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# A record of Antarctic sea ice extent in the Southern Indian Ocean for the past 300 yr and its relationship with global mean temperature

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Received: 16 June 2013 – Accepted: 19 June 2013 – Published: 19 July 2013

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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## Abstract

The differing response of ice extent in the Arctic and Antarctic to global average temperature change, over approximately the last three decades, highlights the importance of reconstructing long-term sea ice history. Here, using high-resolution ice core records of methanesulfonate ( $\text{MS}^-$ ) from the East Antarctic Ice Sheet in Princess Elizabeth Land, we reconstruct southern Indian Ocean sea ice extent (SIE) for the sector  $70^\circ\text{E}$ – $100^\circ\text{E}$  for the period 1708–2000 A.D. Annual  $\text{MS}^-$  concentration positively correlates in this sector with satellite-derived SIE for the period 1973–2000 ( $P < 0.05$ ). The 293 yr  $\text{MS}^-$  record of proxy SIE shows multi-decadal variations, with large decreases occurring in two warm intervals during the Little Ice Age, and during the 1940s. However, after the 1980s there is a change in phase between Antarctic SIE and global temperature change, with both increasing. This paradox is probably attributable to the strong anomaly in the Southern Annular Mode (SAM) in the recent three decades.

## 1 Introduction

Sea ice extent (SIE) is an important climate variable. It influences Earth's surface energy balance, and plays a major feedback role in climate changes at local to hemispheric scales. However, reliable data on sea ice extent are only available for the satellite era, since the 1970s. This hinders our understanding of the role of sea ice in climate forcing and of the mechanisms of long-term changes in SIE. For instance, in recent decades there has been a strong trend of declining Arctic SIE, but a slightly increasing trend in Antarctic SIE. Whether these opposing responses to warming global temperature are a long-term phenomena, or have only appeared in recent decades, is unknown, largely because of the short period of reliable sea ice records.

Although attempts have been made to reconstruct sea ice extent in Antarctica from voyage and whaling records (e.g. Cotte and Guinet, 2005; De la Mare and William, 2009) the early data are sporadic, and the results inconclusive. However in the 1990s,

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methanesulfonate ( $\text{CH}_3\text{SO}^-$  or  $\text{MS}^-$ ) was found to be a sensitive proxy of SIE in some sectors of Antarctica (e.g. Welch et al., 1993). This is because  $\text{MS}^-$  (an oxidation product of dimethylsulphide, DMS, which is produced by sea ice algae) is released when sea ice decays, and there is hence a strong link between the extent of the ice and the amount of  $\text{MS}^-$  produced.

Both positive and negative correlations have been observed between  $\text{MS}^-$  and SIE in different sectors of Antarctica (Welch et al., 1993; Pasteur et al., 1995; Sun et al., 2002; Curran et al., 2003; Foster et al., 2006; Abram et al., 2007, 2010; Myerson et al., 2002; Sneed et al., 2011). But in the Indian Ocean sector, studies from Law Dome ( $110^\circ\text{E}$ ; Curran et al., 2003) and Wilhelm II Land ( $86^\circ\text{E}$ ; Foster et al., 2006) have shown positive correlation between  $\text{MS}^-$  and SIE, suggesting that the homogeneous coastline east of the Lambert Glacier basin (LGB) may be a good region to recover a long SIE record for the Southern Indian Ocean. However, there are still large geographical gaps in such reconstruction, with one of the largest being in the western part of this sector. Here, we analyze  $\text{MS}^-$  records in an ice core that was extracted in January 2002 from site LGB69 ( $70^\circ50'\text{S}$ ,  $77^\circ04'\text{E}$ , 1850 m.a.s.l.). This site is located on the coastal escarpment of the ice sheet, about 160 km from the coast. We statistically tested the relationship between  $\text{MS}^-$  in this ice core and satellite observed SIE between 1973–2000 to establish a basis for a long-term SIE reconstruction.

## 2 Ice core and sea ice data sets and their relationship

The LGB69 ice core was drilled in January 2002 in Princess Elizabeth Land (East Antarctica) during the 18th Chinese National Antarctica Research Expedition (CHINARE-18). The core was 102 m in length and was dated by counting 293 annual cycles of multiple chemical species as well as known volcanic events (Li et al., 2012), with very high dating accuracy ( $\pm 1\text{ yr}$  at the bottom). Over this near-coastal area of Prince Elizabeth Land, the integrated tropospheric moisture flux is southwards (Xiao et al., 2004a), and a high snow accumulation rate was recorded both by an au-

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tomatic weather station and with a stake array (Qin et al., 2004; Ding et al., 2011). Thus ice cores from this region capture climatic signals from the adjacent high latitudes of the Southern Indian Ocean at high resolution. Earlier studies on an ice core from LGB65 (130 km further south), showed that a quasi-stationary low pressure system in the Southern Indian Ocean provides precipitation to Princess Elizabeth Land (Xiao et al., 2004b).

