Proc. NIPR Symp. Polar Meteorol. Glaciol., 8, 111-128, 1994

STUDY ON THE OSCILLATION RELATIONSHIP BETWEEN SEA ICE OF THE ARCTIC AND ANTARCTIC

Simei XIE, Chenglan BAO and Chunjiang HAO

National Research Center for Marine Environment Forecasts,
8 Dahuisi, Haidian Division, Beijing, 100081, China

Abstract: In this paper, the Antarctic sea ice is divided into four regions: SPI1 (0°-120°E), the eastern Antarctic region; SPI2 (120°E-120°W), centered at the Ross Sea; SPI3 (120°W-0°), centered at the Weddell Sea. SPI4, the whole Antarctic sea region. The Arctic sea ice is divided into three regions: NPI1 (90°E-180°-90°W) on the Pacific-side; NPI2 (90°W-0°-90°E) on the Atlantic-side. NPI3, the whole Arctic sea region. In this paper, by mathematical statistical methods, the SIGRID polar sea ice data provided by WDC-A are used to analyze the interrelations between sea ice among the Arctic and Antarctic regions. It is found that complicated interactions exist between sea ice of the Arctic and Antarctic Regions with the most outstanding characteristics as follows: NPI2 plays a leading role in the interactions between the two Poles' sea ice. SPI3 is a positive feedback center affecting the Antarctic sea ice. SPI2 is a negative feedback center affecting the two Poles' sea ice. The strongest interactions among NPI2, SPI3 and SPI2 involve a quasi-periodic intensity variation between sea ice of the Antarctic and Arctic with cycle period of 5-6 years. This cycle period coincides with the principal period of NPI2 and SPI3 variations themselves. An oscillation relationship forms among NPI2, SPI3 and SPI2. The oscillation between SPI3 and SPI2 is of zonal nature while the oscillation between NPI2 and SPI3 or SPI2 is of meridional nature. This kind of oscillation is not at the same time but with a longer lag time difference. NPI2 lags SPI2 lag about 0.5-1 year; SPI3 lags SPI2 lag 2-12 months and 24-48 months; and SPI3 lags NPI2 lag 0.5-2 years.

1. Introduction

Sea ice of two Poles is a vigorous heat sink of the global atmospheric-oceanic thermal engine, and is also a very important factor in the global atmospheric circulation and climate change. Therefore, meteorologists and oceanographers are giving increasing attention to polar sea ice study. In the past, it was extremely difficult to obtain large-scale continuous polar sea ice data due to the severe climate in the polar regions. However, in recent years, with the rapid development of remote sensing techniques and their application to global meteorological-oceanic monitoring, continuous sea ice data in the whole Arctic and Antarctic have became available. This has greatly promoted study of sea ice in the polar regions and its impact on global climate change.

Using ESMR (Electrically Scanning Microwave Radiometer) on NIMBUS-5 based on the large difference between albedo of sea water and sea ice, and also using single wave length radiation brightness, ZWALLY *et al.* (1983) calculated the concentration distribution of sea ice in the Antarctic. They pointed that about 80% of sea ice in the Antarctic is annual ice. They also found an extensive Weddell Polynya in 1974–1976.

Using ESMR on NIMBUS-5 and SMMR (Scanning Multichannel Microwave Radiometer) on NIMBUS-7, PARKINSON *et al.* (1987), PARKINSON and CAVALIERI (1989) and PARKINSON (1992) obtained sea ice distribution charts in the maximum and minimum stage in the Arctic, the marginal ice line with sea ice concentration of 30% and its interannual variation. They continuously used SMMR on NIMBUS-7 and SSM/I (Special Sensor Microwave/Imager) for multiwave observation.

VAN LOON (1967) showed that seasonal variation of air temperature around the Antarctic Continent is of an asymmetric smoothed winter type. The very cold winter continues to the Spring Equinox. The seasonal variation of sea ice around the Antarctic is similar to the air temperature. ENOMOTO and OHMURA (1991) showed a longitude-time section chart of the sea ice area. The maximum sea ice area appears in September–October, 1–2 months later than mid-winter, July–August. There is less open water in the freezing stage from autumn to winter and more in the melting-ice stage from spring to summer; it rapidly decreases from summer to autumn.

In addition, GORDON (1979, 1981) and USHIO and WAKATSUCHI (1990), respectively, studied the seasonal variation of sea ice and its physical features.

WALSH and JOHNSON (1979) investigated interannual variation of sea ice and its relationship with air temperature-pressure fields. WALSH and SATER (1981) found that the sea surface temperature in the Atlantic and Pacific has a good relationship with sea ice variation, and sea ice variation has high correlation with longitudinal wind speed one month before.

Up to now, most studies of sea ice in the two polar regions have focused on, respectively, varying features of sea ice in the Arctic and Antarctic and their relationship with global climate. In our opinion, polar sea ice not only has a great impact on global climate change, but also the icepacks in the two polar regions related. Moreover, BJERKNES (1969) and WALLACE and GUTZLER (1981) revealed an atmospheric teleconnection. In this paper, we study the oscillation relationship between sea ice in the Arctic and Antarctic in order to unify the impact of sea ice in the two polar regions as a heat sink in global climate change.

In this paper, the SIGRID sea ice data from the NAVY-NOAA Joint Ice Center (JIC) are used to calculate the monthly mean net ice area index (excluding open water area inside of the sea ice region) month by month. The monthly mean net ice area index and their anomalies in the Antarctic in 1973–1989 and the Arctic in 1972–1989 are the basic data used in this paper. It is noted that, the quality of SIGRID data is not good. After graphic analysis we found that the quality of the Antarctic sea ice data is rather good with a larger error of the Arctic sea ice in January–February, 1978, May–December, 1982 and October, 1988. Therefore, the accuracy of calculated results in this paper has been affected to some degree. The corresponding correction explanations will be given when we obtain more accurate data in the future.

2. Development of Sea Ice in the Arctic Regions and Their Interrelations

Based on the natural geographical conditions, the meridian of 90°E–90°W is used to divide the Arctic Ocean into three regions: Region I is the sea area on the Pacific-side (90°E–180°–90°W); Region II is the sea area on the Atlantic-side (90°W–0°–90°E); and Region III is the whole Arctic Ocean (as shown in Fig. 1). The sea icepacks in these regions are denoted, respectively, by NPI1, NPI2 and NPI3.

The reason for this division is that the Atlantic and Pacific have a different impact on the Arctic sea ice. In NPI1, blocked by Alaska, it is very difficult for the North Pacific warm current to enter the Arctic Ocean directly and only a small amount of cold water from the Arctic Ocean can flow into the Pacific through the narrow Bering Strait. In contrast, in NPI2, the Arctic connects with the Atlantic through the broad open channel of the Greenland Sea and the Barents Sea. The warm water of the North Atlantic warm current directly enters the Arctic without any blocking, and cold water moves southward from the Arctic in the eastern Greenland cold current. Interaction between the Arctic and

