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Antarctic sea ice: variability and trends from 1978 to 2006

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ABSTRACT

Sea ice plays an important role on Earth's climate. Besides its high albedo, sea ice isolates ocean from atmosphere and also plays an important role in deep water formation through brine rejection. Earth's recent climate changes may be affecting significantly these processes. In this work, we analyzed the variability of sea ice concentration around the Antarctic continent using SMMR and SSMI data for the 1978-2006 period. We investigated the annual trends by linear regression at 95% confidence level. Then, we used the Empirical Orthogonal Functions (EOF) technique to decompose the sea ice cover signal into independent modes of variability. We found a negative annual linear trend around the tip of the west Antarctic Peninsula and in the Bellingshausen/Amundsen Seas over the 32 years period. In the vicinities of the Ross Sea, a positive trend was observed. These results confirm recent trends observed by other studies in Antarctica. Seasonal variability dominated the sea ice over the period as expected. The seasonal-removed sea ice variability has shown the dominance of a 3-4 year period signal. We conclude this to be due to El Niño Southern Oscillation (ENSO) and Southern Annular Mode (SAM) forcing, and intrusion of relatively warmer water into the Bellingshausen/Amundsen Seas. Sea ice cover around Antarctica is a complex matter but as the time series become longer, the non-linearity of many physical processes can be accessed in the future.

Key words: climate change, West Antarctic Peninsula, SMMR, SSM/I.

INTRODUCTION

Sea ice plays an important role on the Earth's climate patterns and variability. Besides its high albedo, which returns the most part of the incoming solar radiation back to space, sea ice reduces both the heat (e.g., Strass and Fahrbach 1998) and carbon dioxide (Stephens and Keeling 2000) transfer between ocean and atmosphere. Sea ice cover plays also an important role on deep water formation because when sea water freezes, it releases salt to the water column through brine rejection (e.g., Spreen et al. 2007).

However, these processes that involve or depend on sea ice can be altered in case of a significant change in its cover. The scientific community concern has grown in the last years since decreasing in sea ice cover is considered an early indicator of global warming (Bjørgo et al. 1997).

Sea Ice studies in the Arctic and Antarctic regions have began in the 70s, when passive microwave sensors were available for monitoring the polar regions. Both the Scanning Multichannel Microwave Radiometer (SMMR) and the Special Sensor Microwave Imager (SSMI) are the most used sensors in polar regions and their data are available since 1978. Several studies have found that sea ice field co-varies linearly with ENSO signal (e.g., Simmonds and Jacka 1995; White and Peterson 1996; Yuan and Martinson 2000; Kwork and Comiso 2002).

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ENSO effects on Antarctic sea ice were detailed by Yuan (2004). Briefly, the sea surface temperature rise on the tropical Pacific causes an increase on the atmospheric convection with consequences on large scale atmospheric circulation. This change leads to an increased (diminished) heat transport to the South Pacific (South Atlantic) polar region on the lowest atmosphere levels. Then, warm (cold) air is brought to Bellingshausen Sea (Weddell Sea). This pattern is the so-called "Antarctic Dipole" (ADP), which influences considerably the observed inter-annual Antarctic sea ice field (Yuan and Li 2008).

Another important mode of variability of the southern hemisphere is the Southern Annular Mode (SAM), which can be defined either as the first principal component of the geopotential high (associated with atmospheric pressure) anomalies at 850hPa, poleward of 20°S (Thompson and Wallace 2000) or as the first EOF of sea level pressure field (Hall and Visbeck 2002). Due to the existence of a low pressure anomaly in the Bellingshausen/Amundsen sector on positive SAM years, the Weddell and Bellingshausen Seas receive predominantly northern winds. Sea ice is compacted on the west coast of Antarctic Peninsula due to Ekman transport, resulting on decreased sea ice extension. On the other hand, the Ross Sea has enhanced southern winds, which causes a sea surface cooling and an increase in the area covered by sea ice (Lefebvre et al. 2004).

On intra-annual scales, the Semi-Annual Oscillation (SAO) stands out on Antarctic pressure field variability. SAO consists of a contraction and expansion of the Circumpolar Pressure Trough (CPT) that occurs twice a year (van den Broeke 2000d). This is due the difference on the energy capture between Antarctica and its oceanic surroundings (van Loon 1967; Meehl 1991). During its maximum contraction (March and September), the CPT low pressure areas migrate to southeast over Amundsen Sea up to the west Antarctic coastline. On the expansion phases (April-July and October-January), this area migrates to northwest (van den Broeke 2000d).

Several works (e.g., Enomoto and Ohmura 1990; van den Broeke 2000d; Watkins and Simmonds 1999) have associated SAO phenomenon with variations on sea ice field. Van den Broeke (2000d) found a positive coupling between SAO amplitude and sea ice extent on Bellingshausen/Amundsen Seas in the winter. Enomoto and Ohmura (1990) pointed out that sea ice areas present fast reduction from spring to early summer, while it shows a slower expansion from fall to winter. Zwally et al. (1983a) considered this fast reduction as a result of, among other things, an increase on sea ice divergence. The air temperature meridional gradient between medium latitudes and Polar Regions becomes larger in the spring and fall. This gradient causes a high cyclonic activity and diminishes sea level pressure on these seasons around Antarctica, which consequently changes wind fields distribution and, than, sea ice field (Enomoto and Ohmura 1990).

Regarding the sea ice extension studies, Parkinson and Cavalieri (2008) have shown that the Arctic's perennial sea ice cover diminished on a rate of $45.1 \pm 4.6 \times 10^3$ km^2/year between 1979 and 2006, while the Antarctic sea ice cover suffered an increase of $11.5 \pm 4.6 \times 10^3$ km^2/year (Cavalieri and Parkinson 2008). Only a few studies have been conducted in the spatial variation of sea ice patterns. Therefore, the present study is focused in filling this gap in the literature.

DATA AND METHODS

Sea ice concentration data was obtained from the National Snow and Ice Data Center (NSIDC), using the Bootstrap algorithm (Comiso 1995). We used monthly mean images from November 1978 to December 2006. Until August 1987, the data were recorded by the SMMR and since then by the SMMI. The images have spatial resolution of 25 km on the stereographic polar projection. There was only one gap (December 1987 to January 1988) in the monthly time series images and it was filled using linear interpolation. In order to deter-

mine the annual linear trend, we used the 1979-2006 period. The annual linear trend was found by fitting a linear regression between sea ice concentration extension and time. Equation (1)

$$y = at + b \quad (1)$$

states that sea ice concentration (y) is dependent on time (t). The coefficients a and b are the linear trend and the sea ice concentration at the beginning of the time series. We applied a hypothesis test using a Student's t distribution to verify if the linear model is consistent.

We also used the Empirical Orthogonal Functions (EOF) technique to separate the sea ice concentration variability in different modes. The statistical modes are linearly independent. Most of time, few modes are enough to explain the signal variability. Thus, the individual modes can be interpreted as a natural process that interacts with and causes changes on sea ice concentration. Besides, the method also shows the relative importance of each mode compared to the whole variability.

