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INSIDE

An Ocean of Ice—Advances in the Estimation of Past Sea Ice in the Southern Ocean

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Divergent winter pack ice illustrating areas of open water between floes that have started to refreeze with a thin cover of nilas. Recent ecological studies have shown that sea-ice diatom communities are differentiated by variations in the type of sea ice formed and the changes that occur over the seasonal cycle of sea-ice advance and decay (Gleitz et al., 1998). Photo by Tony Worby, Antarctic Cooperative Research Centre, University of Tasmania.

ABSTRACT

The estimation of past sea-ice cover has been improved recently by advances in diatom ecology, biogeography, and taxonomy and in the satellite imagery of sea ice. Diatoms live in and around sea ice, are sensitive to sea ice, and are widely distributed as microfossils in Southern Ocean sediments; thus, they provide the best tool available for reconstructing sea-ice cover and oceanographic features in Antarctic regions. New approaches use diatoms to reconstruct sea ice through the late Quaternary from core sites in the Southern Ocean. The sea-ice records provide evidence of increased sea ice at the Last Glacial Maximum (21,000 yr ago) and changing sea-ice cover through the past 190 k.y. Results from such sea-ice estimations may be useful to general circulation and energy balance models that require sea-ice parameters to predict future climate change.

INTRODUCTION

One of the most important modulators of Southern Hemisphere climate is the seasonal sea ice that surrounds Antarctica. Sea ice is a key element in understanding climate change because it acts as a thermal and physical barrier, reducing heat and gaseous exchange between the ocean and the atmosphere. The latitudinal extent and seasonal duration of past sea-ice cover provides information on the atmospheric and oceanic systems and also on the past variations of the climate system to changes in climate forcing (e.g., carbon dioxide and stratospheric dust). During the past 27 years, sea ice has been observed and studied in detail by means of satellite sensors that record the radiation emitted from the ocean and sea ice (Gloersen et al., 1992). Sea-ice algorithms and filters provide corrected sea-ice concentrations (the fraction of open water within the sea-ice cover, 0%–15% = open ocean, 100% = total ice cover) that can be sourced as a modern database for reconstruction of paleo–sea ice. Many new approaches are coming to light in the quest for documenting past sea-ice extent and cover, in part a result of improved satellite imaging of sea-ice cover.

Although satellites can now show us the polar sea-ice cover, we cannot use them to look back at past sea-ice variation. The answer to the past is found in the sea-floor sediments that underlie ice-covered ocean through the annual cycle of sea-ice advance and decay. Sediments around Antarctica are dominated by remains of diatoms (siliceous unicellular algae) that form a belt of diatomaceous ooze between approximately 50° and 60°S (Lisitzin, 1972; Burckle, 1984). The major sedimentation flux of diatom remains from the surface waters to the sea floor occurs over summer in open-water conditions, whereas less than 5% of the total annual diatom flux to the sediments occurs during ice-covered periods (Abelmann and Gersonde, 1991). However, the variation of diatom species between sea-ice and open-ocean environments that remain preserved in the sea-floor sediments allows the signature of sea-ice presence to be studied (Fig. 1). Diatoms are ideal for analysis of past sea-surface conditions, as they are restricted in life to the euphotic (sunlit) zone, typically within the upper 100 m. Some diatom species live specifically within or under the sea ice. Advances in understanding the role sea ice plays in diatom ecology now provides an opportunity to use fossil diatoms to make quantitative sea-ice estimates.

DIATOM ECOLOGY AND THE SEA-ICE HABITAT

Enclosed within, on, and under the sea ice are communities of diatoms that are distinctly different from those in the open water. As the ice melts, sea-ice diatoms are released into the water, where some species equally adapted to the melt-water environ-

