research topic of the global climate change. Data from remote sensing indicates that the trend of sea ice area (SIA) has abruptly decreased after the year 1990 (Parkinson et al., 1999；Rigor et al., 2004; Shimada et al., 2006).

After the Arctic Oscillation (AO) was introduced by Thompson and Wallace (1998), many studies (i.e. Overland et al., 1999; Deser et al., 2000; Wang and Ikeda, 2000) linked SIA variability of the Arctic to changes in the AO/NAO (North Atlantic Oscillation). The results indicate that positive phase of AO corresponds to lower pressure in central Arctic and smaller sea ice extent. In the late 1980s and early 1990s, SLP decreased in central Arctic especially at the Eurasian side, and the anticyclone activity above the Beaufort Sea weakened. At the same time, the transpolar drift stream was enhanced which contributed to the increase of the outflow transport of sea ice through Fram Strait. AO was in its negative phase in most of the time throughout the last 50 years of the 20th century, only between the year 1989 and 1995 it showed an obvious positive phase (Thompson et al., 2000). However, after 1996, the AO index has become mostly neutral or even negative (Maslanik et al., 2007). And the correlation between the sea ice extent in summer Arctic Ocean and AO is not as high as before (Overland and Wang, 2005; Wang et al., 2009; Zhang，2008). Zhao's (2006) result showed not only the phase of AO but also the spatial pattern became ambiguous, and pointed out the core of AO is in the region of the Greenland Sea.

Deser et al (2000) found that main mode of the variation of the sea ice in winter Arctic Ocean shows a dipole characteristic between the east and west in the northern Pacific Ocean, and this variation has some links with AO. Wu et al. (2006) defined this dipole (2nd mode of SLP from 70°N to 90°N) and the anti-phase phenomenon between the Bering Sea and the Okhotsk Sea as the DA (Dipole Anomaly). Long-term numerical simulation from 1900 to 2010 shows that when DA is in positive phase, there is a increase of sea ice export from the Arctic Ocean to the Greenland Sea. The dependence of sea ice export on the DA is comparable to or rather larger than that on the AO (Watanabe et al., 2006). Wang et al. (2009) related recent years' summer extreme values of sea ice extent with DA index. Overland and Wang (2010) indicated the third leading mode (PC3) of winter sea level pressure (SLP) anomaly north of 20°N is similar to but more robust than the DA index. They called this pattern with more meridional anomalous wind pattern as the Arctic Dipole (AD).

Most of the previous studies focus on SIA variability of the whole Arctic Ocean. In fact, the inter-annual variability of SIA differs from one region to another apparently (Polyakov et al., 2003; Overland and Wang, 2007; Tremblay and Mysak, 1998). Figure 1 shows spatial distribution of the rate of sea ice concentration in March and September of the period 1979-2008 using SSMR (Scanning Multichannel Microwave Radiometer) and SSM/I (Special Sensor Microwave Imager) sea ice concentration product of the National Snow and Ice Data Center (NSIDC) (ftp://sidads.colorado.edu/pub/DATASETS/seaice/polar-stereo/nasateam/final-gsfc/). It is clear that the most significant sea ice decrease of September occurs in Pacific sector.

In this paper, we focus on the inter-annual variability of SIA in Pacific sector and its relationship with the principal modes of atmospheric and oceanographic variabilities in the northern hemisphere. We first introduce the data applied in this research and the preprocessing method. Then the main characteristics of variability and occurrence of sea ice area in Pacific sector will be illustrated. We will later move on to analysis of the correlation between variability of SIA and the principal modes of the northern hemisphere atmospheric circulation. The Pacific oceanographic thermodynamic parameters will also be investigated. Lastly, some conclusions and discussions will be provided.

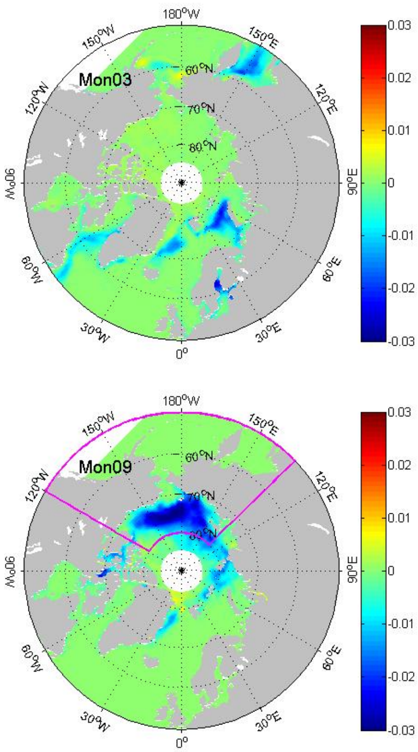

Fig. 1 Sea ice concentration trend of March (top) and September (bottom) during 1979-2008

DATA AND PREPROCESSING

Sea Ice Data

The domain of Pacific sector is set as 50°N~80°N,134°E~120°W (Fig. 1, bottom panel), including the Bering Sea, the Sea of Okhotsk, the East Siberia Sea, the Chukchi Sea, and the majority of the Beaufort Sea.