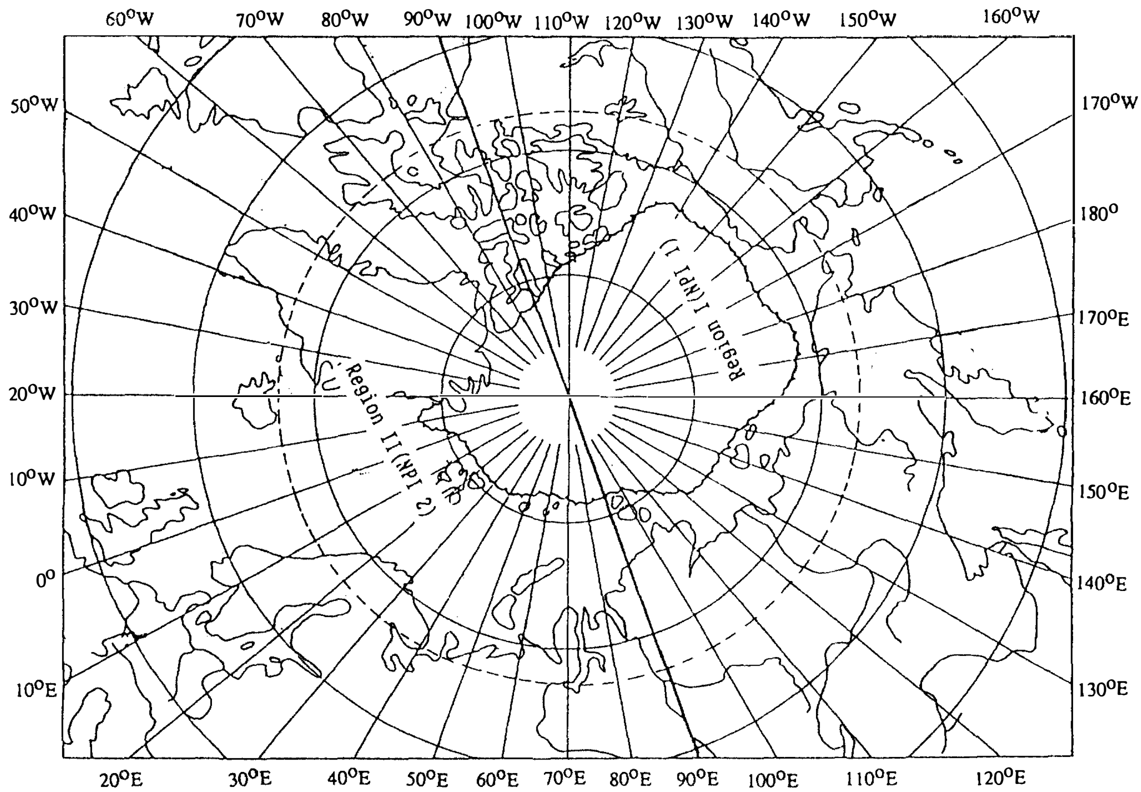


Fig. 1. The divisions of the Arctic sea ice.
Region I (NPI1) is the sea ice area on the Pacific side (90°E–180°–90°W); Region II (NPI2) is the sea ice area on the Atlantic side (90°W–0°–90°E); Region III (NPI3) is the whole Arctic sea ice area.

Atlantic is very strong. At the same time, the seasonal and interannual variations of sea ice in the Greenland Sea and the Barents Sea within NPI2 are very obvious (LEMKE *et al.*, 1980). The aim of this paper is to study the relationship between sea ice in the two polar regions; the Pacific and Atlantic are the only two channels conecting the Arctic and Antarctic. This teleconnection is of global scale and the Arctic sea ice is of large scale so that the smaller scale sea ice characteristics inside of the Arctic can be neglected. As a result, the Arctic sea ice is divided into two regions, the Pacific side and the Atlantic side, with roughly similar sea ice extent.

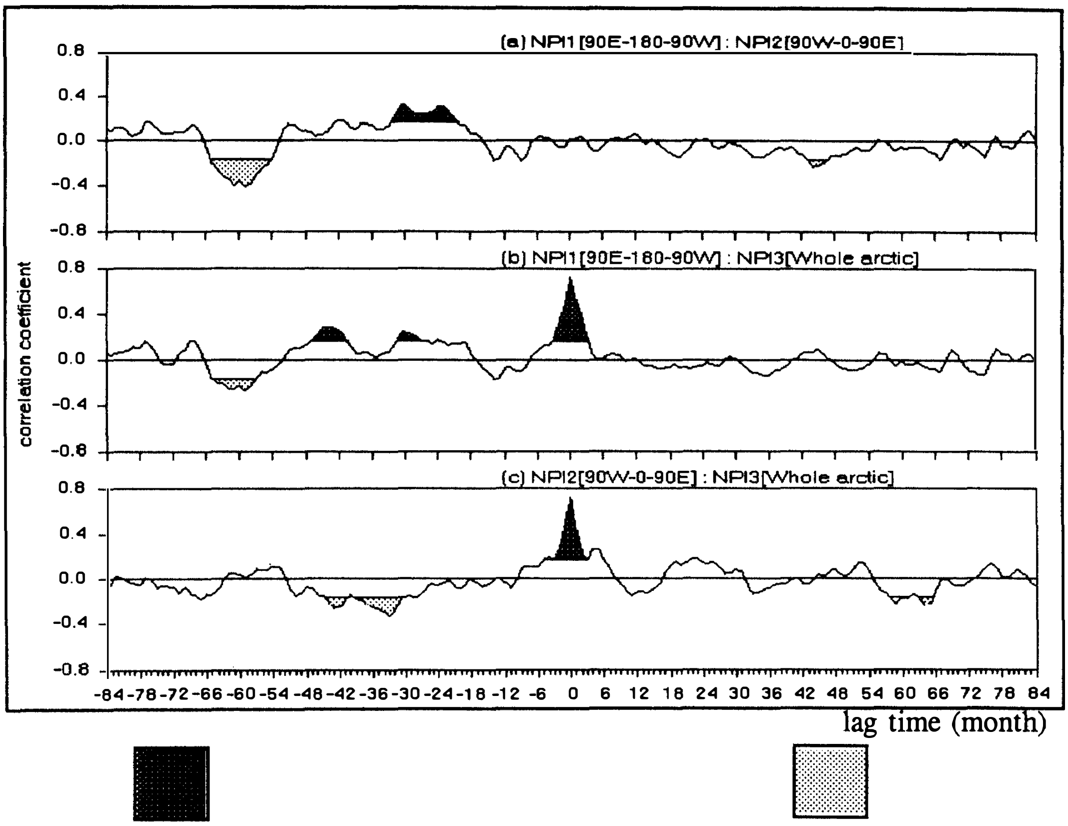
Table 1 shows the principal period and sub-periods of sea ice in the Arctic and Antarctic regions calculated by maximum entropy spectrum analysis.

Figure 2 shows the running cross correlation coefficient curves of the net sea ice area index anomalies of Arctic Regions I, II and III from 7 years before to 7 years later. The data set includes 216 months from 1972 to 1989. The constant sample for the reservation of running cross correlation is 132 months with significant level higher than 95% and 99% when correlation coefficients are, respectively, 0.17 and 0.22 or more. Figure 2a is the cross correlation coefficient time series for NPI1 and NPI2. The followings can be seen from Fig. 2a: (1) correlation coefficients are very small, almost zero when NPI1 is 12 months prior to 12 months later. This means that NPI1 and NPI2 are basically independent sea ice areas for short term correlation in $-1\sim+1$ year. Therefore, this division is reasonable. (2) Strong negative and positive correlation stages are, respectively, observed in NPI1 66–54 and 34–16 months prior to NPI2. The negative-positive variation period is 42 months (-68 to -16 months). This means that the Pacific side Arctic sea ice in an early stage, quasi-5 years and quasi 2–3 years before has an effect on the Atlantic side Arctic sea ice with negative and positive correlations. That is to say, NPI1 on the Pacific side plays an important leading role on the whole Arctic sea ice. The correlation variation period is the same as

Table 1. The low-frequency oscillation periods of 3 Arctic regions and 4 Antarctic regions.