Ocean of Ice *continued on p. 2*

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Ocean of Ice *continued from p. 1*

ment proliferate, making use of the low-salinity, high-nutrient, and stable surface waters. Other sea-ice diatoms dependent on the sea-ice substrate for their habitat do not survive and are lost to the ocean depths (Leventer, 1998). Although many sea-ice taxa dissolve after death and do not leave a permanent record in the sediments, there are several diatom species within the zone between the maximum winter sea-ice edge and the Antarctic coast (known as the sea-ice zone) that are frequently preserved in the sediments (Burckle, 1984; Pichon et al., 1992; Zielinski, 1993; Zielinski and Gersonde, 1997; Armand, 1997). Two species, *Fragilariopsis curta* and *Fragilariopsis cylindrus,* are often used as sea-ice proxies (Leventer, 1998) because of their occurrence in the ice and as "seeded" from the ice into the open water (e.g., Fryxell, 1989; Kang and Fryxell, 1992; Kang et al., 1993; Leventer and Dunbar, 1996; Cunningham and Leventer, 1998). These two species predominate in sediments underlying the sea-ice zone, which is why they are useful in identifying regions influenced by sea ice (Zielinski and Gersonde, 1997; Armand, 1997).

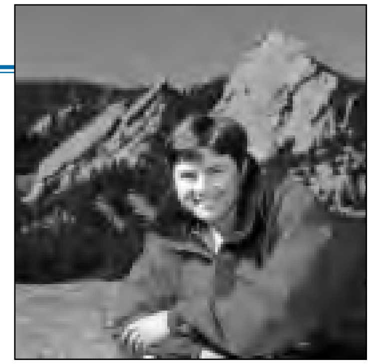
Although diatom assemblages in particle traps and receding sea-ice blooms show a change from ice-seeded, ice-edge species to open-water species (e.g., Fryxell

Dialogue

Sara Foland, CEO

Stewardship of Science

> "We have a hunger of the mind which asks for knowledge of all around us, and the more we gain, the more is our desire; the more we see, the more we are capable of seeing."
>
> —*Maria Mitchell*



At the Flatirons near Boulder, Colorado.

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Last fall we began exploring GSA's commitment to science, stewardship, and service. Science was my topic the past four months, so now let's turn our attention to what GSA does with the tremendous body of work our members generate, and talk about stewardship. First we'll look at our role as stewards of earth science information, and in the coming months, we'll consider ways in which geoscientists are stewards of Earth itself.

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The need for a publication devoted to research in the geological sciences was one of the primary reasons for the founding of GSA in 1888. The first issue of the Geological Society of America *Bulletin* was published in 1890, and our stewardship of geoscience information has grown steadily over the years.

GSA's two monthly journals, *Bulletin* and *Geology,* are primary vehicles for publication of academic research in the geosciences. GSA also co-publishes *Environmental and Engineering Geoscience* with the Association of Engineering Geologists. Other publications include books (Special Paper, Memoir, Treatise on Invertebrate Paleontology series), maps, charts, and memorials.

As a professional society embracing all the geosciences, we are responsible for maintaining this ever-evolving body of work. It's the foundation of our profession and our greatest resource. The financial commitment required to produce, maintain, and make accessible this storehouse of knowledge is significant, and journal subscriptions and other publication sales cover only a fraction of it.

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Some of our publications become part of the collections of other organizations. The most recent example is Special Paper 338, *Classic Cordilleran Concepts: A View from California,* edited by Eldridge Moores, Doris Sloan, and Dorothy Stout. In December 1999, a ceremony in Sacramento, California, marked the entry of this volume into the California State Library. According to Charlene Wear Simmons, assistant director of the library's California Research Bureau, "This GSA publication presents classic geologic concepts about California and the present status of knowledge about them. It's a potentially useful reference source for California policymakers, in a state where geology can be destiny, and is an important historical document."

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Increased member needs, coupled with continued growth of computer capacity and decreasing costs, have set the stage for GSA's expansion into electronic publishing. We began several years ago with on-line submission of abstracts, and now full-text electronic versions of *Bulletin, Geology,* and the science article from *GSA Today* are available on GSA's Web site. Later this year we will add indexing of nonperiodicals, and we're looking at the feasibility of electronic versions of these publications.

Our long-term vision for GSA publications includes completely digital submission, proofing, and editing systems. We also plan to develop enhanced reference and database linking in partnership with other organizations. Combined with more extensive search and retrieval capabilities and faster delivery, these changes offer enormous potential to revolutionize the way research is conducted.

When we talk about GSA's stewardship of geoscience information, the word "stewardship" has a somewhat old-fashioned ring to it. It is anything but.