Considering that the EOF analysis also generates a temporal evolution (time series) for each mode, we performed a harmonic analysis to reconstruct the main cycles of these time series, such as the annual and semi-annual cycles, and afterwards we removed them from the series. A running-mean filter was used to smooth the signal or to attenuate the high frequency signals. In this way, we can enhance the low frequency signal and evaluate the inter-annual variability of sea ice concentration. Before applying the EOF technique, long linear trends of each pixel time series was removed. Spectral analysis was also performed to fractionate the signal variance (energy), as a function of frequency, and thus we can distinguish at which frequency most part of sea ice variability is concentrated.

RESULTS

Figure 1 shows the linear trend of sea ice concentration around the Antarctic continent after we applied the linear regression technique to the time series of annual mean sea ice concentration for the 1978-2006 period. The more positive (negative) the pixel value is, the quicker sea ice concentration tends to increase (decrease) with time.

Intense sea ice reduction is observed in the neighborhood of the Antarctic Peninsula (∼1%/year reduction), in the Bellingshausen and in Amundsen Seas sector, but an increase is present in the Ross Sea sector (∼1%/year increase) over the 27-years period. Other regions show relatively smaller trends. Figure 2 shows the resulting linear trends (%/year) at 95% confidence level.

The processes that act on the linear variability of sea ice can be detected by each of the EOF modes. In this work, we present only the two leading modes since they account for more than 74% of the sea ice concentration variability over the studied period (Figs. 3 and 4). The evolution in time of the expansion coefficients of the first two modes was subject to spectral analysis to verify their predominant frequencies. The frequency variance-preserving spectrum peaks are indicated by their respective periods (Figs. 3c and 4c) and their confidence intervals (dashed lines). As will be shown, all peaks, except for the ones on Figures 7c and 8c, are above the red noise at 95% level.

The interpretation of Figures 3a and 4a, in terms of sea ice concentration variability, is directly associated with their grayscales. Sea ice concentrations co-vary in time if they are represented by the same tone. On Figure 4a, for instance, while the sea ice concentration diminishes (increases) on the dark grey region, it increases (diminishes) on the light grey region, with a dominant semi-annual frequency (Fig. 4c). When the value indicated on the figure is zero, no sea ice variability is noticed by the mode in this region.

The first mode of variability shows a strong co-variance between the areas around the Antarctic continent. No sea ice concentration variability exists on the east of Antarctic Peninsula and on the ice edge region. The first mode explains 66.74% of the total sea ice concentration variability. The

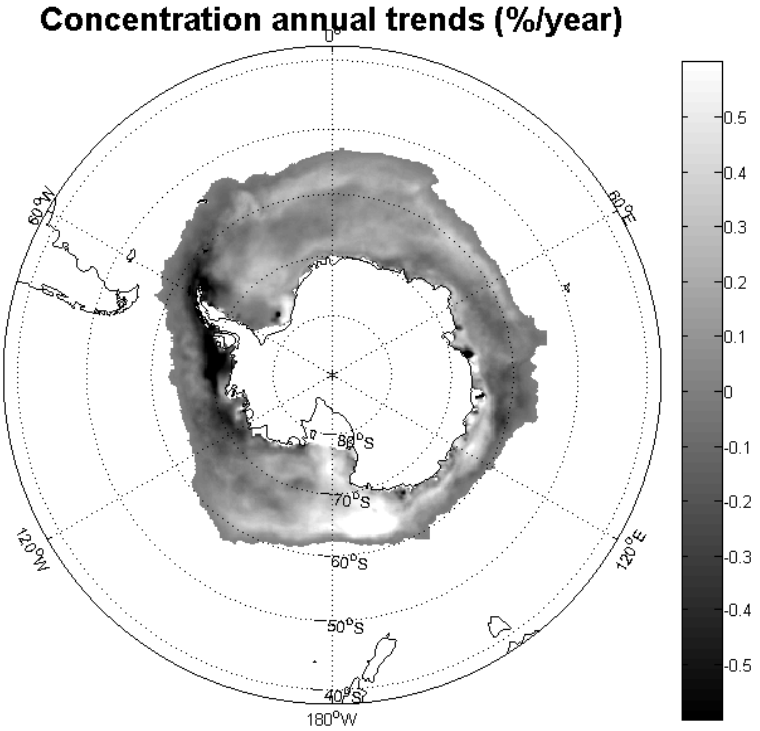


Fig. 1 – Sea ice concentration annual trend (%/year) around Antarctic continent based on the 1979-2006 period. The trends were calculated based on the yearly microwave images.

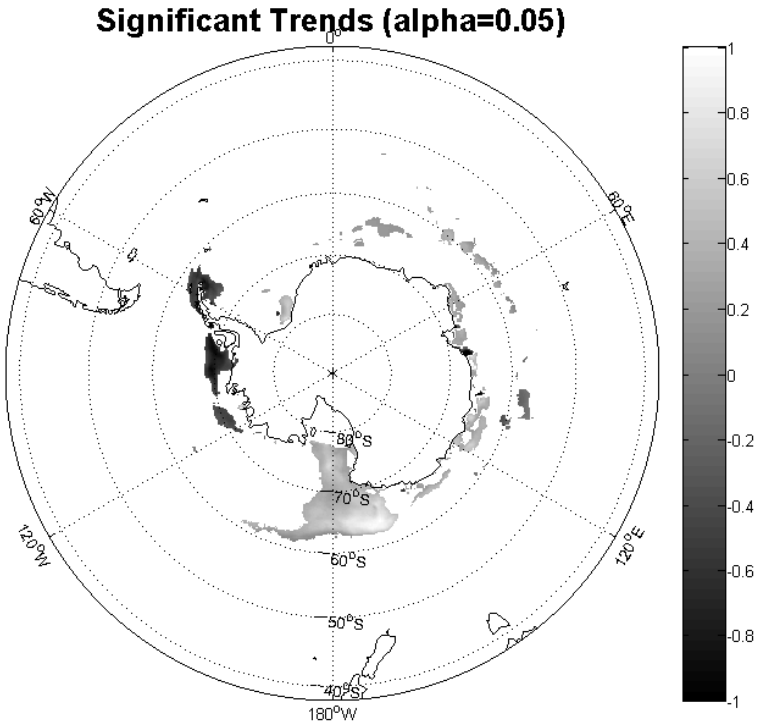


Fig. 2 – Annual linear trend (%/year) at 95% of confidence level.

most dominant frequency of the expansion coefficient time evolution is about 1/12 cycles per month (cpm), the so-called annual frequency. The second mode explains 7.83% of the total variability. The evolution of the expansion coefficient time series shows three frequency peaks at 12, 6 and 4 months. However, most of the signal energy is concentrated at semi-annual (1/6 cpm) frequency. This signal dominates in the region closer to the Antarctic continent, opposite to the outer region.

The annual and semi-annual cycles were the most important signals on the first EOF modes. We then reconstructed these cycles from each pixel time series using the harmonic analysis. The determination coefficient (r^2) between the original sea ice time series and reconstructed cycles (Fig. 5) has shown that much of the total variability of the sea ice concentration (up to 90%) resides on the annual cycle. This was expected since a strong annual signal prevails on the sea ice concentration due to cooling (winter) and warming (summer) seasons.

