Consideration of the Kerguelen-Davis Oscillation Index (KDOI) influencing variability on the environmental ecosystem in the Prydz Bay Region, east Antarctic: data exploration

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ABSTRACT

Significant changes in the environment (climate-sea ice-ocean) and the ecosystem of the Antarctic Ocean have occurred frequently in recent decades. A key factor that has brought about these changes in the environmental ecosystem of the Antarctic Ocean seems to be a large change in the westerlies around the Antarctica analyzing Southern Annular Mode (SAM), alias Antarctic Oscillation Index (AOI). On the other hand, JARPA I and II have various datasets on whales over two decades since 1989/90. From these aspects, we have hypothetically thought that the variability of in westerlies has influenced the ocean including sea ice, biological factors and the whale ecosystem as upper predators. We therefore tried to search, arrange and analyze accessible relevant data in the complex systems of climate-ocean-ecosystem as data exploration in stages. As a basic environmental regional climate index, we made determinations from sea level pressure differences between the Kerguelen Islands and the Davis Station, the east Antarctica (Kerguelen-Davis Oscillation Index; KDOI). KDOI during 2006 and 2013 showed the variability of an upward trend with approximately 2-year periodicity. Sea ice extent in austral summer from 1979 to 2011 showed the upward trend taking yearly variability suggesting some relationship with KDOI. In addition, the lower abundance estimate of Antarctic minke whales coincided with the larger sea ice extent as in 1997/98 and 2007/08, probably due to navigational limited survey by sea ice. Rapid southward shift of the Southern Boundary of the Antarctic Circumpolar Current (SBACC) coincided with a rapid increase in humpback whales as in 1995/96 and 2001/02, probably due to the Antarctic Circumpolar Water shifts southward. KDOI indicates the characteristic variability and suggests the relationships to the regional environmental ecosystems such as sea ice, ocean and biological ecosystem including whales with the coordinate environmental regional index as a future possibility.

KEY WORDS: EAST ANTARCTIC OCEAN, ENVIRONMENTAL ECOSYSTEM, KDOI, WESTERLIES VARIABILITY, WHALE

INTRODUCTION

Significant changes in the environment (climate-sea ice-ocean) and the ecosystem of the Antarctic Ocean frequently have occurred in recent decades (as review, IPCC, 2001; IPCC, 2007; Turner *et al*., 2009; Rintoul *et al*., 2012). The key factor that has brought about these changes in the environmental ecosystem of the Antarctic Ocean seems to be a large change in the westerlies around the Antarctica analyzing Southern Annular Mode (SAM), alias Antarctic Oscillation Index (AOI) (Gong and Wang, 1999; Thompson and Solomon, 2002; Arblaster and Meehl, 2006; Stammerjohn *et al*., 2008; Kang *et al*., 2011; Thompson *et al*., 2011; Villalba *et al*., 2012, Miles *et al*., 2013).

On the other hand, there are many reports on variability in the biological ecosystem (as review, Turner *et al*., 2009; Rintoul *et al*., 2012). Especially, the abundance of Antarctic krill (*Euphausia superba*) , a key species of the Antarctic Ocean ecosystem, has decreased in recent decades (Siegel and Loeb, 1995 ; Siegel *et al*., 1997; Loeb *et al*., 1997 ; Naganobu *et al*., 1999; Atkinson *et.al*., 2004). It is often discussed that remarkable decreases in krill and its predators such as penguins around the Antarctic Peninsula area depend on regional environmental changes due to the entire climate change in the Antarctic/Southern Ocean (Loeb *et al*., 1997; Naganobu et al., *et al*., 1999; Loeb *et al*., 2009; Trivelpiece *et al*., 2011, Loeb *et al*., 2013). In these various phenomena, how can we take an approach to examine the relationships between the climate and/or oceanic environmental variability and relevant issues of

JARPA I and II surveys (Pastene *et al*., 2014)? As these relationships are basically complex and controversial, various approaches can be attempted. Here we try to apply an original climate regional index of westerlies variability for the biological ecosystem around Prydz Bay relating the JARPA survey area as a hypothetical approach. .

Changes in the ocean and sea ice are closely related to SAM. However, SAM is a macro scale of the entire Southern Ocean. The targeted ecosystem phenomena are on a regional scale. It is better to use an environmental index corresponding to the regional scale of the targeted ecosystem phenomena. Then, we try to apply the proven approach on a climate oscillation index; Drake Passage Oscillation Index (DPOI) (Naganobu *et al*., 1999) in the Antarctic Peninsula area, the west Antarctic Ocean, to the Prydz Bay region related to the JARPA area, the east Antarctic Ocean. DPOI indicated high correlations with several factors such as krill recruitment, sea ice and chlorophyll-a (Naganobu *et al*., 1999). IPCC (2001) reviewed these results and had the interest in the long-term continuous trend to DPOI. The continuous studies of DPOI have been indicating additional preliminary results using the long-term period data for approximately 60 years since 1952 (Kondo, 2009; Naganobu *et al*., 2009; Yoda, 2011). Then, the methodology of DPOI in the west Antarctic Ocean is applied to the Prydz bay area, the east Antarctic Ocean (Fig. 1).

