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INTERACTION BETWEEN ANTARCTIC SEA ICE AND ENSO EVENTS

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Abstract: In this paper, the theory of the cross-coupled correlation-resonance of two wave spectra is used to study the interaction between Antarctic sea ice and ENSO events. It is found that: (1) The principal period of the correlation time series oscillation is usually coincident with the principal period of sea ice itself. If the same periods of two elements were in resonance, the correlation oscillation period would be more significant. (2) The sea ice of the Ross Sea area with its principal period of quasi-11 years has a strong cross correlation oscillation with SSTA of Niño 4. Their common period produces a resonance from 96 months leading to 36 months lagging causing a sine-shaped correlation variation with a strong positive SSTA from 87 to 50 months leading and a strong negative one from 20 months leading to 24 months lagging. (3) The same is true for the Weddell Sea ice and SSTA of the central-eastern equatorial Pacific but with a common period of quasi-5 years. ENSO events have a good correlation with sea ice in the eastern Antarctic in their later stage. The feedback of sea ice to SSTA in the western equatorial Pacific is also significant with a quasi-5 year period, but it is very weak to SSTA of the central-eastern equatorial Pacific. SST of the central equatorial Pacific has a quasi-contemporary oscillation relationship with Ross Sea ice and a 1.5 years lag oscillation relationship with Weddell Sea ice. We call this oscillation relationship between Antarctic sea ice and ENSO events, the Southern Oceanic Oscillation (SOO).

1. Introduction

The interaction between Antarctic sea ice and ENSO events is a component of interaction among atmosphere, ocean and sea ice. The latter is a very active research field in oceanography and meteorology, and also an important project of the World Climate Research Program. The interaction among sea ice-atmosphere-ocean is an important factor of climate change which directly affects the environment of mankind.

The world-wide climate anomaly in the 1980s', especially extensive, sustained drought, flooding and desertification has been paid considerable attention by scientists and governments. Therefore, within the "Tropical Ocean and Global Atmosphere" (TOGA) program lasting 10 years, it has been suggested to develop the study of sea-ice interaction.

As a vigorous heat source, the tropical ocean and its anomalous changes have a strong impact on global climate change. Similarly, as two vigorous heat sinks, the Polar ice-snow caps have a similarly important impact on global climate change. But due to the hard climatic environment in the two polar regions, it is difficult to obtain continuous, large-scale ice-snow observations of high quality. With the development of satellite and remote sensing techniques, especially the ESMR (Electrically Scanning Microwave Radiometer), Arctic and Antarctic sea ice observations, respectively, have become possible since 1972 and 1973. Using the albedo difference of sea water and sea ice, ESMR can observe and confirm sea ice under cloudy and polar night periods (ZWALLY *et al.*, 1983; PARKINSON *et al.*, 1987). Sea ice concentration can be calculated by brightness temperature. Time-spatial continuous sea ice data of high quality were first obtained in October 1978 by use of ESMR. This has promoted the advance of study of sea ice-atmosphere-ocean interaction.

GORDON (1975, 1981) studied the impact of the ocean on sea ice growth, and pointed out that in the Antarctic, heat flux from the ocean provides about 50% of the melting heat of sea ice; heat flux is dominated by instability of sea surface water, instability depends on salinity, and salinity of sea surface water is controlled by rainfall and evaporation. He also pointed out that Ekman divergence of the Antarctic sea surface water exists in the southern ocean causing much sea ice drifts to low latitude. This kind of drift promotes the expansion of the sea ice pack in winter.

CARLETON (1981a, b); VAN LOON (1967); and SCHWERDTFEGER and KACHELHOFFER. (1973), respectively, studied the relationship between the marginal sea ice zone and extra-tropical cyclone activity, and pointed out that cyclone activity is most frequently concentrated in the oceanic polar front (OPF) zone, with secondary concentrations in the marginal sea ice zone in some areas of the Pacific. Cyclone frequency tends to decrease from June to September with a tendency of cyclone tracks to shift toward high latitude; also, polynyas appear in the Weddell Sea corresponding to increasing of the number of cyclones.

With continuous accumulation of sea ice data, study of sea ice-atmosphere-ocean over a several years or longer time-scale and large spatial-scale becomes possible.

NIEBAUER (1980, 1988) analyzed interannual variations of Bering Sea ice. It was found that a good correlation exists in the cycle of low (high) sea surface temperature–sea ice increase (decrease)–low (high) air temperature–northerly (southerly) wind, and this relationship is related to ENSO events. Sea ice distribution in the eastern Bering Sea in winter is dominated by the Aleutian low pressure system which is in turn closely related to ENSO events. Therefore, an ENSO event becomes a key factor in sea ice variation.

HAO *et al.* (1990) analyzed the long-range (on several years scale) impact of Antarctic sea ice on ENSO, and pointed out that Weddell Sea ice 1–2 and 3–4 years before has a very strong negative-positive correlationship with ENSO events, SSTA in the eastern equatorial Pacific; and it is just opposite for impact on SSTA in the western equatorial Pacific and SOI. It is concluded that Antarctic sea ice is an important indicator for ENSO event occurrence. Ross Sea ice 0–1 year before has, respectively, a strong negative and positive correlation on SSTA in Region Niño 4 and SOI, sea ice 2.5–3 years before has a strong negative correlation to SSTA in Regions Niño 3; a strong negative correlation period also exists for sea ice 3–3.5 years before to SSTA in the western equatorial Pacific and SOI. The lag time from the western to eastern equatorial Pacific is half a year, *i.e.*, Ross Sea ice first affects the western equatorial Pacific and SOI, then gradually expands to the eastern equatorial Pacific a half year later.

In this paper, the interaction between Antarctic sea ice and ENSO events is surveyed over an increasing time-scale to investigate the impact of polar sea ice on ENSO events, as well as the impact of ENSO on sea ice. We attempted to find key correlation periods of their interaction and how they vary, and then to understand the physical mechanism of interaction.

2. Data and Analysis Methods

In this paper, the sea ice data used are the SIGRID data in 1973–1989 provided by WDC-A. The net sea ice area index anomaly (subtracting open water area in the ice region) is calculated for four Antarctic ice regions (Fig. 1)