Ice region		Principal period (months)		Sub-periods (months)			
				First	Second	Third	Fourth
Arctic	NPI1	10.8	(432)*	48	24	14.4	
	NPI2	61.7		27	4.4	9.2	
	NPI3	54	(432)*	24	10.8	5.9	7.2
Antarctic	SPI1	58.3		18.6	12.8	10	6.9
	SPI2	132					
	SPI3	68		15.1	10.5		
	SPI4	10	(204)	18.5	12.4		

* Numeral in brackets is the maximum spectrum value while one wave. It is twice of year number of whole data set, therefore is only used for reference.



positive correlation
r≥0.17
signficance level≥95%

negative correlation
|r|≥0.17
significance level ≥95%

Fig. 2. The time series curves of the running cross correlation coefficients(r) of the net sea ice area index anomaly of three Arctic regions. Abscissa is the lag time (months) of first variate to the second. (−) is prior and (+) is lag. For example in Fig. 2a, (−24) is NPI1 leading NPI2 by 24 months, and (+12) is NPI1 lagging NPI2 by 12 months. NPI1 (90°E–0°–90°W), Pacific side Arctic sea ice. NPI2 (90°W–0°–90°E), Atlantic side Arctic sea ice. NPI3, whole Arctic sea ice.

sub-period of 2 years of NPI1 and principal period of 5 years of NPI3 (Table 1). But in the recent stage from −1 to +1 year, the two are independent.

Figure 2b is a correlation curve of NPI1-NPI3. There exists a very strong positive correlation stage at the same time within −4 to +4 months. The maximum contemporary correlation coefficient is +0.82 with significance level more than 99.99%. A stronger negative and two positive correlation stages appear, respectively, in NPI1 of 68–58, 48–40 and 30 months before. This means that the Pacific side sea ice plays an important role on the whole Arctic sea ice variation. NPI1 about 5, 4, 3 years before has strong negative and positive feedback actions on NPI3 in a later stage.

Figure 2c is a correlation curve of NPI2–NPI3. It has the same features as Fig. 2b. There is a very strong positive correlation at and near the same time with maximum correlation coefficient of +0.68. A stronger negative correlation appears in NPI1 44–30 months before. Its periodicity of negative-positive variation is obvious with a period of 64 months (from −54 to −10 months), quasi-5 years, the same as the periods of both NPI2 and NPI3 (see Table 1). This shows the important role of the Atlantic side sea ice on the whole Arctic sea ice.

3. Development of Sea Ice in the Antarctic Regions and Their Interrelations

Antarctica is a continent centered at the South Pole and surrounded by sea ice, and bordering on the Pacific, Atlantic and Indian Oceans. Based on this natural geographical condition, the Antarctic sea ice is divided into four regions (Fig. 3): Region I (0°−120°E), the eastern Antarctic sea area, connected to the Indian Ocean; Region II (120°E–180°–120°W) is centred in the Ross Sea facing the Pacific; Region III is centred in the Weddell Sea facing the eastern South Pacific and the Atlantic (120°W–0°); Region IV is the whole Antarctic. Sea ice packs in these four regions are, respectively, expressed by SPI1, SPI2, SPI3 and SPI4. Variation periods of sea ice in these four regions are also shown in Table 1.

The reason for this division are as follows. First, these three sectors are

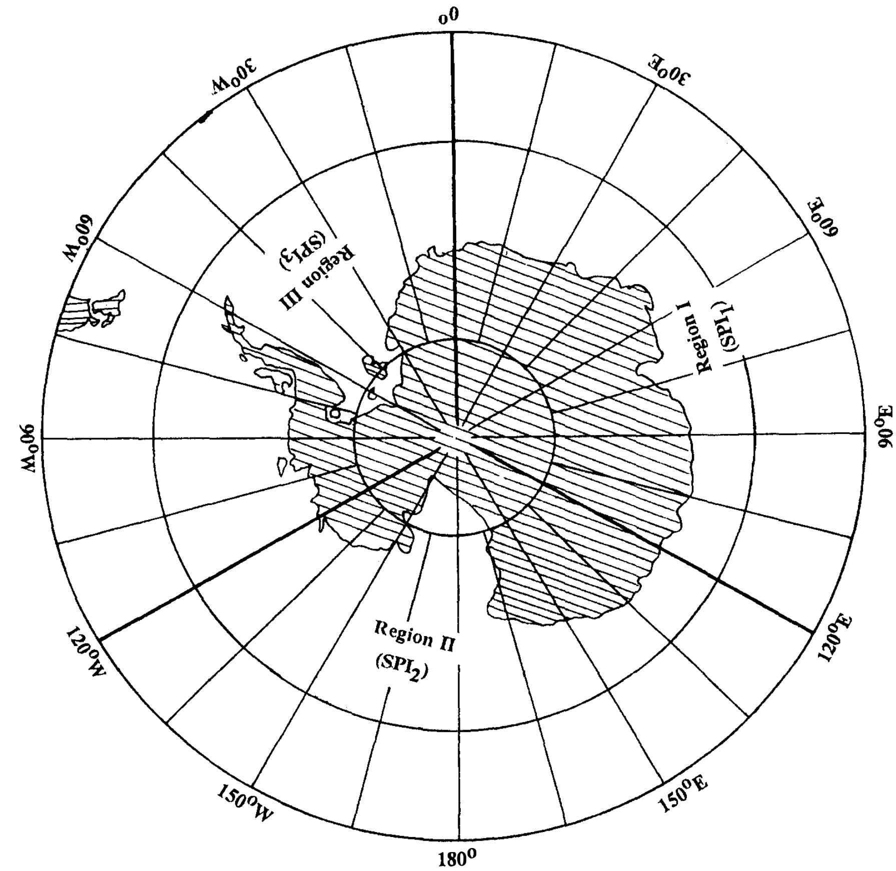


Fig. 3. The divisions of the Antarctic sea ice.
Region I (SPI1) (0°–120°E): Eastern Antarctic sea ice area. Region II (SPI2) (120°E–120°W): Ross sea ice area. Region III (SPI3) (120°W–0°): Weddell sea ice area. Region IV (SPI4): whole Antarctic sea ice area.