Although both east and west areas have common circumpolar structure, each area indicates the regional characteristics of each region. The Prydz Bay area has the aspects of the typical east Antarctic Ocean ecosystem (Anonymous, 1985; Hosie *et al*., 2000; Nicol *et al*., 2000; Nicol and Meiners, 2010) including the traditional krill fishing grounds (Naganobu *et al.*, 2008) compared with the west Antarctic Ocean ecosystem (Hewitt *et al*., 2004; Watkins *et al.*, 2004). However, analysis on the time series of the environment and ecosystem is a complex subject with limited datasets. Therefore, it first noticed the climatic variation of the complex subject. The same methodology of DPOI was applied to the Prydz Bay area. Two climate observation stations to obtain each Sea Level Pressure (SLP) were selected; the north, Port-aux-francais, Kerguelen Islands in the Southern Ocean and the south, Davis Station, Antarctica (Fig. 2). The differences in SLP between Kerguelen and Davis indicate strength of westerlies as geostrophic wind. Fluctuations in the differences are hereinafter referred to as the Kerguelen-Davis Oscillation Index (KDOI).

MATERIALS AND METHODS

We tried to search, arrange and analyze accessible relevant data in the complex systems of climate-ocean-ecosystem as data exploration in stages.

First, we have assessed a climate environmental index, as a regional basic indictor, determined from sea level pressure differences between Port-aux-francais (surface meteorological observation ID: 61998, location 49°-21’S 70°-15’E), Kerguelen Islands as the northern station and Davis Station (ID: 89571, 68°-34’S, 77°-58’E) as the southern station from 2006 to 2013 (Fig. 3). KDOI can be obtained to calculate the differences in sea level pressure (SLP) between two meteorological stations crossing the westerlies zone.

KDOI=SLP (Kerguelen) －SLP (Davis)
SLP: sea level pressure (monthly), hPa

KDOI is understood as geostrophic wind. A higher KDOI means stronger westerlies. On the other hand, a weaker KDOI means weaker westerlies. The northern station requires a suitable position in the Southern Ocean and the southern station on the Antarctic Continent. We considered some meteorological observation stations in the eastern Antarctic Ocean. Finally, we adopted Port-aux-francais, Kerguelen Islands and Davis Station because of its suitable position in the Prydz Bay region with regards to high productivity waters.

The SLP data at Kerguelen were acquired from the public web site of German Weather Service (The Global Climate Observing System Surface Network Monitoring Centre data set, Deutscher Wetterdienst).
http://www.dwd.de/bvbw/appmanager/bvbw/dwdwwwDesktop?_nfpb=true&_windowLabel=dwdwww_main_book&T15806838371147176099165gsbDocumentPath=Content%2FOeffentlichkeit%2FKU%2FKU4%2FKU42%2FGSNMC%2Fteaser__datensaetze.html&switchLang=en&_pageLabel=_dwdwww_klima_umwelt_datenzentren_gsnmc
The SLP data at Davis station were acquired from the public web site of the British Antarctic Survey.
http://www.antarctica.ac.uk/met/READER/surface/Davis.06.msl_pressure.html

The period of the Kerguelen data that can be actually used is comparatively short from 2006 up to the present time. On the other hand, the period of the Davis data that can be actually used is long from 1957 up to the present time. Therefore, we calculated KDOI from January 2006 to May 2013 due to the availability of both data periods.

Second, the variability in the extent of sea ice enclosed within 60°S south and 70°E -90°E, from 1979 to 2011 was examined. The data on sea ice concentration measured by the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) sensor from the Japan Aerospace Exploration Agency (JAXA) satellite was used. The geographical range of the analysis was enclosed within 70°E-90°E and 60°S- of the coast of Antarctica. We calculated the monthly average of the sea ice area (more than 15% per a pixel (25×25km) in December, January and February (austral summer season) from 1979-2011.

Third, we used the estimates of abundance and distribution patterns of humpback whales (*Megaptera novaeangliae*) and Antarctic minke whales (*Balaenoptera bonaerensis*) in Area IV from 1989/90 to 2007/08 based on JARPA and JARPA II sighting survey data south of 60 °S (Hakamada and Matsuoka, 2014a, 2014b; Matsuoka and Hakamada, 2014; Murase *et al*., 2014) to examine relationships between KDOI, sea ice and the latitudinal variability of the Southern Boundary of Antarctic Circumpolar Current in the existing paper.

RESULTS AND DISCUSSION

Time-series of KDOI showed the following results. (1) KDOI indicated that the available data of Kerguelen was limited to the years since 2006 while the Davis's data was spread over 56 years since 1957 (Fig. 4) Therefore, the analytical period of KDOI was limited to seven and half years at this stage. (2) The monthly KDOI from 2006 to 2013 showed the variability of an upward trend (Fig. 5a). The seasonal KDOI, 3-month running mean showed numerically higher values during austral summer and lower during winter with an upward trend (Fig. 5b). The yearly KDOI, 12-month running mean showed approximately a 2-year periodicity with an upward trend (Fig. 5c). The combined graph of the monthly with its liner approximation and yearly KDOI shows the trends moving upward with a 2-year periodicity, although the period from 2006 to 2013 was limited and short (Fig. 5d). Although this available period of KDOI has difficulty examining minute relationships with whales, KDOI has a role as a background environmental factor.