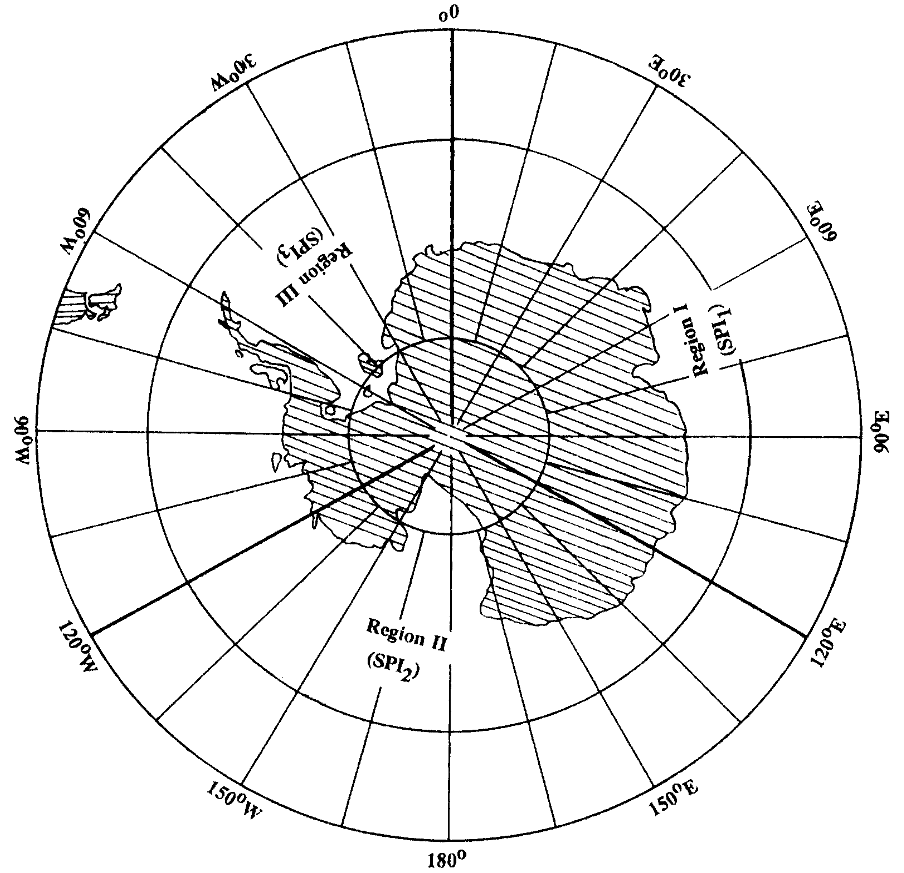

Fig. 1. The division of the Antarctic sea ice.
Region I (SPI1) (0°-120°E): Eastern Antarctic sea ice area. Region II (SPI2) (120°E-120°W): Ross Sea ice area. Region III (SPI3) (120°W-0°): Weddell Sea ice area. Region IV (SPI4): whole Antarctic sea ice area.

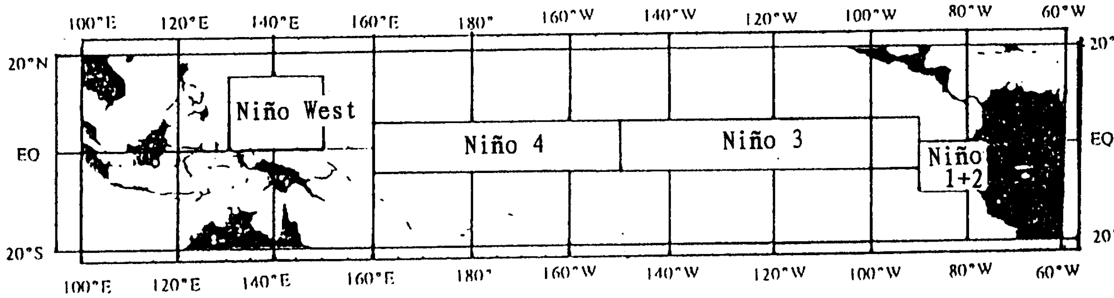

Fig. 2. The four Niño regions in the tropical Pacific.

using the calculation method described by Xie *et al.* (1991).

An ENSO event consists of five elements: SSTA in Regions Niño 3, 4 and Niño West (Fig. 2) and the SOI (southern oscillation index) in 1966–1992. Data are taken from the Monthly Report on Climate System, Japan Meteorological Agency.

Time series of monthly cross correlation coefficients between five elements of ENSO event from 8 years leading to 5 years lag to sea ice of four Antarctic Regions are calculated.

3. Interaction of Antarctic Sea Ice and ENSO Events

First, using the maximum entropy spectrum method, the variation periods of net sea ice area index of four Antarctic sea ice Regions and five elements of ENSO events were calculated, as shown in Tables 1 and 2.

Figure 3 is a month by month time series chart of the cross-coupled correlation coefficient over 168 months from ENSO event 8 years leading to 6 years lagging the Region I (the eastern Antarctic) sea ice . During this correlation process, the sample length is fixed as 156 months. Its significance level is

Table 1. Variation periods (month) of net ice area index anomaly in four Antarctic sea ice regions (Xie et al., 1991).

Region	Principal period	Sub-period			
		First	Second	Third	Fourth
I	58.3	18.5	12.8	10.0	6.9
II	132				
III	68	15.1	10.5		
IV	204	18.5	12.4	10.0	

Region I (0°–120°E): eastern Antarctic connected with Indian Ocean.
Region II (120°E–120°W): centered at Ross Sea connected with Pacific Ocean.
Region III (120°W–0°): centered at Weddell Sea connected with eastern Pacific and South Atlantic Ocean.
Region IV (0°–180°–0°): the whole Antarctic sea ice area.

*Table 2. Variation periods SSTA of five ENSO elements, SSTA in Regions Niño 1+2, 3, 4 and Niño West and SOI (*Xie* et al., 1991).*

Region	Principal period	Sub-period					
		First	Second	Third	Fourth	Fifth	Sixth
Niño 1+2	42.8	75.7	25.2	17.2			
Niño 3	49.4	25.4	19.5				
Niño 4	48.0	13.4	29.2				
Niño West	93.6	44.6	24.0	15.1	12.6	10.6	9.1
SOI	57.8	196.8	28.9	18.9	15.6		

Niño 1+2 (75° -90°W, 0°-10°S), Niño 3 (150°W-90°W, 5°N-5°S), Niño 4 (150°W-180°-160°E, 5°N-5°S), Niño West (130°E-150°E, 0°-15°N).