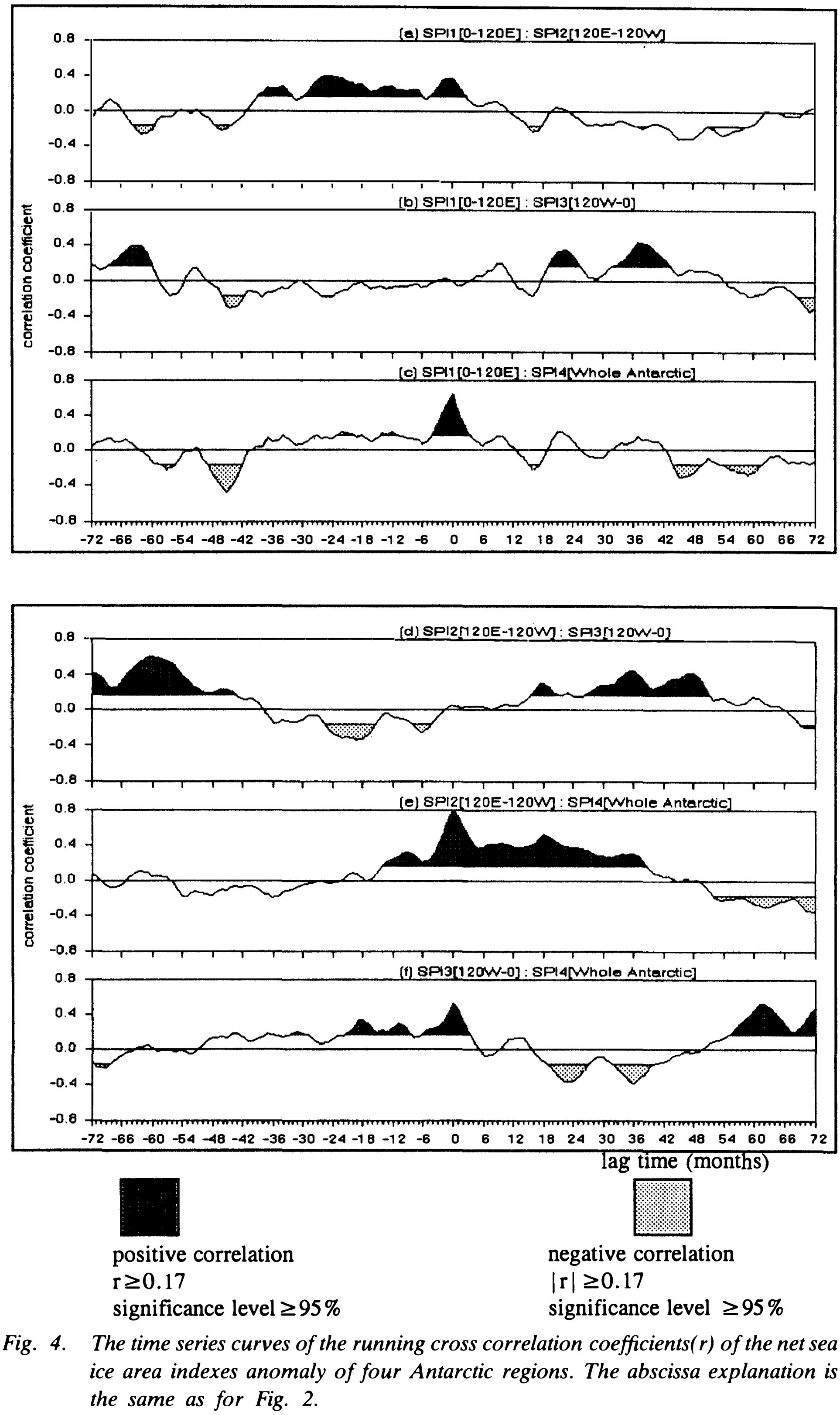


Fig. 4. The time series curves of the running cross correlation coefficients(r) of the net sea ice area indexes anomaly of four Antarctic regions. The abscissa explanation is the same as for Fig. 2.
SPI1 (0°–120°E), eastern Antarctic sea ice region. SPI2 (120°E–120°W), Ross sea ice area. SPI3 (120°W–0°), Weddell sea ice area. SPI4, whole Antarctic sea ice area.

exactly equal in extent. Second and more importantly, China has two Antarctic stations, one on the Antarctic Peninsula, and the China Antarctic vessel navigates through the Bellinghausen Sea and the Weddell Sea, so these two seas are considered as a sector. Third, the Bellinghausen Sea ice extent is much smaller than the Ross and Weddell Seas. It is considered as part of the Weddell Sea sector. Possibly, the Bellinghausen Sea ice is important; it may be studied in future research.

Similarly, the time series change curves of running cross correlation coefficient of the Antarctic Regions from 6 years before to 6 years later are also calculated (Fig. 4). The time series length is 204 months, 1973–1989; the constant sample length for running cross correlation is 132 months.

In Fig. 4a, a very strong positive value of SPI1–SPI2 lasts for as long as 4 years ($-40\sim+4$ months). In addition, other stronger negative stages also appear, respectively, in SPI1 of 64, 46 months before and 16, 38–60 months later. This means that SPI1 in -64, -46, $-40\sim+4$ months in an early stage has strong negative and positive feedbacks on SPI2 in a later stage to determine the variation of the latter. Conversely, SPI2 16 and 38–60 months prior has a strong negative feedback on SPI1. Obviously there is a long term periodic variation of 102 months (from -42 to $+63$ months) in the correlation time series. Two short term periods of 18 and 12 months are superimposed upon the long term period. These periodic variations obviously approach the principal period of 132 months (quasi-11 years) of SPI2 and principal period of 58 and sub-periods of 18 and 12 months of SPI1.

SPI1 is strongly positively correlated 68–60 months prior to and 16–24, 32–42 months lagging SPI3, and negatively 45 months before with SPI3. Obviously, the positive correlation is the strongest when SPI1 lags. This shows that the impact of SPI3 about 2 and 3 years before on SPI1 is larger than the impact of SPI1 in an early stage on SPI3 in a later stage. The Weddell Sea ice plays a principal controlling function on the whole Antarctic sea ice variation. The long term variation period is also 102 months (from -48 to $+54$ months) (Fig. 4b).

SPI1 has a strong negative correlation 49–42 months prior to SPI4, and a strong positive correlation near the same time ($-5\sim+4$ months). It is an evidently symmetric periodic strong negative-positive correlation variation with period of 62 months (from -50 to $+12$ months), approaching the principal period of quasi-5 years (58 months) of SPI1. In addition, a double-peaked negative stage is observed in SPI1 lagging SPI4 by 43–60 months (Fig. 4c). This means that SPI1 4 years before has a negative feedback effect on the whole Antarctic sea ice while there is a stronger positive correlation near and at the same time. Conversely, the whole Antarctic sea ice 4–5 years before also has a negative feedback effect on SPI1.

The most outstanding feature of the correlation time series between SPI2 and SPI3 is a long term periodic variation of strong negative-positive correlation. A strong positive and a stronger negative correlation, respectively, appear in SPI2 72–42 and 28–16 months before, while a strong positive correlation appears in SPI3 12–48 months prior. This means that the Ross Sea ice variation 4–6 and

1–2 years before affects on Weddell Sea ice with strong positive and stronger negative feedback functions, respectively. In contrast, the Weddell Sea ice 1–4 years before has a strong positive feedback effect on the Ross Sea ice. This kind of strong variation period is about 100 months (from −42 to +48 months). A short term period of quasi-1 year is superimposed on the long term period variation. Moreover, the contemporary correlation of these two ice regions (from 0 to +6 months) is almost zero. This means that they are basically independent at and near the same time, but they are two key ice regions of very strong interaction in long term variations over several years.

The outstanding feature of SPI2–SPI4 is that a sustained strong positive correlation lasts for 54 months in SPI2 from −16 to +38 months with maximum correlation coefficient at zero lag of +0.7. It shows a very close positive correlation between the Ross sea ice in −1 to +3 years to the whole Antarctic sea ice. But SPI4 has a stronger negative feedback over 52–74 months (5–6 years) prior to SPI2 (Fig. 4e).

SPI3 from −24 to +3 months also has a stronger positive correlation with SPI4 (Fig. 4f), but much weaker than in Fig. 4e. During 18–40 months of SPI3 lagging behind SPI4, there exists a negative stage with double valleys at +24 and +36 months of SPI3 lag, and other two peaks at +60 and +72 months (5 and 6 years) of SPI3 lag. This shows that the whole Antarctic sea ice 5–6 and 2–3 years before has a strong positive and negative feedbacks on the Weddell Sea ice. This has an evident long periodic variation of 100 months superimposed on a quasi-1 year short term variation. It is of a double peaks and double valleys type.

