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A PRELIMINARY STUDY ON DECADAL OSCILLATION AND ITS OSCILLATION SOURCE IN THE SEA-ICE-AIR SYSTEM IN THE NORTHERN HEMISPHERE*

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Abstract: By using maximum entropy and band-pass filter methods, the variation periods of sea ice area index in the Kara/Barents Seas, the intensity index of the Siberian High and winter monsoon over East Asia during winters from 1953 to 1990 were analyzed. And sea ice area variation in winter in the Kara/Barents Seas was compared with the area and intensity indices of the subtropical high in the following spring and summer. The results indicate that there is an obvious decadal variation in the sea-ice-air system in the Northern Hemisphere. The variations of intensity index of the winter Siberian High and the winter monsoon over East Asia are out of phase with that of sea ice area in winter in the Kara/Barents Seas. The more (less) sea ice there is, the weaker (stronger) the winter Siberian High and winter monsoon are. The variation trend of sea ice area is similar to that of the area and the intensity of the subtropical high in the coming spring and summer, with a lag period of 0–1 year. The decadal oscillation sources in the atmosphere are closely linked to specific sea regions. The center of the strongest oscillation source excited by winter sea ice in the Kara/Barents Seas is near 70°E, 60°N.

1. Introduction

Interdecadal variation of the climate system was initially discovered by analyzing Atlantic Sea Surface Temperature (SST). BJERKNES (1964) proposed that North Atlantic current variations result in SST variation on a decadal time scale. Recently, observations and simulations suggest that there exist decadal and longer than decadal time scale variations in the atmosphere-ocean-sea ice system overlying the Atlantic area (LEVITUS *et al.*, 1994; HURRELL, 1995; WEAVER *et al.*, 1991; DELWORTH *et al.*, 1993). LEVITUS *et al.* (1994) pointed out that there was a quasi-decadal temperature oscillation in the Atlantic region between 1947 and 1990. HURRELL (1995) found that the recent decadal drought in winter in southern Europe and the Mediterranean, and the wet anomalies from Iceland to Scandinavia, were related to the persistent positive phase of the North Atlantic Oscillation (NAO). There also existed a decadal variability in the global thermohaline circulation (THC) of the ocean driven by density (WEAVER *et al.*, 1991). By means of a coupled atmosphere-ocean general circulation model, DELWORTH *et al.* (1993) simulated the decadal variation of THC and suggested that the decadal variation is closely associated with salinity anomalies in the sink-

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ing region of the THC (North Atlantic) and causes the decadal oscillation of SST which leads to air temperature anomalies over the North Atlantic, North Europe, and the Arctic. DESER and BLACKMON (1993) pointed out that the decadal fluctuation of SST in eastern Newfoundland is closely linked to decadal variation of sea ice in the Labrador Sea, with a lag period of ~2 years for the former. LAZIER (1988) suggested that there were a salinity anomaly and cold climate in the North Atlantic during the early 20th century, and the late 1960s corresponded to the two periods of positive sea ice area anomaly around Greenland from 1905 to 1915 and from 1965 to 1975.

Recently, a number of studies have shown that there existed decadal and longer than decadal variations after 1976 in the atmosphere-ocean system overlying the Northern Pacific. TRENBERTH and HURRELL (1994) showed that the decadal variation overlying the North Pacific can be attributed to the variation of strength and frequency of El Niño (La Niña) events and its oscillation source is in the tropics. In the meantime, the observations and the simulations indicated that the decadal variation over the extratropical Pacific is related to the SST of the tropical Pacific and Indian Ocean (KAWAMURA, 1994; LAU and NATH, 1994). From the above results, the dominant characteristics of the decadal variation in the climate system exist in the ocean or are closely linked to ocean conditions. Information on the decadal variation in atmospheric circulation is less than that in the ocean, KELLOGG (1975) pointed out that the feedback mechanism for decadal variation might be found in the sea ice and oceanic circulation, because the atmospheric response is short-term and unable to produce the decadal variation by itself. Therefore, the decadal variation in the atmosphere might be in response to the oceanic circulation and sea ice. The goals of this paper are to investigate the decadal variation in the atmosphere and discuss the relation between the decadal variation in the atmosphere and the oceanic variation.

