Quasi-Decadal Circumpolar Variability of Antarctic Sea Ice

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Abstract

Decadal variability of Antarctic sea ice and a role of ocean dynamics are examined with sea ice concentration (SIC) and sea surface temperature (SST) derived from satellite microwave observation and obtained by a high resolution coupled ocean-atmosphere-ice general circulation model (CGCM). Sea ice observations revealed a circumpolar variability of sea ice edge (SIE) on quasi-decadal time scale. SST also showed variation on similar time scale with warm (cool) anomaly roughly corresponding to retreat (extension) of SIE at negative (positive) southern annular mode (SAM). CGCM run without anthropogenic forcing and volcanic eruptions revealed that the leading mode of SIC is quasi-circumpolar pattern with a dominant time scale of 12−17 years and the leading mode of SST also has a similar pattern with the SIC showing a high degree of inverse correlation. The modeled SAM significantly correlates with these leading modes of both SIC and SST, representing the same structure with the observations. This indicates that the oceanic natural variability is the key to understand the quasi-decadal variability in sea ice.

(**Citation:** Bajish, C. C., S. Aoki, B. Taguchi, N. Komori and S.-J. Kim, 2013: Quasi-decadal circumpolar variability of Antarctic sea ice. *SOLA*, **9**, 31−34, doi:10.2151/sola.2013-008.)

1. Introduction

Antarctic sea ice is important for its role in the global and regional climate. Recent satellite records revealed that unlike the Arctic, the total Antarctic sea ice extent shows a slightly increasing trend, with regional variations of increase at the Ross Sea (RS) sector and decrease at the Bellingshausen Sea (BS) sector (Zwally et al. 2002; Cavalieri and Parkinson 2008; Parkinson and Cavalieri 2012). This long-term increasing trend in Antarctic sea ice has not been clearly reproduced by the IPCC-class models to date (e.g., Landrum et al. 2012) and the mechanism of its long-term variability has not been sufficiently addressed yet.

There are distinct climate modes of variability acting on the high-latitude region of the Southern Hemisphere (Yuan and Li 2008) and these modes have a primary role in illustrating the patterns of sea ice variability. SAM, or referred to as the Antarctic Oscillation (AAO) is one of the dominant climate modes in the southern hemisphere. SAM is represented by annular shaped zonally symmetric out of phase pressure anomalies over the Antarctic continent and the mid latitude region (Gong and Wang 1999; Thompson et al. 2000). Using a numerical model, Hall and Visbeck (2002) explained that positive SAM is associated with stronger westerly with increased ice transport towards the north resulting in the increase of total sea ice cover as a circumpolar mode.

Recently Yuan and Yonekura (2011) showed that SAM has a prominent variability on the qausi-decadal (8−16 year) time scale from observational records. This quasi-decadal SAM is accompanied with a circumpolar SST pattern, with cooler SST anomaly around the Antarctic coast for high SAM years. However, the response of sea ice on this time scale is not sufficiently studied both from observation and models. Some model studies (Holland et al. 2005; Goosse et al. 2008) indicate that SAM may have a larger influence on the sea ice variability from decadal to multi-decadal time scales. Most of the 20th century runs of IPCC models (CMIP3), including green house gases and ozone forcings, revealed the quasi-decadal variability in SAM, whereas only some models could reveal the variability of SST in this timescale, which might be primarily caused by ocean dynamics (Yuan and Yonekura 2011). The uncertainty in the behavior of decadal variabilites in the ocean and thereby its impact on sea ice has to be addressed. It is also necessary to differentiate the dynamics inherent to the coupled ocean-atmosphere-sea ice system from the conditions with anthropogenic and/or geological forcing. Hence detailed analysis on natural variability in the unforced atmosphere-ocean-sea ice model and comparisons with reality are indispensable.

In our present study, we investigate the decadal variability of sea ice and its relationship with atmosphere and ocean from observation and model. From around 30-year observational data of sea ice and SST, dominant patterns of decadal/long-term variability are studied, especially in relation to SAM. Dominant modes revealed in a coupled atmosphere-ocean-sea ice model run (longer than 100 years), without anthropogenic forcings and volcanic eruptions, are then examined to compare and explain the observed patterns by natural variability of climate system.