Exceptions to this pattern occur in certain areas around the Antarctic continent (e.g. on the sea ice edge, eastern side of the Peninsula Antarctic, among others). In Figure 5a, the higher (smaller) r^2 value is, the stronger (weaker) the annual signal will be. On the other hand, Figure 5b shows low r^2 values, indicating that the semi-annual cycle explains at most 20% of total sea ice concentration variation in some regions, especially on the ice edge and Weddell Sea and Ross Sea sectors. These results agree with those obtained by the EOF technique, as expected, since the first mode explains much of the variability and presented an annual signal.

With the purpose of identifying (or estimating) sea ice concentration inter-annual variability, we removed the fitted annual cycle from the original data series. A 12-month running mean filter was applied to the new sea ice concentration time series and the EOF technique was applied again.

The results are shown in Figures 6, 7 and 8. The first mode presented stronger spatial patterns (higher values) on the west side of Antarctica (Fig. 6a) where the co-variance on the Atlantic region is opposite to the co-variance on the East Pacific. This mode explains about 22.6% of the sea ice total variability and presents its frequency peak at about 1/37 cpm (Fig. 6c). The second mode shows a pronounced polarity between the Bellingshausen/Amundsen/inner Weddell sectors and Ross Sea/ outer Weddell regions, and a weaker signal on both the Weddell Sea and Indian Ocean (Fig. 7a). The dominant frequency is 1/48 cpm (Fig. 7b) and the mode explains 10.41% of the total sea ice concentration variability. Finally, the third mode presented its frequency peak at about 1/56 cpm (Fig. 8b) with the spatial patterns showing some covariance between the inner part of Weddell Sea, the Indian sector and the Amundsen Sea, in opposition of ice edge on Weddell and Bellingshausen Seas and Ross Sea (Fig. 8a). This mode explains 9.01% of the total variability.

We should add that in the power spectrum figures, the dominant frequencies are not well resolved because they shifted to the low-frequency end and thus are limited by the extent of our time-series. Besides, we cannot affirm that peaks on Figures 7c and 8c are significant at the 95% level. However, based on the expected physics resulting from the known forcings in the region (such as SAM and ENSO), we believe those peaks are indeed representing real variability on the related frequencies.

DISCUSSION AND CONCLUSIONS

The Antarctic spatial distribution of trends in sea ice concentration is more intense in the Pacific sector. Global climate-related processes, such as ENSO and SAM, may have a strong influence on the observed spatial pattern of trends.

The application of EOF analysis on the original sea ice concentration time series showed that the mode responsible for the most part of the Antarctic sea ice linear variation presents an annual cycle (Fig. 3c). This annual variability is expected since sea ice varies seasonally according to incoming solar radiation through the year. Antarctic sea

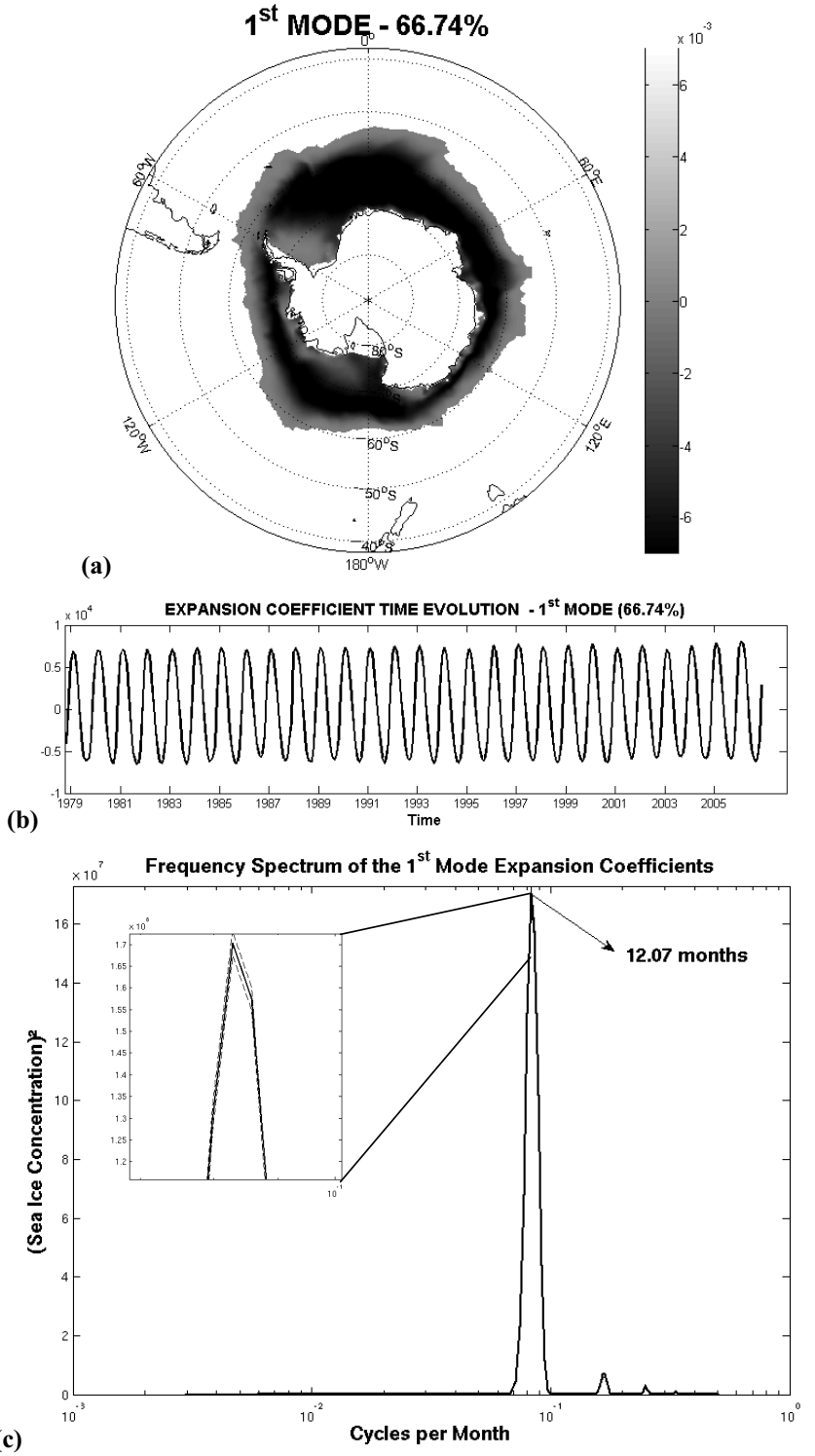


Fig. 3 – (a) First EOF mode, (b) the time evolution of its expansion coefficient and (c) the frequency spectrum of the expansion coefficient time series (the dashed lines correspond to confidence interval limits at 95% level); on the detail, the zoom of the mean peak.