Time-series of sea ice suggested concurrent trends with abundance estimates of Antarctic minke whales (Fig. 6). Sea ice extent in austral summer (December, January and February) from 1979 to 2011 showed the upward trend taking yearly variability suggesting some relationship with KDOI. In addition, the lower abundance estimate of Antarctic minke whales coincided with the larger sea ice extent as in 1997/98 and 2007/08, probably due to a navigational survey limited by the hard conditions of sea ice.

Although we initially hypothesised the effect of KDOI with regards to the question on the recent rapid increase in humpback whales in the JARPA area (Pastene *et al*., 2014), the available period of KDOI is too short to examine it. On the other hand, we searched different ways using existing papers on the long-term oceanographic variability, especially SBACC which might affect the biological ecosystem (Tynan, 1998; Matsuoka *et al*., 2003; Naganobu et al., 2010). We therefore found the coincidental phenomena between SBACC and whale as follows. Rapid southward shift of SBACC (Yabuki, 2006) coincided with a rapid increase in humpback whales as in 1995/96 and 2001/02, probably due to the Antarctic Circumpolar Water southward shift (Fig. 7). The variability of the Antarctic Circumpolar Water is an important subject for the Antarctic Ocean ecosystem and a detailed analysis is encourage (Iida *et al*., 2013; Watanabe *et al*., 2014).

KDOI indicates the characteristic variability and suggests relationships with the regional environmental ecosystems such as sea ice, ocean and biological ecosystem including whales. In addition, KDOI is just one regional climate phenomena compared with the entire Southern Ocean scale such as SAM. The limited data made it difficult to depend to construct the process of the regional environmental ecosystem around whales as scientific results have to depend on the evidence data. Fig. 8 shows the comprehensive linkages of the periods of JARPA and KDOI with the variability of SAM. During the period of JARPA, SAM showed large variability with an upward trend. SAM as the entire scale index and KDOI as the regional scale index must have some syncronisations. KDOI has potential as the coordinate environmental index in the east Antarctic Ocean with the increasing SLP and relevant oceanic/biological datasets.

CONCLUSIONS

KDOI from 2006 to 2013 showed the variability of an upward trend with approximately 2-year periodicity. Sea ice extent in austral summer from 1979 to 2011 showed the upward trend taking yearly variability suggesting some relationship with KDOI. In addition, the lower abundance estimate of Antarctic minke whales coincided with the larger sea ice extent as in 1997/98 and 2007/08, probably due to a navigational survey limited by sea ice. Rapid southward shift of SBACC coincided with the rapid increase in humpback whales as in 1995/96 and 2001/02, probably due to the Antarctic Circumpolar Water southward shift. KDOI indicates the characteristic variability and suggests relationships with the regional environmental ecosystems such as sea ice, ocean and biological ecosystem including krill and whales with the coordinate climate index as a future possibility.

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<Figure 1-8 and captions>

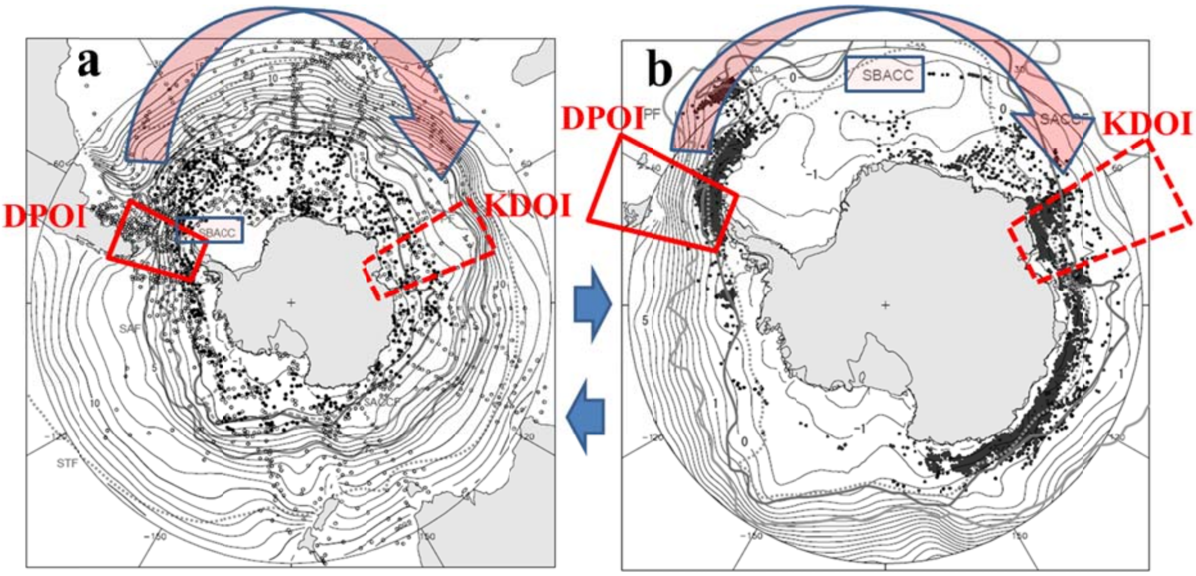

Figure 1. Connectional image from DPOI to KDOI: (a) the scientific geographical distribution of krill (from Marr, 1962) and (b) the world fishing positions of krill with MTEM-200 (Mean TEMperature from 0 to 200m) indicating the locations of oceanic fronts such as SBACC (the Southern Boundary of the Antarctic Circumpolar Current) and others (modified from Orsi *et al*., 1995; Naganobu *et al*., 2008). SBACC is the key front for krill and its predators such as whales in the circum Antarctic Ocean ecosystem.