2. Data

To investigate the sea ice dynamics and its relationship with the oceanic and atmospheric variabilities, satellite-derived SIC and observed SST are used. Monthly SIC data are derived using AMSR-E Bootstrap Algorithm (Comiso 2000) from SMMR and SSM/I sensors to a polar stereographic grid (25 × 25 km) from 1979−2010. Monthly SST data set is NOAA Optimum Interpolation (OI) SST V.2 on a 1° × 1° grid from 1982−2010. Since we are interested in circumpolar variabilities, the atmospheric condition is represented by monthly mean SAM index from 1979−2010 from Climate Prediction Center (CPC).

To complement the observational record and examine the dynamics of the climate system, a CGCM is indispensable. The model used in this study is the CGCM for the Earth Simulator (CFES), which consists of the AFES3, AGCM (Kuwano-Yoshida et al. 2010; Ohfuchi et al. 2004) and the OIFES ocean-sea ice coupled model (Komori et al. 2005, 2008). The atmospheric component of the model has a horizontal resolution of T119 (the triangle truncation at wave number 119, ~1° in gaussian grid) and has 48 layers vertically, and the ocean component has a horizontal resolution of 0.5° and 54 vertical levels (Richter et al. 2010; Taguchi et al. 2012). The model was integrated for 120 years of which the last 100 years are analyzed. The trend was removed at each grid point. CFES has a higher resolution than most of the IPCC class (CMIP3) models, without anthropogenic forcing and it achieves rather realistic simulation of the Antarctic sea ice. Hence it is very useful tool to study the "natural" variability of sea ice.

In the present study all the variables are analyzed using their annually averaged time series unless stated otherwise. To study

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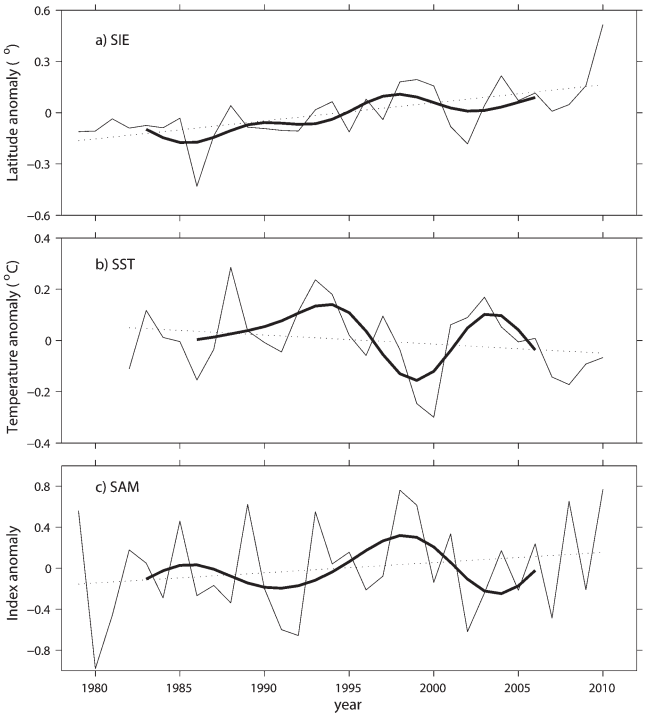

Fig. 1. a) Observed circumpolar averaged annual SIE anomaly time series (1979−2010) b) observed annual circumpolar SST [northward 5° latitude band from the SIE] anomaly time series (1982−2010) and c) annual SAM index (1979−2010) from Climate Prediction Center. The bold line represents a low passed (7 years) time series using a fft filter.

the variability of the Antarctic sea ice, we use statistical methods such as empirical orthogonal function (EOF) analysis, regression, correlation and spectral analysis. The analyzed model variables include SIC, SST and Geo-potential height (GPH) at 700 hPa. The data are detrended, and its climatological mean removed and normalized by dividing the standard deviation.

3. Results

3.1 Quasi-decadal variabilities in observed sea ice, SST and SAM

To examine the decadal variability of circumpolar SIE pattern, zonally averaged SIE is examined from the 32-year satellite observation record (Fig. 1a). SIE is defined by the equatorward latitudinal position of 30% isopleth of SIC (Yuan and Martinson 2000). The low-pass filtered (7-yr fft) circumpolar SIE shows the increasing trend with negative anomalies from late-1980s to early 1990s and early 2000s and positive anomalies in late 1990s. Taking zero-crossing points after subtracting the trend, the SIE exhibits quasi-decadal variability with the period of 11−16 years.