In summary, the schematic model in Fig. 5 can be used to show the interaction between three Antarctic ice regions. The Weddell Sea ice (SPI3) exerts a strong positive feedback on the Ross Sea ice (SPI2) 1.5, 3 and 4 years later and on the eastern Antarctic sea ice (SPI1) quasi-2 and 3 years later. That is to say, when SPI3 is anomalously more/less, it induces a whole Antarctic sea ice anomaly (more/less) within 2–4 years. However, Ross Sea and eastern Antarctic sea ice anomalies (more/less) also induce Weddell Sea ice anomalies (more/less) with a longer lag time scale (quasi-5 years) positive feedback. SPI1 has a strong positive correlation impact on SPI2 at the same time and about 1, 2, and 3 years later. Such a strong positive cycle would be a monotonic change if negative feedback did not occur. In fact, SPI2 restricts the SPI3 development trend by negative feedback 0.5 and 1–2 years later; SPI1 also restricts SPI3 development with negative feedback quasi-4 years (45 months) later; and SPI1 and SPI2 restrict each other too. Such an interaction of positive-negative feedback makes the Antarctic sea ice change periodically. But it can be seen from Fig. 4 that the positive is strong and the negative is weak. So, if only interaction of the Antarctic sea ice itself is considered, it would develop toward a single intensifying or weakening direction. Nevertheless, the Antarctic is not isolated, but interacts with the global atmosphere, ocean and climate, as well as the Arctic sea ice. As a result, the global climate change roughly approaches equilibrium.

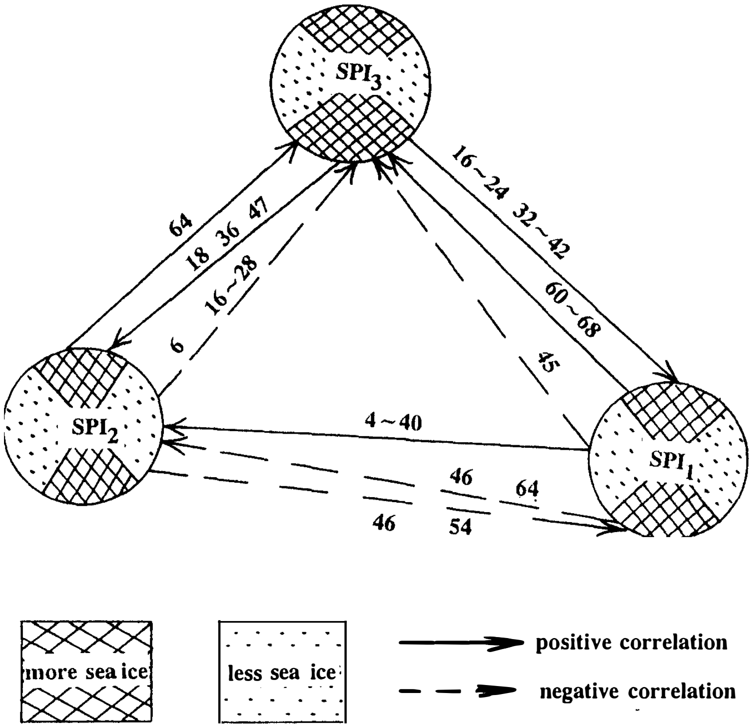


Fig. 5. Interaction relationship model of three Antarctic ice regions. Numerals on arrow line are lag times (months). Thick solid or dashed line is strong positive or negative correlation. The definition of strong correlation is a correlation coefficient (r) ≥0.36 with significance level ≥99.9%.

4. The Oscillation Relationship Between Sea Ice of the Arctic and Antarctic

In this section, Antarctic and Arctic sea ice are linked to analyze their interaction. Figure 6 shows time series of running cross correlation coefficients of the Antarctic and Arctic regions with the Antarctic lagging the Arctic −72 months to 84 months. The constant sample length is 132 months.

The eastern Antarctic sea ice (SPI1) has a stronger negative correlation with NPI1 from −8 to 4 months. The maximum value of 0.39 appears SPI1 in 6 months prior with significance level more than 99.9%. A strong positive stage is observed in 44–64 months of SPI1 lag to NPI1 with maximum coefficient of +0.35, with the same significance level. This shows that the eastern Antarctic sea a ice half year before has a negative feedback effect on the Pacific side Arctic sea ice; in contrast, NPI1 has a strong positive feedback effect on SPI1 with a longer lag time of 4–5 years. Their interaction obviously shows a long term variation of 112 months (−30~+82 months) (Fig. 6a).

Figure 6b shows that the positive correlation stage of the Ross Sea ice (SPI2) 72–8 months prior to NPI1 lasts for as long as 5.5 years. Many peaks appear in this stage at SPI2 at −62, −54, −42, −34, −24, −12 months, with the time difference between two peaks being about 12 months. The maximum coefficient is +0.42 with significance level 99.99% at −54 months. In addition, a

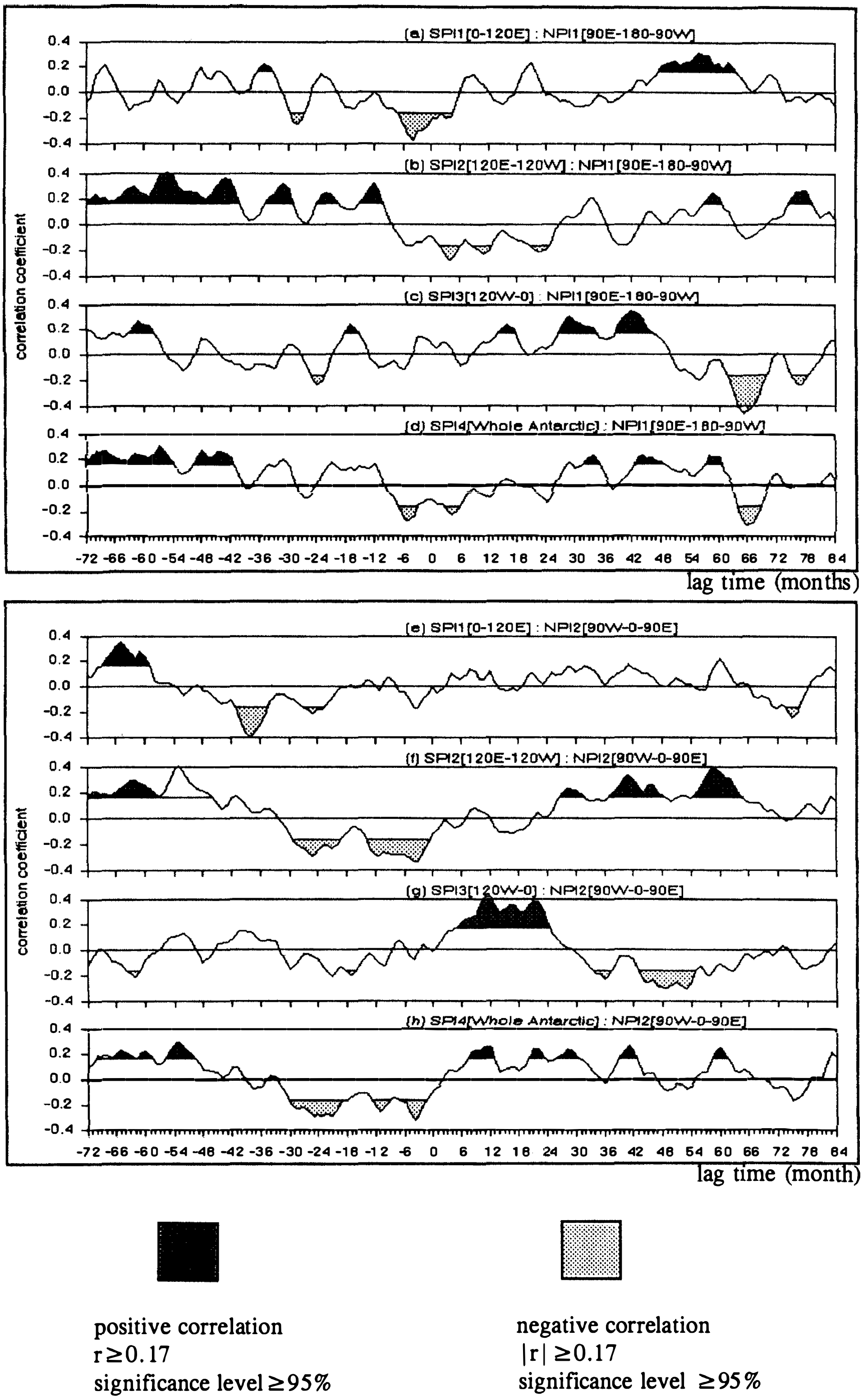


Fig. 6. Time series curves of running cross correlation coefficients(r) of the sea ice area index anomaly of three Arctic regions and four Antarctic regions. The abscissa explanation is the same as for Fig. 2.

negative stage with multiple valleys is also observed in SPI2 with 4–24 months lag. The negative correlations are not as strong as the positive ones and have shorter duration. Their variation period is about 100 months. These facts explains that SPI2 6–1 years before has a strong positive feedback effect on NPI1; however, negative feedback of NPI1 is rather weaker with shorter duration and shorter lag time difference.