Monthly SIA time series is produced by summing the ice coverage area of all grid cells of the study domain with at least 15 percent of sea ice. The calculating formula is given as Eq. 1.

$$SIA = \sum_{i=1}^{n} w_i C_i A_i \qquad \begin{cases} w_i = 1 & C_i \geq 15\% \\ w_i = 0 & C_i < 15\% \end{cases} \qquad (1)$$

Where C_i is the ice concentration in grid i, A_i is the area of that grid, and w_i is weight coefficient.

The monthly sea ice concentration is archived from NSIDC. The grid data is obtained from SMMR for the period of 1978-1987 and from SSM/I for 1987-2008. The spatial resolution is 25km×25km.

Atmospheric Data

Monthly sea level pressure reanalysis data (1948~2010) from the National Centers for Environmental Prediction / National Center for Atmospheric Research (NCEP/NCAR) is used. The horizontal resolution is 2.5°×2.5° in latitude and longitude directions. Based on our research purpose, we only use the data in period of 1979~2008 and the region north of 20°N in this paper.

We also use atmospheric circulation indices including AO (Arctic Oscillation) index and NPI (North Pacific Index) (Hurrell, 1995) from this NCEP/NCAR dataset.

Oceanic Data

The large scale ocean index PDO (Pacific Decadal Oscillation) is used in this study as well. It was defined as the leading principal component of North Pacific monthly sea surface temperature variability (poleward of 20°N for the 1900-1993 period) (Mantua et al, 1997).

RESULTS

Sea Ice Area (SIA) in the Pacific Sector of the Arctic

General features

Monthly mean SIA from the year of 1979 to 2008 in the Pacific sector of the Arctic is given in the upper panel of Fig. 2. During this period the rate of SIA decreasing is 1565km^2/yr. It is obvious that the most significant inter-annual variability of SIA occurs in summer. This is also represented in the lower panel of Fig. 3.

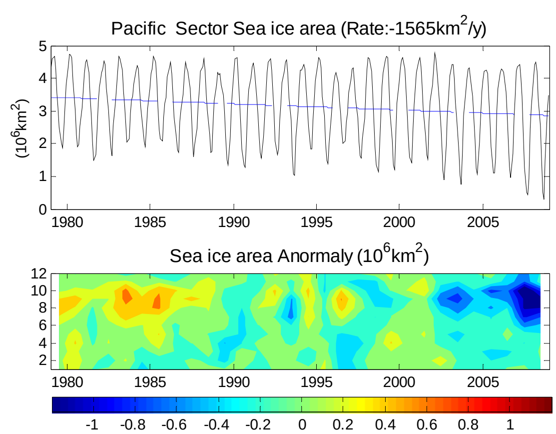

Fig. 2 Monthly mean (upper panel) and anomaly (lower panel) sea ice area in Pacific sector of the Arctic during 1979-2008

As we all know, Arctic sea ice varies seasonally, especially in the marginal ice zone. The most region of the domain we study in this paper belongs to the area with seasonal ice. Fig. 3 shows the multi-year mean monthly SIA (upper panel) and average amplitude of (lower panel) SIA anomaly in this region. Maximum SIA occurs in March, with the monthly mean SIA reaching 4.5×10^{6}km^2, while the minimum SIA is about 1.45×10^{6}km^2 which appears in September.