2. Data and Methods

The monthly sea ice concentration data during 1953 and 1990 were obtained from John Walsh of the University of Illinois. Monthly mean height data at 500 hPa are taken from the National Meteorological Center (NMC) for the years 1946–1979 and from the European Center for Medium-Range Weather Forecast (ECMWF) for the years 1980–1989. Monthly mean eigenvalues for the subtropical high over various regions in the Northern Hemisphere for the years 1951–1989, including the area index and the intensity index, were obtained from the National Meteorological Center in China. First, according to geographical position, the Arctic sea ice is divided into different sea regions. This paper looks at winter sea ice variation in the Kara/Barents Seas, as the Kara/Barents Seas are the Northernmost sea regions in the world, as shown in Fig. 1, and should be a crucial region for the Ocean-sea ice-air feedback. Cold air accumulates over these seas in winter, and frequently breaks out southward. The strength of the cold air originating from the Kara/Barents Seas is stronger than that which originates from other regions. In winter, transport of heat flux between atmosphere and ocean is quite sensitive to sea ice area and thickness. Heat flux variation from ocean to atmosphere is closely associated with that of the sea ice thickness. When sea ice thickness changes from 1 to 100 cm, the heat flux variation is over 2 orders

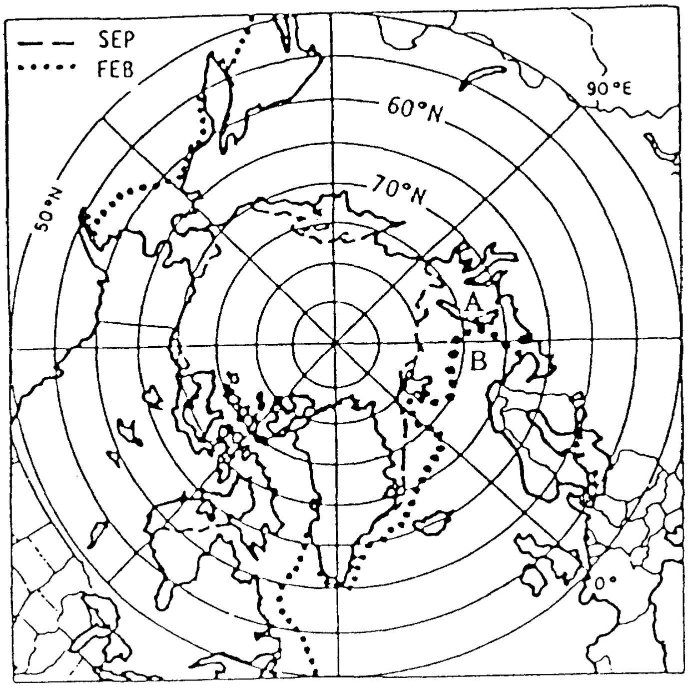

Fig. 1. September and February sea-ice area averaged for 1973–1976, reproduced from Figs. 4-1 of PARKINSON *et al. (1987). A: Kara Sea, B: Barents Sea.*

of magnitude (ALEKSANDR, 1984), which means that the variation of sea ice area and thickness during winter inevitably affects the strength of the cold wave. To investigate the variation periods of sea ice area, a maximum entropy method (MEM) is applied to a time series of sea ice area index, which can discriminate longer variation periods from a shorter than normal time series comparing with other methods. A sea ice area index averaged from December to February is used to express the winter sea ice condition in this paper. According to the variation periods analyzed by MEM for a time series of climatic element, the band-pass filter method of Butterworth (MURAKAMI, 1979) is applied to the time series of height data at 500 hPa. And then Complex Empirical Orthogonal Function (CEOF) analysis is used to filter data to seek the source and propagation of the oscillation in the atmosphere, and investigate further the relation between the oscillation source and sea ice area variation in the Kara/Barents Seas.

3. Diagnostic Analyses

An interdecadal variation (Fig. 2a) with a period of 10 years was found by the MEM analysis (Fig. 2b) for the original time series of sea ice area index in winter in the Kara/Barents Seas. There is also an interdecadal variation (omitted) for the time series of sea ice area index in winter throughout the Kara/Barents and Greenland Seas, although the variation period in the Greenland Sea is 6 years. Clearly the variation of sea ice area in winter in the Kara/Barents Seas plays an important role in the decadal variation of the Arctic climate system.