GSA Publication Highlights

GSA expects to publish 12 special papers in 2000, including *Large Meteorite Impacts and Planetary Evolution II* (Special Paper 339).

Later this year, watch for the *Fourth Hutton Symposium on the Origin of Granites and Related Rocks* and Treatise on Invertebrate Paleontology, Part H (Revised), Vol. 2 and 3, *Brachiopoda.*

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and Kendrick, 1988; Fryxell, 1989; Abelmann and Gersonde, 1991; Garrison and Buck, 1991; Leventer, 1991; Garrison and Close, 1993), there is still considerable ecological work needed to sufficiently delineate tight ecological realms for the many diatom species occurring within the sea-ice environment. Only a few preliminary studies separate diatoms specific to sea-ice types (e.g., congelation or frazil sea-ice), thicknesses, and evolving nutrient conditions (e.g., Scott et al., 1994; Gleitz et al., 1998). Such studies, when used in conjunction with observations of diatoms that are associated expressly with open-ocean conditions, underpin the future ability to define the sea-ice edge and variations in cover from the sedimentary record.

In essence, the preserved diatom assemblage is used to interpret the development of overlying open-water conditions through the abundance and variation in diatom species observed, and their increased flux to the sea floor as a function of increased productivity during open-water conditions (Fig. 1). This simple interpretation neglects other important factors that may modulate diatom assemblages at the surface waters, such as water-column stability, nutrient supply, light availability, dissolution, advection, and grazing. However, many of these additional factors are also related to sea-ice presence. Comparison of sea-ice concentration (the amount of sea ice versus open ocean in a defined area) and annual duration with preserved diatom assemblages in the sediments reveals relationships between sea ice and species biogeography (Armand, 1997; Crosta et al., 1998a). It is the total assemblage and the relationships observed with the sea-ice cover and duration that make diatoms the most useful proxy available for estimating past sea ice. The limit to this relationship and the historical sea-ice record that is possible depend on the fundamental assumption that the relationship of diatom species to

Ocean of Ice *continued on p. 4*

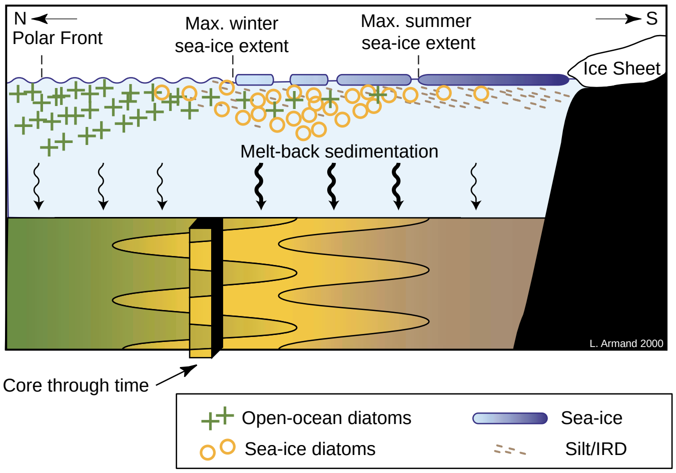

Figure 1. Relationships between sea-ice and open-ocean diatoms in surface waters, sediments, and sea-ice cover. Open-ocean diatoms are dominant north of maximum winter sea-ice edge. Sea-ice diatoms live within, on, and under sea ice and bloom (dependent on nutrient and other oceanic conditions) when sea ice melts back to its summer limit. Open-ocean diatoms produced when open-ocean conditions are established in the zone between maximum winter and summer sea-ice edges are preserved in sediments, along with sea-ice-related diatoms. This sedimentary signal provides basic reconstruction of Antarctic sea-ice cover. The assumption of this method is that the greater the proportion of open-ocean diatoms to sea-ice diatoms, the longer the duration of open-water conditions between winter and summer sea-ice cover. By studying these open-ocean and sea-ice diatoms in sedimentary cores, past natural variability of sea-ice cover can be estimated. Extended sea-ice cover with no summer melt-back results in reduced sea-ice diatom abundance and increased silt to the sediments. Polar Front is an oceanographical boundary separating Antarctic waters from Subantarctic waters and is usually defined by 2 °C subsurface temperature minimum of Antarctic surface waters. Sediments below Polar Front show elevated levels of diatom preservation around Southern Ocean (Burckle et al., 1982; Burckle and Mortlock, 1998).

