한국환경과학회지 제21권(제2호), 125～133, 2012
Journal of the Environmental Sciences
http://dx.doi.org/10.5322/JES.2012.21.2.125

Climatological Trend of Sea Water Temperature around the Antarctic Peninsula Waters in the Southern Ocean

Chung Il Lee*, Sang-Woo Kim[1)], Dong-Sun Kim[2)], Moongeun Yoon[3)]

Department of Marine Bioscience, Gangneung-Wonju National University, Gangwon 210-702, Korea
[1)]Fisheries Resources and Environment Division, East Sea Fisheries Research Institute, Gangneung 210-861, Korea
[2)]Research Center for Ocean Industrial Development, Pukyong National University, Busan 608-737, Korea
[3)]Yangyang Salmon Station, Korea Fisheries Resources Agency, Yangyang 215-851, Korea
(Manuscript received 19 October, 2011; revised 21 December, 2011; accepted 26 January, 2012)

Abstract

Climatological trend for the period of 1970 to 2009 in sea water temperature around the Antarctic Peninsular waters in the Southern Ocean was investigated. During the period from 1970 to 2009, sea water temperature in the top 500 m water column except 100 m increased at a rate of 0.003 - 0.011 $℃ \cdot yr^{-1}$, but at 100 m it decreased at a rate of -0.003 $℃ \cdot yr^{-1}$. Although long-term trend is generally warming, there were several periods of sharp changes between 1970 and 2009. Annual mean sea water temperature between surface and 500 m except 100 m decreased from the early of 1970s to the end of 1980s, and then it increased to the end of 2000s. In the entire water column between the surface and 500 m, sea water temperature closely correlated with the El Nino events expressed as the Southern Oscillation Index(SOI), and SOI and sea water temperature have a dominant period of about 3-5 years and decade.

Key Words : Sea water temperature, Southern Ocean, Antarctic Peninsular, Climatological trend, Long-term variability

1. Introduction

The Southern Ocean which it contains the strong eastward flow of the Antarctic Circumpolar is the only oceanic domain encircling the earth (Fig. 1). It it is bordered on the north by major ocean basins (the Pacific Ocean, the Atlantic Ocean, the Indian Ocean) and there is an exchange of water mass at all depth with the basins (Schmitz, 1995). The exchange of water mass between the Southern Ocean and the major ocean basins plays an important role on control of global climate, and this exchange through the Southern Ocean transfers climate anomalies to the globe (White and Peterson, 1996). Therefore, a change in sea water temperature around the Southern Ocean could be a crucial clue that led to the understanding and prediction on climate change.

On account of this important in the Southern Ocean, many studies (Ainley et al., 2007; Gloersen and Campbell, 1991; Lee et al., 2010; Rott et al., 1996; Zwally, 1991) report that the Antarctic Ocean including the Antarctic Peninsula has become warmer, in particular warm water around the Antarctic Peninsular has extended toward Antarctic continent over the last 30 years. Over the past century, a warming trend has been demonstrated for the Antarctic

*Corresponding author : Chung Il Lee, Department of Marine Bioscience, Gangneung-Wonju National University, Gangwon 210-702, Korea
Phone: +81-33-640-2855
E-mail: leeci@gwnu.ac.kr

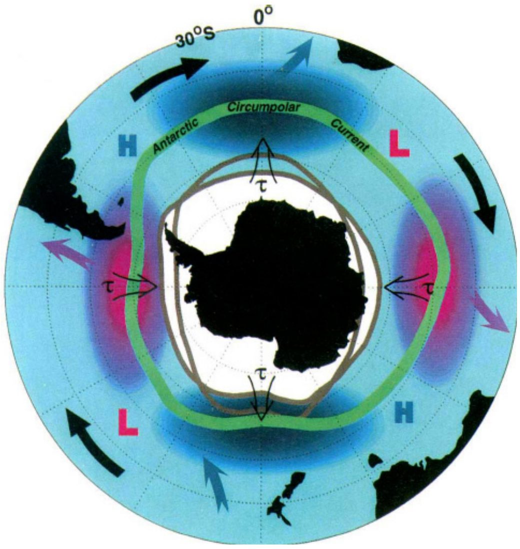

Fig. 1. Simplified schematic summary of interannual variations in sea surface temperature (red, warm; blue, cold), atmospheric sea-level pressure (bold H and L), meridional wind stress (denoted by tau), and sea-ice extent (grey lines), together with the mean course of the Antarctic Circumpolar Current (green) (Orsi et al., 1995; White and Peterson, 1996).