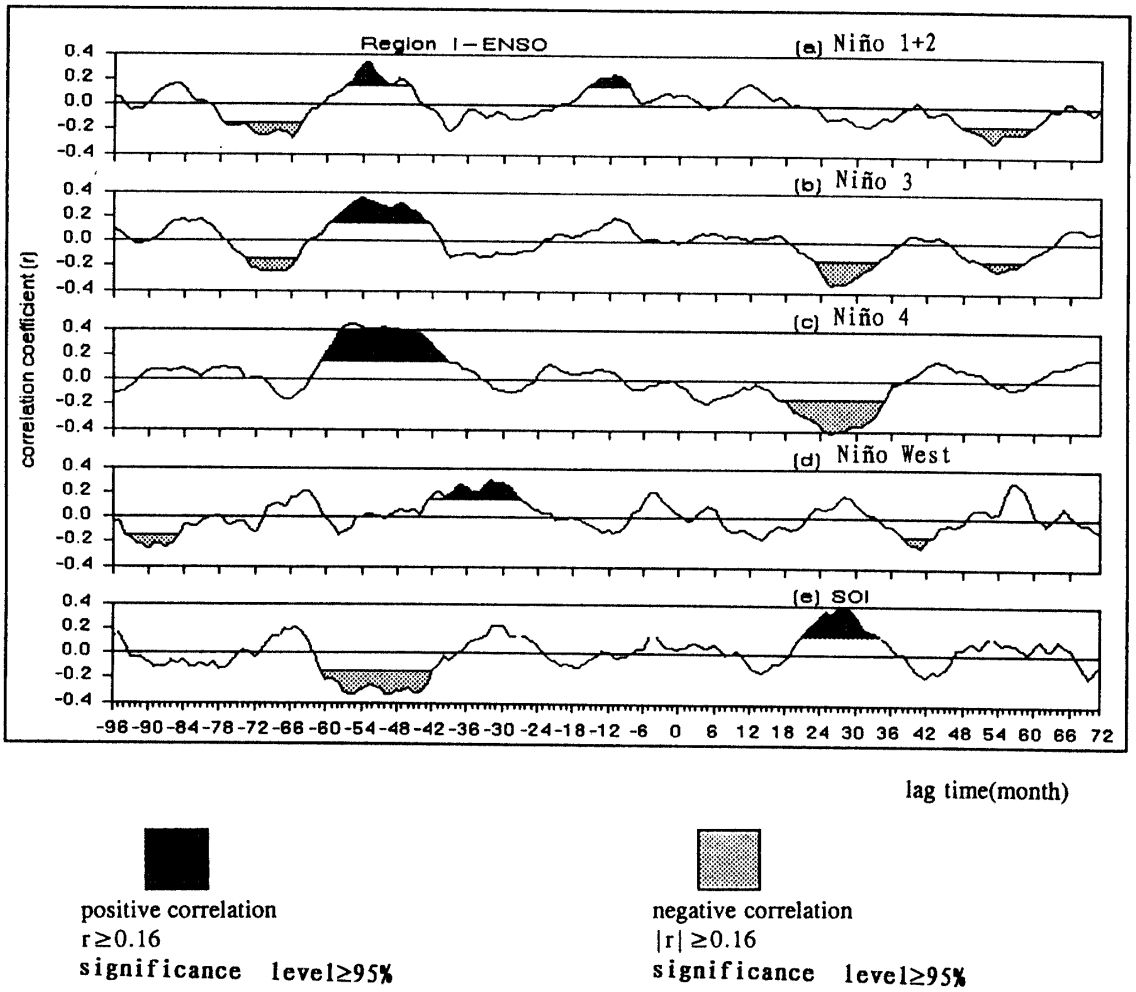

Fig. 3. The cross correlation time series chart between sea ice in Region I and ENSO events. An ENSO event consists of five elements: SSTA in regions of Niño 1+2, 3, 4, and Niño West, and SOI. The abscissa is the number of months by which an ENSO event leads (−) or lags (+) sea ice over a total period of 14 years (168 months) from −8 years (96 months) to +6 years (72 months). Region I is the eastern Antarctic (0°–120°E). Niño 1+2 (90°W–75°W, 0°–10°S); Niño 3 (150°W–90°W, 5°N–5°S); Niño 4 (160°E–150°W, 5°N–5°S); Niño West (130°E–150°E, 0°–15°N).

≥95% when the correlation coefficient is ≥0.16. For Niño 1+2 Region (Fig. 3a), during the 3 years or 80–44 months of SSTA leading, and from −44 to +6 months, the correlation coefficient changes with a cosine-shaped oscillation period. The best negative period is 74–60 months of SSTA leading the sea ice. The best positive period is 56–44 months leading.

The characteristics of the cross correlation time series between SSTA in Niño 3 and sea ice in Region I (Fig. 3b) is almost the same as in Fig. 3a .

In Fig. 3c, the maximum correlation coefficient period of cross correlation between SSTA in Niño4 and sea ice in Region I is 100 months from SSTA 63 months leading to 37 months lagging the sea ice. The periodic variation is sinusoidal positive in the first half and negative in the second half. The best positive correlation period is in SSTA of Niño 4 in 60–36 months leading while the best negative is 18–30 months lag. The best correlation periods of 100 months is the couple cross period caused by superimposition- resonance of the first sub-period (134 months) of SSTA of Niño 4 and the principal period (58 months) in Region I sea ice.

Figure 3d shows the cross correlation time series between SSTA in Niño West and sea ice in Region I. When SSTA is leading, although the correlation changes periodically, the correlation intensity is rather weak and the variation period is short, basically quasi-4–5 years. The best positive correlation appears in SSTA 42–26 months leading, this time scale is roughly the same as that of the western equatorial Pacific SSTA (44 months).

Figure 3e shows the cross correlation time series of the southern oscillation index and sea ice in the eastern Antarctic. the SOI is a characteristic element of the atmospheric circulation. The SOI is basically opposite in phase to the SSTA in Niño 1+2, 3, 4 while it is basically in the same phase as the SSTA in Niño West. The regularity of periodic change is more obvious with a period of about 30 months. The best negative correlation period is in SOI in 60–42 months leading while the best positive is 24–34 months lag. This means that the SOI 4–5 years leading has a strong negative feedback to the eastern Antarctic sea ice in a later stage while eastern Antarctic sea ice 2–3 years leading has a positive feedback on SOI in a later stage.

From Fig. 3, when SSTA variation in the eastern-central equatorial Pacific (Niño 1+2~4) is leading the sea ice, its positive correlation is stronger than that during the lagging period. This means that SST variation in the eastern-central equatorial Pacific very closely relates to sea ice in the eastern Antarctic in a later stage. The negative correlation is strong.

Figure 4 is a chart of cross correlation time series between sea ice in Region II and ENSO event.

The development states in Fig. 4a and 4b are similar. The variation period is mainly quasi-4 years with only one weaker positive correlation in 36 to 28 months leading SSTA of Niño 1+2 and Niño 3 and a stronger negative one during +27~+40 months lag.

Figure 4c is the cross correlation between sea ice in the Ross Sea area and SSTA of Niño 4. The variation characteristic is very simple and striking. It is a