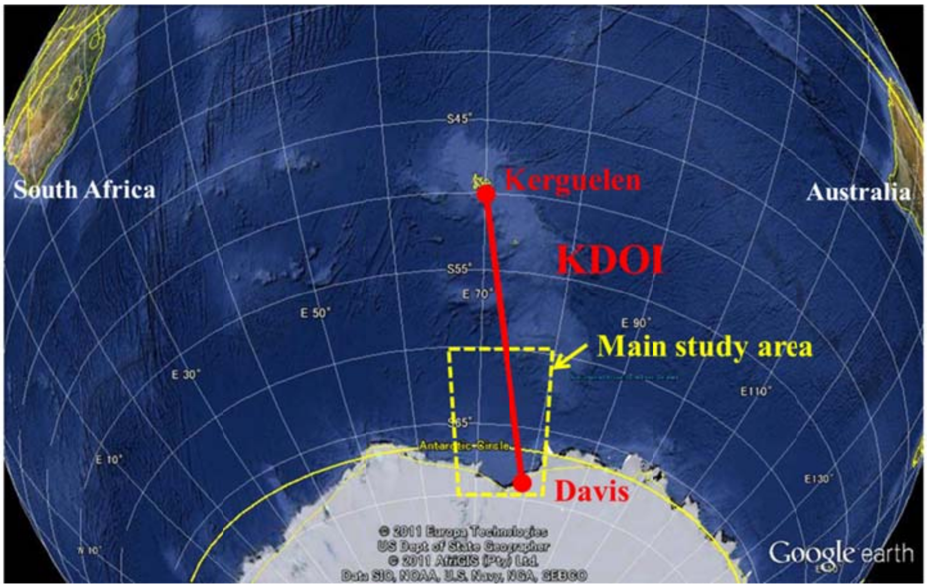

Figure 2. KDOI (Kerguelen-Davis Oscillation Index: the differences in sea level pressures between Kerguelen and Davis station) with the main oceanic study area around Prydz Bay referring to JARPA's area, east Antarctica.

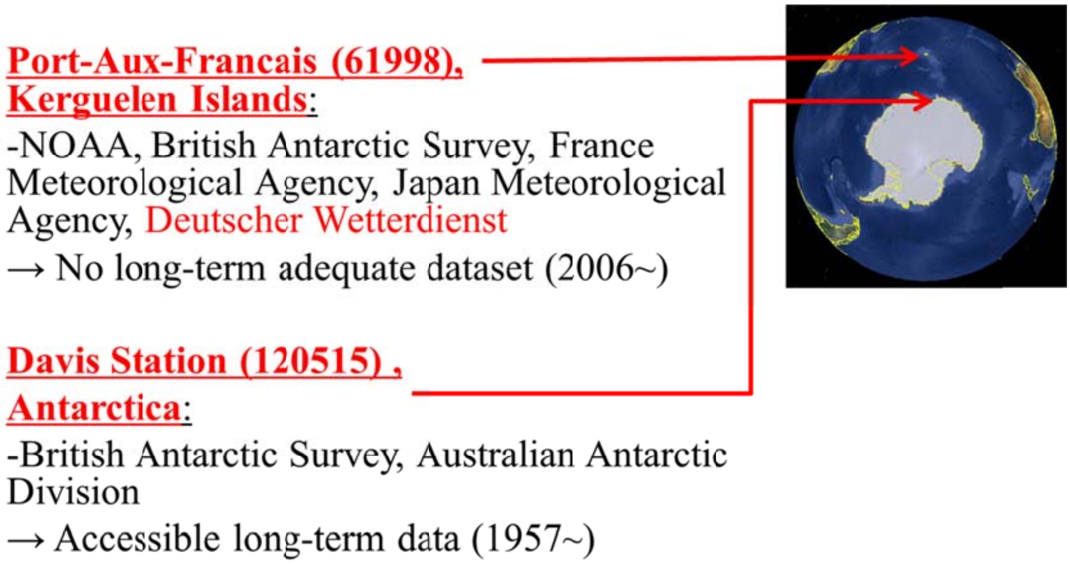

Figure 3. Data exploration on Sea Level Pressure (monthly) at Port-Aux-Francais (world surface meteorological station ID: 61998), Kerguelen Islands and Davis Station (ID: 120515) for KDOI.