Figure 6c shows that the correlation of the Weddell Sea ice (SPI3) with NPI1 is rather weaker, but it is strongly positive and negative when SPI3 lags NPI1. The long period of positive-negative correlation is obviously periodic, but due to limitation of the data set, the negative stage has not been completed. Using the positive correlation period as a half period ($-20\sim50$ months), the period is estimated as 140 months. The maximum positive peaks are in SPI3 (16, 30, 42 months lag) while a negative value of -0.49 with significance level of 99.99% occurs at 66 months lag.

The whole Antarctic sea ice SPI4 has a strong positive correlation period 72–40 months prior to NPI1, and a strong negative one lagging NPI1 by 66 months. Both correlations in the long term lead and lag stages are greater than over a shorter lag time of 3 years (Fig. 6d). SPI1–NPI2 has a long term positive-negative variation period of about 4–5 years for SPI1 $-72\sim-18$ months prior to NPI2. But correlation values of SPI1 over -18 to $+84$ months are very weak. This means that rather strong positive and negative feedback exist for SPI1 over a long time scale of 1.5 years prior to 6 years lagging NPI2 (Fig. 6e).

The running correlation of SPI2 and NPI2 shown in Fig. 6f has an obviously long term positive-negative-positive periodic variation of about 108 months for SPI2 from -34 months before to 74 months lag to NPI2. The maximum negative stage with two valleys is in SPI2 32–2 months before, and the maximum positive stage with three peaks has 24–62 months lag. The short period variations of quasi-1 and 1.5 years are superimposed on the long term period. Another strong positive stage with double peaks is also observed in SPI2 72–48 months before. These statistical facts show that SPI2 6–4 years and 3–0.5 years before, respectively, have strong positive and negative feedback effects on NPI2. In the contrast, NPI2 2–5 years before also has a strong positive feedback effect on SPI2. Both are situated at the south and north ends of the Atlantic Ocean. As a result, a long term oscillation relationship forms between both. This oscillation is not at the same time, but has a lag time difference of 3–0.5 year.

Correlation of SPI3 shown in Fig. 6g in an early stage with NPI2 in a later stage is weak. But a strong double-peaked positive correlation appears in SPI3 with 6–24 months lag with peaks at $+12$ and $+20$ months, while a negative stage lags by 34–54 months with a valley lagging by 48 months. This means that NPI2 has strongly positive and negative feedback effects on SPI3. The Atlantic side Arctic sea ice plays a leading role in affecting the Antarctic key ice region. Correlation of the whole Antarctic sea ice SPI4 with NPI2 is much less than that of the sub-region (Fig. 6h).

Summing up from the above analyses, the interaction of sea ice of the Antarctic and Arctic Regions can be expressed by a schematical model (Fig. 7)

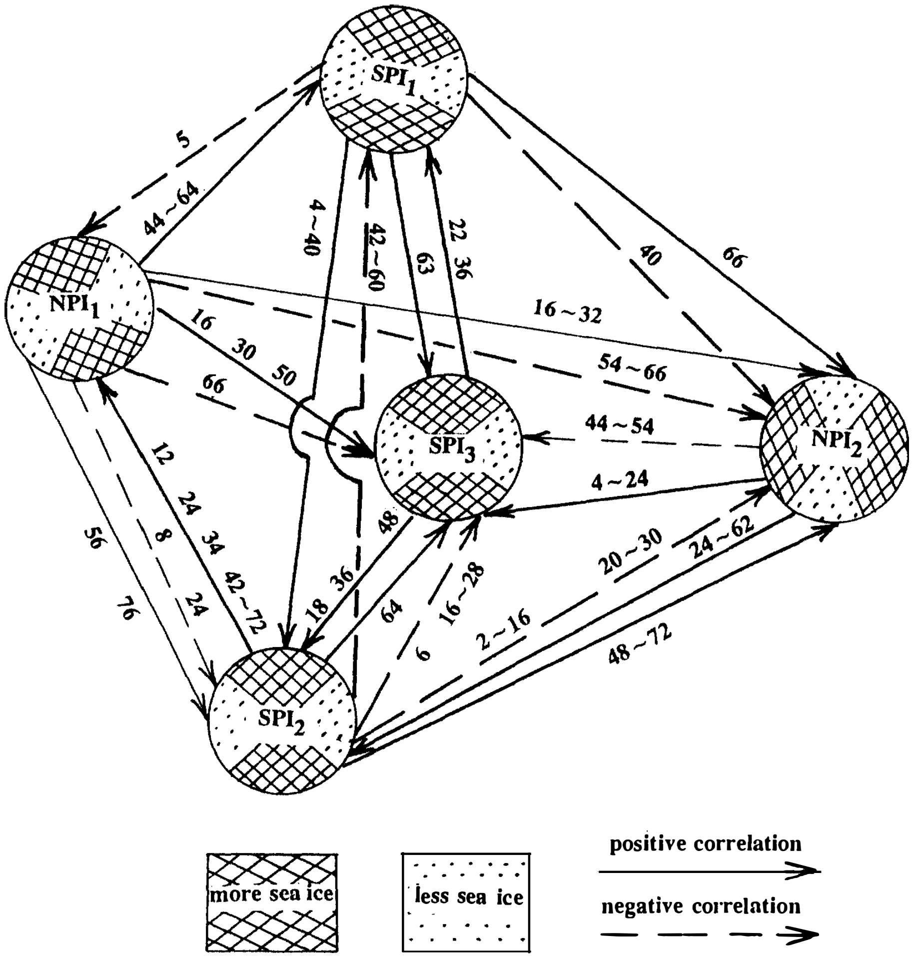


Fig. 7. A schematical model of interaction of the sea ice of the Arctic regions and Antarctic regions. Numerals on arrow lines are lead times (months). Thick lines are strong correlation with definition of correlation coefficient ≥0.36 and significance level ≥99.9%.

as follows:

(1) Arctic sea ice plays a leading role in sea ice variation between the two poles. Both NPI1 and NPI2 have strong positive feedback effects on the Antarctic SPI3, but feedbacks of SPI3 effect on NPI1–NPI2 are very weak. NPI1 anomaly (more/less) quasi 1, 3, 4 years and NPI2 4–24 months before strongly positively affect SPI3, and NPI1 strongly negatively affects on SPI3 again over a longer lag time of 66 months.

(2) SPI3 is a positive feedback center affecting the other two Antarctic regions. SPI3 has strong positive feedback effects on SPI1 22, and 36 months later and on SPI2 18, 36, and 48 months later. However, SPI1 and SPI2 over longer time scale of quasi-5 years (63 and 64 months) has a positive feedback effect on SPI3 and NPI2.