We use SIE data between 1973–1996 derived by Jacka and Budd (1998) from the US Navy/NOAA Joint Ice Center (JIC) weekly maps of sea ice extent and concentration to provide the northern edge of the sea ice cover every 10° of longitude and each month (<http://staff.acecrc.org.au/~jacka/seaice.html>). We extend the SIE data to 2000 AD using SMMR/SSM/I passive microwave remote sensing data from the US National Snow and Ice Data Center (NSIDC).

The mean monthly position of the SIE around Antarctica is shown in Fig. 2a for the period 1973–2000. The northernmost extent reaches 55° S over the sector 20° E–30° E at the seasonal maximum in September, and retreats as far south as 75° S over the sector 180° E–190° E at seasonal minimum in February. These extremes are due to ice drift resulting from complex ocean and atmospheric circulation in the deep embayments of the Ross and Weddell seas, which also produce the well-known sea ice dipole between the two sectors (Yuan et al., 2001). Over the more uniform coastline of East Antarctica between 60° E and 150° E, SIE changes have a relatively small seasonal amplitude, and are generally similar across the region. Hence this may be a better region for the reconstruction of year-to-year long-term changes and we focus on the relationship between  $MS^-$  in LGB69 and sea ice in this region.

We correlate the annual average  $MS^-$  (from June to the following July) in the LGB69 core with maximum SIE (average of August to October extent in the first winter of each record) over 36 sub-sectors of 10° longitude for the period 1973–2000 (inclusive, 28 yr). The highest correlation occurs over the sector 70° E–100° E ( $r = 0.40$ ,  $P < 0.05$ ) and within this sector, the highest correlation ( $r = 0.41$ ) is in the sub-sector 70° E–80° E (Fig. 2b). Although there are strong correlations between LGB69  $MS^-$  and SIE over

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other more distant sectors of the Southern Ocean, they are largely due to the autocorrelation of the maximum SIE there with SIE at 70° E (red lines in Fig. 2b). Clearly, MS<sup>-</sup> in LGB69 most strongly reflects the sea ice changes over the 70° E–100° E sector of the Southern Indian Ocean.

### 3 Sea ice extent and global temperature

In Fig. 3a we present the 293 yr MS<sup>-</sup> record from LGB69. It shows that there have been multi-decadal fluctuations of MS<sup>-</sup> (and thus of SIE) since 1708 AD. Large retreat of SIE occurred in the 1750s, 1830s, 1940s and 1980s. To study the relationship between SIE and global temperature we use the 300 yr temperature anomaly for the Northern Hemisphere from the IPCC Fourth Assessment Report (Jansen et al., 2007). In Fig. 3b we compare the smoothed MS<sup>-</sup> record with the HadCRUT2v temperature data since 1856 AD; the CRUTEM2V data since 1781 AD; and data from four European stations (central England, De Bilt, Berlin and Uppsala) since 1721 AD. Because data from the Southern Hemisphere are very sparse, and because current average trends are quiet similar between the hemispheres, we use the longer term NH record to investigate the relationship between Antarctic SIE and global temperature.

The LGB69 MS<sup>-</sup> proxy SIE record reflects the major cooling/warming cycles over approximately the last 300 yr. In particular, it shows SIE retreat during two relatively warm periods during the late Little Ice Age, in 1740–1770 AD and in 1820–1840 AD. It also shows smaller SIE retreat occurring in the 20th century, around the 1940s, and in the late 1970s to early 1980s. There is a relative expansion in SIE (derived from the MS<sup>-</sup> proxy) between these warm periods.

However, since the late 1980s, the global temperature and proxy sea ice relationship has switched phase: MS<sup>-</sup> and temperature have been increasing together. This is also evidenced from direct satellite observations of Antarctic SIE and ground-based observations of global average temperature. We suggest that this paradox is due to regional cooling in the high latitude SH during recent decades, which itself has been

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attributed to ozone depletion and resulting anomalies in the Southern Annular Mode (SAM) (Thompson and Solomon, 2002; Thompson et al., 2011).