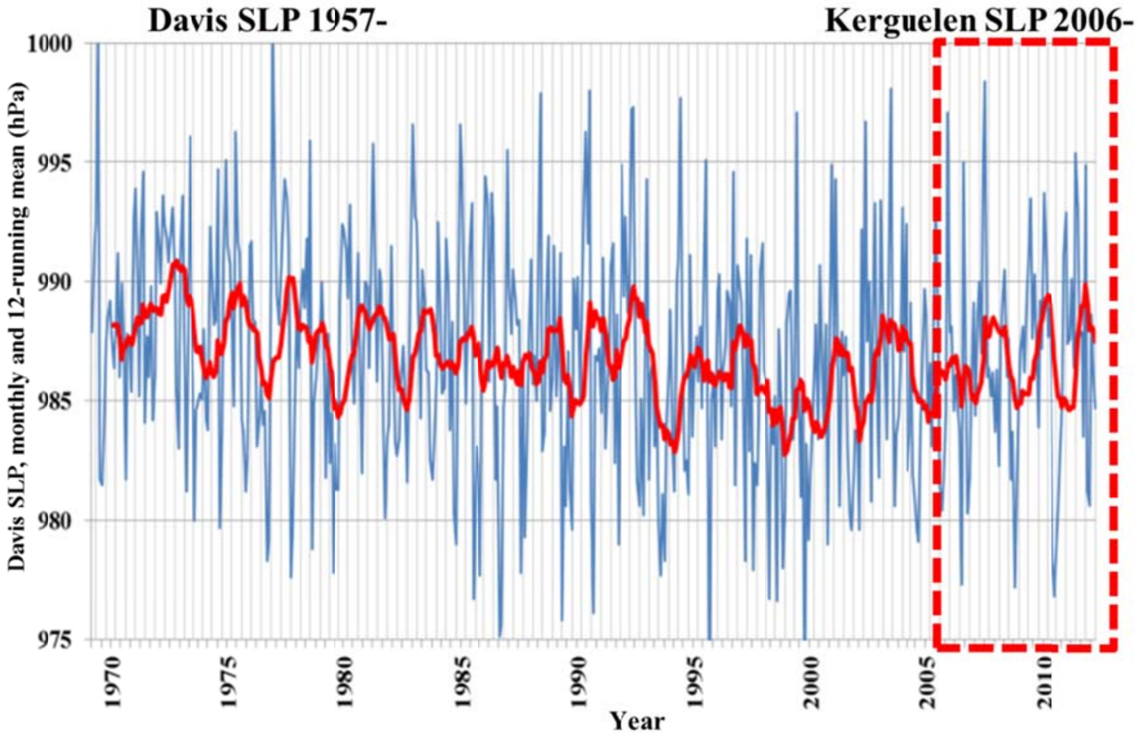

Figure 4. Comparison between the available data periods at Kerguelen and Davis. The available data of Kerguelen was limited to the years from 2006 while Davis's data was over 56 years since 1957.

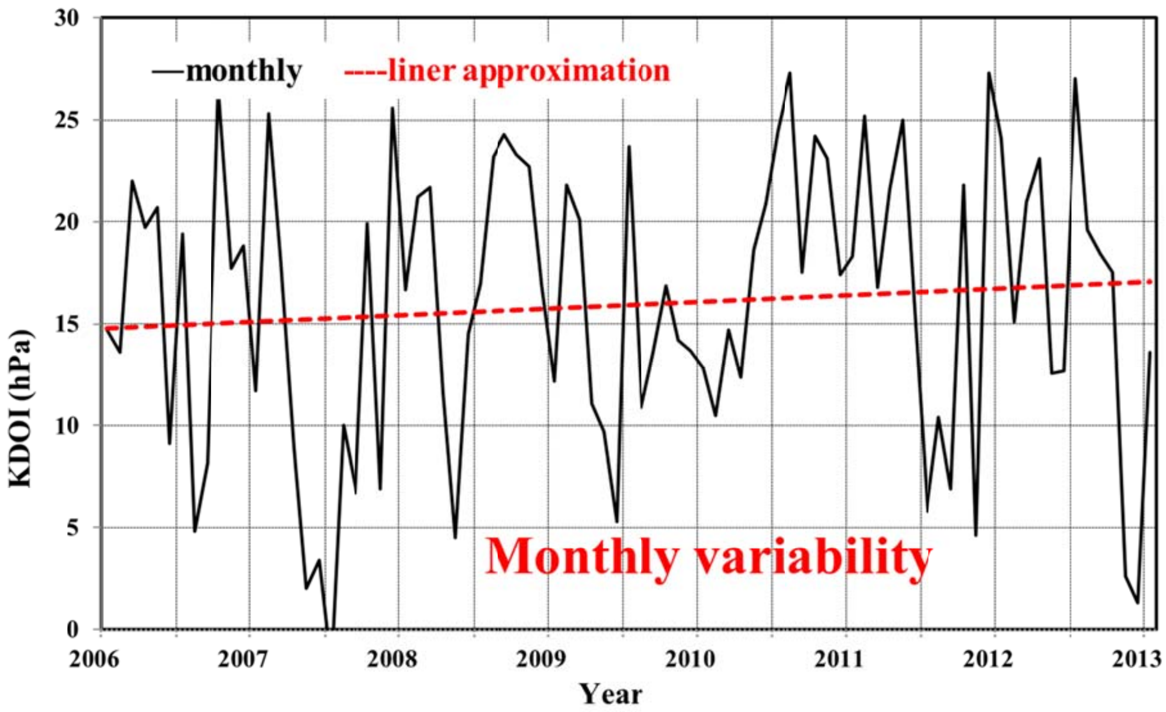

Figure 5a. Time series of sea level pressure difference between Kerguelen and Davis Oscillation Index (KDOI)), monthly mean from 2006 to 20013 shows upward trend.