Since the variation of sea ice area in winter in the Kara/Barents Seas plays an important role in the decadal variation of climate system and this sea region is an origin area of cold waves which influence weather conditions over East Asia, conceivably there is a decadal variation in the atmosphere. If it exists, we naturally want to determine the relation between the decadal variation in the atmosphere and that of the sea ice area. To explore the decadal variation in the atmosphere, the periodic variations for the intensity index of the Siberian High (105°–110°E and 50°–55°N) in winter, and the winter monsoon over East Asia (Shi *et al.*, 1996), the area index and the

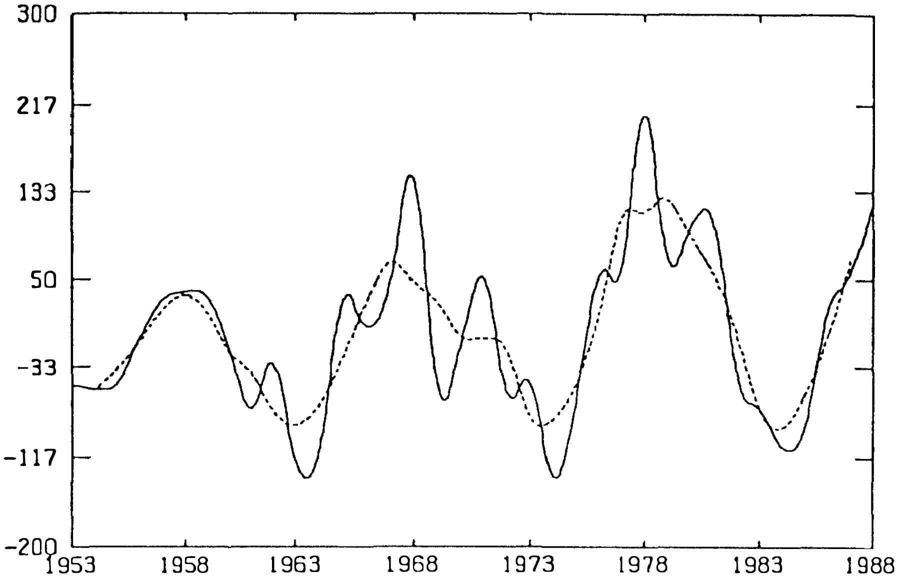

Fig. 2a. Interannual variation of winter sea-ice area index in the Kara/Barents Seas (solid curve) and its 3-year running mean (dashed curve).

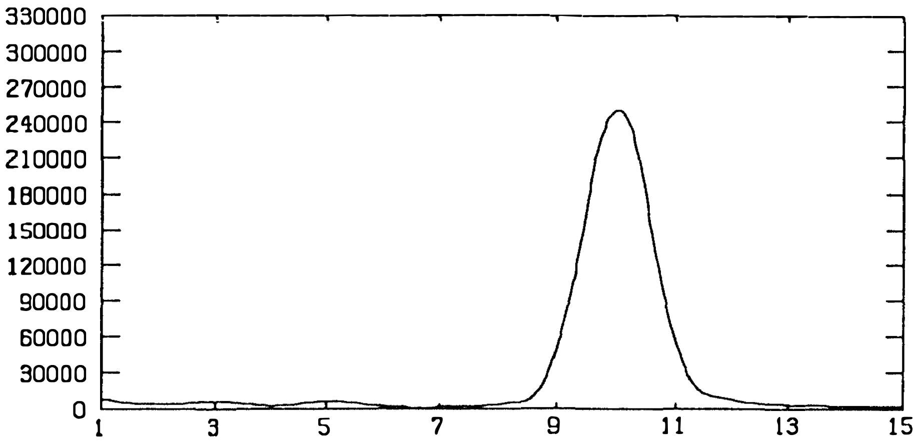

Fig. 2b. Spectral densities of winter sea-ice area index in the Kara/Barents Seas.

intensity index of the subtropical high over the Western Pacific, North America and North America/the North Atlantic in spring and summer are studied in this paper.