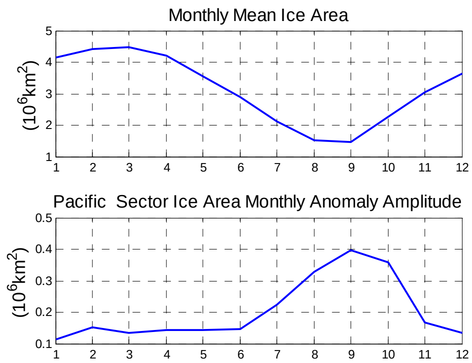

Fig.3 Multi-year mean monthly ice area and its anomaly amplitude

Fig. 3 shows that the SIA in summer time (Aug.-Oct.) has a larger inter-annual variability than during other months. The amplitude of the monthly SIA anomaly in September is 0.4×10^6km^2, almost four times as that during the winter. This can be seen more directly and with inter-annual information in lower panel of Fig. 2. From this figure we can see there might be a shift in SIA periodicity. SIA anomaly was in positive phase for a long time before 1990, but it varied frequently in the middle of 1990's. Then after a short positive SIA anomaly period (longer in winter but shorter in summer), the SIA anomaly has become negative for a relatively long period since 2003 (for summer) or 2004 (for winter).

Periodicity

To study the periodicity of the SIA in inter-annual variability time scale, the significant seasonal variation needs to be removed. However, we cannot count on removing the seasonal variability by just subtracting the monthly average value as the resulted time series of monthly SIA anomaly still displays to have a strong seasonal signal as seen in Fig. 2 and Fig. 3.

We process the time series of SIA monthly anomaly with low-pass filter (LPF), band-pass filter (BPF) and running mean (RM). While different methods will cause small differences in determining the significant period's magnitude, the results of wavelet analysis are very similar. For that reason, we just show the periodicity using wavelet analysis after processing the anomaly data with LPF.

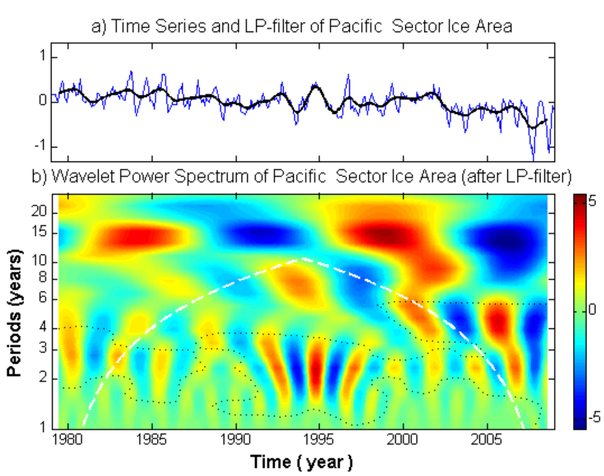

Fig. 4 Time series of sea SIA anomaly (1979-2008) and that is processed by 18 months LPF (upper panel) and the Wavelet Power spectrum periodicity (lower panel)

The upper panel of Fig. 4 shows the time series of SIA anomaly (blue line) and that of 18 months LPF (bold black line). To avoid the problem of the end points, data of the first and the last half year are removed from LPF time series before periodicity analysis.

The significant period is 2.4 years from power spectrum analysis. Morlet wavelet analysis (Torrence and Compo, 1998) was applied to the LPF time series above to obtain more detailed periodic variation over time (see the lower panel of Fig.4). During the year of 1979-1985 the main periodicity is about 3 years. It is obvious that there is a quasi-biennial oscillation after 1992, and it is relatively strong during the year of 1992-1998. This is matched with what we have seen in the lower panel of Fig.2. This signal does not exist in the SIA inter-annual variability in the Atlantic sector of the Arctic, which has a significant period of about 6 years (Figure omitted).

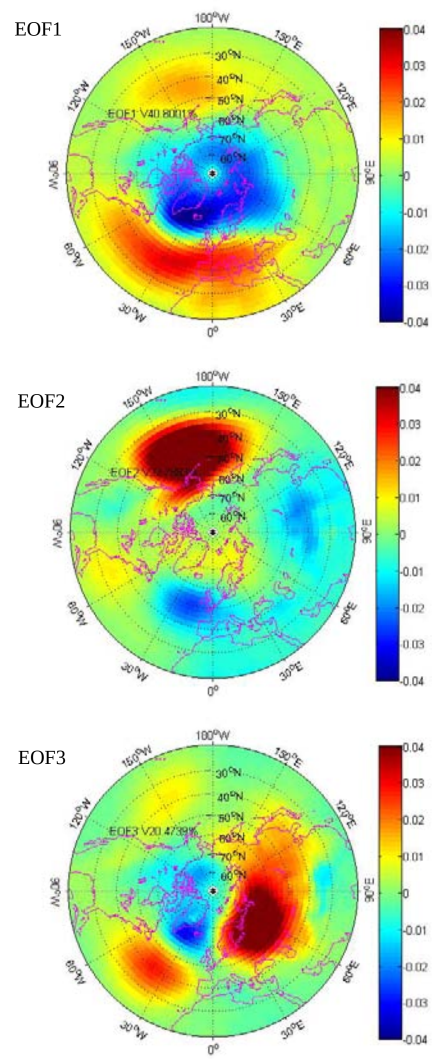

Fig. 5 Three leading EOF patterns of monthly SLP anomaly for the period of 1948-2010