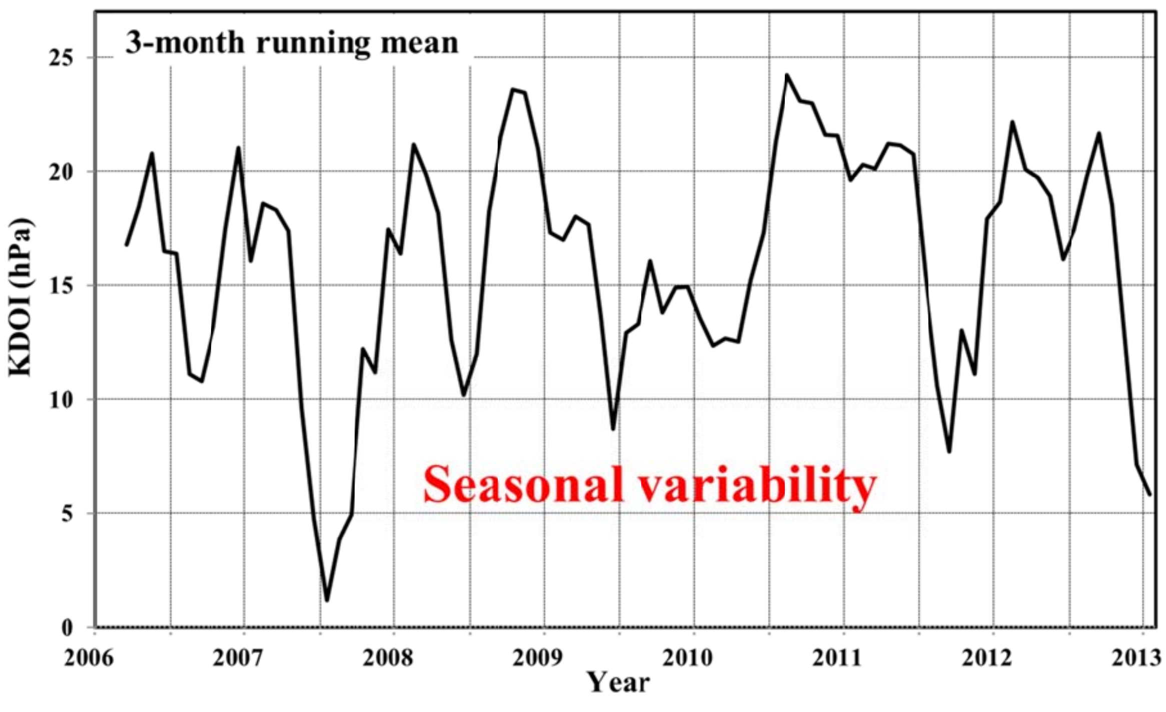

Figure 5b. Time series of KDOI, 3-month running mean from 2006 to 2013 shows numerically higher during austral summer and lower during winter.

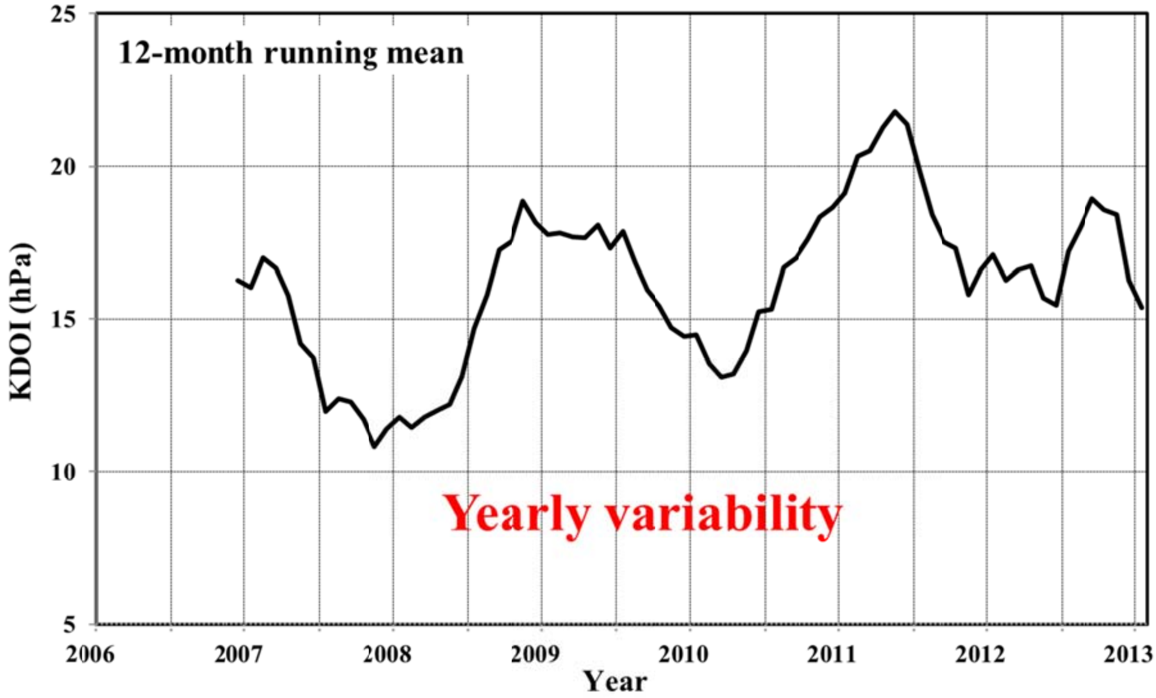

Figure 5c. Time series of KDOI, 12-month running mean from 2006 to 2013 shows approximately 2-year periodicity.