Figure 3a shows that both the intensity index of the winter monsoon over East Asia and the intensity index of the Siberian High in winter show decadal variations. To clearly describe the decadal variations, the band-pass filter of Butterworth is applied to three time series: the sea ice area index, the winter monsoon intensity index and the Siberian High intensity index. The central frequency of the band-pass filter corresponds to a period of 10 years, and the periods of the two half frequencies correspond to 8 years and 12.5 years, respectively. The percentages of the variances for the intensity index of the winter monsoon over East Asia , the intensity index of the Siberian

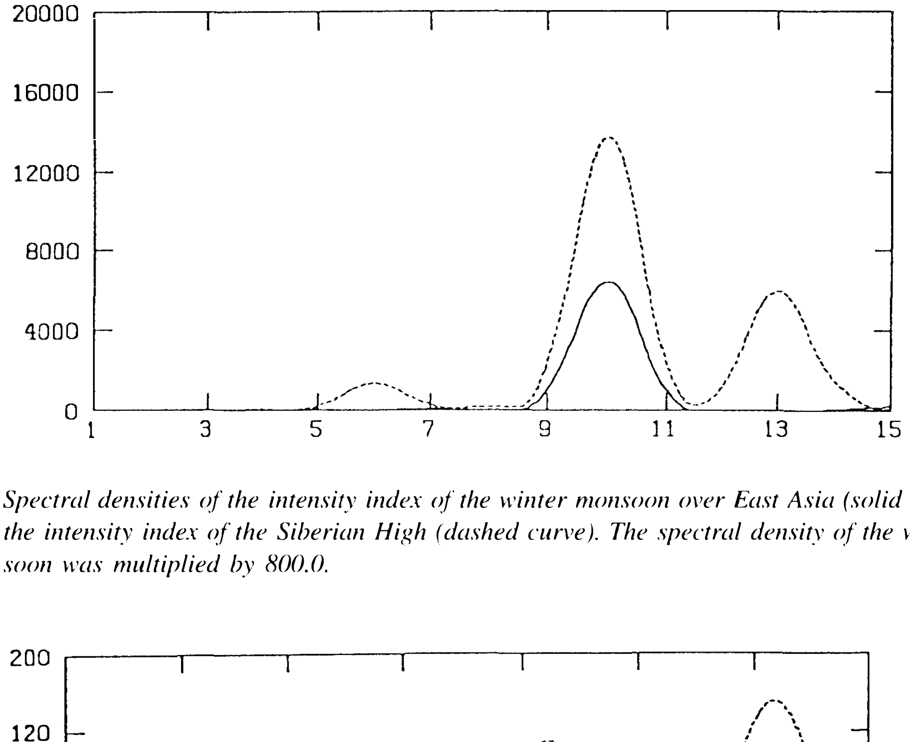

Fig. 3a. Spectral densities of the intensity index of the winter monsoon over East Asia (solid curve), and the intensity index of the Siberian High (dashed curve). The spectral density of the winter monsoon was multiplied by 800.0.

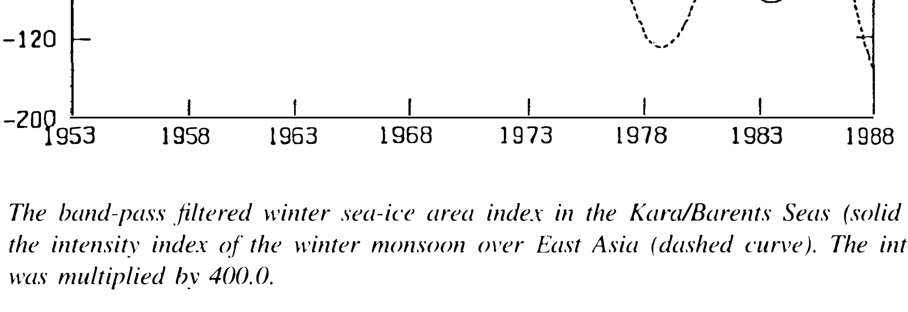

Fig. 3b. The band-pass filtered winter sea-ice area index in the Kara/Barents Seas (solid curve), and the intensity index of the winter monsoon over East Asia (dashed curve). The intensity index was multiplied by 400.0.