Main Patterns of North Hemisphere Atmosphere and Pacific Ocean

Monthly SLP anomalies, with respect of 1950-2001, are used to derive the EOF modes north of 20°N from 1948 to 2010. The variance contributions of the three leading EOF modes are 40.80%, 22.79% and 20.47%. The spatial patterns are shown in Fig.5. The leading mode pattern (top panel) is similar to AO, which has a zonal pattern of SLP anomalies with one sign in the central Arctic and the opposite sign centered about 37-45°N in both Atlantic and Pacific. The one in Atlantic is stronger than that in Pacific. The correlation coefficient between the first principal component time series (PC1) and the download AO index (see "data and preprocessing" section) is 0.99. Considering the convenience to compare with others work we use AO index as the time series for the current study.

People have linked the second mode to PNA (Pacific-North America pattern) (Overland and Wang, 2010), while from the middle panel of Fig. 5, it seems that the second mode is dominated by the Aleutian Low Pressure. Trenberth and Hurrell (1994) defined a north Pacific index (NPI) as the area-weighted mean SLP over the north Pacific, which measures the changes in the intensity of the Aleutian low. The time series of second mode has a correlation coefficient of 0.91 with the North Pacific Index (NPI), and -0.63 with the Pacific-North America (PNA). So we take NPI as the second atmospheric index in our study.

The spatial pattern of the third mode is similar to the Dipole Anomaly (Wu et al, 2006). In our present study, the most prominent action centers are respectively located at European continent and southeast of the Greenland. Overland and Wang (2010) named this meridional anomalous wind pattern as AD. Both of the indices are set based on winter SLP anomaly. However, for Pacific sector of the Arctic, the sea ice inter-annual variation is more significant in summer. Following this meridional wind pattern, we defined an index which indicates the SLP difference between west and east Arctic in Pacific sector as WED (West and East Difference of SLP). The two selected regions are 65°N-75°N, 120°E-160°E and 70°N-80°N, 160°W-120°W. The correlation coefficient between WED and the time series of the third mode (PC3) is 0.52.

Although PDO is prominent of its decadal variation, the result of power spectrum analysis shows the 2-3 years inter-annual variation also passes the significant test. This fluctuation rides on the decadal periodicity. Table 1 gives the periodicities of all the indices used in the current paper as well as the SIA in Pacific sector of the Arctic. The analysis is based on the time series of LPF, BPF and RM.

Table 1: Predominant Periods of different Indices (Unit: years)

Indices	After Low-pass filtering		After Band-pass filtering		After Running Mean	
	Period 1	Period 2	Period 1	Period 2	Period 1	Period 2
AO	2.4	1.8	2.4	1.8	2.4	-
NPI	2.8	4.8/1.8	2.8	4.8/1.8	2.8	1.8
PNA	4.8	2.4	4.8	2.4	2.4	-
WED	1.9	-	1.9	-	1.9	-
PDO	6.4	1.9	4.8	1.9/2.8	6.4	1.9
SIA-Pac	2.4	-	2.4	4.8	2.4	-

Correlation Analysis

Synchronous Correlation

To remove of long-term oscillation, we process the data with band passing filter before the synchronous correlation analysis. Only the periods between 18 months and 11 years remain. The correlation coefficients between the BPF time series of the four indices (AO, NPI, WED and PDO) and that of SIA are lower than 0.5, but all pass the significant test.

Then the consecutive correlations are derived by using the method of running correlation with a 60 months window. Since the time series is processed by filtering, when calculating the confidence level, the degree of freedom is reduced to similar as the wave number (Livezey and Chen, 1983). Fig.6 shows the correlations between SIA and each of the four indices all have several stage changes during the whole time period. The periodicity analysis (Table 1) above shows AO has a quasi-biennial significant period, while SIA changed to a quasi-biennial oscillation during 1992-1998 (Fig. 4). These two variables match well and reach a high correlation. However as previous work (i.e. Wang et al., 2009) has shown, the correlation becomes very small, especially in recent years. This is because the magnitude of the AO becomes small, while the SIA has a sharp decrease in the last ten years. The NPI has performed much better than the AO after 2001 in the correlation with SIA. Both NPI and WED can catch the sharp decrease in 2007 of SIA in Pacific sector. It suggests that in different time ranges, the Pacific sector SIA is influenced by different atmospheric factors.