Ocean of Ice *continued from p. 3*

sea ice has not changed over time. A sea-ice record covering the past 200 k.y. is currently possible, but with additional assumptions related to the introduction of extinct species with unknown sea-ice relationships, estimation could go back more generally through the Neogene.

SIGNIFICANCE FOR FUTURE CLIMATE CHANGE

Sea ice, as the reflective interface and thermal and physical barrier between the ocean and the atmosphere, strongly influences climate-governing energy fluxes across this boundary. Thus, sea-ice extent is a key factor that must be considered in coupled oceanic-atmospheric models that are beginning to be applied to past climates (Ganopolski et al., 1998; Kim et al., 1998; Weaver et al., 1998). Without some estimates of the past natural variability of sea ice, modelers are forced to estimate future world climates using unrealistic conditions (e.g., prescribed fixed concentrations of 100%, 50%, or 0% sea-ice cover). Alternatively, they can rely on the CLIMAP reconstructions (e.g., Ramstein and Joussame, 1995), which, although still useful for glacial winter extent alone, are constantly being improved by approaches such as those presented below.

By reconstructing the natural variability of sea-ice cover over a range of geologic time scales, the chances of arriving at better models of our environment are enhanced. There are already general circulation models capable of simulating ocean-atmosphere surface flux conditions when modern sea-ice concentrations are provided to the model (Budd et al., 1997). Such work reveals the usefulness of past sea-ice estimation in the development of Southern Hemisphere climate dynamics.

LATE QUATERNARY SEA-ICE ESTIMATIONS

A focus of past climate and sea-ice estimation has been directed at Earth's most recent glacial period, the Last Glacial Maximum (LGM, ~21,000 yr B.P.). A recent coupled model by Weaver et al. (1998) provided data of modeled winter and summer sea-ice extent around Antarctica for the LGM. Their estimated expansion of sea ice through the LGM in winter exceeds current satellite-observed sea-ice extents, but only barely so in the summer season. Such mathematical models are not bounded by micropaleontological evidence of sea-ice conditions during this LGM period and do not compare as favorably against that evidence (Fig. 2).

Attempts to pinpoint the extent of Southern Ocean sea ice during the LGM have been made from changes in ice-rafted debris, foraminiferal and radiolarian faunal changes, and lithological boundaries between diatomaceous ooze and terrigenous silt (CLIMAP, 1981; Cooke and Hays, 1982). The CLIMAP compilation (CLIMAP, 1976, 1981) provided a large-scale circum-polar reconstruction of past sea ice, constructed by delineating the halfway point between the faunally identified Polar Front (Fig. 1) and the summer ice boundary (defined from changes in clay and diatomaceous sediments) (Fig. 3). Through the advance of diatom assemblage analysis in sediments of the Southern Ocean and satellite imagery of sea ice, the methods of past sea-ice reconstruction can be improved from these earlier sedimentological interpretations.

Two new approaches have tackled the LGM extent of sea ice around Antarctica. The first of these methods estimates sea-ice extent by finding similar diatom assemblages (or analogs) for past samples