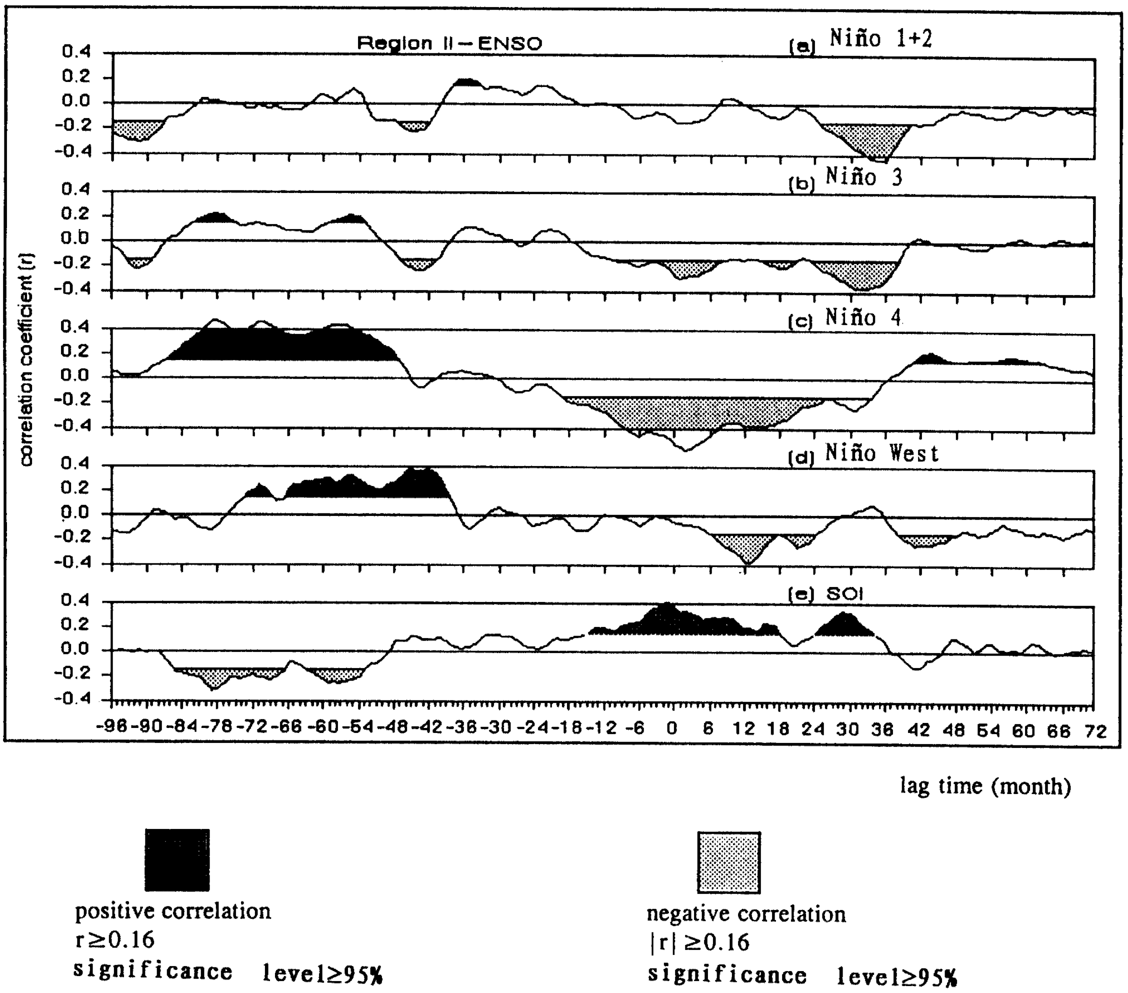

Fig. 4. Same as Fig. 3 but for Region II (120°E–180°–120°W) is the Antarctic sea area including the Ross Sea and the adjacent South Pacific Ocean.

strong correlation oscillation period of 11 years from SSTA of 96 months leading to 36 months lag with a sinusoidal variation. This period is just the principal period (132 months) of sea ice in the Ross Sea area, and is also the first sub-period (134 months) of SSTA of Niño 4. Both have the same scale of oscillation period and the resonance in −96~+36 months of phase difference introduces a periodic variation of strong correlation. The best positive correlation is observed in SSTA of 87–48 months leading with correlation significant level of 99%. This strong positive correlation lasts for 39 months, or more than 3 years. This means that when the central equatorial Pacific SST is anomalously high/low, Antarctic Ross Sea ice will be anomalously more/less in an extra long-range lag of 87–48 months. Based on this calculation, in the strongest El Niño event in 1982–1983, SST in Niño 4 was very high in April 1982–June 1983; then there should be a period of more ice in the Ross Sea area during 1987–1989. Actually this is true: Ross Sea ice decreased to a minimum in 1986, began to increase in 1987, and there was a period of more ice during 1988–1989 (Xie *et al.*, 1991). The best negative correlation with a significanve level over 99% appears during

−18 to +24 months, lasting for 3.5 years. This shows that Ross Sea ice has strong negative feedback on SST of the central equatorial Pacific to its north side in a later stage.

Figure 4d is a cross correlation time series between SSTA in the western equatorial Pacific (Niño West) and the sea ice in Region II. The outstanding feature is that the correlation is positive while SSTA is leading and negative while lagging, thus there forms a long periodic sinusoidal variation.

The best positive period is during −72~−36 months, which is the first sub-period of quasi-4 years of SSTA in Niño West superimposing on the long-periodic principal peak. The best negative periods are during +6~+24 and +38~+48 months which coincide with sub-periods of quasi-1, 2, and 4 years of SSTA and sea ice, also superimposing on the principal period to form this strong oscillation.

Figure 4e is the cross correlation time series between the southern oscillation index (SOI) and sea ice in the Ross Sea (Region II). The positive correlation during −12~36 months is much stronger than the negative one during −82~−52 months before, and there is a short-periodic oscillation with the two best positive correlation periods of SOI lagging −12~+12, and 20–32 months and the two best negative correlation periods of SOI leading 85–66 and 62–54 months.

Figure 5 shows the cross correlation time series between sea ice in Region III and ENSO events. SSTA in Niño 1+2 has two cosine-shaped correlation periods leading sea ice from −48 to −1 month and lagging sea ice from −1 to +60 months (Fig. 5a). The period lengths are 47 and 61 months respectively. This shows that when SSTA in Niño 1+2 is 43 months (the principal period of itself) leading sea ice, both periods resonate to cause a correlation oscillation period of 47 months. SSTA in Niño 1+2 plays a leading role to affect the sea ice variation in the Weddell Sea area. When SSTA lags sea ice, the principal period of sea ice (68 months) affects SSTA to cause a strong positive-negative correlationship and a periodic variation (Fig. 5a).

Figure 5b gives the relation of sea ice in Region III and SSTA of Niño 3 with a similar variation characteristic to Fig. 5a. This may be due to the similar period of SSTA variation in Niño 1+2 and Niño 3. The common feature of Fig. 5 a–b is that both SSTA of Niño 1+2 and Niño 3 have a strong positive correlation period lagging sea ice by 3–4 years. This means that there is strong positive feedback of Weddell Sea ice on SST of the eastern equatorial Pacific in a later stage.

In Fig. 5c, the correlation period of sea ice of Region III 54 months leading to 24 months lagging SSTA in Niño 4 which is almost synchronous to the variation period in Fig. 5a and 5b but with very significant positive and negative correlations. The variation period is quasi-5 years, during −26~36 months approaching the principal period of 68 months in the Weddell Sea ice and of 48 months in the Niño 4 SSTA. When two principal periods become close, resonance is observed at the half period of phase difference, causing a strong correlation. There are two best positive correlation periods for SSTA, −24~−2 and +38~+48 months, while the best negative is in SSTA, 2–34 months lag.

