ANTARCTIC SEA ICE HISTORY, LATE QUATERNARY

Introduction

Sea ice results from the freezing of surface sea water. In the Southern Ocean, sea ice surrounds the Antarctic continent and it today covers 20×10^6 km^2 in winter and only 4×10^6 km^2 in summer (Gloersen et al., 1992). This pronounced seasonal cycle strongly affects the climate of the Southern Hemisphere through its impacts on the energy and gas budget, on the atmospheric circulation, on the hydrological cycle, and on the biological productivity (Figure A21). Sea ice also modulates the climate of remote places through its impact on the deep and intermediate oceanic circulations. More details about sea ice formation, seasonal cycle and its importance in the climate and ocean systems can be found in the entry on *Arctic sea ice*, this volume.

Sea ice is a very reactive component of the cryosphere that has experienced drastic changes through time. Whaling ship records (de la Mare, 1997), satellite measurements (Cavalieri et al., 2003), and ice core data (Curran et al., 2003) indicate that Antarctic sea ice underwent a dramatic decrease in maximum extent since the 1950s. Such a reduction may accelerate in the near future because of global warming, and this will in turn have important feedbacks on future climate. However, sea ice is still not well-computed in climate models because of its complicated relationship to climate change over a large range of timescales. One way to ameliorate our understanding of such relationship is to reconstruct sea ice extent over long time periods and certain key periods for which the global climate is reasonably well-known. These reconstructions that started in the early 1980s are still very sparse in numbers and coverage because of the scarcity of good sediment sequences in the Southern Ocean.

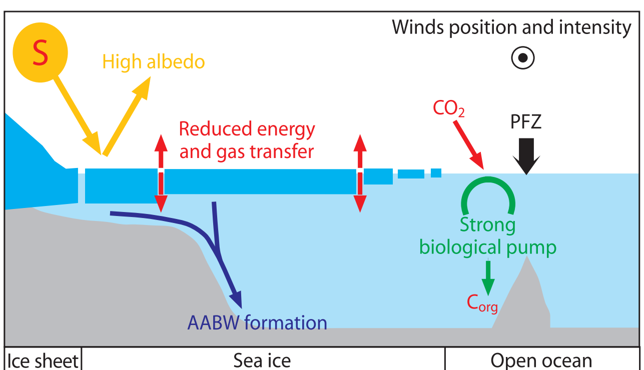


Figure A21 Schematic illustration of sea ice impacts on the Southern Hemisphere climatic system. *AABW:* Antarctic Bottom Water; *MYSI:* Multi-Year Sea Ice; *FYSI:* First-Year Sea Ice that freezes and melts every year. *FYSI* can be separated in consolidated ice (concentration above 40%) and unconsolidated ice (concentration below 40%).

Three long records from the Atlantic and Indian sectors of the Southern Ocean are presented here to give an idea of sea ice dynamics over the last two climatic cycles, and then present a map of winter and summer sea ice extent at the Last Glacial Maximum (LGM) is also shown to illustrate sea ice distribution under a very different climatic state from the present.

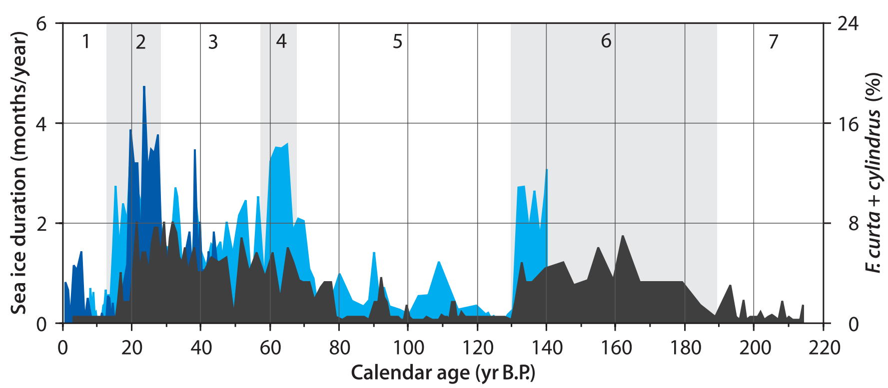
Long records

Long records of sea ice extent result almost exclusively from the investigation of fossil diatom assemblages preserved in deep-sea sediments. Diatoms are the most abundant photosynthetic micro-algae in Southern Ocean surface waters. The cell is surrounded by a test of biogenic silica that is generally well preserved in sediments subsequent to the organism's death. Some diatom species thriving in Antarctic waters present a strong affinity to sea ice (Horner, 1985) and are therefore most useful to estimate sea ice cover in the past.