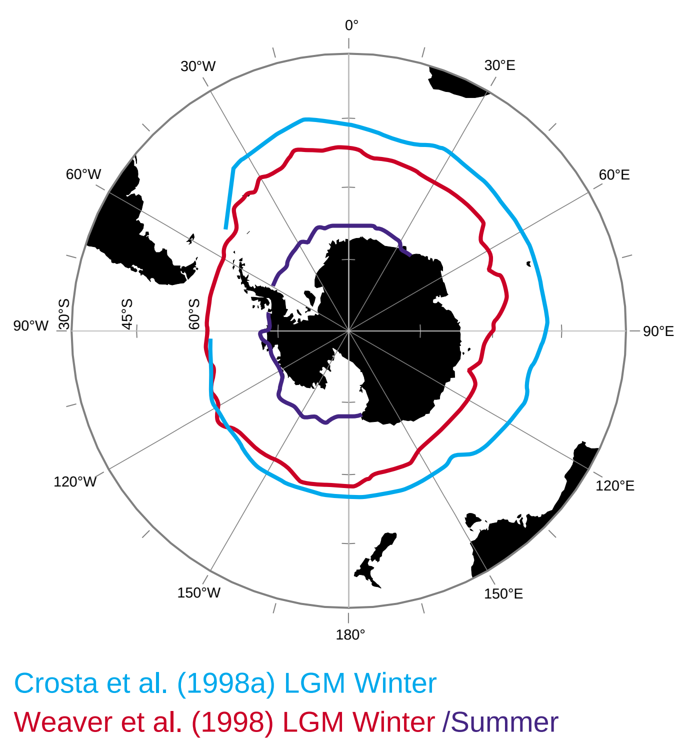

Figure 2. Comparison of modeled and micropaleontological reconstructions of LGM sea-ice extents. Coupled general circulation model (Weaver et al., 1998; purple line) consistently underestimates winter LGM sea ice compared to geological-paleontological reconstructions (e.g., Crosta et al., 1998a; blue line). Coupled models also indicate that summer LGM sea-ice extent (red line) was similar to today's summer extent. Modeled reconstructions including that of Weaver et al. (1998) also have problems simulating modern sea-ice extents, especially in Southern Hemisphere, as pointed out by Kim et al. (1998). Use of paleontological sea-ice reconstructions will provide modelers with boundary conditions to refine simulations of past and future sea-ice conditions.

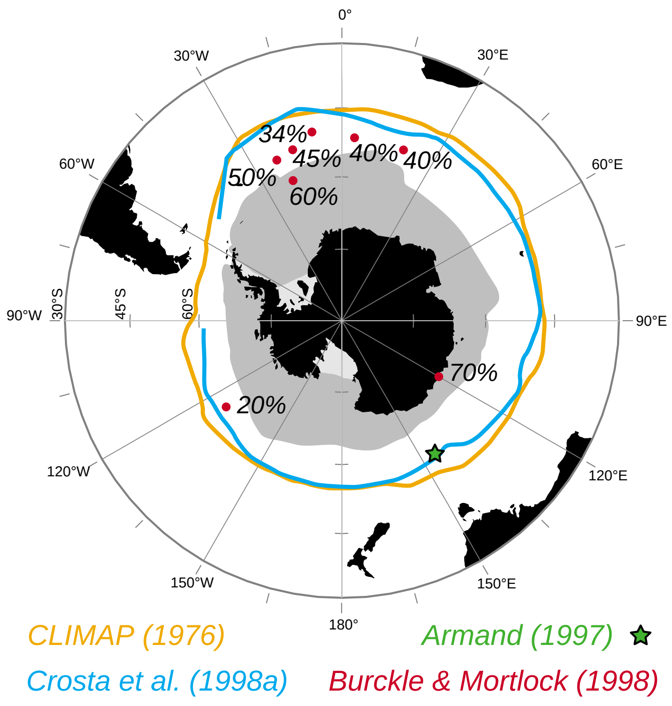

Figure 3. Positions of estimated LGM sea-ice extents of CLIMAP (orange line; CLIMAP, 1976) and Crosta et al. (1998a; blue line), and spot estimates of sea-ice concentration from Burckle and Mortlock (1998; red spots). Crosta et al. (1998a) winter sea-ice-extent reconstruction is similar to the CLIMAP reconstruction owing in part to a similar LGM data set employed. Diatom-based LGM reconstruction of Crosta et al. (1998a) reaffirms sedimentological and faunal based CLIMAP reconstruction. Averaged sea-ice concentration estimates of Burckle and Mortlock (1998) appear comparable to extent of sea ice estimated by Crosta et al. (1998a) and to modern sea-ice concentrations that increase from 15% at the sea-ice edge through unconsolidated (15%–40%) and consolidated (>40%) sea ice within the pack ice today (Schweitzer, 1995). Green star indicates core site of Armand (1997) in southeast Indian Ocean. See Figure 4 for continuous sea-ice concentration data from this core.

throughout a Southern Ocean data set and uses an averaged estimate of the environmental conditions of those sites to estimate paleo-conditions (in this case, sea ice) (Crosta et al., 1998a, 1998b). The Crosta et al. (1998a) estimated maximum LGM winter sea-ice edge lies well to the north of the modern sea-ice limit (northern boundary of the shaded region in Fig. 3), doubling the modern sea-ice surface area coverage of 19 x 10^6 km^2 (Gloersen et al., 1992).