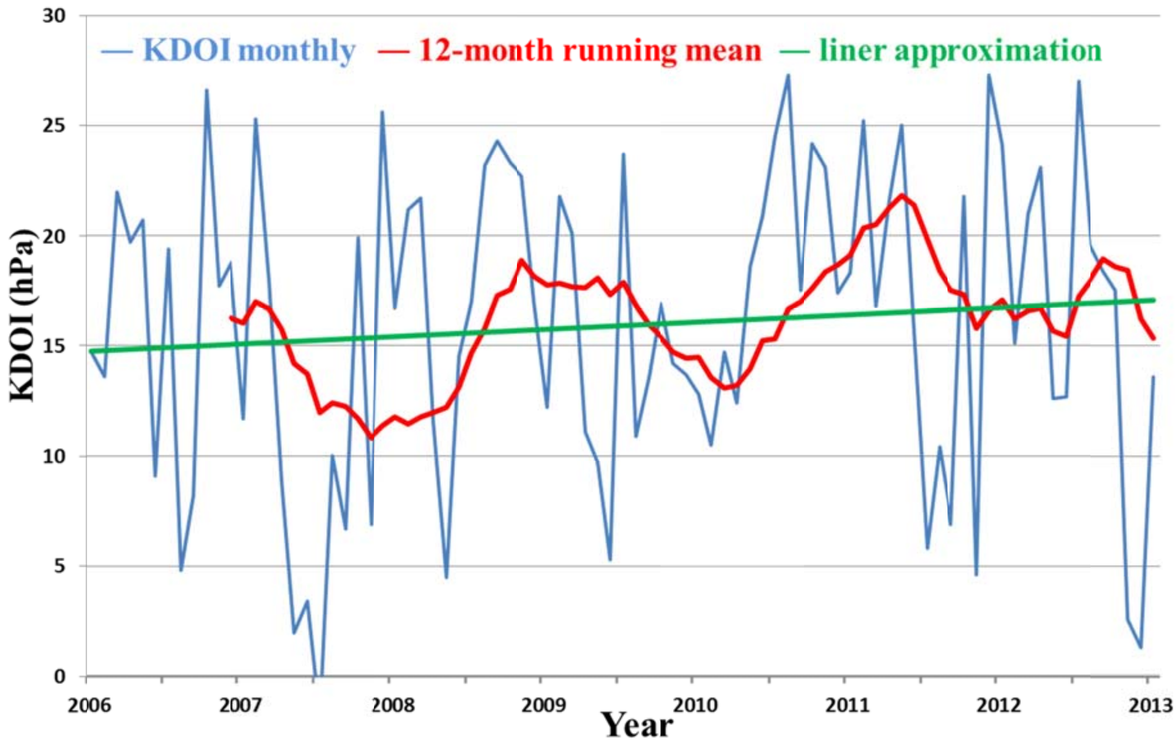

Figure 5d. The combined graph of the monthly, liner approximation and yearly KDOI. Variability of KDOI from 2006 to 2013 shows upward trend with approximately 2-year periodicity.

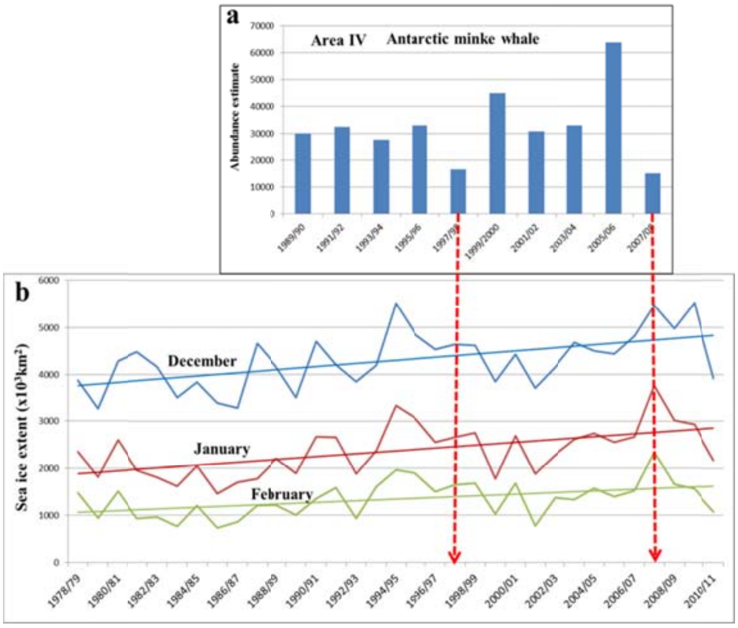

Figure 6. (a) Abundance estimate of Antarctic minke whales in Area IV from 1989/90 to 2007/08, JARPA (data from Hakamada and Matsuoka., 2014a) and (b) sea ice extent in December, January and February in the region between 70-90E south of 60S, from 1978/79 to 2010/11. The lower abundance estimate coincided with the larger sea ice extent as in 1997/98 and 2007/08.