Peninsula region and around South Georgia (Rott et al., 1996; Whitehouse et al., 2008; Zwally, 1991). On the global scale, this warming trend may be related to a global warming trend as the world ocean has warmed by 0.037°C during the last 50 years (Levitus et al., 2005; Levitus et al., 2000). Antarctic Peninsula waters are also directly linked to the Pacific and Atlantic sector of the Southern Ocean, and in particular, the Antarctic Peninsula waters are considered as one of main habitats of krill, *Euphausia superba,* and salpa , *Salpa thompsoni* , which they are regarded as two of the most important filter-feeding species and may prefer different environments. Therefore, understanding on the long-term trend in sea water temperature is important to illustrate oceanic and fisheries conditions. For instance, salps have a tendency to prefer warmer water than krill (Nicol et al., 2000; Siegel et al., 1992), and to prefer oceanic regions with lower food concentration (Nicol et al., 2000; Pakhomov et al., 2002). These two species show different pattern in long-term change of abundance, and sea water temperature is main factor controlling the distribution and abundance of these two species (Lee et al., 2010). In previous study, Lee et al. (2010) tried to analysis long-and short-term variation of marine environmental factors in the Atlantic sectors of the Southern Ocean including this study area, but they did not find the significant trend due to inherent immense variability in the large area.

The main aim of this paper was therefore to illustrate long- and short-term trends of sea water temperature in the upper layer around the Antarctic Peninsular waters where this area has the best data coverage for climatological trend analysis and it contains main habitats for krill and salpa which they play an important role in supporting the marine ecosystem in the Antarctic Ocean.

2. Materials and Methods

2.1. World Ocean Database 2009

Sea water temperatures for climatological trend in this study area were collected from the World Ocean Database 2009 (WOD09, http://www.nodc.noaa.gov/OC5/WOD09/pr_wod09.html) offered by the National Oceanographic Data Center (Fig. 2). The WOD09 contain data measured from various instrument types shown in Table 1 and various countries (Boyer et al., 2006), and the OSD, CTD, MBT, XBT, PFL datasets are available in this study.

Sea water temperature from surface to 500 m was extracted from WOD09 for the period from 1970 to 2009. Sea water temperature was averaged to calculate climatological trend the whole study area for every

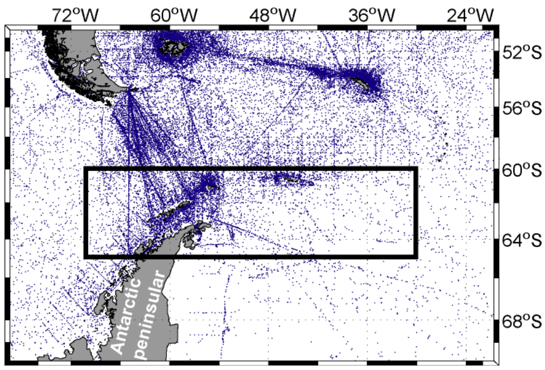

Fig. 2. Sampling coverage for sea water temperature from WOD09 in the Southern Ocean. Rectangular box represents study area: 60-65°S and 30-70°W.