Hence we investigate the relationship between the LGB69  $MS^-$  proxy and SAM intensity over the last five decades. SAM was originally defined as the mean pressure difference between  $40^\circ S$  and  $60^\circ S$  (e.g. Gong and Wang, 1999), but Nan and Li (2003) found that the pressure difference between  $40^\circ S$  and  $70^\circ S$  is a better indicator, and we use that later SAM index for monthly mean data between 1948 and 2010.

Both the summer SAM (December to March) and the LGB69  $MS^-$  in Fig. 4 display very high annual variability. The LGB69  $MS^-$  record broadly reflects the variations in summer SAM, and over the total period, correlates well with summer SAM ( $r = 0.25$ ,  $N = 53$ ,  $p = 0.10$ ). This could result either because SAM and SIE are themselves correlated, or because circulation changes associated with SAM directly influence  $MS^-$  deposition on the ice sheet. For example, it is believed that there is a tight relation between SAM and the strength of westerlies in the Southern Ocean (Bian et al., 2009), and a positive SAM tends to favor transportation of  $MS^-$  from the sea ice zone to the Antarctic continent. Greater extent of sea ice melt in the summer season also produces more  $MS^-$ .

#### 4 Sea ice changes over the wider Southern Indian Ocean

In Fig. 5 we compare the 20 yr smoothed SIE anomalies from our proxy for  $70-100^\circ E$  with those derived by Curran et al. (2003) for the sector  $80-140^\circ E$ . The anomalies in both cases are calculated as the difference from the average proxy SIE for the 100 yr period from 1887 to 1986 (inclusive). The average proxy SIE for the  $70-100^\circ E$  sector over this period is  $58.7^\circ S$  and for the  $80-140^\circ E$  sector, where the ice extent is narrower (Fig. 2a), it is  $59.9^\circ S$ .

The two anomaly curves show broad similarities in the timing of SIE changes, although there are differences in the magnitude of the change and in the finer detail. In particular, an increase in SIE from about the 1930s to the 1960s followed by a rapid

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decrease is indicated in both records, although the decrease for the 80–140° E sector is about one degree of latitude, whereas for 70–100° E it is less than half a degree of latitude. Satellite observations show that trends in sea ice extent are not uniform around Antarctica (e.g. Comiso and Nishio, 2008), and may even be of opposite sign in different regions. Sea ice concentration trends may also be regionally out of phase (Comiso, 2010) and the differences have been linked to large scale atmospheric circulation patterns. For example, Raphael (2007) shows a relationship between atmospheric zonal wave three and variability of Antarctic sea ice concentration, with a strong positive correlation between the two occurring in our study area off the Amery ice shelf (70–80° E).

The proxy record for the 70–100° E sector also shows a subsequent increase in SIE since about 1985, which is confirmed by satellite observations, but is not covered in the DSS proxy record.

## 5 Conclusions

Methanesulfonate from an ice core from LGB69 in Princess Elizabeth Land, East Antarctica provides a proxy record of variations in Antarctic sea ice extent between 70° E and 100° E over about the past 300 yr. For most of this period there is a good relationship between ice extent and global temperature with decreases in ice extent of about half a degree of latitude coinciding with warm periods around 1750 and 1830. Over the last 30 yr however the relationship between Antarctic SIE in this sector and global temperature has reversed, which is possibly a result of high latitude SH regional cooling due to anomalies in the Southern Annular Mode (SAM). Factors other than SIE, such as SAM related circulation changes, may however also directly influence MS<sup>−</sup> deposition on Antarctica.

The proxy record of SIE for the 70–100° E sector shows similar broad trends to an earlier MS<sup>−</sup> proxy record for the adjoining 80–140° E sector. In particular there was a major decrease in SIE in this broader region from about 1950 until the early 1980s. However there are differences in the timing and magnitude of SIE trends in the two

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sectors. This highlights the fact that MS<sup>-</sup> records from ice cores generally provide proxy sea ice information over only a limited longitude band, and that no single ice core record is likely to provide a good record of overall Antarctic sea ice changes.