(3) A strong positive correlation of SPI1 4–40 months before acts on SPI2. SPI2 is a negative feedback center which has strong negative feedback effects on SPI3 6, and 16–28 months later and on NPI2 2–16 and 20–30 months later. Then,

SPI2 has a strong positive feedback effect on SPI3 over a longer lag time of 64 months. Similarly, the Antarctic SPI2 on a longer time scale of 4–6 years strongly positively affects the Arctic NPI1 and NPI2.

(4) SPI1 over a longer time scale of 66 months affects NPI2 and over half year time scale negatively affects NPI1. In contrast, NPI1 on a longer time scale of 44–64 months positively affects SPI1.

Summing up, interaction between the Antarctic and Arctic sea ice starts from the Arctic sea ice variation; first it has a strong positive correlative effect on the Antarctic SPI3 over 1–3 years lag time; then SPI3 has a strong positive feedback effect on the Antarctic SPI2 and SPI1 over 2–4 years lag time. Finally, as a negative feedback center, SPI2 has a strong negative feedback effect on NPI2 and SPI3 over 2–3 years lag time. As a result, an oscillation cycle period of quasi-5 years exists. In addition, SPI2 has a strong positive feedback effect on NPI2, SPI3, NPI1 over a longer lag time difference of 4–6 years. Then SPI1 has negative and positive feedback effects on NPI2 over a longer lag time difference of 66 months. There is another cycle period of about 9–11 years.

5. Discussion

Three well known atmospheric oscillations had been found. The most famous is the southern oscillation (WALKER and BLISS, 1932): when pressure in the South Pacific increases (or decreases), pressure in the South Indian Ocean decreases (or increases). A similar oscillation also exists in the North Pacific; it is called the northern oscillation (CHEN *et al.*, 1984).

The southern and northern oscillations are one kind of zonal significant negative oscillation of sea surface pressure and sea surface temperature fields between the eastern-western parts of an ocean basically at the same time (2–3 months lag). This kind of "seesaw" phenomenon, referred as El Niño or ENSO, has an important impact on global atmospheric circulation and climate change.

The sea ice oscillation between the Arctic and Antarctic is a complicated atmospheric-oceanic interaction process, with both zonal and meridional oscillation, which is different from the southern and northern oscillations. Its most outstanding feature is that the Arctic sea ice on the Atlantic side (NPI2) is an oscillation source: when NPI2 is anomalously more/less, it induces the anomalously more/less Weddell Sea ice (SPI3) at the south end of the Atlantic after 4–24 months lag, and in a chain reaction, it has a strong positive feedback effect causing anomalously more/less sea ice in the Ross Sea (SPI2) after another 18–48 months lag. Then, Ross Sea ice has a strong negative feedback effect on NPI2 2–16 and 20–30 months later and on SPI3 both 6 and 16–28 months later. Finally, a periodic variation of sea ice intensity is observed among NPI2, SPI3 and SPI2 with a cycle period of the whole process NPI2–SPI3–SPI2–NPI2 (SPI3) of about 5–6 years. 5–6 years just coincides with the quasi 5–6 years principal oscillation periods of NPI2 (61.7 months) and SPI3 (68 months) themselves (see Table 1). In addition, SPI2 has a longer time scale strong positive feedback effect on SPI3 quasi-5 years (64 months) later and on NPI2 4–6 years (48–72 months) later. NPI2 has a negative feedback effect on SPI3 44--54 months later, and SPI3 has a positive feedback effect on SPI2 1.5--4 years later. Such a whole cycle process needs about 10–14 years, which coincides with the principal period of 132 months (quasi-11 years) of SPI2, as well as with the principal period of sunspot activity. This means that maybe a certain connection exists between them.

It can be seen from the thick black lines in Fig. 7 that the polar sea ice interaction starts from NPI2 and NPI1 in the Arctic as an oscillation source, and

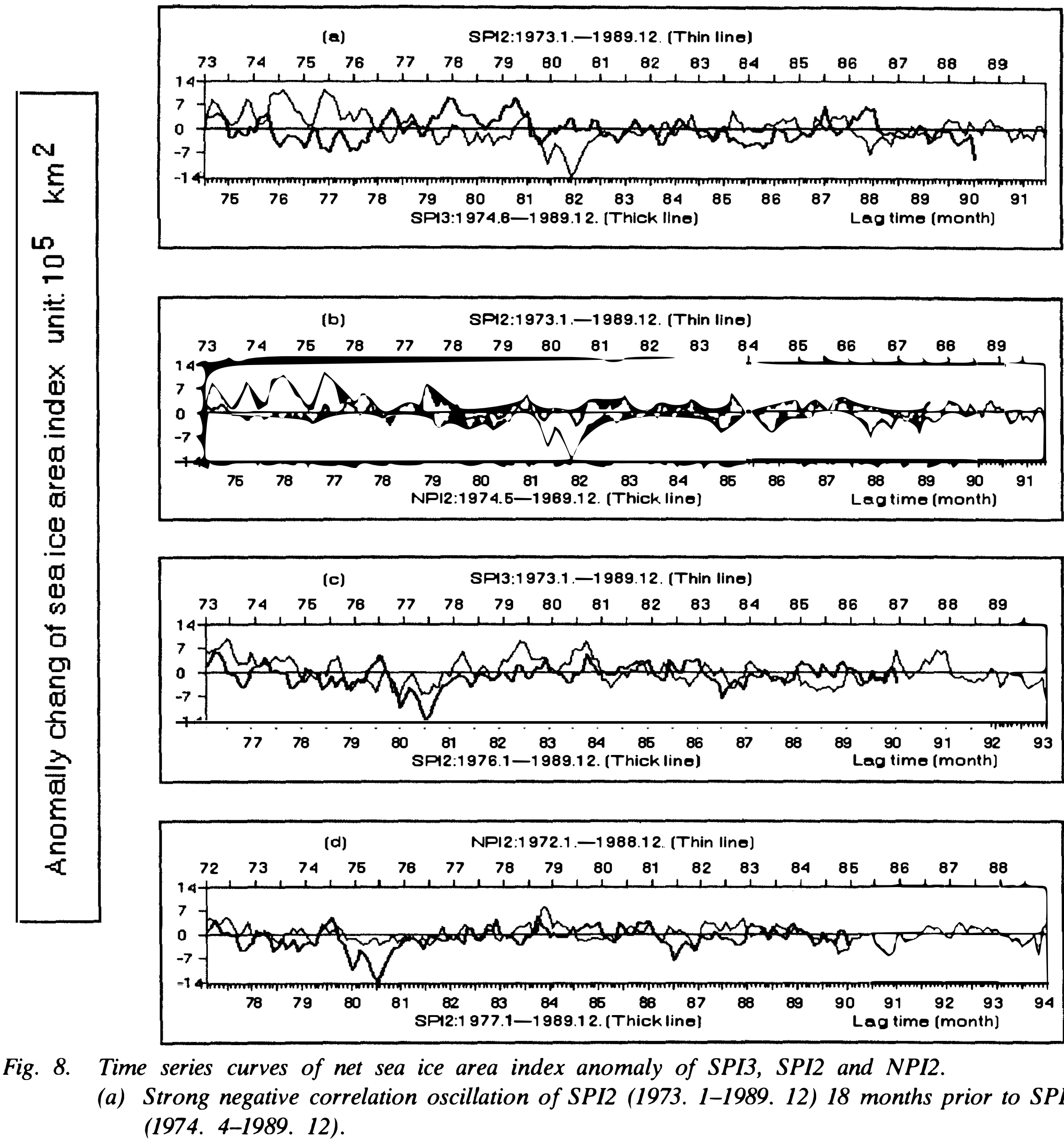


Fig. 8. Time series curves of net sea ice area index anomaly of SPI3, SPI2 and NPI2.

(a) Strong negative correlation oscillation of SPI2 (1973. 1–1989. 12) 18 months prior to SPI3 (1974. 4–1989. 12).