Table 1. Instrument types in the World Ocean Database (Lee et al., 2010, WOD09, http://www.nodc.noaa.gov/OC5/WOD09/pr_wod09.html)

Datasets	Datasets include
OSD	Ocean Station Data, Low-resolution CTD/XCTD, Plankton data
CTD	CTD High-resolution Conductivity-Temperature-Depth / XCTD data
MBT	Mechanical / Digital / Micro Bathythermograph data
XBT	Expendable Bathythermograph data
SUR	Surface-only data
APB	Autonomous Pinniped Bathythermograph data
MRB	Moored buoy data
PFL	Profiling float data
DRB	Drifting buoy data
UOR	Undulating Oceanographic Recorder data
GLD	Glider data

austral summer season (January-March) at 100 m interval from surface to 500 m where krill and salps were largely concentrated during the summer (Pakhomov et al., 2002).

2.2. El Nino Southern Oscillation Index (SOI)

As mentioned above, the Southern Ocean is linked to the major ocean basins and to around the equator, and various environmental changes in these areas are transmitted to each other through teleconnection. In this study, relationships between El Nino activities expressed as the Southern Oscillation Index (SOI) and sea water temperature around the study area were calculated using wavelet spectrum analysis. The SOI was available at 'http://www.cgd.ucar.edu/cas/catalog/climind/soi.html' and was used to analyze the influence of the climate variability on sea water temperature and the linking between the El Nino activities and sea water temperatures in the study area.

3. Results and Discussions

The warming trends were similar at mostly sampling depths except 100 m (Fig. 3). Sea water temperatures throughout the entire water column except 100 m increased gradually. During the 40 years from 1970 to 2009, sea water temperature in the top 500 m water column except 100 m increased at a rate of 0.003 - 0.011℃ yr^{-1}, but at 100 m it decreased at a rate of -0.003℃ yr^{-1}. In the case of 100 m depth, warming trend was not clear, and there was little difference in every 10-year average compared to the other depths. In general, this warming trend probably is higher than a global trend as the world ocean has warmed by 0.037℃ during the last 50 years (Levitus et al., 2005; Levitus et al., 2000). Also, this trend was comparable to increase around the Antarctic Front and South Georgia (range 0.003-0.007℃yr^{-1}) (Levitus et al., 2005), but it was lower than warming of the Weddell Sea between 1992 and 1998 (range ~0.05℃ yr^{-1})

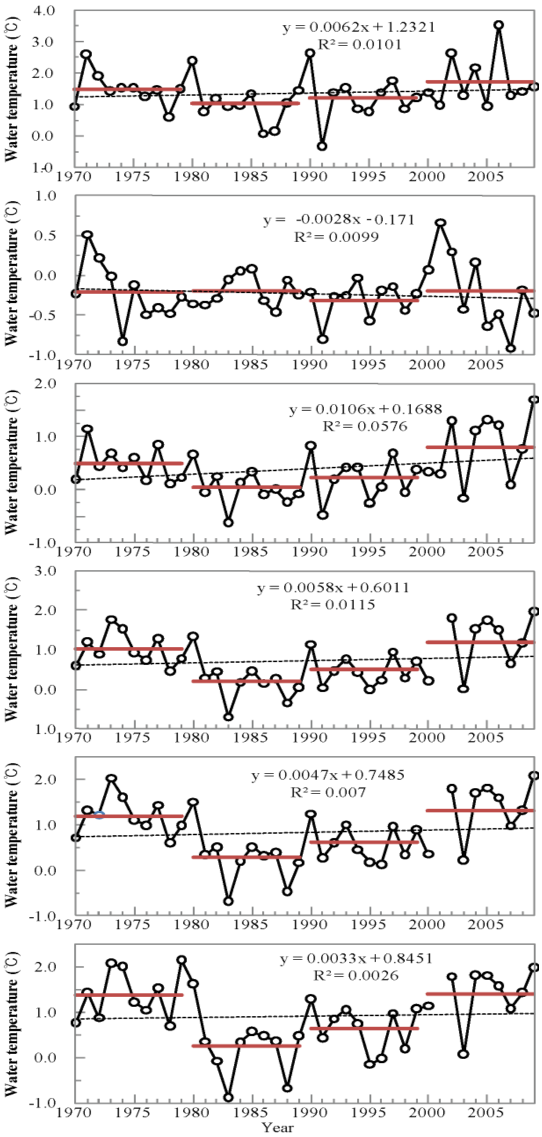

Fig. 3. Long-term time series of the mean sea water temperature at the surface, 100 m, 200 m, 300 m, 400 m, 500 m during austral summer (January-March) between 1970 and 2009. Dashed lines represent linear regressions.