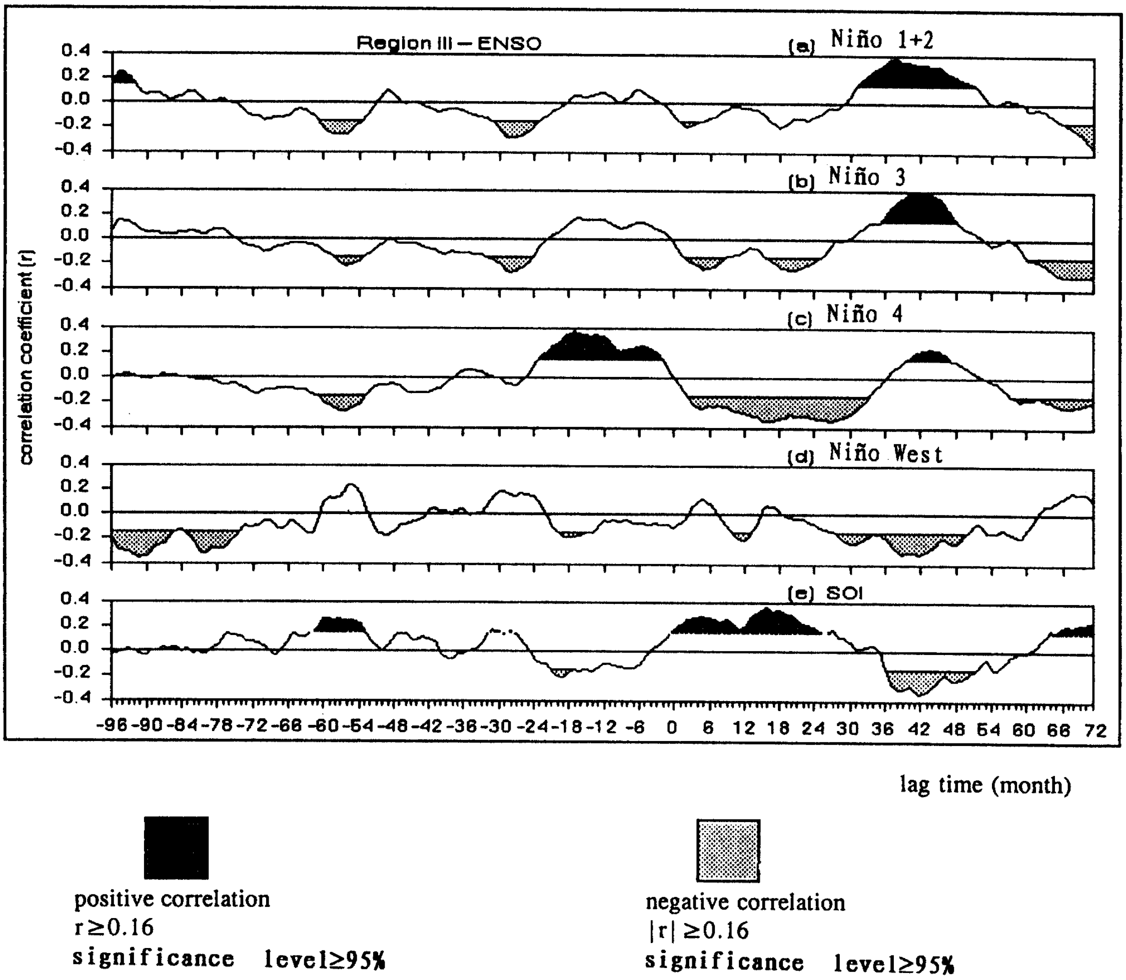

Fig. 5. Same as Fig. 3 but for Region III (120°W–0°) is the Antarctic sea area including the Weddell Sea and the adjacent eastern South Pacific and South Atlantic.

Both are very strong with the significance level much more than 99%.

This shows that SST of the central equatorial Pacific from 2 years before to 2 months lag has a very strong positive feedback on the Weddell Sea ice. The Weddell Sea ice during 3-half years before also has a very strong negative feedback on the SST of the central equatorial Pacific.

Figure 5d shows that SSTA in Niño West and sea ice in the Weddell Sea also have a periodic correlation change, but very weak, excepting a rather strong negative correlation for SSTA with 28–50 months lag. This negative correlation period is opposite to the positive periods in the same time in Fig. 5a–c. This is because SSTA in the western equatorial Pacific is opposite to SSTA in the eastern equatorial Pacific.

The cross correlation between SOI and sea ice in the Weddell Sea (Fig. 5e) has a negative correlation with roughly the same period but with a phase difference of half a period to Fig. 5a–c. There are two cosine-shaped significant periods for SOI, −60∼−2 and −2∼+60 months. Another strong negative period also appears in SSTA, −96∼−74 months before.

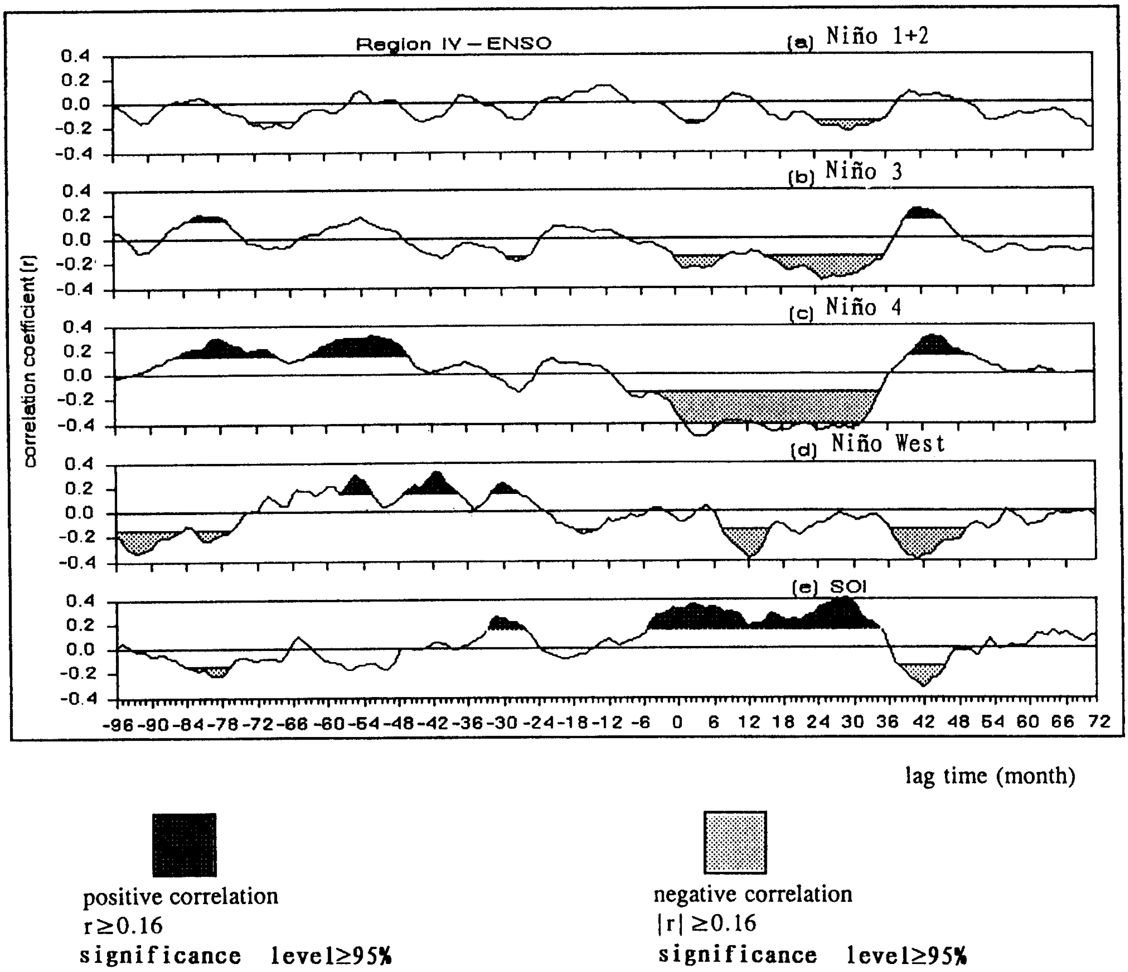

Fig. 6. Same as Fig. 3 but for Region IV (the whole Antarctic).