To examine the coupling between the sea ice and ocean, SST anomaly, averaged for the 5 degree bin from the climatological SIE, are derived and averaged zonally. The SST shows a decreasing trend with a prominent temporal fluctuation with positive anomalies in early 1990s and 2000s and negative in late 1990s (Fig. 1b). After taking the low-pass and subtracting the trend, the period of 10−13 years is estimated by zero-crossing. The correlation coefficient between the SIE and SST was −0.68 and −0.51 at 1 and 0 year lag, respectively. This negative correlation indicates that high (low) SST corresponds to retreat (expanded) SIE, although it is not highly statistically significant due to the low degree of freedom.

The SAM index, which represents the circumpolar atmospheric field, shows a decadal period of 11−13 years with the general increasing trend (Fig. 1c). The correlation between SIE and SAM is positive (0.78 and 0.63 at 1 and 0 year lag, respectively), although the correlation coefficients are not statistically significant. To summarize, there is a long-term Antarctic SIE increasing trend, associated with the long-term cooling surface ocean and increasing SAM trends on the quasi-decadal time scale from about 30-year observation records, although statistical significance is low presumably due to a short observation period.

3.2 Mode of sea ice variability

To examine the sea ice-ocean-atmosphere coupled dynamics, outputs of CGCM are examined. The simulated climatological mean fields of annually averaged SIC agree fairly well with the observation (Figs. 2a and 2b). The latitude of annually averaged SIE of the model (62.6°S) corresponds to that of the observation with the zonally averaged difference of only 0.2 degree (Fig. 2c). Overall, the model represents the observed pattern of sea ice variability fairly well.

To examine the modes of simulated sea ice variability on the decadal or longer time scales, spatial patterns and temporal characteristics are investigated. The leading mode of SIC is a quasi-circumpolar pattern explaining ~13% of variance (Fig. 3a). A prominent variability is located at the eastern end of the Weddell Gyre and the eastern Ross sea sector. The spectrum analysis reveals a broad peak at time scales of 12−17 years (Fig. 4), whereas the second mode (not shown) has no significant power in the decadal time scale. Hence the model's leading mode is the quasi-circumpolar pattern on the quasi-decadal time scale, which

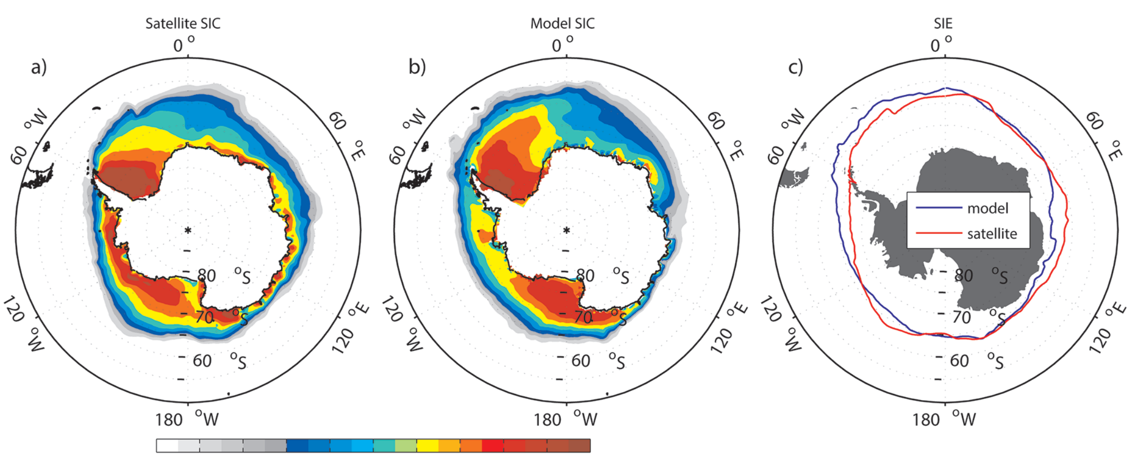

Fig. 2. The annual climatology of a) SIC (%) from the satellite data and b) CFES. c) SIE of annual mean SIC (%) from satellite data and CFES. The red line indicates the satellite and the blue line the model.