PDO has a higher synchronous correlation with SIA than the AO. After the year of 1992, there is a relatively stable negative correlation between PDO and SIA. The running correlation coefficients during this period mostly pass the significant test.

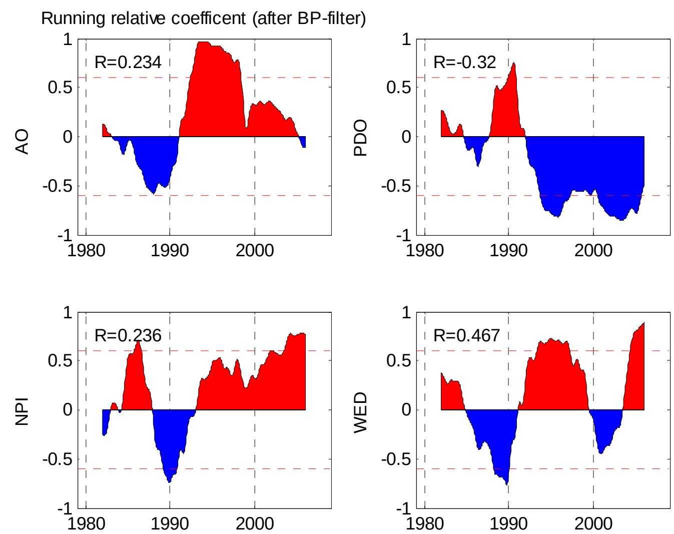

Fig. 6 Running correlation of SIA and Indices (after BPF)

Spatial regress analysis

Fig. 6 implies that the stable relationship might not exist during the whole time series. So segmental processing is needed. Fig.7 gives regression coefficients by linearly regressing monthly SIA anomaly in Pacific sector of the Arctic to monthly SLP anomalies field in five periods of 1979-1985, 1986-1991, 1992-1997, 1998-2003, and 2004-2008. The period division is based on 1) the periodicity of SIA (Figure 4); 2) the periodicity of the main atmospheric and ocean indices (Table1); 3) the running correlations of these two time series along of the time (Figure 6).

Fig. 6 shows the obvious differences in spatial pattern during different periods of the time series. This might be resulted from SIA intrinsic variability (see Fig.4) and also from the phase of atmospheric oscillation pattern, as Zhang et al. (2008) indicated. They found the drastic, systematic spatial changes in atmospheric circulations, showing a shift from the conventional tri-polar AO/NAO to a dipolar leading pattern after 2001. From Fig. 6 we can see that only during the third period (1992-1997), the regressed field of SLP represents an AO-like pattern. Although the fourth period (1998-2003) also shows a polar low pressure in Atlantic side of the Arctic, in Pacific sector the SLP in the Chukchi Sea has the same symbol as that in middle latitude, no longer corresponding to AO pattern in Pacific sector. This matches very well with what Fig. 5 (upper left-hand panel) shows. We can also find the corresponding link in the last period (2004-2008) between regression field which shows SLP difference between west and east region (Fig. 7) and the high running correlation coefficient between WED and SIA (Fig. 6, lower right-hand panels). However, when SIA, atmosphere and ocean interact with each other in the polar region coupled system, it becomes difficult to explain all the phenomena by linear analysis method.