*Acknowledgements.* The study is supported by Ministry of Science and Technology of China (MoST, 2013CBA01804), Chinese Arctic and Antarctic Administration (CHINARE2012-01-02, 03) and State Key Laboratory of Cryospheric Sciences (SKLCS2012-05), Chinese Academy of Sciences. The contribution of IA was supported by a grant from the Chinese Academy of Sciences Visiting Professorship for Senior International Scientists (No. Y129N31001). We thank Mark Curran for providing proxy sea ice data from the Law Dome DSS ice core.

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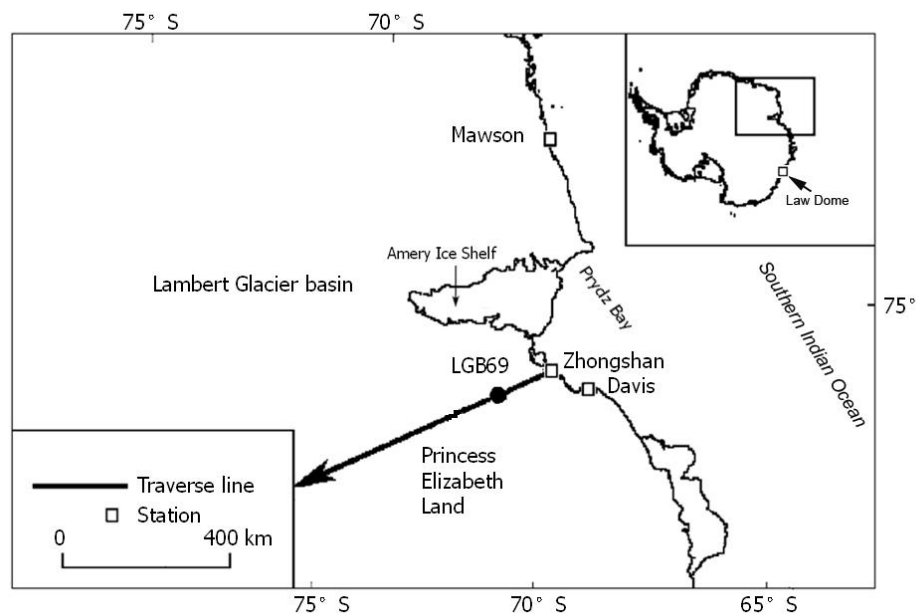
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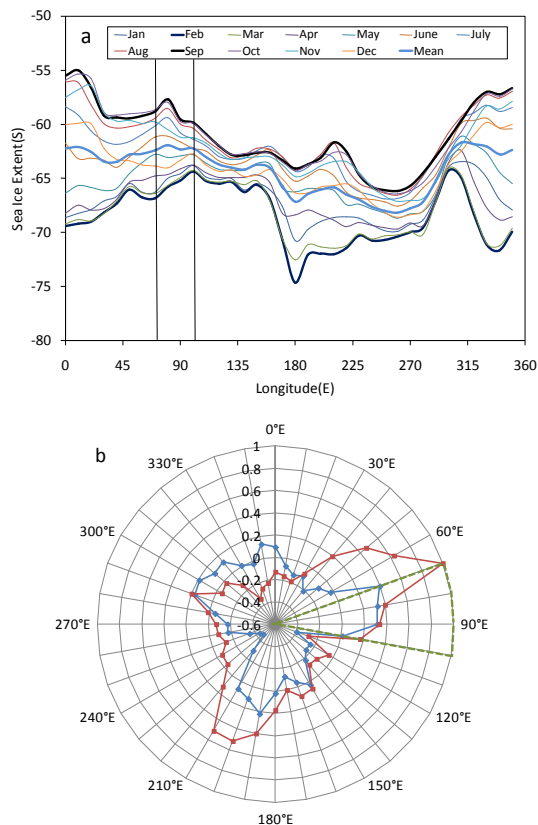
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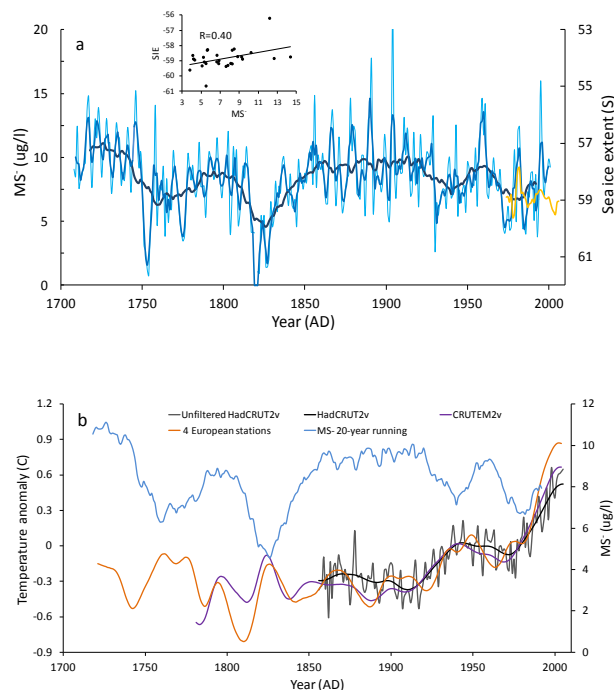
**Fig. 1.** Location of LGB69, Princess Elizabeth Land, East Antarctica.