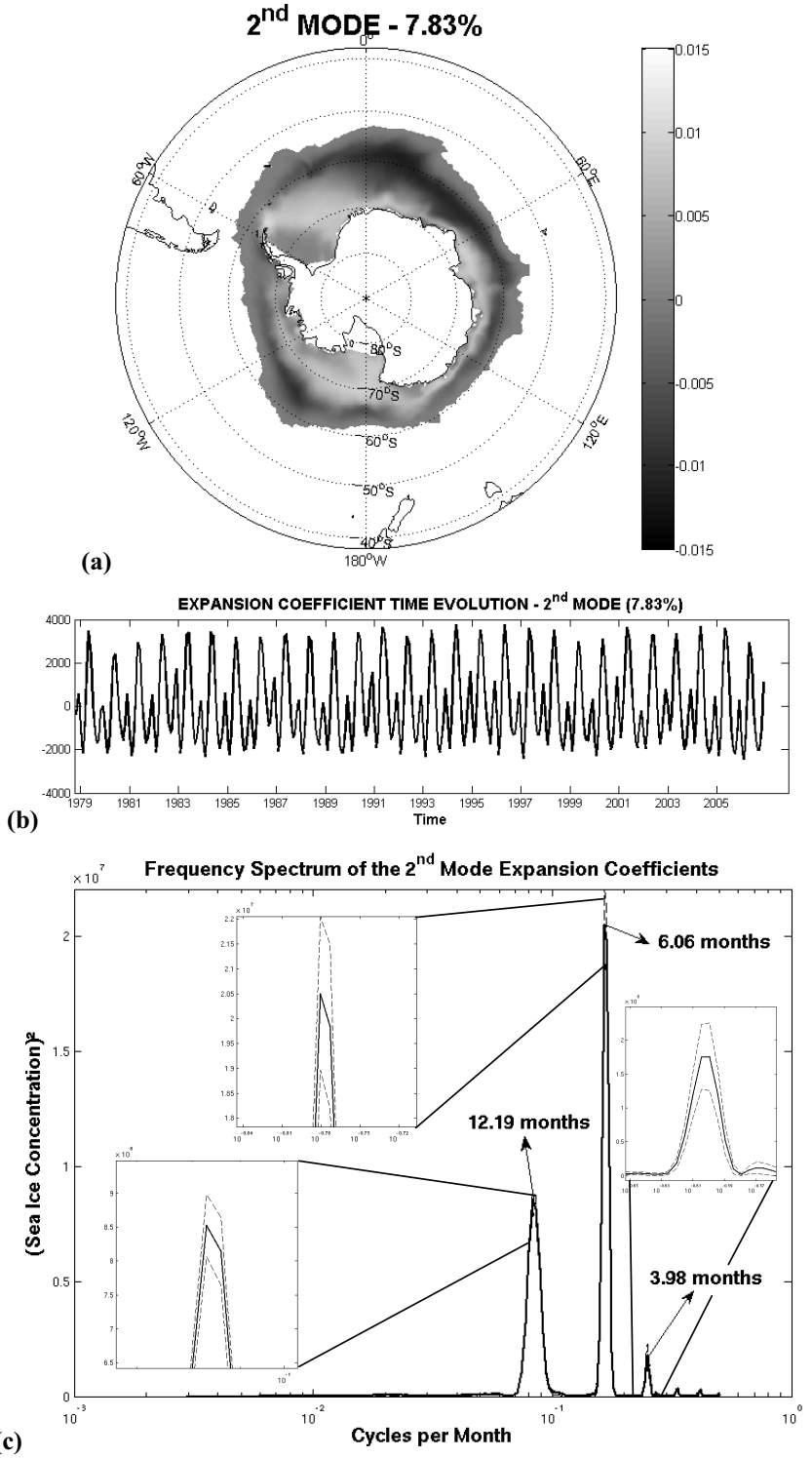
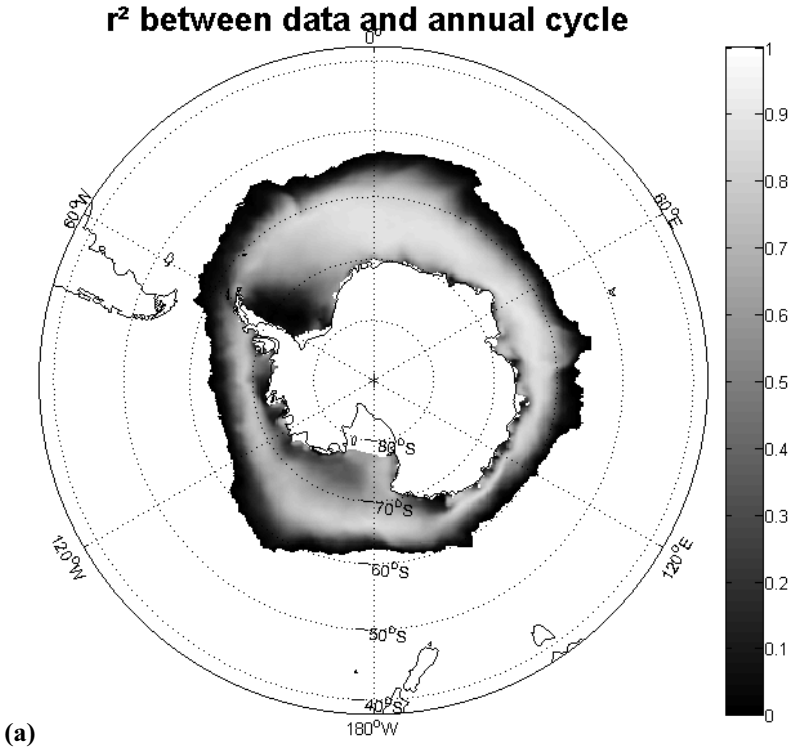
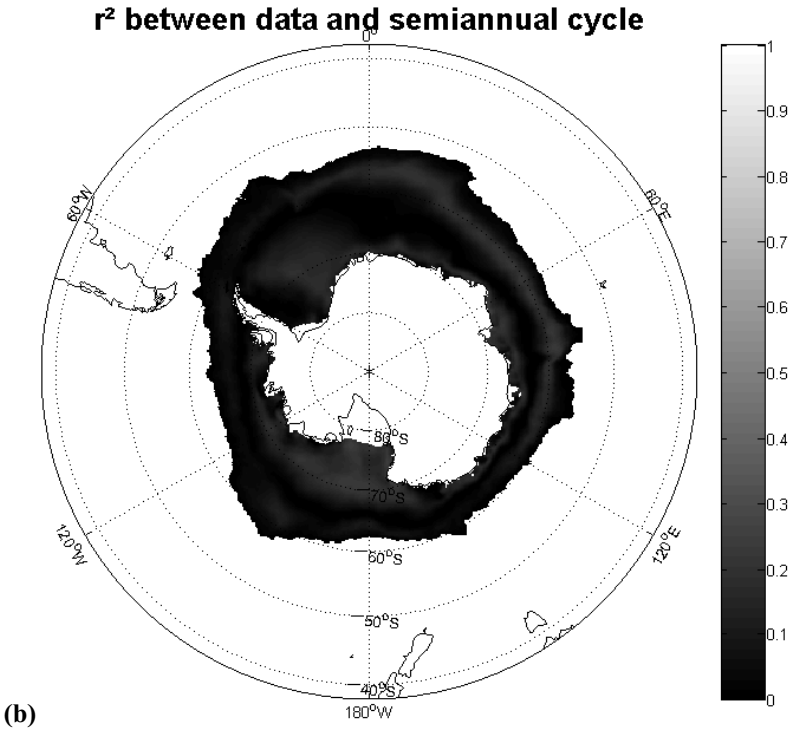


Fig. 4 – (a) Second EOF mode, (b) the time evolution of its expansion coefficient and (c) the frequency spectrum of the expansion coefficient time series (the dashed lines correspond to confidence interval limits at 95% level); on the details, the zoom of the peaks.