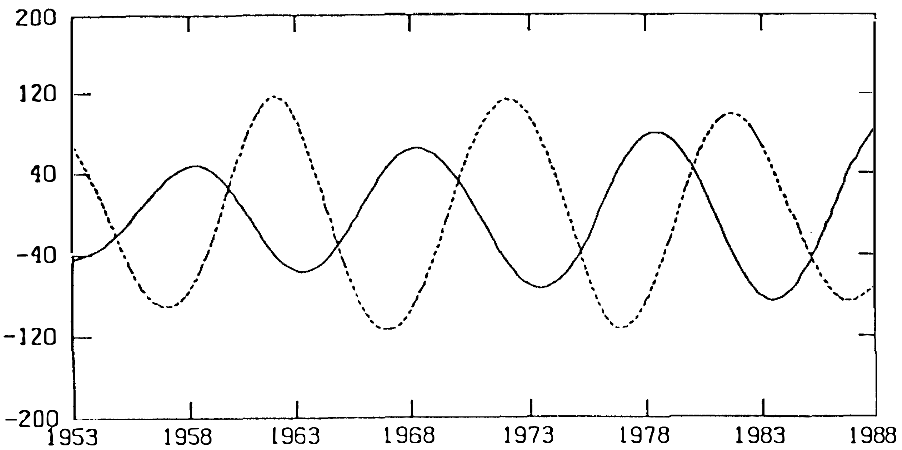

Fig. 3c. *The panel as in Fig. 3b but for the intensity index of the Siberian High in winter (dashed curve). The intensity index was multiplied by 10.0.*

High and the area index of sea ice in winter are about 54.4%, 16.9% and 24.1% in their origin variances, respectively. The variation of sea ice area index in winter is out of phase with both the intensity index of the Siberian High and winter monsoon (Fig. 3b, c), which means that the larger the sea ice area in winter, the weaker the intensity indices of both the winter monsoon and the Siberian High in winter.

The variation trend of the sea ice area index in winter is consistent with the trends of the area index and the intensity index of the subtropical high over the Western Pacific, North America (omitted) and North America/North Atlantic in the following spring and summer, respectively (Fig. 4). This indicates that the eigenvalue indices in the atmosphere also exhibit the decadal time scale variation, and their decadal variations lag that of the sea ice area by 0–1 year. The larger the sea ice area in winter, the stronger the subtropical high in the following spring and summer. The sea ice area in winter is more closely related to the subtropical high over the Western Pacific especially in spring. Clearly there is a decadal variation in the atmospheric circulation.

To examine further the relation between the variation of atmospheric circulation and that of the sea ice area in winter, as an example, the cross-correlations between the area index of winter sea ice and the eigenvalue indices of the subtropical high over the Western Pacific were calculated. It can be seen (Fig. 5) that the maximum correlation coefficient is above the 95% significance level for the area index and intensity index of the subtropical high lagging the area index of sea ice in winter by 0–1 year.

Since the eigenvalue indices of atmospheric circulation indicate a decadal variation, lagging the winter sea ice area, we ask whether the variation of winter sea ice area plays an important role in driving the decadal variation in the atmosphere. Where is the source of the decadal variation in the atmosphere?

To explore the above questions, the geopotential heights at 500 hPa, averaged during January and March in 1946–1989, were passed through the decade-band-pass filter described above. Then Complex Empirical Orthogonal Function (CEOF) analysis was applied to analyze the filtered data to distinguish the travelling wave, station-