**Fig. 2. (a)** Average Antarctic SIE as a function of longitude in different months for 1973–2000. The vertical lines indicate the sector with the highest correlation between LGB69  $MS^-$  and seasonal maximum SIE. **(b)** Correlation of LGB69  $MS^-$  with the seasonal maximum SIE in  $10^\circ$  longitude sub-sectors (blue). The autocorrelation of SIE at  $70^\circ$  E with other sub-sectors is also shown (red).

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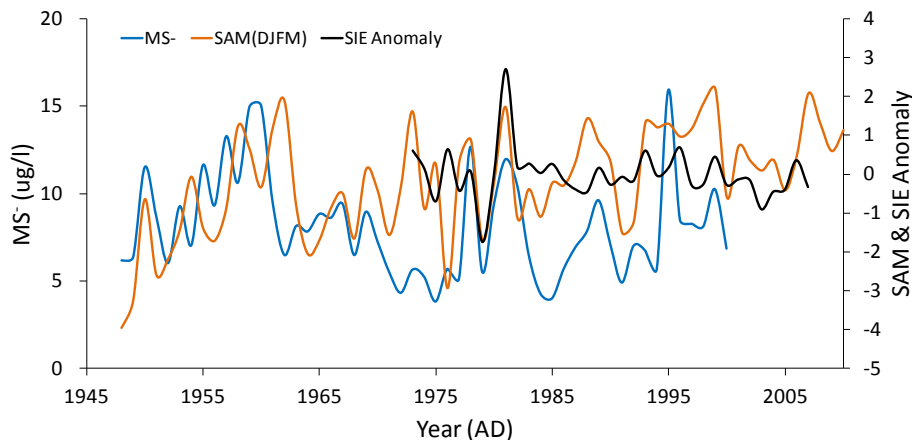


**Fig. 3. (a)** Variations in LGB69  $MS^-$  since 1708 AD (blue) and in SIE since 1973 AD (yellow). The 3yr-smoothed and 20 yr-smoothed  $MS^-$  records are also shown. The linear correlation between  $MS^-$  and SIE for 1973–2000 is shown inset. **(b)** Temperature changes in the North Hemisphere from IPCC AR4 (see legend) and the 20 yr-smoothed LGB69  $MS^-$  changes (blue).

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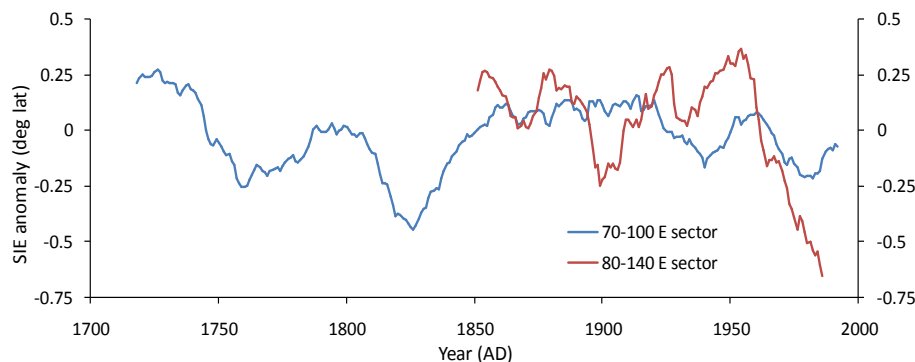


**Fig. 4.** Variations of the summer Southern Annular Mode (SAM);  $MS^-$  in LGB69; and the August to October SIE anomaly (non-dimensional) for 70–100° E over the last five decades.

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**Fig. 5.** Antarctic sea ice extent anomalies for the 70–100° E sector (LGB69 proxy) and the 80–140° E sector (DSS; Curran et al., 2003).

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