(b) Strong negative correlation oscillation of SPI2 (1973. 1–1989. 12) 4 months prior to NPI2 (1973. 5–1989. 12).

(c) Strong positive correlation corresponding to SPI3 (1973. 1–1989. 12) 36 months prior to SPI2 (1976. 1–1989. 12).

(d) Strong positive correlation corresponding to NPI2 (1972. 1–1989. 12) 60 months prior to SPI2 (1977. 1–1989. 12).

has a strong positive effect on Antarctic Weddell Sea ice (SPI3) 0.5–2 years later. The function of NPI2 is more significant. Therefore, it is considered that, the Atlantic circulation plays an important role in the interaction between NPI2 and SPI3.

As mentioned above, Arctic sea ice on the Atlantic side (NPI2) includes the Greenland Sea and Barents Sea with the biggest seasonal and interannual variation which is of high significance level, and is a key sea area for the Arctic sea ice variation (LEMKE *et al.*, 1980). NPI1 has a strong negative feedback effect lagging NPI2 by quasi-5 years (54--66 months) and a strong positive feedback lagging NPI2 by 16–32 months. Sea ice variation in the Weddell Sea has a strong positive effect, with 1–4 years lag, on SPI1 and SPI2. Therefore, Weddell Sea ice acts as a strong positive feedback center to the Antarctic sea ice. Possibly, it is concerned with the characteristics of the Weddell Sea ice which is a vigorous sea ice production field in winter, and almost fully melts in summer, icebergs continuously form and float from the Weddell Sea toward other sea areas.

Antarctic Ross Sea ice (SPI2) is a negative feedback center in interaction between sea ice in the two polar regions. It induces a strong periodic change of sea ice intensity in the two polar regions to form a polar sea ice oscillation relationship. Figure 8 shows the time series change of net sea ice area index anomalies of NPI2, SPI2 and SPI3 corresponding to their strongest correlation stage. For example, in Fig. 8a, at the same physical point on the horizontal axis, SPI2 starts from January, 1973 and SPI3 starts from June, 1974. In this situation, the two curves of sea ice area index anomaly have opposite phases. This means that SPI2 and SPI3 have a negative correlation with an 18-month time lag. It can be seen that, with different lag time differences, a negative correlation oscillation exists between SPI2 and SPI3, as well as between SPI2 and NPI2. However, a corresponding positive correlation exists between prior SPI3 and SPI2, as well as between prior NPI2 and SPI2. This kind of oscillation is both of zonal nature between SPI3/SPI2 and of meridional nature striding across the Arctic and Antarctic between NPI2 and SPI2/SPI3.

In this paper, the sea ice oscillation relationship is revealed only by statistical facts. The occurrence mechanism of this oscillation, its impact on global atmospheric circulation and climate anomaly, and its interaction with the equatorial Pacific as a heat source are three important problems left for further study.

6. Conclusions

(1) A complicated oscillation relationship exists between sea ice of the Arctic and Antarctic. The Arctic sea ice anomaly on the Atlantic-side (NPI2) plays a leading role in this oscillation. It first affects to Antarctic Weddell Sea ice at the southern end of the Atlantic with a time lag of about 0.5–2 years. However, NPI1 shows a negative feedback on NPI2 over a quasi-5 years lag time scale.

(2) The Antarctic Weddell Sea ice (SPI3) is a positive feedback center affecting the Antarctic sea ice. The sea ice anomaly (more/less) in the Weddell Sea impacts the Ross Sea and eastern Antarctic sea ice anomaly (more/less)

within 1–3 years later.

(3) The Antarctic Ross Sea ice (SPI2) is the negative feedback center affecting the sea ice of the Arctic and Antarctic. It has a strong negative feedback effect on two key positive feedback regions NPI2 and SPI3. Then it introduces a periodic variation of sea ice intensity in the Arctic and Antarctic. One cycle period is about 5–6 years, which is just coincident with the principal period of NPI2 and SPI3 variation themselves. There is another longer cycle period of quasi-11 years, coincident with the principal period of SPI2.

(4) The Antarctic sea ice (SPI2 and SPI1) affects the Arctic sea ice (NPI1 and NPI2) with positive feedback over a longer 4–6 years lag.

(5) The above three sea ice regions (SPI3, SPI2, NPI2) are three key regions of sea ice variation of the Arctic and Antarctic. They form an oscillation relationship among each other. The time lag of oscillation between SPI2 and NPI2 is about 0.5–2 years while the Weddell Sea ice has two lag times 6 and 16–28 months.

Acknowledgments

The authors would like to express their sincere thanks to World Data Center A and NAVY-NASA JIC for providing the SIGRID sea ice data, and also to Prof. T. Yamanouchi of the National Institute of Polar Research, Japan for his strong support and direct useful help.

References

Bjerknes, J. (1969): Atmospheric teleconnections from the equatorial Pacific. Mon. Weather Rev., **97**, 163–172.

Chen, L.T. *et al.* (1984) : Telecorrelation of pressure anomalies between eastern and western parts of the North Pacific. Sci. Bull., China, **8**, 481–483.

Enomoto, H. and Ohmura, A. (1991) : Fluctuations of sea ice extent in the Antarctic. Proc. NIPR Symp. Polar Meteorol. Glaciol., **4**, 58–73.

Gordon, A.L. (1979) : Seasonal change of Antarctic sea ice cover. Science, **187**, 346–347.

Gordon, A.L. (1981) : Seasonality of Southern Ocean sea ice. J. Geophys. Res., **86**, 193–197.

Lemke, P. *et al.* (1980) : Stochastic dynamic analysis of polar sea ice variability. J. Geophys. Ocean., **5**, 3–29.

Parkinson, C.L. (1992): Interannual variability of monthly southern ocean sea ice distributions. J. Geophys. Res., **97**, 5353–5363.

Parkinson, C.L. and Cavalieri, D.J. (1989) : Arctic sea ice, 1973–1987: Seasonal, regional and interannual variability. J. Geophys. Res., **94**, 14499–14523.

Parkinson, C.L. *et al.* (1987) : Arctic Sea Ice, 1973–1976 : Satellite Passive-Microwave Observations. Washington, D.C., NASA, 296 p. (NASA SP-480).

Ushio, S. and Wakatsuchi, M. (1990) : A laboratory study of heat flux through coastal polynyas during freezing-ice production. Ann. Glaciol., **14**, 298–300.

Van Loon, H. (1967) : The half-yearly oscillations in middle and high southern latitudes and the core-less winter. J. Atmos. Sci., **24**, 472–486.

Walker, E.T. and Bliss, E.W. (1932) : World weather V. Mem. R. Meteorol. Soc., **4**, 54–84.

Wallace, J.M. and Gutzler, K.S. (1981) : Teleconnections in the geopotential height field during northern hemisphere winter. Mon. Weather Rev., **109**, 784–812.

WALSH, J.E. and JOHNSON, C.M. (1979): Interannual atmospheric variability and associated fluctuations in the Arctic sea ice extent. J. Geophys. Res., **84**, 6915–6928.

WALSH, J.E. and SATER, J.E. (1981): Monthly and seasonal variability in the ocean-ice-atmosphere systems of the North Pacific and North Atlantic. J. Geophys. Res., **86**, 7425–7445.

ZWALLY, H.J., COMISO, J.C., PARKINSON, C.L., CAMPBELL, W.J., CARSEY, F.D. and GLOERSEN, P. (1983): Antarctic Sea Ice, 1973–1976: Satellite Passive-Microwave Observations. Washington, D.C., NASA, 206 p. (NASA SP-459).

(Received October 14, 1993; Revised manuscript received June 13, 1994)