(Gille, 2002) and the Atlantic sector of the Southern Ocean (range 0.02-0.03 ℃yr^{-1}) (Lee et al., 2010).

According to the other studies (Gille, 2002; Gille, 2008; Levitus et al., 2000; Levitus et al., 2005; Smedsrud, 2004; Whitehouse et al., 2008), the mean warming of the Weddell Deep Water was about 0.0032℃yr^{-1}, and this increasing rate was comparable to that around South Georgia (range 0.003-0.007 ℃ yr^{-1}). It means that the warming trend in the study area was probably more intensively than other regions of the Southern Ocean. In addition, Lee et al. (2010) suggested that warm water from the early of 1970s to the early of 2000s in the Atlantic sector of the Southern Ocean gradually spread southward and cold water mass shrank to Antarctic continent, and this spreading of warm waters has been coupled with the shrinkage of the sea ice.

In this study, short-term variations were also dominant with long-term trend. That is, although long-term trend is generally warming, annual fluctuation in sea water temperature showed that there were several periods of sharp changes between 1970 and 2009. On the annual basis, annual mean sea water temperature between surface and 500 m except 100 m decreased from the early of 1970s to the end of 1980s, and then it increased to the end of 2000s.

The main aim of this study was to show inter-annual variability and longer-term trends in sea water temperature in the Antarctic Peninsular waters where there are the most significant habitat of the Antarctic krill and salps. As mentioned above, although long-term trends in sea water temperature were clear, there were also several periods of abrupt changes and short-term periodicities within the long-term trend. In relation to abrupt changes, Lee et al. (2010), Loeb et al. (2009) and Jenouvrier et al. (2004) suggested that the change might be related to a regime shift which it has occurred around the Antarctic Peninsula and Elephant Island in the early of 1990s, and the regime shift may has a close correlation with the several sudden change observed in the period 1970-2009. In case of the northern hemisphere, several regime shifts between 1970s and 1990s were reported (Francis and Hare, 1994; ; Ingraham et al., 1998; Kondo, 1988; Minobe, 1997; Polovina et al., 1994) such as in the late 1970s, 1980s and 1990s. However, rapid change periods in sea water temperature in this study were not matched exactly with those in northern hemisphere, that is, there were time lags in the abrupt changes in sea water temperature between the northern hemisphere and the southern hemisphere. Although several abrupt changes such as suggested from previous studies (Jenouvrier et al., 2004; Lee et al., 2010; Loeb et al. , 2009) were also found from 1970s to 1990s, it may not be difficult to consider these periods to regime-shift, mostly due to several periods of high fluctuation and discordance of abrupt changes with depth. On the other hand, teleconnections between hemispheres is that linking marine environmental factors across tens of thousands of kilometers. Therefore, if the northern hemisphere regime shifts could be communicated to similar changes in the Southern Ocean by teleconnections, a regime shifts between hemispheres may have a substantial lag in time and should be explained.

In a parallel study, statistically significant trends through the whole depth were observed but were mostly non-significant likely due to inherent enormous natural variability of sea water temperature within the Atlantic sector of the Southern Ocean (Lee et al., 2010). However, they found that statistically analysis using climatological data within large area explained partially long-term and short-term variations. In addition, previous researches (Jenouvrier et al., 2004; White et al., 2002;, Carleton, 2003; Yuan, 2004; Lee et al., 2010) suggested that these short-and long-term changes in sea water temperature in the Southern Ocean was linked to ENSO events, and these change in sea water temperature matched well with the sea-ice extent and the propagation of the Antarctic Circumpolar Wave (ACW). In particular, the ACW and ENSO cycles are considered as main factors driving the warming trend around the Southern Ocean (Karoly et al., 1989; Rasmusson and MO, 1993; White and Peterson, 1996), and the ACW which propagates eastward with the circumpolar flow with a period of 4-5 years also has been linked to the ENSO cycles. Although they are also linked to each other by teleconnection, there are still questions which one is first, that is, weather ENSO activities leads the ACW or the ACW leads ENSO activities.