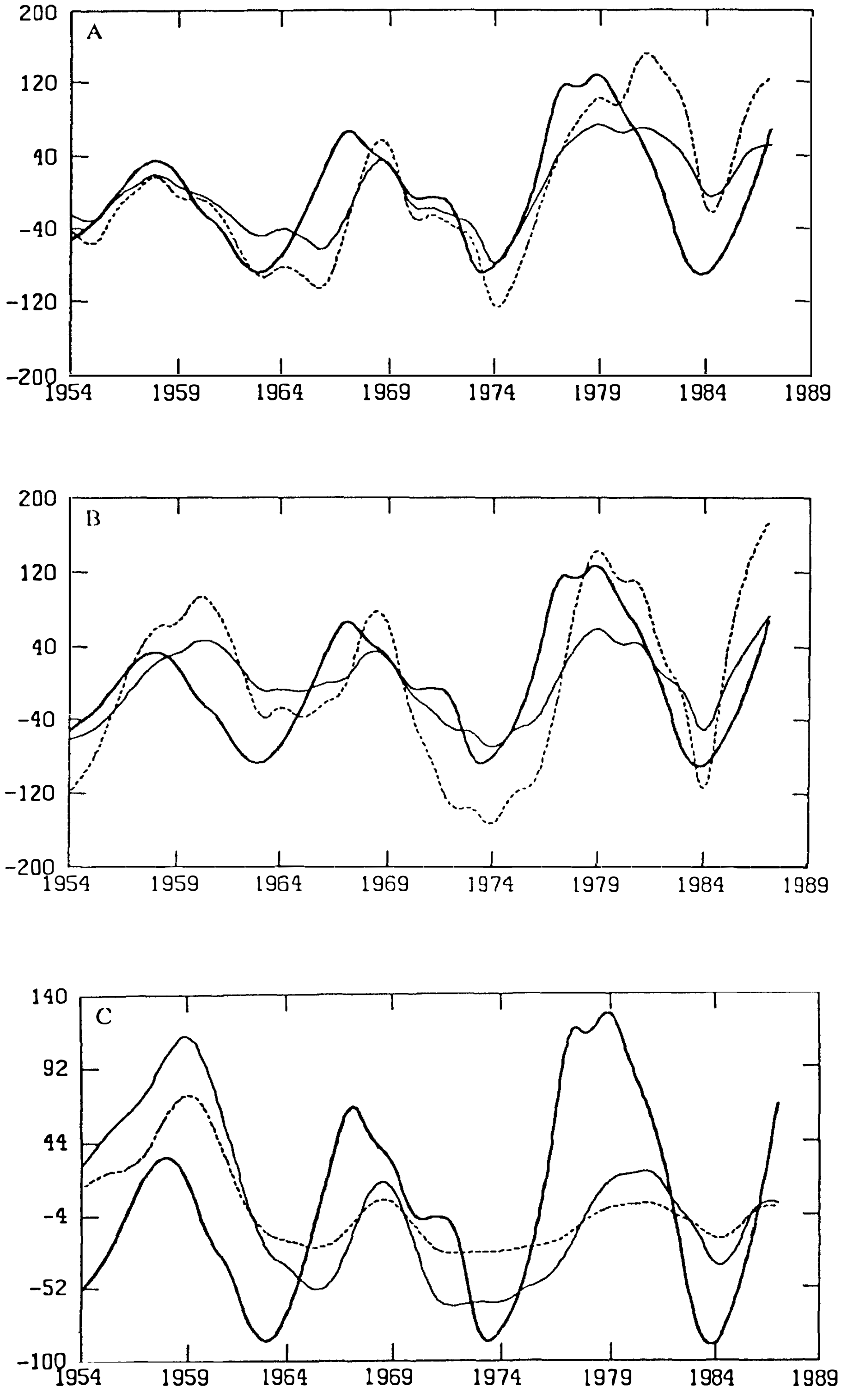
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Fig. 4.

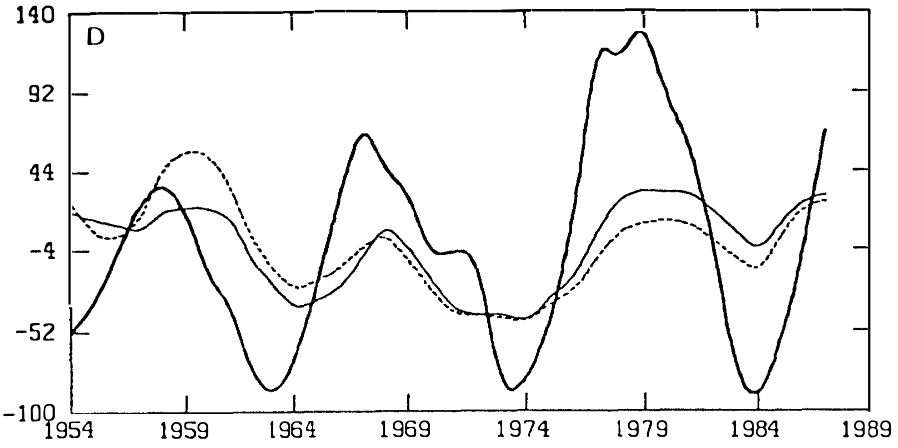

Fig. 4. The 3-year running average curves of winter sea-ice area index in the Kara/Barents Seas (thick solid curve), the area index (thin solid curve) and the intensity index (dashed curve) of the subtropical high in the following spring and summer.