Figure 6 is the cross correlation time series between sea ice in the whole Antarctic and five ENSO elements. This chart basically reflects, but is weaker than the characteristics in Fig. 3–5.

Figure 7 shows the time series change of the SSTA of the central equatorial Pacific and net sea ice area index anomaly in Region II and III for the strongest correlation time periods selected from Fig. 5 and Fig. 6.

It can be seen from Fig. 7b that SSTA of the central equatorial Pacific (Niño 4) has a quasi-contemporary (2 month lag) strong negative correlation with sea ice of the Ross Sea (Region II) to its south side. That is to say, there exists a quasi-contemporary oscillation relationship, the "seesaw" phenomenon between SSTA and the sea ice area index. In Fig. 7d, there appears an oscillation relationship of SSTA of Niño 4 in 17 months lag, behind sea ice in the Weddell Sea. Niño 4 and the Weddell Sea lay the two ends of the Atlantic Ocean. Therefore, about one and a half years after more/less sea ice in the Weddell Sea, SST of the central equatorial Pacific is low/high; and another one month later, the sea ice of the Ross Sea is, correspondingly, more/less.

In Fig. 7a, SSTA of the central equatorial Pacific has a strong positive

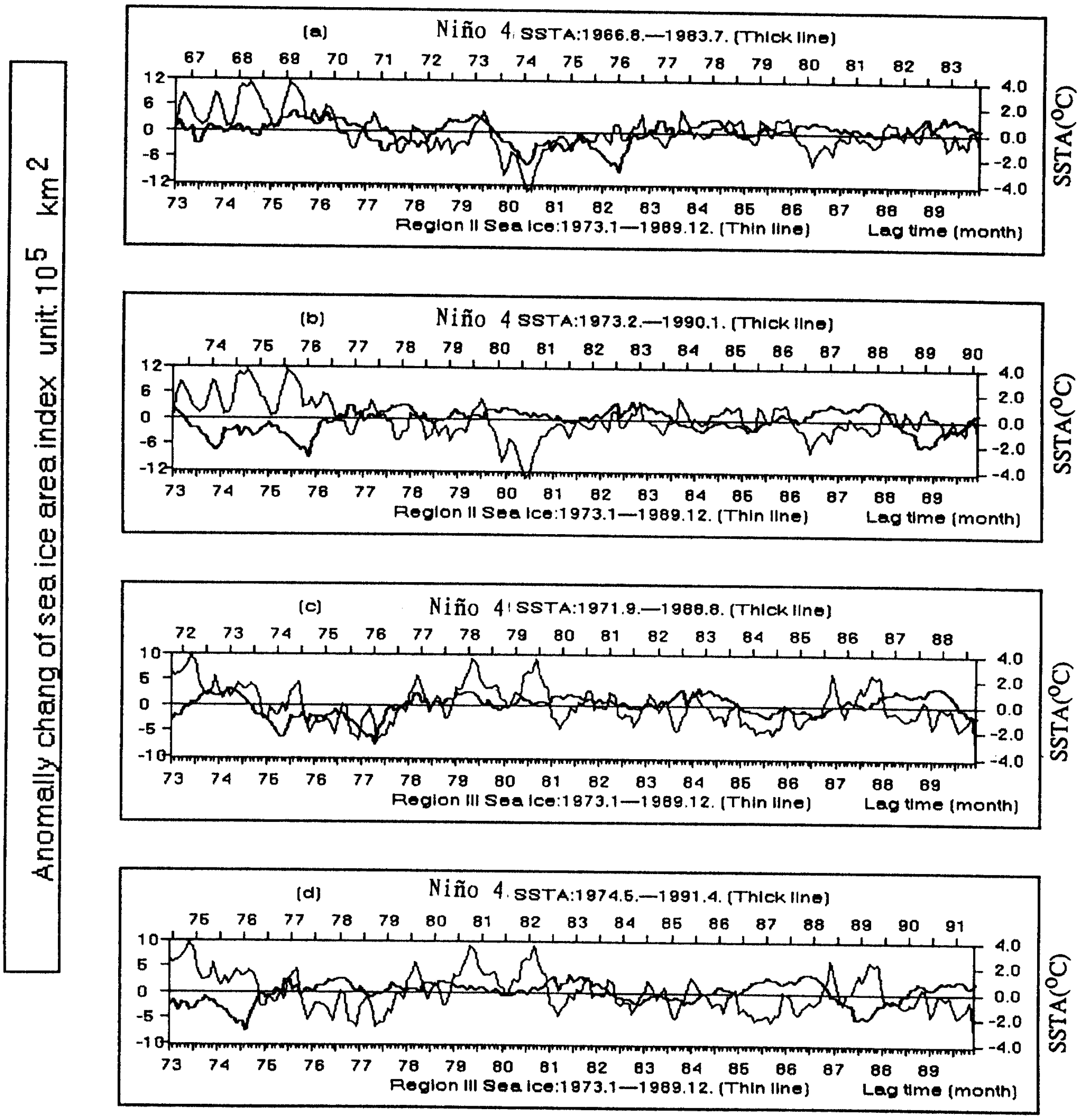

Fig. 7. *The time series of SSTA change in the central equatorial Pacific (Niño 4) and net sea ice area index anomaly (NSIAIA) of the Ross Sea (Region II) and the Weddell Sea (Region III) during corresponding strong positive and negative correlation periods.*

a) SSTA in Niño 4 in 78 months leads NSIAIA in Region II.
SSTA: Aug. 1966–July 1983; NSIAIA: Jan. 1973–Dec. 1989.

b) SSTA in Niño 4 in 2 months leads NSIAIA in Region II.
SSTA: Feb. 1973–Jan. 1990; NSIAIA: Jan. 1973–Dec. 1989.

c) SSTA in Niño 4 in 17 months leads NSIAIA in Region III.
SSTA: Sept. 1971–Aug. 1988; NSIAIA: Jan. 1973–Dec. 1989.

d) SSTA in Niño 4 in 17 months lags NSIAIA in Region III.
SSTA: May 1974–Apr. 1991; NSIAIA: Jan. 1973–Dec. 1989.

feedback on sea ice of Region II with 78 months lag and another strong positive feedback on sea ice of the Region III with 17 months lag. This means that the SST variation of the central equatorial Pacific plays a very important role in sea ice change in two big ice producing fields of the Antarctic, the Ross Sea and the Weddell Sea.

4. Discussion

Like the meteorological elements, the oceanic elements vary periodically, and the time change series of every element results from superimposition of different periods of various scales. Using the spectrum method, make it possible to distinguish the main periodic changes. One of the aims in this paper is to investigate whether the correlation between two elements relates to their own change period, and how they interact and affect each other. The analysis gives a partial answer to the first problem. The regularity of variation relationships is of value in studying their interaction and long-range forecasting. Now, we discuss the cross correlation between SST of the central equatorial Pacific and sea ice in Regions II and III.