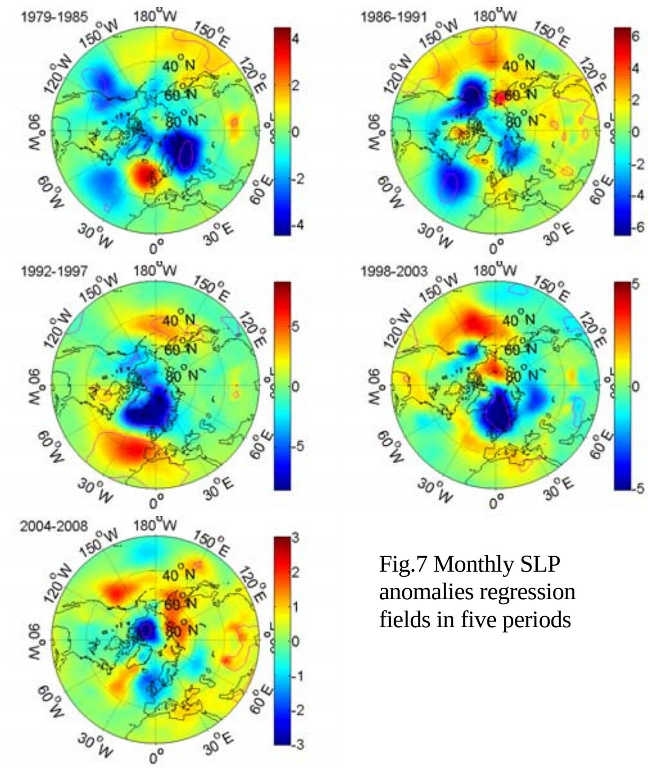

Fig.7 Monthly SLP anomalies regression fields in five periods

Lead and lag Correlation

As we indicate above, the most significant inter-annual variability of SIA in Pacific sector of the Arctic occurs in summer, while most of the main atmosphere patterns inter-annual variabilities occur in the winter. So a lead and lag correlation is needed to get an intuitive knowledge about the interaction between SIA and each of these indices. Lead and lag correlation of BPF time series is shown in Fig. 8. Among the four indices, WED has the highest positive correlation with the SIA when it leads 2-3 months. This indicates that the intensity of the west-east SLP difference may dramatically influence the SIA in Pacific sector of the Arctic. PDO has a relatively high correlation with SIA in lead 1 month (negative correlation) and lag 13 months (positive correlation). Both AO and NPI's correlation with SIA imply that there should be an interaction between sea ice and atmosphere, and the time scale is about 12-16 months. The latter result needs further study.

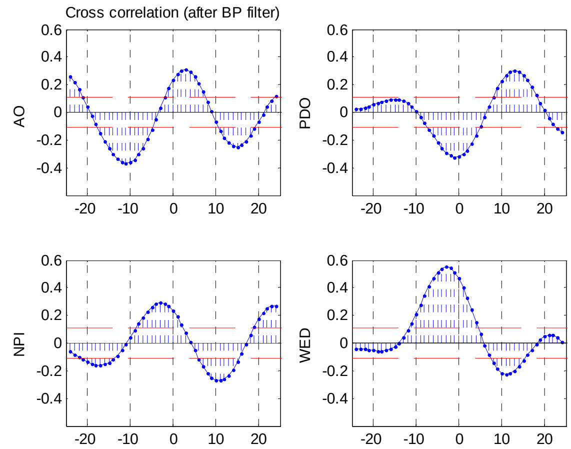

Fig.8 Lead and lag correlation of the band passing filter time series of SIA and the four indices using

CONCLUSIONS AND DISCUSSION

In this paper we studied the general features and periodicity of sea ice area in Pacific sector of the Arctic as well as its correlation with the main patterns of northern hemisphere atmosphere and the Pacific Ocean. The results show that:

1) The most significant inter-annual variability of SIA in Pacific sector of the Arctic is during August to October.
2) The periodicity of SIA in Pacific sector of the Arctic has a frequency shift in inter-annual variability over the 1979~2008 period. During middle 1990's, the strong quasi-biennial oscillation matched the Arctic oscillation in the atmosphere.
3) The effects of the main patterns of large scale atmospheric circulation on SIA vary in different periods of the total time series. The results of running correlation and the segmented SIA to SLP regressed fields can depict this in a great extent. While AO has a high correlation with SIA only for the period of 1992-1997, the NPI has a higher correlation with the SIA than AO for the period after 2001. SLP difference between west and east region (WED) which represents meridional anomalous wind pattern has a high positive correlation with SIA after 2004. Both NPI and WED can explain the sharp decrease of SIA in 2007.
4) For the band-pass filter (BPF) time series, PDO is a relatively ideal index on studying the inter-annual variation of SIA in Pacific sector of the Arctic. It has a stable negative correlation with SIA after the year of 1992.
5) Lead and lag correlation analysis indicates the interaction time scale between SIA and large scale atmosphere circulation patterns is 12-16 months.

It is very difficult to find an index in the SLP field which corresponds well with the SIA through the total 1979~2008 period. The inter-annual variability of SIA in the Pacific sector occurs mainly in summer, yet the main variability for the atmospheric circulation occurs in the winter. The lag correlation analysis result shows that the atmosphere and the sea ice indeed interact with each other. Because of the tremendous storage capacity, the ocean stores the information of changes from both atmosphere and ice. Therefore, we may have to pay more attention to the thermodynamic process in the Pacific Ocean in order to enhance the explanation of the inter-annual variability of Pacific sector SIA in further research.

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