(a)



(b)

Fig. 5 – Determination coefficient r^2 between (a) the original time series and annual cycle and (b) original time series and the semi-annual cycle.

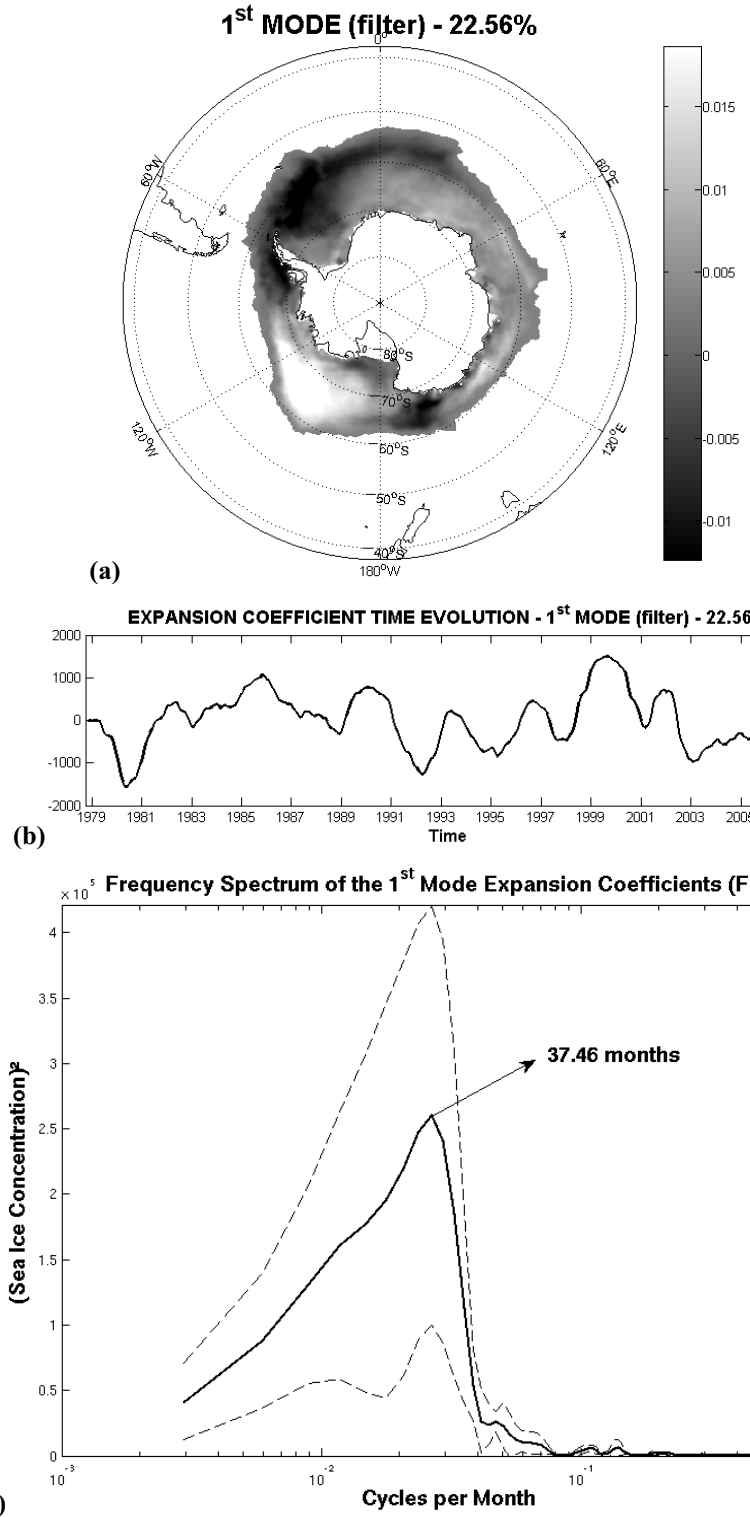


Fig. 6 – (a) First EOF mode, (b) the time evolution of its expansion coefficient and (c) the frequency spectrum of the expansion coefficient time series (the dashed lines correspond to confidence interval limits at 95% level).