In this study, El Nino activity (SOI index) and water temperature from surface to 500 m show the repeated periodicity of 2-6 years, particularly 3-5 years, throughout the whole period from 1970 to 2009 (Fig. 4). The cross spectrum between SOI and the water temperature from surface to 500 m in the study area suggested that they may be closely connected to each other (Fig. 5). Lee et al. (2010) suggested that fluctuation of sea water temperature was similar to the ACW cycle, and the ACW interacted with the ENSO activities. This interaction between the ACW and ENSO cycle could be explained from feedbacks which are proceeded by teleconnections linking the ACW and ENSO cycle (White and Peterson, 1996). As mentioned above, sea water exchange including heat, sea water properties, climate anomalies between the Southern Ocean and the major ocean basins is an important in controlling the global climate change, and the feedbacks between the ACW and ENSO are considered to be one of factors

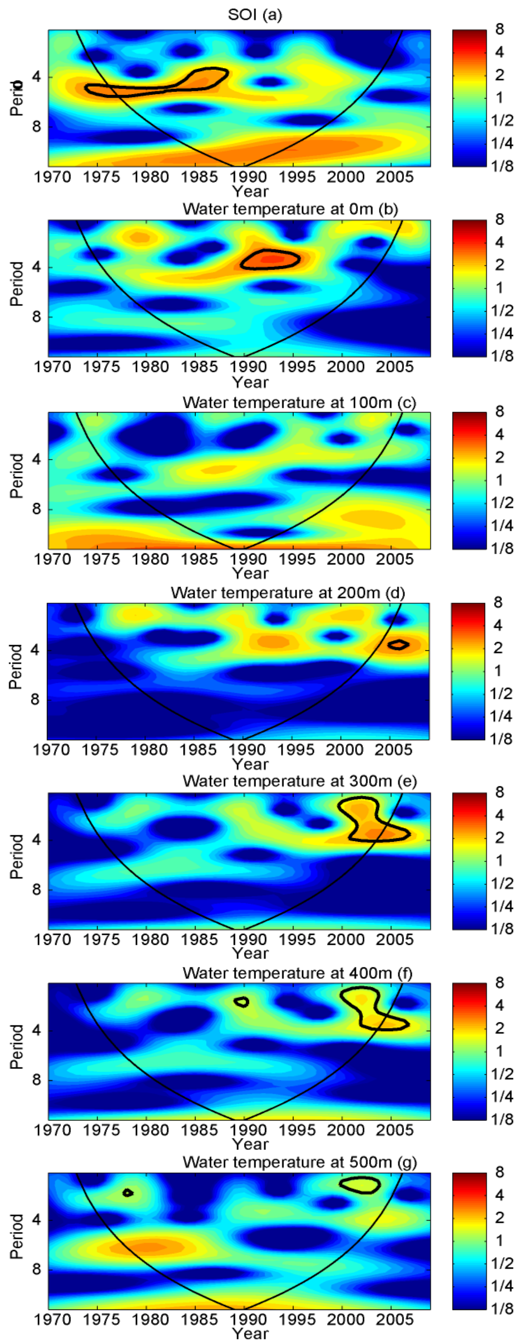

Fig. 4. The wavelet auto-spectrum of SOI (a), water temperature at 0 m (b), 100 m (c), 200 m (d), 300 m (e), 400 m (f), and 500 m (g). The 5% significance level against red noise is shown as a tick contour and the thin black line indicates the cone of the influence.

causing warming trend in the study area. In particular, long-term environmental change in the study area which is adjacent to the Weddell Sea connected to the major basins could be clue to understand warming trend. It seems that the influence of the ACW on El Niño through the study area may be related to global warming.