Fossil sea ice diatoms can be used qualitatively to estimate past seasonal sea ice extent. Abundances greater than 3% of *Fragilariopsis curta* and *F. cylindrus* denotes a recurrent presence of seasonal winter sea ice while greater than 3% abundance of *F. obliquecostata* marks returning presence of summer sea ice at the core location (Gersonde and Zielinski, 2000). Increasing abundances of these taxa indicate greater sea ice cover. Fossil diatoms can also be used quantitatively based on a statistical treatment of 30 diatom species including sea ice taxa and open ocean taxa (Crosta et al., 1998a). In this statistical method, called the Modern Analog Technique or MAT, open ocean taxa are essential in constraining the seasonal sea ice edge. The MAT compares the fossil diatom assemblages to a set of core-top diatom assemblages with known modern surface conditions that are subsequently used to attribute an estimate of sea ice duration in number of months per year to the fossil sample.

Long records of Antarctic sea ice extent are very rare and are restricted to the Atlantic and Indian sectors to date. Three records from the east Indian sector (core SO136-111, *black curve* in Figure A22), and the Atlantic sector (core TNO57-13PC4, *dark blue curve* in Figure A22; and core PS1768-8, *light blue*

Figure A22
Sea ice history over the last 220 kyr BP. Sea ice duration was estimated by MAT in core SO136-111 from the east Indian sector of the Southern Ocean (*black curve*) and in core TNO57-13PC4 from the Atlantic Sector of the Southern Ocean (*dark blue curve*). Sea ice duration is compared to relative abundances of *F. curta* + *cylindrus* proxy of sea ice presence in core PS1768-8 (*light blue curve*). Core SO136-111 covers the last 220 kyr BP, core TNO57-13PC4 covers the last 40 kyr BP, and core PS1768-8 covers the last 140 kyr BP. *Odd numbers* and *white areas* represent interglacial stages while *even numbers* and *shaded areas* represent glacial stages.



curve in Figure A22) are shown. Sea ice conditions at the first two core locations were estimated by MAT (Hodell et al., 2000; Shemesh et al., 2002; Crosta et al., 2004), while winter sea ice conditions at the third core site were documented by relative abundances of *F. curta* + *cylindrus* (Gersonde and Zielinski, 2000).

The three records give a very coherent picture of sea ice advance and retreat around Antarctica during the Late Quaternary, although the amplitude of sea ice changes are more important in the Atlantic sector (Figure A22) in relation to the presence of the Weddell Gyre promoting northward ice transport. Today the cores are a few degrees latitude northward of the winter sea ice edge (Figure A23), and were similarly ice free during other warm periods such as Marine Isotopic Stages 5 and 7 (MIS 5 and MIS 7 respectively). Winter sea ice extent during these periods was certainly very comparable to that of today. At interglacial-glacial transitions, sea ice advanced very rapidly to reach its full glacial extent within a few thousand years (Figure A22). The two longest records indicate that sea ice conditions were certainly comparable during every glacial stages of the last 220 kyr BP. During glacial-interglacial transitions, sea ice retreats back very rapidly to its modern position within a few thousand years.

Sea ice advance and retreat are initiated by atmospheric and oceanic temperature changes but, due to the very reactive nature of sea ice, it reaches full glacial or full interglacial conditions before the completion of the temperature change (Bianchi and Gersonde, 2002). Conversely, variations of sea ice cover during full glacial conditions are linked to feedback processes of wind stress and atmospheric temperatures.

Last Glacial Maximum

In the early 1980s, a tremendous effort was applied to reconstruct global conditions of the Earth at the Last Glacial Maximum (LGM), (CLIMAP, 1981). For the Southern Ocean, the reconstruction was based on estimates of sea-surface temperatures via a radiolarian-based transfer function and winter and summer sea ice limits via a combination of micropaleontological and lithological tracers. According to CLIMAP (1981), winter sea ice edge was 5–10° latitude northward of its modern position, overlying the modern Antarctic Polar Front (Figure A23), in relation to colder air and sea-surface temperatures and more intense winds. The winter sea ice cover at the LGM was therefore twice that of the modern surface. Similarly, the LGM summer sea ice edge was projected northward of its modern position, overlying the modern winter sea ice margin (Figure A23). The summer sea ice cover was thus 5–6 times greater than the modern counter part. A permanently covered area of around 20×10^6 km^2 was estimated, strongly affecting the Southern Hemisphere climate. For example, paleoclimatic models attribute to the Southern Ocean a 70 ppm impact on atmospheric CO_2 out of the 80 ppm drop observed on the glacial-interglacial timescale, when CLIMAP sea ice limits are introduced as boundary conditions (Stephens and Keeling, 2000).