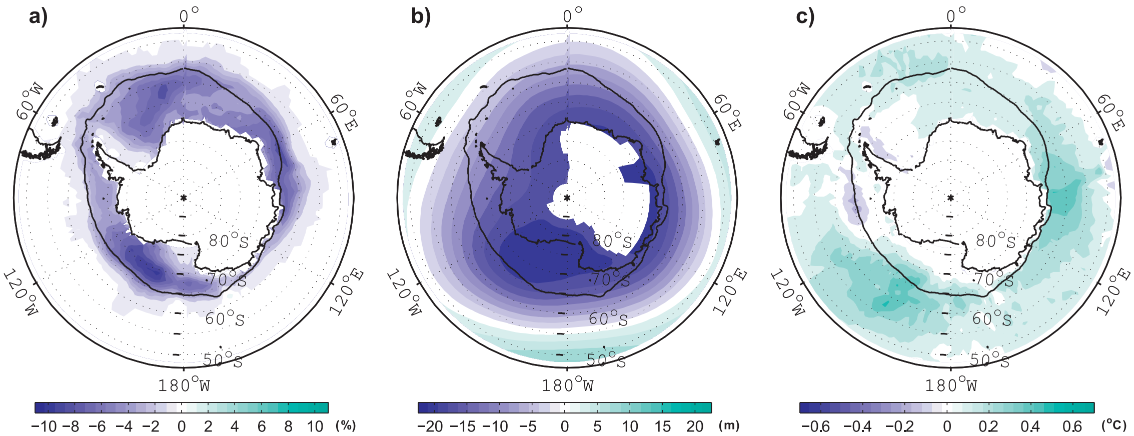

Fig. 3. Spatial patterns of leading mode of annual mean a) SIC anomalies [12.9% variance] b) GPH anomalies at 700 hPa [31.3% variance] and c) SST [13.3% variance] anomalies from CFES. The EOFs have been scaled by 1 standard deviation of the corresponding principal components to show the dimensional standard deviation at each grid point in the EOF. The black line indicates the mean SIE of the model.

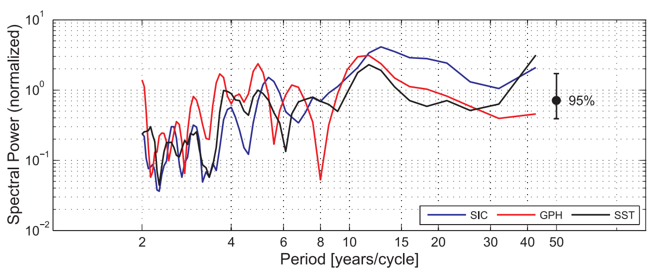

Fig. 4. Power spectrum of the principal components of first mode of SIC (blue line), GPH (red line) and SST (black line).

was not revealed in the shorter-satellite records of SIC (e.g., Udagawa et al. 2009; Landrum et al. 2012).

3.3 Dominant oceanic and atmospheric patterns and their relationship with sea ice

To explain the dynamics of the dominant mode of sea ice variability, EOFs of the model atmospheric and oceanic variables are examined. EOFs are calculated in the area of 20°S−90°S latitude band.

The spatial pattern of the leading mode of annual-mean GPH is the circumpolar pattern with out-of-phase anomalies between the polar and sub-polar region (Fig. 3b), corresponding to that of SAM (Thompson and Wallace 2000). This mode explains about 31%, which is also comparable to the SAM revealed in various reanalysis studies (Thompson and Wallace 2000; Yuan and Li 2008). Its time score has a prominent spectral peak at around 11−12 years with additional interannual peaks at 3−5 years (Fig. 4).

The EOF analysis of SST reveals that the first mode is a circumpolar pattern, which explains about 14%, with high variability in the Indian ocean and Ross sea sector (Fig. 3c). This pattern is similar to the first mode in the SIC anomaly. The spectral structure of time score has peaks on around 11−13 years (Fig. 4). Hence the modeled leading mode of SIC, GPH, and SST are the quasi-circumpolar patterns which have large amplitudes on quasi-decadal time scales.

The covariability among the quasi-circumpolar modes of SIC, GPH and SST is examined by lagged correlation analysis of the low-passed (5-year running average) time scores (Fig. 5). The quasi-circumpolar SIC has a high correlation (~0.69) with the circumpolar SST at zero lag at significance level of 95%, indicating that less (more) sea ice corresponds to the warmer (cooler) temperature around the SIE. The quasi-circumpolar SIC shows a correlation of ~ −0.35 with GPH at zero lag, indicating less (more) sea ice corresponding to negative (positive) SAM, although it is not statistically significant. SST and GPH circumpolar modes show a high negative correlation (~ −0.57) at zero lag; the cooler (warmer) SST around the SIE corresponds to the positive (negative) SAM. Hence the lagged correlation between the principal components of the circumpolar modes of SIC, GPH and SST shows qualitatively the same relationship that were revealed in the observation records, suggesting the presence of the coupled variability among those variables. The higher correlation between the oceanic and sea ice variability than that of the atmosphere and sea ice suggests that the quasi-circumpolar SIC variability is mainly driven by oceanic variability on this quasi-decadal time period.