Figure 8 is the mathematical-physical mechanism chart of the relationships between sea ice in the Ross Sea and SSTA of Niño 4. The most outstanding feature is the significant long-period variation with the period length of 132 months, which is the same as those of 132 months of sea ice and 134 months of SSTA. When two oceanic elements have the same variation period, their cross correlation should be resonant and produce a variation period on the same time scale, but the best correlation period depends upon the phase difference. In Fig. 8, strong resonance appears in SSTA at 96–36 months, leading the sea ice with a sine curve of strong positive correlation in the early stage, −87~−48 months, and strong negative period in the late stage, −24~30 months.

The best negative correlation period during −18~+22 months of SSTA of Niño 4 lags the Ross Sea ice (120°E–120°W) as long as 3.5 years. The maximum correlation coefficient of −0.58 appears in SSTA after 2 months lag with a significance level >99.99% (in a sample length of 156). That is to say, SST of the central equatorial Pacific has a strong negative oscillation relationship at the same time and from 1.5 years before to 2 years lag behind the sea ice in the Pacific seactor of the Antarctic. This kind of strong "seesaw" phenomenon is comparable to the southern oscillation both in intensity and duration. In short, a zonal atmospheric oscillation exists over the tropical South Pacific; moreover, in the meridional direction, a strong oceanic oscillation phenomenon, correspondingly, exists between both sides of the South Pacific-the central equatorial Pacific and the Ross Sea regions. This is called the South Pacific oceanic oscillation, or Southern Oceanic Oscillation (SOO).

Corresponding to this strong negative correlation, a strong positive correlation period lasts as long as 4 years for SSTA from −87 to −48 months leading Antarctic sea ice. The maximum correlation of +0.46 with significant level >99.99% appears in −78 months. This means that the central equatorial Pacific 6.5 years prior has a strong positive feedback on sea ice of the Antarctic Pacific (120°E–120°W) in a later stage; *i.e.*, 6.5 years after SST of the equatorial central Pacific is anomalously high/low, sea ice of the Antarctic Ross Sea Region (120°E–120°W) is anomalously more/less. This plays a controlling and dominating role on a long time scale. Conversely, SST in 2 months later, is given a strong negative feedback by sea ice.

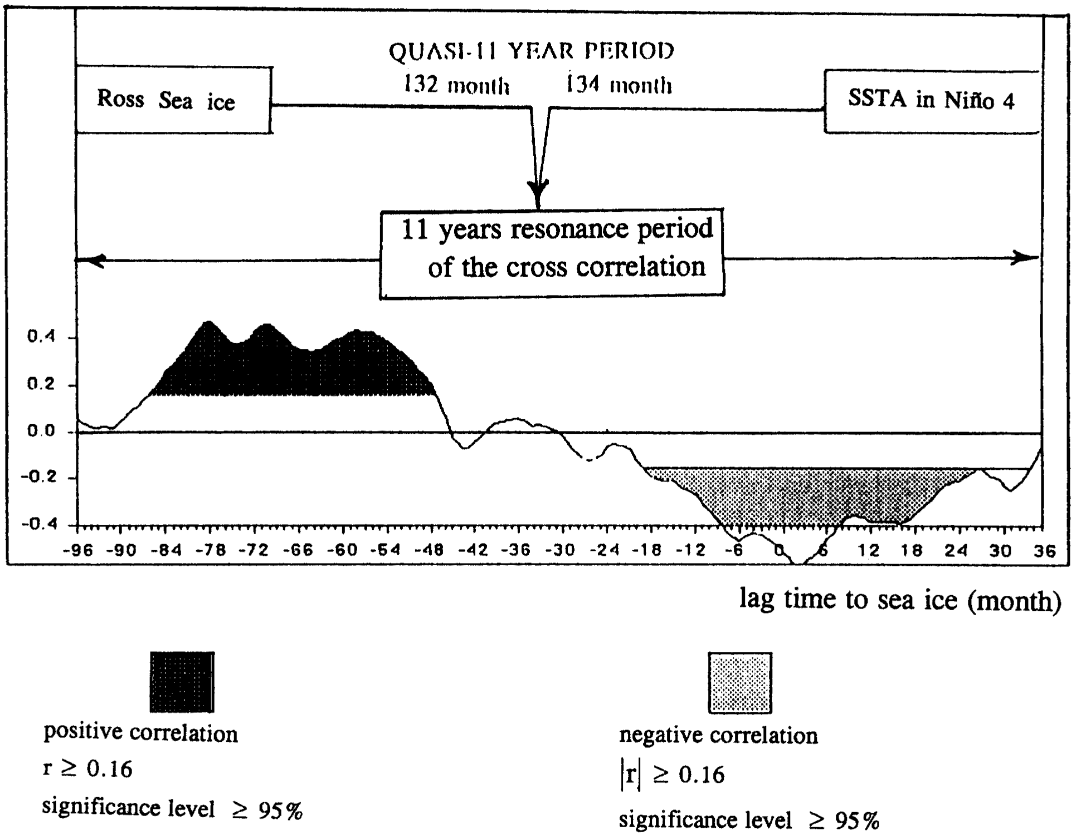

Fig. 8. The mechanism model chart of cross correlation time series between SSTA in Niño 4 and sea ice in the Ross sea area (120°E–120°W). The abscissa is number of months by which a SSTA leads (−) or lags (+) sea ice.

As mentioned above, the cycle period of this kind of strong positive-negative feedback interaction is quasi-11 years. Because both principal periods of SSTA of the central equatorial Pacific and the Ross Sea ice are quasi-11 years too, once these two waves with same oscillation period resonate, naturally, a very strong vibration should occur. The phase difference of this resonance is SST lagging by from −96 to +36 months. This kind of physical mechanism must also be related to the thermal effect of solar radiation because the period of solar sunspot activity is also quasi-11 years. The equatorial Pacific absorbs much more solar radiation heat due to large heat capacity while polar sea ice directly absorbs much less solar radiation heat due to its large albedo. Therefore, a long time, 6–7 years, is necessary for the process since the equatorial Pacific is heated and affects the Antarctic Ross Sea ice through the surface current and heat transmission from intermediate and bottom water. Moreover, a strong oscillation relationship—"seesaw" phenomenon— occurs for SST from −17 before to 24 months lag. The physical mechanism of this interaction between SST of the equatorial Pacific and Antarctic sea ice is left for further study.

Only the interaction between SST of Niño 4 and the Ross Sea ice is analyzed here. Actually, both SSTA of Niño 3 and Niño West have similar sinusoidal (cosine for SOI) correlation series of quasi-11 years period with sea ice of the Ross Sea region (Fig. 4b and 4d). The regions of Niño 3, Niño 4 and Niño West stride almost the same longitude span of the Ross Sea region (120°E–120°W). It can be concluded that, SST of the equatorial Pacific not only has a contemporary oscillation relationship with, but also 6–7 years before gives a strong positive feedback effect on Antarctic Ross Sea ice. Therefore, the anomalously high/low SST of the equatorial Pacific, *i.e.*, El Niño/La Nina event occurrence 6–7 years in advance, can be used to predict anomalously more/less sea ice in the Antarctic Ross Sea region. In addition, whether both will be anomalous can also be predicted by an ENSO event from −17 before to +24 months lag.