Soon after the CLIMAP (1981) report, summer sea ice extent was found to actually represent spring sea ice extent (Burckle et al., 1982). However no proxy was calibrated to document summer sea ice cover until the development of diatom-based transfer functions in the late 1990s that crystallized the relationships between diatoms and surface conditions (Zielinski and Gersonde,

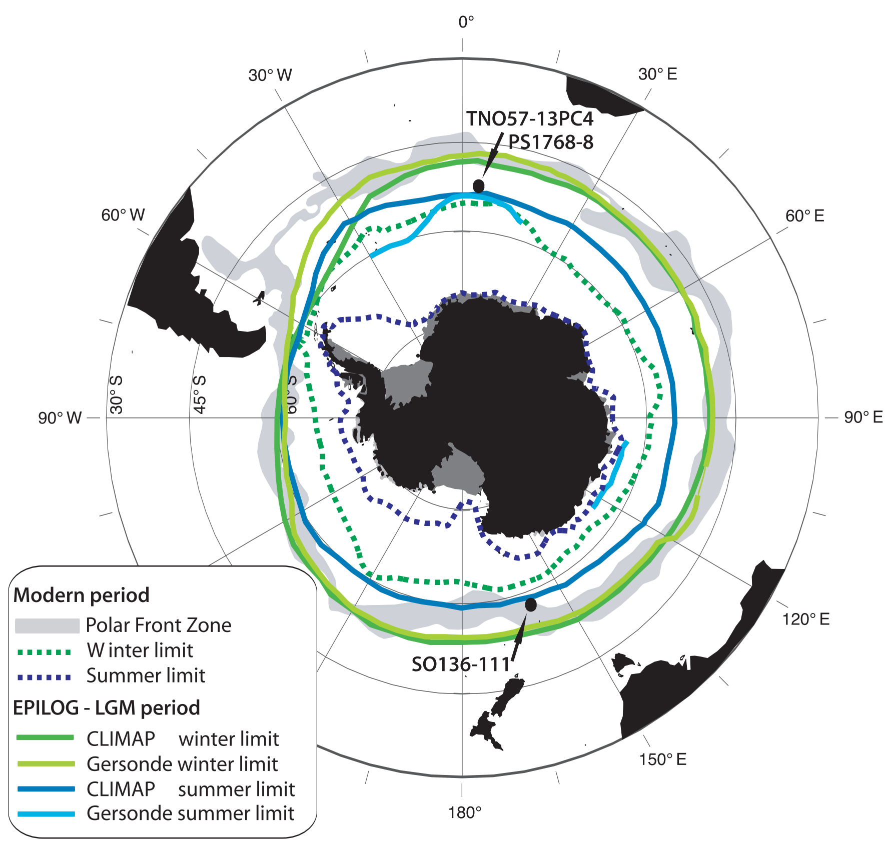


Figure A23
Comparison of LGM winter and summer sea ice edge reconstructions by CLIMAP (1981) and Gersonde et al. (2005) with modern winter and summer sea ice edges (Schweitzer, 1995).

1997; Crosta et al., 1998a). Diatom assemblages confirm a doubling of the winter sea ice cover at the LGM mainly due to the progression of the compacted sea ice (Burckle and Mortlock, 1998; Crosta et al., 1998b). Conversely, diatom assemblages argue for a more restricted summer sea ice cover than previously estimated (Figure A23). In the Atlantic sector, off the Weddell Sea, glacial summer sea ice margin was certainly displaced northward to overlie the modern Antarctic Polar Front (Armand and Leventer, 2003). A similar situation probably prevailed in the western Pacific off the Ross Sea. In the Indian and the eastern Pacific, however, glacial summer sea ice cover was more comparable to modern conditions prevailing in these sectors. In the Northern Hemisphere, similarly, LGM winter sea ice cover was greatly expanded, while summer sea ice cover was comparable to today (de Vernal and Hillaire-Marcel, 2000). Paleoclimatic models estimate a 5–30 ppm impact of Antarctic sea ice cover on the glacial atmospheric CO_2 drop when diatom-based sea ice extent and concentration data are used as boundary conditions (Morales-Maqueda and Rahmstorf, 2002; Bopp et al., 2003). Although Antarctic sea ice, and more globally the Southern Ocean, is certainly a key component in regulating atmospheric CO_2 variations through the albedo feedback, and therefore climate changes, it alone cannot explain glacial-interglacial changes in pCO_2 that are dependant upon feedbacks of involving several components of the internal climate system.

Conclusion

Despite its importance in global climate change, Antarctic sea ice extent during the Late Quaternary has been weakly documented, in part because few proxies have been developed that can document past sea ice conditions and, in part, because of the lack of good sediment records. Early reconstructions of sea ice extent focused on the Last Glacial Maximum. Such reconstructions were still recently used in modeling. But the evolution of paleoclimate models requires long records of sea ice cover to confront its dynamic response to climate changes. Very few such records exist, but they all argue for very rapid waxing and waning at climate transitions, leading to double or to half Antarctic sea ice cover in a few thousand years. Such variations in ice cover have deep impacts on the global climate through the albedo, the hydrological and wind systems, the deep and intermediate oceanic circulations, the transfer of gas and energy at the ocean-atmosphere interface, and the biological pump.

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Cross-references

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