4. Conclusions

The Southern Ocean is known to play an important role in controlling climate change through teleconnections linking the Southern Ocean and the major basins. In particular, environmental change in the Antarctic Peninsular waters where is close to the Weddell Sea which it is main source of deep water formation is considered as one of indicators for climatological trend. In this study, warming trends through the whole depth were generally dominant, and there was dominant periodicity in sea water temperature variations. The warming trend within the study area is slightly higher than a global trend, and it was comparable to increase around the Antarctic Front and South Georgia. Sea water temperature variation around the Antarctic Peninsular waters was closely connected the ENSO activities with the about 3-5 year cycle, and this correlation seems to be related with teleconnections between the ENSO event and time-series change in sea water temperature. In this study, feedback between ENSO event and sea water temperature was not analyzed, however, feedback through teleconnections linking the ENSO event and marine environmental change in the Southern Ocean should hereafter be illustrated to understand influence in the Southern Ocean on global climate change.

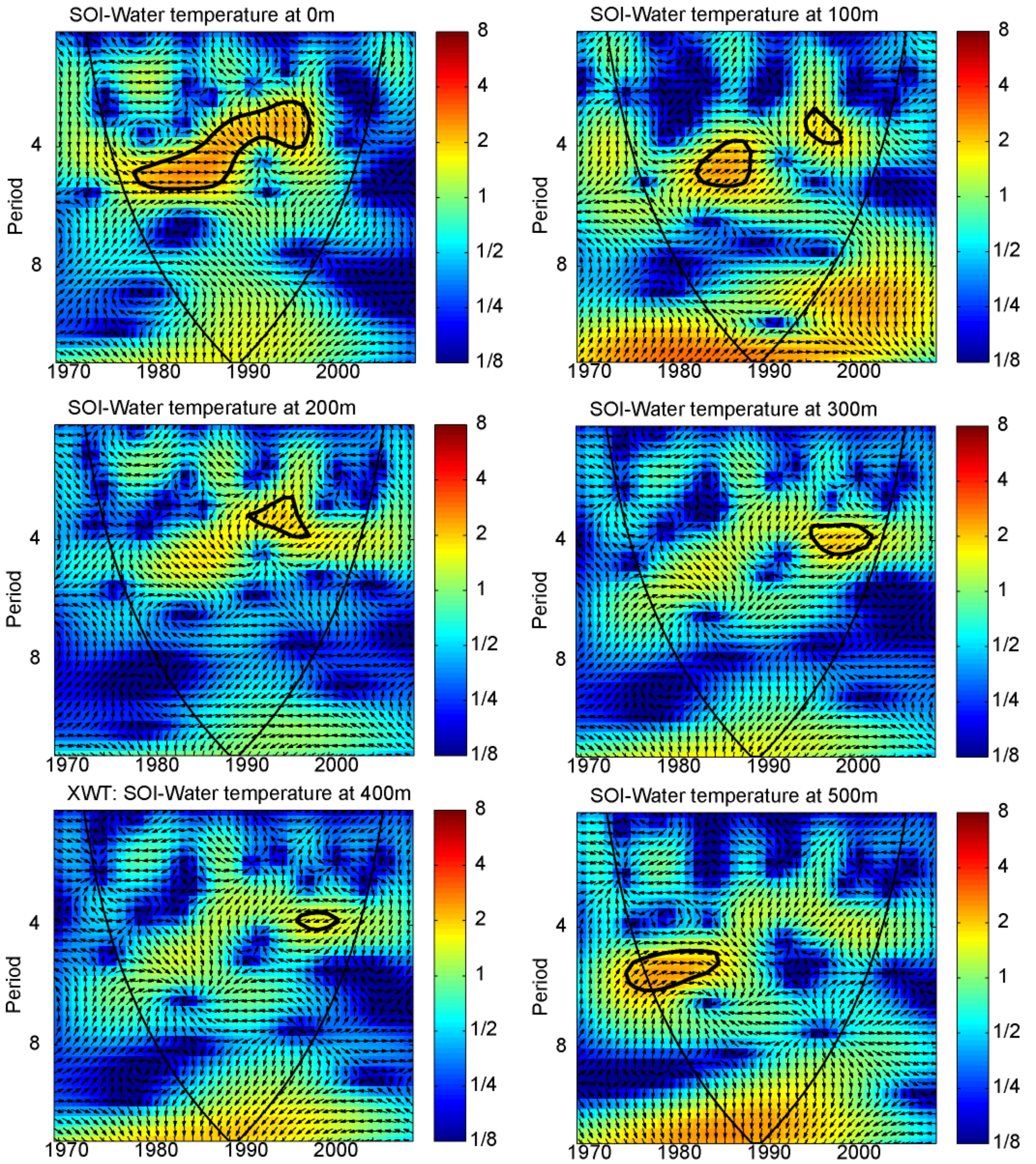

Fig. 5. The wavelet cross-spectrum between the SOI and water temperature at 0 m, 100 m, 200 m, 300 m, 400 m and 500 m. The vectors indicate the phase difference between the SOI and water temperature (with in-phase pointing right, anti-phase pointing left, an arrow pointing vertically means the second time series lags the first by 90◦, i.e. the phase angle is 270˚. The 5% significance level against red noise is shown as a tick contour and the thin black line indicates the cone of the influence.

Acknowledgements

This research was supported by the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2010-0004617) and a part of the project titled "Long-term change of structure and function in marine ecosystems of Korea" funded by the Ministry of Land, Transport and Maritime Affairs, Korea.