(A) The subtropical high in the following spring over the Western Pacific.

(B) As in (A) but for the following summer.

(C) The subtropical high in the following spring over North America/the North Atlantic.

(D) As in (C) but for the following summer.

The area index of the subtropical high was multiplied by 10.0 in Fig. 4A, B, C and by 5.0 in Fig. 4D.

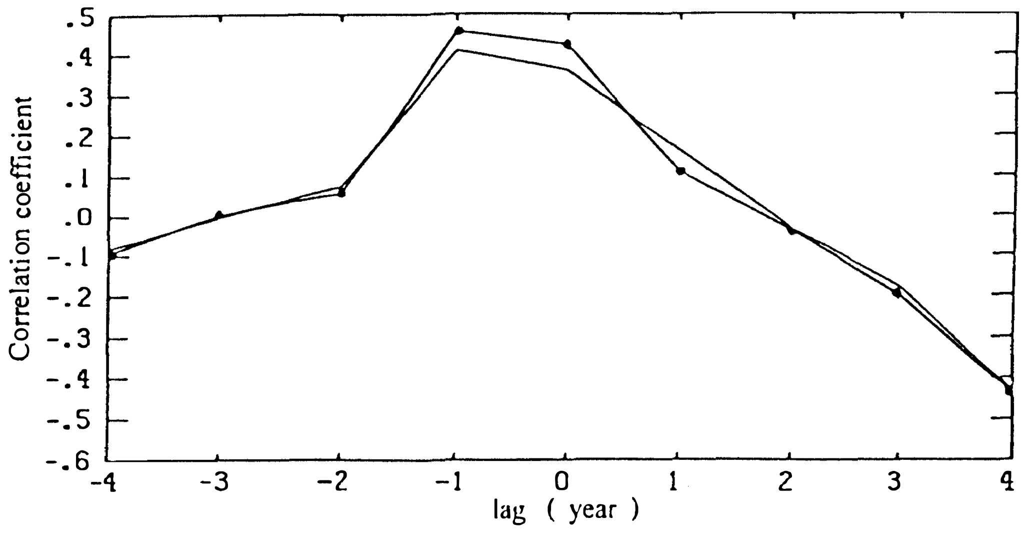

Fig. 5. The curve linking the dots indicates the lag cross-correlation between the area index of winter sea-ice in the Kara/Barents Seas and the area (intensity) index of the subtropical high in the following summer over the Western Pacific. Negative lag indicates that the sea-ice precedes the subtropical high.

ary wave and the oscillation source of the decadal variation.

For a time series of a meteorological element A_j (t), an estimate of $\hat{A}_j$ (t) was obtained by performing the Hilbert Transform A_j (t).

$$\hat{A}_J(t)=\sum_{L=-\infty}^{\infty} A_J(t-L)\,h(L),$$

$$h(L)=\begin{cases}\dfrac{2}{\pi L}\sin\left(\dfrac{\pi L}{2}\right), & L\neq 0\\ 0, & L=0\end{cases}$$

where J is a spatial position index and t is time. In this study, $L=7$ years provided an adequate amplitude response. In fact, the Hilbert Transform for $A_J(t)$ is a kind of filtering process. Therefore, CEOF analysis can reveal the different phase oscillations for the same frequency.

$A_J(t)$ and $\hat{A}_J(t)$ constitute a complex time series:

$$B_J(t)=A_J(t)+i\hat{A}_J(t).$$

The covariance matrix of $B_J(t)$ is given by

$$C_{JK}=\langle B_J^*(t)\,B_K(t)\rangle,$$

where the asterisk denotes complex conjugation and < >, a time average. V_n is a complex eigenvectors of the covariance matrix C for the eigenvalue λ_n. A spatial phase function is defined by

$$\theta_K(J)=\arctan\left[\frac{\mathrm{Im}V_K(J)}{\mathrm{Re}V_K(J)}\right],$$

where J is a spatial position. The first and the second eigenvectors can explain 45.6% and 38.9% of the total variance, respectively. As the spatial field of the CEOF1 stands for a stationary wave, the spatial characteristic of the CEOF2 is analyzed with emphasis. The spatial distribution of the phase associated with CEOF2, as shown in Fig. 6, indicates that there is a center of the minimum of the phase at 70°E, 65°N over the southern Kara Sea, corresponding to a source of cold air outbreaks and of climatic oscillation which propagates away from the source region. The oscillation source in the atmosphere is excited by variation of sea ice in the Kara/Barents Seas.