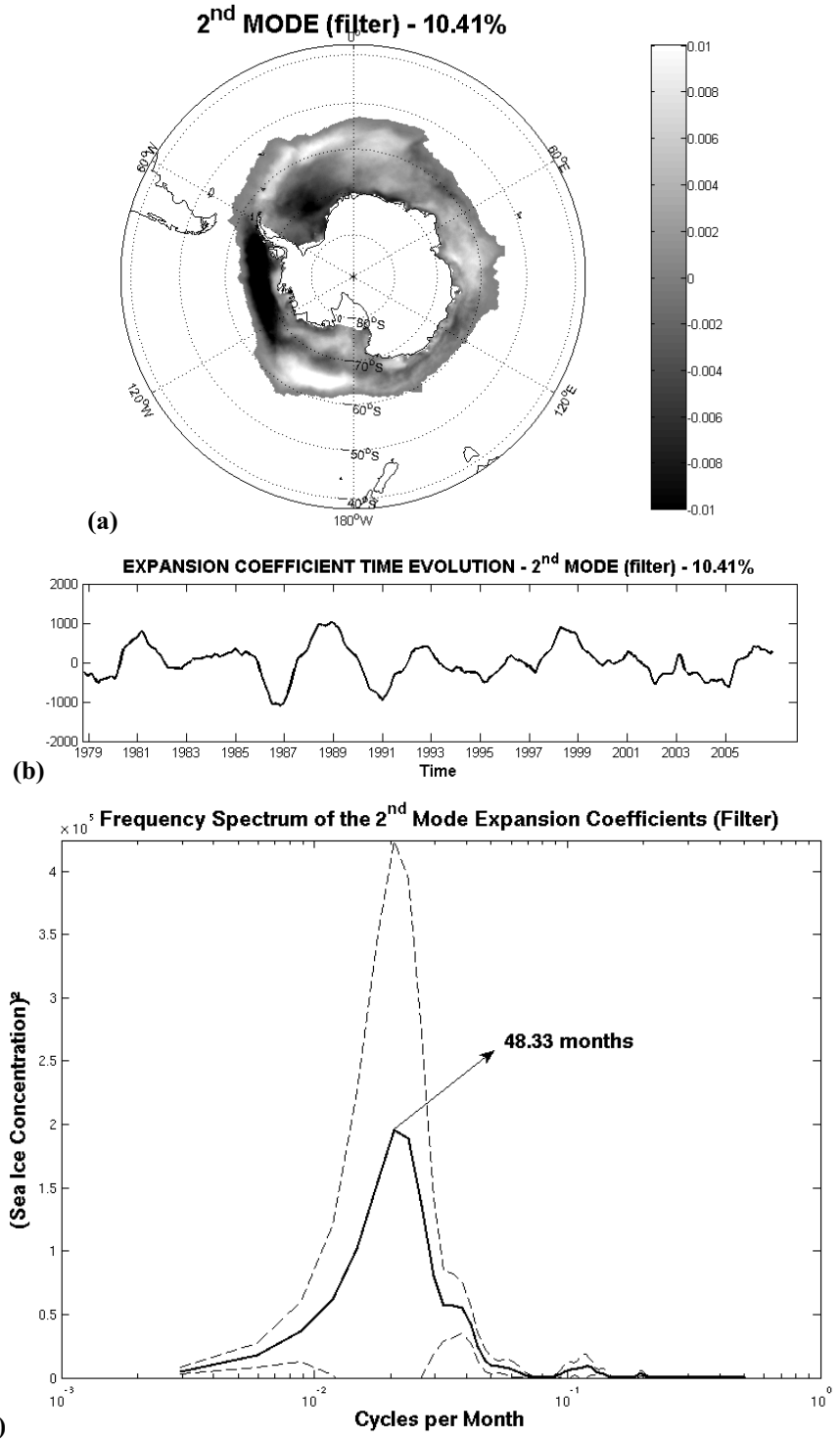


Fig. 7 – (a) Second EOF mode, (b) the time evolution of its expansion coefficient and (c) the frequency spectrum of the expansion coefficient time series (the dashed lines correspond to confidence interval limits at 95% level).

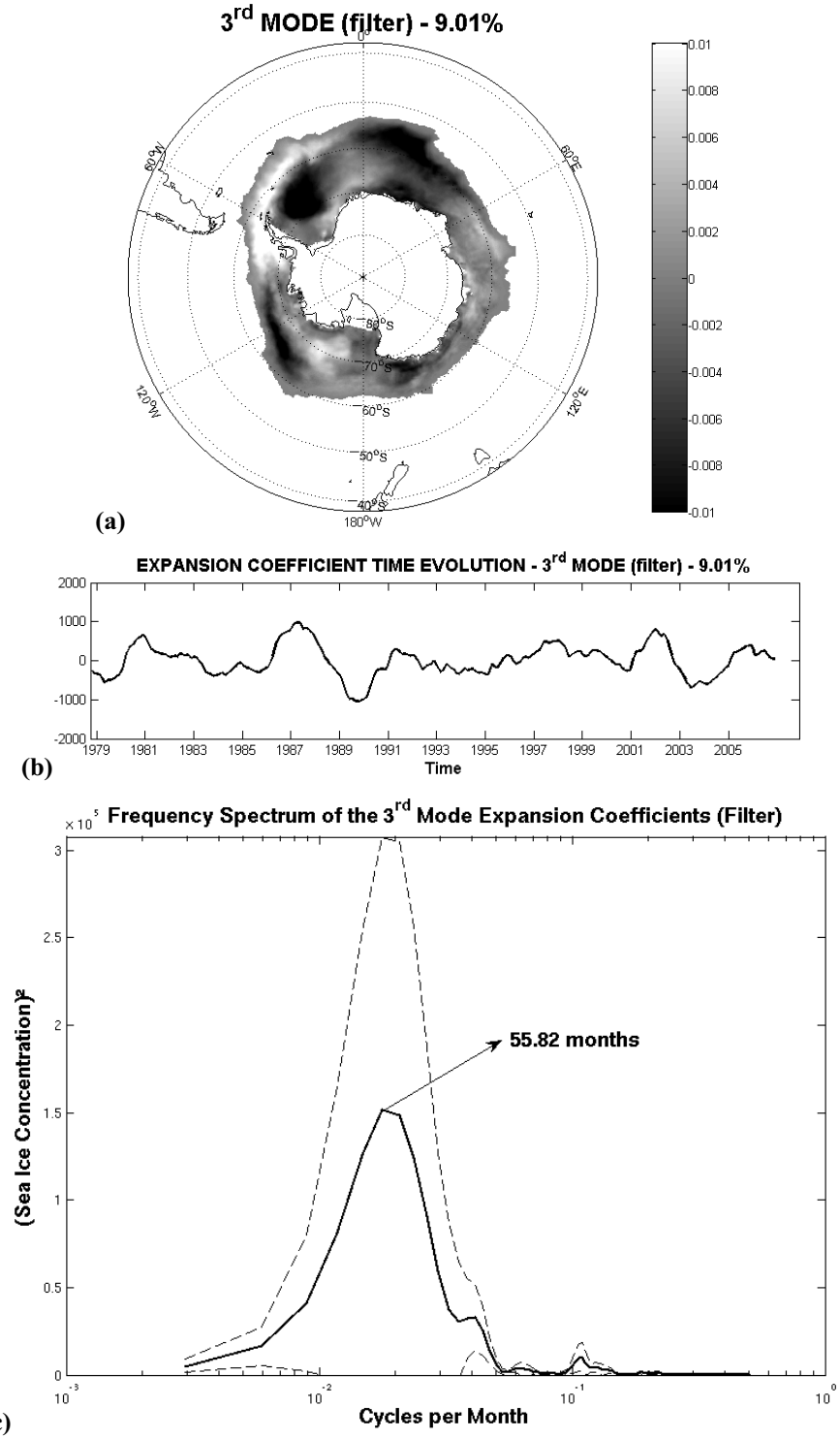


Fig. 8 – (a) Third EOF mode, (b) the time evolution of its expansion coefficient and (c) the frequency spectrum of the expansion coefficient time series (the dashed lines correspond to confidence interval limits at 95% level).

ice peaks in September, and reaches a minimum in February. In some places, sea ice melts completely in the summer. In regions where the first mode spatial patterns were approximately null (e.g. the eastern side of Antarctic Peninsula), sea ice persisted all over the year, including summer.

The second mode (Fig. 4) presented its larger frequency peak on 1/6 cpm, which coincides with SAO mean frequency. As shown by Figure 4b, every year has two peaks, apparently at the beginning of March and September. These months correspond to the Earth equinoxes, when the temperature meridional gradient reaches its maximum. In September, the CPT is located at south of sea ice edge, which can drive a wind regime to west on marginal ice pack (Enomoto and Ohmura 1990). As a result, the Ekman transport will advect this ice northward, and then the ice been melted on the north limit is replenished with sea ice coming from growth areas at south (Watkins and Simmonds 1999). Then, CPT advances slowly northward as the oceanic/continental temperature gradient diminishes (van Loon 1967; Simmonds et al. 1998). When the CPT crosses the ice edge, the dominant wind over the ice pack becomes easterly causing an Ekman transport southward, which reduces sea ice concentration on central areas (Watkins and Simmonds 1999).