References

Ainley, D. G., Ballard, G., Ackley, S., Blight, L. K., Eastman, J. T., Emslie, S. D., Lescroel, A., Olmastroni, S., Townsend, S. E., Tynan, C. T., Wilson, P., Woehler, E., 2007, Paradigm lost, or is top-down forcing no longer significant in the Antarctic marine ecosystem?, Antarc. Sci., 19, 283-290.

Boyer, T. P., Atonov, J. I., Garcia, H. E., Johnson, D. R., Locarnini, R. A., Mishonov, A. V., Pitcher, M. T., Baranova, O. K., Smolyar, I. V., 2006. World Ocean Database 2005, in NOAA Atlas NESDIS 60, S. Levitus, Eds., DVDs, U.S. Government Printing Office, Washington, D.C., 15-20.

Carleton, A. M., 2003, Atmospheric teleconnections involving the Southern Ocean, Journal of Geophys. Res., 108(8080), doi: 10.1029/2000JC000379.

Francis, R. C., Hare, S. R., 1994, Decadal-scale regime shift in the large marine ecosystems of the North-east Pacific: a case for historical science, Fish. Oceanogr., 3, 279-291.

Gille, S. T., 2002, Warming of the Southern Ocean since the 1950s, Science, 295, 1275-1277.

Gille, S. T., 2008, Decadal-scale temperature trends in the Southern Hemisphere Ocean, J. Clim., 21, 4749-4765.

Gloersen, P., Campbell, W. J., 1991, Recent variations in Arctic and Antarctic Sea-Ice Covers, Nature, 352, 33-36.

Ingraham, W. J., Ebbesmeyer, C. C., Hinrichsen, R. A., 1998, Imminent climate and circulation shift in Northeast Pacific Ocean could have major impact on marine resources, EOS: Transactions, Am. Geophys. Union, 79, 197-201.

Jenouvrier, S., Weimerskirch, H., Barbraud, C., Pakr, Y. H., Cazelles, B, 2011, Evidence of a shift in the cyclicity of Antarctic seabird dynamics linked to climate, Proc. R. Soc., B2005(272), 887-895.

Karoly, D. V., Plumb, R. A., Ting, M., 1989, Examples of the horizontal propagation of quasi-stationary waves, J. Atmos. Sci., 46(18), 2802-2811.

Kondo, J., 1988, Volcanic eruptions, cool summers and famines in the Northeastern part of Japan, J. Clim., 1, 775-788.