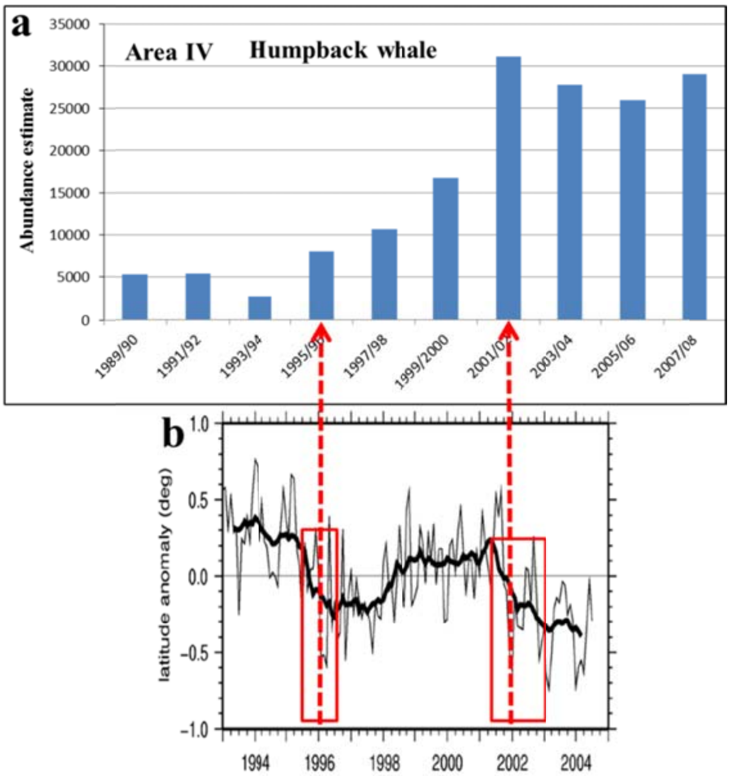

Figure 7. (a) Abundance estimate of humpback whales in Area IV from 1989/90 to 2007/08, JARPA (data from Hakamada and Matsuoka., 2014b) and (b) zonal average (black thick line indicates 11-month running mean, negative anomaly indicates southward shift) of SBACC (the Southern Boundary of the Antarctic Circumpolar Current) in the Indian sector from 1993 to 2005 (modified from Yabuki, 2006). Rapid southward shift of SBACC coincided with rapid increase of humpback whales as in 1995/96 and 2001/02.

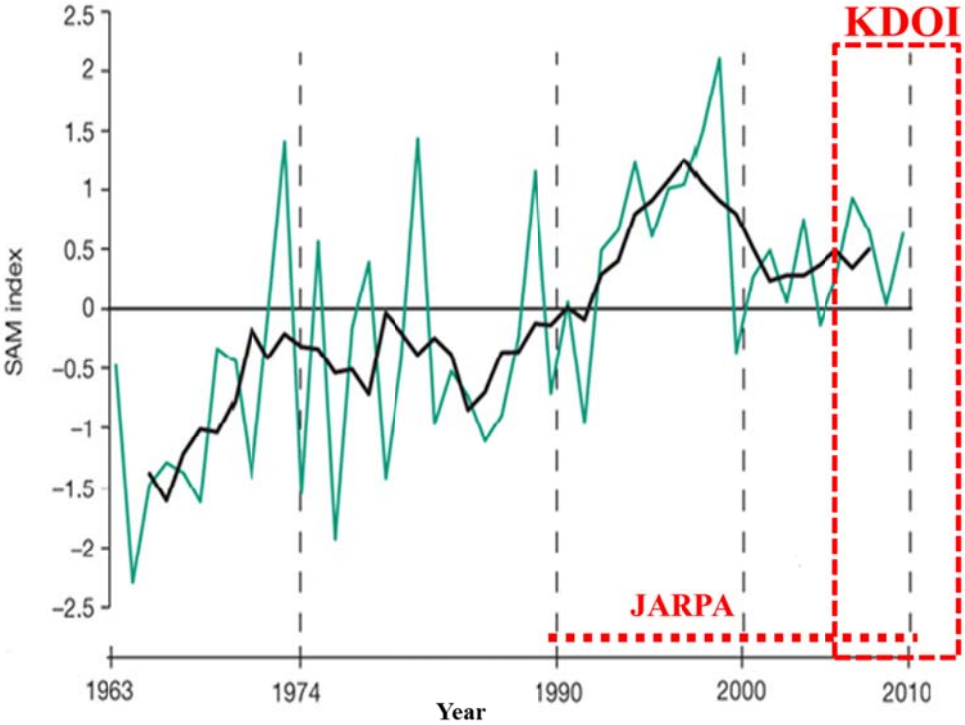

Figure 8. Time series of the December-May SAM (Southern Annular Mode) index (black thick line indicates 5-year moving) from 1963 to 2010 (modified from Miles *et al.*, 2013) with the available periods of JARPA and KDOI data. The SAM trend shows upward movement which means a strengthening of the circumpolar westerlies.