Though the SAO physical explanation to the second mode is reasonable, as the variability explained by this mode is relatively low, this signal could be a result of noise, since it is still contaminated by the annual cycle (first peak on Fig. 4c).

To associate the sea ice variability to specific climate phenomena, we had to apply a running-mean filter, and hence enhance the inter-annual variability. Spectral analysis results showed that the most important inter-annual variations have approximately 3 years and 4 years periods, although the frequency peaks are broad due to the relatively short original time-series. Gloersen (1995), using a multiple-window harmonic analysis, has shown that sea-ice cover in the Antarctic contain statistically significant quasi-biennial and quasi-quadrennial periodicities that are well correlated with variations in the ENSO index. Our results are very similar, according to Figures 6c and 7c, despite our dataset has a longer time span. He also found that the response of sea ice to these two frequency components varies greatly for different regions in Antarctica. A linkage between El Niño Southern Oscillation (ENSO) index phenomena with the Antarctic sea ice variability has been found in this work as well. Figure 9 shows the cross-correlation between the Southern Oscillation Index (SOI) and the first mode coefficient expansion time series. We can observe that the largest correlation happens with a lag of 6 months. This means that sea ice field takes about six months to respond to ENSO events. At this lag, the correlation between SOI and sea ice concentration is significant, with a 95% confidence interval.

The observed sea ice cover trends in Antarctic cannot be explained just by this process, given the complexity of interactions between natural processes and the difference between the Antarctic Dipole pattern and trends spatial pattern. However, this could be the most important driver for these trends in the last years.

Sea ice reduction on the West Antarctic Peninsula is probably also responding to an increase of surface water temperature. But, again, this rise on surface water temperature can be attributed to an increased warm air advection into the region, brought by anomalous cyclonic atmospheric conditions, which is reinforced by El Niño events and positive SAM index (Meredith and King 2005).

Sea ice concentration on the West Antarctic Peninsula is probably also been affected by the increase of Antarctic Circumpolar Current temperature (Gille 2002). The Circumpolar Deep Water flows very close to the Antarctic Peninsula, when it intrudes on the Marguerite Bay shelf (e.g., Klinck et al. 2004), which can limit sea ice formation on this region due to its relatively high temperature.

The reduced sea ice formation on Bellinghausen/Amunsen Seas has a positive feedback, as observed by Meredith and King (2005). When sea

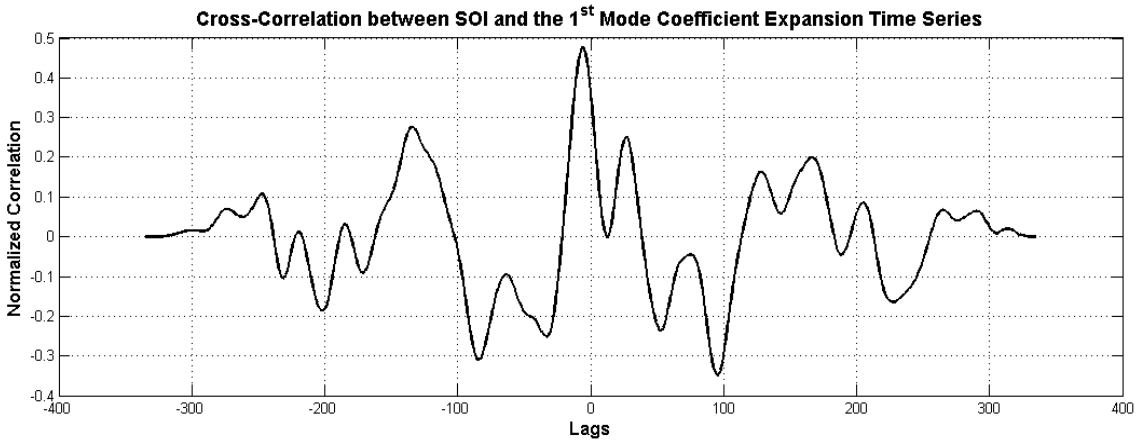


Fig. 9 – Cross-correlation between the Southern Oscillation Index (SOI) and the first mode coefficient expansion time series.

ice cover is smaller than usual there is an increase in surface salinity (since melt-water is reduced). The relatively higher temperature makes even more difficult the formation of sea ice. The less sea ice cover, the more the air temperature increases, because of the increased heat flux into the ocean. Once sea ice cover starts to diminish at a rate higher than usual, this rate tends to increase even more.

Natural variability and rising temperatures linked to global warming appear to have played a role in the decline of sea ice cover in the Arctic Sea (e.g., Parkinson and Cavalieri 2008), and some researchers point out that the Arctic may be ice-free in summer before the end of this century (Johannessen 2004). Natural variability also occur in the Antarctic sea ice cover but the complexity of the dictating physical phenomena on sea ice concentration is higher in Antarctica then in the Arctic. In the Antarctic, trends are smaller than in the Arctic and vary regionally.

Antarctic sea ice trends are smaller and more complex. Through 2008, the total annual Antarctic sea ice extent increased about 1 percent per decade, but the trends were not consistent for all areas or all seasons. The variability in Antarctic sea ice patterns makes it harder for scientists to explain Antarctic sea ice trends and to predict how Southern Hemisphere sea ice may change as the Earth continues to warm. Climate models do predict that Antarctic sea ice will respond slower than Arctic sea ice to global warming, but as air temperatures continue to rise, a long-term decline is also expected in the south hemisphere sea ice (Cavalieri et al. 1997).

A positive sea ice extent trend in the Southern Ocean was also found by Zhang (2007) modeling studies. He suggested that a reduction on the convective circulation on the ocean below sea ice would reduce the heat flux available to melt ice (or inhibit its formation). The general overcome is an increase on sea ice extent but not enough to explain the observed regional changes.

Care has to be taken when analyzing sea ice concentration time series derived from satellites data, because it is relatively short. Curran et al. (2003) used methanesulphonic acid (MSA) records between 1841 and 1995 to show a reduction on sea ice extent since the 50s around the Antarctica. However, they noticed an "apparent" sea ice increase in the last years is due to the periodicity within the record. The longer record reveals a long-term decreasing trend.

Another example of how an analysis based on short time series can be biased is found in Zwally et al. (1983). A 3-year period (1973-1976) of sea ice cover was used by them to conclude that there was a decreasing trend on sea ice cover for both Weddell and Ross Seas and a rising trend for Bellingshausen Sea. Our work is based on a longer

time series, therefore our results should be more robust and approach to the longer period trend.

Finally, we should realize that analyzing long trends with a relatively small time series is like looking a whole horizon through a little window. Moreover, linear variations cannot explain the most part of the total sea ice variability in Antarctic and then subsequent studies including the non-linearity of variations must be carried out.