In addition, there are three other sources of the oscillation, *i.e.*, the central Northern Pacific, the Arabian Sea to the South China Sea and Southwest of Svalbard.

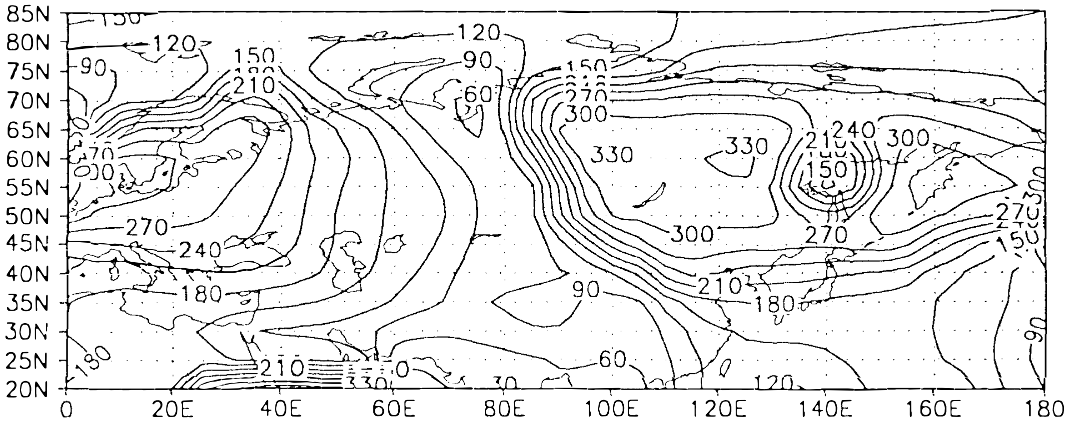

Fig. 6. The spatial distribution of the phase associated with CEOF2; the unit is degrees.

Significantly, the oscillation sources are over oceans. This means that the atmospheric variation on the decadal time scale is driven by the ocean circulation, in good agreement with previous studies (KAWAMURA, 1994; LAU and NATH, 1994). However, it is very difficult to determine the cause of the oceanic (including sea ice) variation on a decadal time scale.

Previous research has revealed a period of 11 years in solar activity (including sunspot number). When the sunspot number is below (above) normal, the SST averaged over global will be dropping (going up). The solar constant also varies with a period of 11 years; the amplitude of its variation is about 0.039% of its average value. Unless doubt that the variation of solar activity can provide enough energy to cause climate anomalies. However, the accumulated effect of solar activity on the climate system could appear as a long-term-trend. To answer the above question, more research is needed.

4. Conclusions

From the above, the following conclusions can be obtained:

1) The variation of sea ice area in the Kara/Barents Seas plays an important role in the Arctic climatic system on a decadal time scale. There exists a decadal variation in winter sea ice area in the Kara/Barents Seas and the Siberian High intensity in winter, the intensity of winter monsoon over East Asia, and the area and intensity of subtropical highs over various regions (the Western Pacific, North America, North America/the North Atlantic).

2) The variations of the Siberian High intensity in winter and the intensity of the winter monsoon over East Asia are out of phase with that of sea ice area in winter in the Kara/Barents Seas, which means that the more (less) sea ice there is, the weaker (stronger) the winter Siberian High and the winter monsoon will be.

3) The variation trend of sea ice area in winter in the Kara/Barents Seas is similar to that of the area and the intensity of the subtropical highs over the various regions in the following spring and summer, with a lag period of 0–1 year.

4) The decadal oscillation sources in the atmosphere on are closely linked to some sea regions. Including the Kara/Barents Seas, the central Northern Pacific, the Arabian Sea to South China Sea and the ocean southwest of Svalbard. The center of the strongest oscillation source excited by winter sea ice is near 70°E, 60°N in the Kara/Barents Seas.

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