The second approach has been directed at the distribution of opal in sediments of the Southern Ocean (Burckle and Mortlock, 1998). Here, the inference underpinning the work is that the maximum winter sea-ice edge is a limiting boundary to surface water productivity of the diatoms and the abundance of biogenic opal contained in the sediments. Near the seasonal sea-ice edge, less biogenic opal will be preserved in the sediments, whereas in the open ocean near the Antarctic Polar Front, more opal will be preserved in the sediments. A comprehensive database of biogenic opal in surface sediments around Antarctica provides the data from which LGM biogenic opal data can be compared to current sea-ice concentrations. Eight LGM sites around Antarctica revealed increases in sea-ice concentration (i.e., decreases in opal) compared with the present-day sea-ice distribution, but the eight sites do not allow a reconstruction of the maximum sea-ice extent during the LGM. The sea-ice concentration results do compare favorably to the estimated sea-ice edge of Crosta et al. (1998b) and the understanding of sea-ice concentration distributions in the Antarctic winter ice field (Fig. 3). Although both large-scale LGM reconstructions show increased winter sea-ice conditions and an extension of the sea-ice edge as suggested by the lithological study of CLIMAP (1976; Fig. 3), they do not provide detail that will allow us to understand the natural variation of sea-ice cover through time. It is here that sedimentary cores from around Antarctica can demonstrate this variability.

The first attempt to construct a continuous record of past sea-ice concentration has been made from two cores in the southeast Indian Ocean along the 145°E meridian at 54° and 56°S (Armand, 1997). This approach is similar to that used by Crosta et al. (1998a, 1998b), where the Southern Ocean diatom data set has been matched to satellite observations of sea-ice concentrations which are used to construct statistical equations. Armand (1997) constructed equations for the estimation of minimum February sea-ice concentration, maximum September sea-ice concentration, and the number of months per year in sea-ice cover. Results from the 54°S core indicated no sea-ice cover through the past 60 k.y. In contrast, during periods of glacial conditions over the past 190 k.y., unconsolidated (20%–40% concentration) and consolidated (>40%) sea-ice cover occurred over 56°S during winter (September) (Fig. 4). In agreement with Crosta et al. (1998a, 1998b), a reduction of sea-ice cover during peak summer (February) is supported by the estimated open-ocean conditions over the site. The results did not indicate summer sea ice at 52°S as in the CLIMAP reconstruction (CLIMAP, 1981). Estimates of sea-ice cover in months per year are generally consistent with the seasonal variation shown by the winter and summer concentration estimates. Through additional comparisons with sea-surface temperature estimates and the presence of other sea-ice indicator species (i.e., *C. davisiana* abundances; Armand, 1997), I considered that my estimates reflected past sea-ice conditions in the Southern Ocean.