4. Discussions

The observational records of sea ice have revealed a circumpolar variability of SIE on quasi-decadal time scale. SST observations and SAM record also showed variation on similar time scales with warm (cool) anomaly corresponding to retreat (extension) of SIE at negative (positive) SAM. The presence and periodicity of the quasi-decadal variabilities in SST and SAM are consistent with those described by Yuan and Yonekura (2011), who estimated from different observation and reanalysis data. These relationships are also confirmed from our model study. The model and observation shows a good quantitative agreement. The correlation coefficients between the circumpolar SIE and SST anomalies are similar between model and observation (~0.6−0.7). The magnitudes of the variabilities compared reasonably well quantitatively between the observation and model. When the circumpolar average anomalies at SIE are calculated as in the same manner with the observation (Fig. 1), the model circumpolar SST decrease (increase) of 1°C corresponds to 1.4 degree extension (retreat) of circumpolar SIE latitude towards north (south) from the linear regression, while the SST anomaly of 1°C corresponds to 0.4 degree in latitude in the observation. The model response is slightly larger than that of the observation, given the uncertainty caused by different record lengths.

A possible interplay of feedback mechanisms can set the time scale of this coupled variability in the climate system. Cooler SST in the south (during positive SAM), and hence stronger temperature gradient, enhances the atmospheric cyclogenesis and intensifies the near surface westerlies (Marshall and Connolley 2006), leading SAM towards a more positive state. The lower SST and stronger SAM contributes the equator-ward expansion of SIE. This is a positive feedback. On the other hand, stronger westerly enhances upwelling around the vicinity of the Antarctic continent and brings warmer subsurface water to the surface (Lefebvre 2004). This warmer SST then sets up a negative feedback, weakening the cyclogensis and SAM and causing a pole-ward retreat

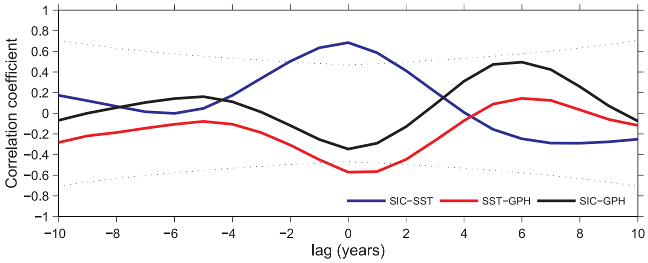

Fig. 5. Lagged correlation between the 5 year running averaged principal components of the first modes of SIC and SST (blue line) [r = 0.69 at 0 lag], SST and GPH (red line) [r = −0.57 at 0 lag] and SIC and GPH (black) [r = −0.35 at 0 lag]. The dotted line indicates the 95% confidence limit.

of SIE. The coupled feedback mechanism could be the driving mechanism causing the circumpolar variability on a quasi-decadal time scale.

5. Conclusion

Both observation and model show a coupled circumpolar variability in a quasi-decadal time scale for the Antarctic sea ice. The oceanic variations in the SST drive the decadal variability in the sea ice. The atmosphere, especially SAM, initiates the decadal sea ice variability. The decadal SAM and oceanic variability are coupled through natural dynamic and thermodynamic feedback. This indicates that the natural quasi-decadal variability of the ocean and its impact to the atmosphere is the key in the coupled system. The feedback mechanisms on the longer timescale between ocean-ice-atmosphere have to be understood properly to predict future change in the Antarctic sea ice.

Acknowledgments

NOAA_OI_SST_V2 data was provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website at http://www.esrl.noaa.gov/psd/. The monthly mean Antarctic Oscillation index was provided by the NOAA/NCEP Climate Prediction Center in Camp Springs, MD (http://www.cpc.ncep.noaa.gov). This work was supported by Grants-in-Aids for Scientific Research of the Ministry of Education, Culture, Sports, Science and Technology in Japan. S.-J. Kim was supported by the project "Reconstruction and observation of components for the Annular Mode to investigate the cause of climate change at polar regions" (PE13010) of Korea Polar Research Institute. This study was carried out under the Joint Research Program of the Institute of Low Temperature Science, Hokkaido University. The integration of the CFES was carried out on the Earth Simulator under the support of JAMSTEC. The authors thank the manuscript reviewers for their valuable comments.

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Manuscript received 6 January 2013, accepted 8 February 2013
SOLA: http://www.jstage.jst.go.jp/browse/sola