Lee, C. I., Paknomov, E. A., Atkinson, A., Siegel, V., 2010, Long-term relationships between the marine environment, krill and salps in the Southern Ocean, J. Mar. Biol., 2010, ID 410129.

Levitus, S., Antonov, J. I., Boyer, T. P., 2005, Warming of the World Ocean, 1955-2003, Geophys. Res. Lett., 32, LO2604, doi: 10.1029/2004GRL021592.

Levitus, S., Antonov, J. I., Boyer, T. P., Stephens, C., 2000, Warming of the World Ocean, Science, 287, 2225-2229.

Loeb, V., Hofmann, E. E., Klinck, J. M., Holm-Nansen, O., White, W. B., 2009, ENSO and variability of the Antarctic Peninsula pelagic marine ecosystem, Antarc. Sci., 21, 135-148.

Minobe, S., 1997, A 50-70 year oscillation over the North Pacific and North America, Geophys. Res. Lett., 24,. 683-686.

Nicol, S., Pauly, T., Bindoff, N. L., Wright, S., Thiele, D., Hosie, G. W., Strutton, P.G., Woehler, E., 2000, Ocean circulation off east Antarctic affects ecosystem structure and sea-ice extent, Nature, 406, 504-507.

Pakhomov, E. A., 2000, Demography and life cycle of Antarctic krill, Euphausia superba, in the Indian sector of the Southern Ocean: long-term comparison between coastal and open-ocean regions, Can. J. Fish. Aquat. Sci., 57, 68-90.

Pakhomov, E. A., Froneman, P. W., Perissinotto, R., 2002, Salp/krill interactions in the Southern Ocean: spatial segregation and implications for the carbon flux, Deep-Sea Res. Part II, 49, 1881-1907.

Polovina, J. J., Mitchum, G. T., Graham, N. E., Craig, M. P., DeMartini, E. E., Flint, E. N., 1994, Physical and biological consequences of a climate event in the central North Pacific, Fish. Oceanogr., 3, 15-21.

Rasmusson, E. M., Mo, K., 1993, Linkages between 200-mb tropical and extratropical circulation anomalies during the 1986-1989 ENSO cycle, J. Clim., 6, 595-616.

Rott, H., Skvarca, P., Nagle, T., 1996, Rapid collapse of Northern Larsen Ice Shelf, Antarctica, Science, 271, 788-792, 1996.

Schmitz, W. J. Jr., 1995, On the interbasin thermohaline circulation, Rev. Geophys., 33, 151-173.

Siegel, V., Skibowski, A., Harm, U., 1992, Community structure of the epipelagic zooplankton community under the sea-ice of the Northern Weddell Sea, Polar Biol., 12(15), 15-24.

Smedsrud, L. H., 2004, Warming of the deep water in the Weddell Sea along Greenwich meridian: 1977-2001, Deep-Sea Res. Part I, 52, 241-258.

White, W. B., Peterson, R. G., 1996, An Antarctic Circumpolar Wave in surface pressure, wind, temperature and sea-ice extent, Nature, 380, 699-702.

White, W. B., Peterson, R. G., 1996, An Antarctic circumpolar wave in the surface pressure, wind, temperature, and sea ice extent, Nature, 380, 699-702.

White, W. B., Chen, S. C., Allan, R. J., Stone, R. C., 2002, Positive feedbacks between the Antarctic Circumpolar Wave and the global El Nino – Southern Oscillation Wave, J. Geophys. Res., 107(3165), doi: 10.1029/2000JC000581.

Whitehouse, M. J., Meredith, M. P., Rothery, P., Atkinson, A., Ward, P., Korbet, R. E., 2008, Rapid warming of the ocean around South Georgia, Southern Ocean, during the 20th century: Forcings, characteristics and implications for lower trophic levels, Deep-Sea Res. Part I, 55, 1218-1228.

Yuan, X., 2004, ENSO-related impacts on Antarctic sea ice: A synthesis of phenomenon and mechanisms, Antarc. Sci., 16, 415-425.

Zwally, H. J., 1991, Breakup of Antarctic ice, Nature, 350, doi: 10.1038/350274a0.