ACKNOWLEDGMENTS

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RESUMO

O gelo marinho tem um importante papel no clima da Terra. Além de seu elevado albedo, ele isola o oceano da atmosfera e também possui um importante papel na formação de águas profundas através da rejeição de sal. As recentes mudanças climáticas da Terra podem estar afetando significativamente estes processos. Neste trabalho, nós analisamos a variabilidade da concentração de gelo marinho ao redor do continente Antártico usando dados do SMMR e SSMI para o período de 1978-2006. Nós investigamos as tendências anuais através de uma regressão linear a um nível de confiança de 95%. Então, utilizamos a técnica de Funções Ortogonais Empíricas (EOF) para decompor o sinal da cobertura de gelo marinho em modos independentes de variabilidade. Encontramos uma tendência linear anual negativa ao redor do oeste da Península Antártica nos Mares de Bellingshausen/Amundsen ao longo dos 32 anos. Nas proximidades do Mar de Ross, uma tendência positiva foi observada. Estes resultados confirmam tendências recentes observadas por outros pesquisadores na Antártica. A variabilidade sazonal dominou o gelo marinho ao longo do período como esperado. A variabilidade do gelo marinho sem a sazonalidade mostrou a dominância de um sinal com período de 3-4 anos. Concluímos que isso é causado pelos índices El Niño Oscilação Sul (ENSO) e Modo Anular Sul (SAM) e intrusão de uma água relativamente mais quente nos Mares de Bellingshausen/Amundsen. A cobertura de gelo marinho na Antártica é um assunto complexo, mas conforme a série temporal se torna mais longa, a não-linearidade de muitos processos físicos podem ser visualizados no futuro.

Palavras-chave: mudanças climáticas, oeste da Península Antártica, SMMR, SSM/I.

REFERENCES

BJØRGO E, JOHANNESSEN OM AND MILES MW. 1997. Analysis of merged SMMR-SSMI time series of Arctic and Antarctic sea ice parameters 1978-1995. Geophys Res Lett 24(4): 413–416.

CAVALIERI DJ, GLOERSN P, PARKINSON CL, COMISO JC AND ZWALLY HJ. 1997. Observed hemispheric asymmetry in global sea ice changes. Science 278: 1104–1106.

CAVALIERI DJ AND PARKINSON CL. 2008. Antarctic sea ice variability and trends, 1979-2006. J Geophys Res 113: C07007.

COMISO JC. 1995. SSM/I sea ice concentrations using the Bootstrap Algorithm. NASA RP, 1380.

CURRAN MAJ, VAN OMMEN TD, MORGAN VI, PHILLIPS KL AND PALMER AS. 2003. Ice core evidence for Antarctic sea ice decline since the 1950s. Science 302: 1203–1206.

ENOMOTO H AND OHMURA A. 1990. Influences of atmospheric half-yearly cycle on the sea ice extent in the Antarctic. J Geophys Res 95: 9497–9511.

GILLE ST. 2002. Warming of the southern ocean since the 1950s. Science 295: 1275–1277.

GLOERSEN P. 1995. Modulation of hemispheric sea-ice cover by ENSO events. Nature 373: 503–506, doi: 10.1038/373503a0.

HALL A AND VISBECK M. 2002. Synchronous Variability in the Southern Hemisphere Atmosphere, Sea Ice, and Ocean Resulting from the Annular Mode. American Meteorological Society 15: 3043–3057.

JOHANNESSEN OM, BENGTSSON L, MILES MW, KUZMINA SI, SEMENOV VA, ALEKSEEV GV, NAGURNYI AP, ZAKHAROV VF, BOBYLEV LP, PETTERSSON LH, HASSELMANN K AND CATTLE HP. 2004. Arctic climate change: observed and modeled temperature and sea-ice variability. Tellus A56: 328–341.

KLINCK JM, HOFMANN EE, BEARDSLEY RC, SALIHOGLU B AND HOWARD S. 2004. Water-mass properties and circulation on the west Antarctic Peninsula Continental Shelf in Austral Fall and Winter 2001. Deep Sea Res II 51: 1925–1946.

KWOK R AND COMISO JC. 2002. Southern Ocean climate and sea ice anomalies associated with the Southern Oscillation. J Clim 15: 487–501.

LEFEBVRE W, GOOSSE H, TIMMERMANN R AND FICHEFET T. 2004. Influence of the Southern Annular Mode on the sea ice-ocean system. J Geophys Res 109: C09005.

MEEHL GA. 1991. A re-examination of the mechanism of the semiannual cycle in the Southern Hemisphere. J Climate 4: 911–926.

MEREDITH MP AND KING JC. 2005. Rapid climate change in the ocean west of the Antarctic Peninsula during the second half of the 20th century. Geophys Res Lett 32: L19604.

PARKINSON CL AND CAVALIERI DJ. 2008. Arctic sea ice variability and trends, 1979-2006. J Geophys Res 113: C07003.

SIMMONDS I AND JACKA TH. 1995. Relationships between the interannual variability of Antarctic sea ice and the Southern Oscillation. J Clim 8: 637–647.

SIMMONDS I, JONES DA AND WALLAND DJ. 1998. Multi-decadal climate variability in the Antarctic region and global change. Ann Glaciol 27: 617–622.

SPREEN G, KALESCHKE L AND HEYGSTER G. 2007. Sea ice remote sensing using AMSR-E 89 GHz Channels. J Geophys Res 113: C02S03.

STEPHENS BB AND KEELING RF. 2000. The influence of Antarctic sea ice on glacial-interglacial CO_2 variations. Nature 404: 171–174.

STRASS VH AND FAHRBACH E. 1998. Temporal and regional variation of sea ice draft and coverage in the Weddell Sea obtained from upward looking sonars. Antarctic Sea Ice: Physical Processes, Interactions, and Variability, Antarctic Research Series, AGU, Washington DC, 74: 123–139.

THOMPSON DWJ AND WALLACE JM. 2000. Annular modes in the extra-tropical circulation: I. Month-to-month variability. J Clim 13: 1000–1016.

VAN DEN BROEKE MR. 2000d. The semi-annual oscillation and Antarctic Climate. Part 4: A note on sea ice cover in the Amundsen and Bellingshausen Seas. Internat J Climatol 20: 455–462.

VAN LOON H. 1967. The half-yearly oscillation in the middle and high southern latitudes and the coreless winter. J Atmos Sci 24: 472–486.

WATKINS AB AND SIMMONDS I. 1999. A late spring surge in the open water of the Antarctic sea ice pack. Geophysical Research Letters 26: 1481–1484.

WHITE WB AND PETERSON RG. 1996. An Antarctic circumpolar wave in surface pressure, wind, temperature and sea-ice extent. Nature vol. 380.

YUAN X AND MARTINSON DG. 2000. Antarctic sea ice extent variability and its global connectivity. J Clim 13: 1697–1717.

YUAN X. 2004. ENSO-related impacts on Antarctic sea ice: a synthesis of phenomenon and mechanisms. Antarct Sci, 16: 415–425.

YUAN X AND LI C. 2008. Climate modes in southern high latitudes and their impacts on Antarctic sea ice. J Geophys Res 113: C06S91.

ZHANG J. 2007. Increasing Antarctic sea ice under warming atmospheric and oceanic conditions. J Clim 20: 2515–2529.

ZWALLY HJ, COMISO JC, PARKINSON CL, CAMPBELL WJ, CARSEY FD AND GLOERSEN P. 1983a. Antarctic sea ice, 1973-1976: Satellite passive-microwave observations. NASA Spec Publ 459: 206 pp.