Figure 9 is a schematic mathematical-physical model of cross correlation time series between the Weddell Sea ice and SSTA in Niño 4. The principal period of their cross correlation series is 62 months (−26~+36 months), basically reflecting the principal period of 68 months, quasi-5 years of the Weddell Sea ice. The time series is sinusoidal, positive in the early stage (−24~0 months) and negative in the late stage (2–36 months). The best positive and negative periods appear at −24~−3 and 2~+30 months, which is the common sub-period of quasi-2 years

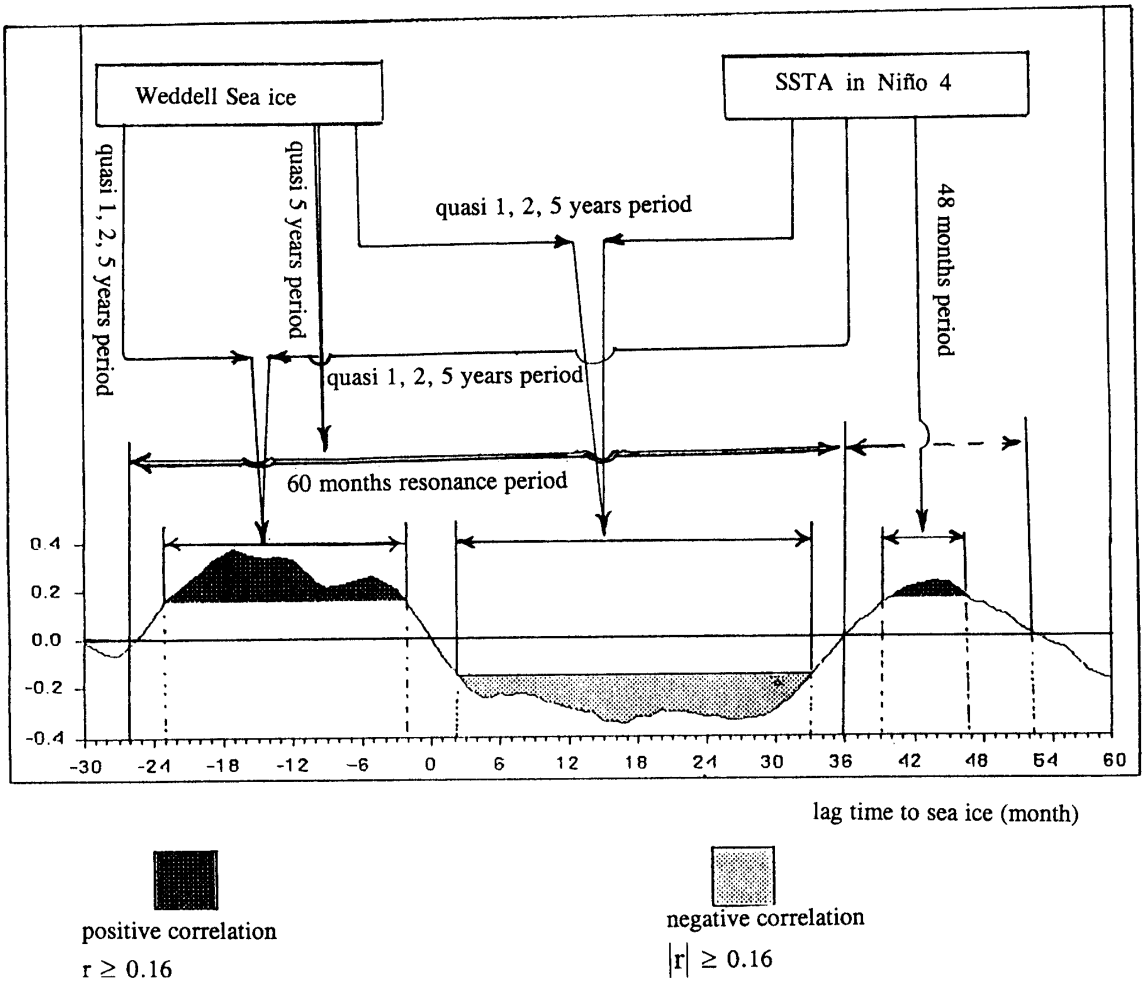

Fig. 9. Same as Fig. 8 but for Weddell sea area (120°W–0°).

of both SSTA of Niño 4 and sea ice in Region III. The maximum positive correlation value of 0.37 is in SSTA, 17 months leading, with significance level ≥99.9%, while the maximum negative of −0.36 in SSTA is 17 months lag with significance level ≥99.9%.

The second positive period is in SSTA, +36~+54 months lag, which is the principal period of 48 months of SSTA of Niño 4 variation.

The above representative case analysis shows that, variation of cross correlation time series between the Antarctic sea ice and ENSO events relates to the oscillation periods of both elements. When two principal periods are the same or similar, a strong resonance and significant periodic variation happen only in the proper phase difference (lag time scale). The time scale of the principal period is roughly the same as the principal periods of the primitive elements. Most of the strong positive and negative correlation periods usually appear when the corresponding sub-periods are superimposed upon the principal period. Wave resonance theory can easily explain mechanism of long-range interaction between oceanic and atmospheric elements.

5. Conclusions

(1) The interrelation between sea ice in the Ross Sea area and ENSO events is very close. The strong correlation periods of both ENSO leading or lagging sea ice are significant. This means that the positive and negative feedbacks are equal.

(2) The principal oscillation period of quasi-11 years of the cross couple correlation series between sea ice in the Ross Sea area and SSTA of Niño 4 plays a critical role relating to the common significant quasi-11 year periodic variation of both sea ice and SSTA, especially the Ross Sea ice. The best positive and negative correlation periods appear, respectively, in SSTA, −87~−48 and −18~24 months leading. The best positive and negative correlations, respectively, appear in SSTA, 78 months leading, with correlation of 0.46 and 2 months lag with correlation of −0.58. There is an oscillation relationship between both ends of the South Pacific, the equatorial Pacific and the Antarctic sea ice.

(3) As a main feature, the variation period of cross-coupled correlation between the Weddell Sea ice and ENSO events is quasi-5 years. This is closely related to the significant principal period of 68 months of the Weddell Sea area itself. Thus, the principal period of sea ice plays a controlling role. The relationship of SSTA in Niño 4 and sea ice is extremely good. The best positive and negative periods are, respectively, in SSTA, −22~0 months leading with maximum at −17 months leading, and 0~+32 months, with the maximum at +17 months lag.

(4) Both SSTA in the western equatorial Pacific and the southern oscillation index have very weak correlation with the Weddell Sea ice, but significantly lags sea ice. This shows that the Weddell Sea ice plays a leading and controlling role on SST in Niño West and SOI.

(5) The anomalous SST variation of the central equatorial Pacific (Niño 4)

plays an important leading role leads the Ross Sea ice by 6.5 years, and leads the Weddell Sea by quasi-1.5 years, so that SST in Niño 4 plays an important leading role affecting sea ice.

(6) SST of the central equatorial Pacific has an oscillation relationship (the "seesaw" phenomenon) with sea ice in the Ross Sea to its south that is quasi-contemporary, and with sea ice in the Weddell Sea at the southern end of the Atlantic Ocean with quasi-1.5 years lag. This is an oscillation relationship between the Antarctic sea ice and ENSO events, and is called the Southern Oceanic Oscillation (SOO).

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