When we compare the detailed core data at the LGM with the large-scale esti-

Ocean of Ice *continued on p. 6*

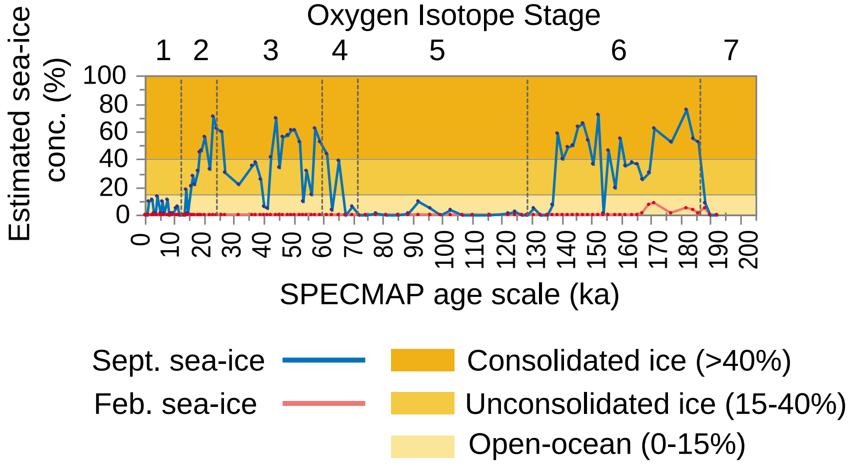

Figure 4. Sea-ice estimation results from core MD88-787 (56°S, 145°E; see Fig. 3). Estimates of September (blue line) and February (red line) sea-ice concentrations are plotted over time. During glacial intervals (marine oxygen isotope stages 2, 3/4, and 6), there are indications of unconsolidated (15%–40% concentration) and consolidated (>40%) sea-ice cover in September (Austral winter). In contrast, there was no sea ice (0%–15% considered open ocean) during LGM summer (February). Results from Armand (1997) suggest that during LGM winter (~21 ka) this site was covered by consolidated sea ice (70% ± 20%) for up to 8 months of the year.

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The next time you call GSA to change your address, renew your dues, order a book, register for a meeting, or just ask questions, chances are that you will talk to a staff member in the recently enhanced Member Service Center. The center staff includes Joan Clark, Rebecca Freeman, and Kymber Rock.

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Joan Clark, Rebecca Freeman, and Kymber Rock (left to right) staff the new Member Services Center.

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Ocean of Ice *continued from p. 5*

mates of sea-ice extent (compare Figs. 3 and 4), it is evident that although all estimates agree with sea ice out to 56°S in the southeast Indian Ocean, there is a difference in the amount of sea ice estimated. My results suggest 8 m/yr sea-ice cover and 70% concentration in September; in other words, consolidated sea-ice cover rather than ice-edge conditions as implied by the CLIMAP and Crosta et al. (1998a) reconstructions. It would appear that bias from the geographical distribution of samples in the diatom data set and corresponding sea-ice attributes for these sample sites used by me elevates my sea-ice estimates. The important point to consider is whether the disconnection between the large-scale studies and those of the more detailed down-core work will continue to be seen in future down-core estimations. The other main finding gaining support from the new approaches and that of the modeling community (e.g., Weaver et al., 1998) is the idea that large-scale melt-back of winter sea ice to near the modern summer sea-ice extent occurred during the LGM. Such large-scale melt-back has significant implications about the heat balance of the ocean, the atmospheric system, and the oceanographic circulation during glacial periods. The search continues for additional evidence of the LGM summer sea-ice extent from cores closer to the Antarctic coast; however, this task is a difficult one because of the expansion of the continental ice shelf around Antarctica and the ensuing disturbance of sediments along the Antarctic shelf. Finally, comparison between the fossil and modeled LGM sea-ice extents (Fig. 2) highlights the current discrepancies between the estimation efforts and the role that independent sea-ice data from diatom reconstructions can provide toward modeling of past climatic conditions.

CONCLUSIONS

The development of sea-ice concentration histories is a challenge, given the physical and biological information we have at hand, especially when trying to estimate past conditions for which we may not have applicable analogs in the Antarctic (e.g., multi-year ice, differing polynya systems). However, exciting new studies are now deciphering the composition and succession of sea-ice diatom assemblages in various sea-ice types (Scott et al., 1994; Gleitz et al., 1998). This information will become more crucial to the development of sea-ice histories (particularly those that work with sea-ice concentrations) from the sedimentological record in the future.

Since the CLIMAP years, we have learned that the remains of diatoms in the sediments of the sea floor are the keys to recovering the history of sea-ice cover around Antarctica; this includes the understanding of differences between the sea-ice and open-ocean diatom community structure in the Southern Ocean. Diatom remains allow us to estimate a crucial climate parameter. Our results have great capacity to further our understanding and interpretation of the historical sea-ice records and further our knowledge of our present climate dynamics. Because they provide natural variability boundaries, these same results have great appeal to potential users such as modelers. The current approaches discussed here focus on two components of the diatom sedimentary record (species and abundances versus opal content). Whether it will ultimately be easier to extricate a sea-ice history from the diatom species and their abundances or from their percentage contribution to the sediments is yet to be determined. There are still many gaps to fill in piecing together sea-ice histories from the diatom record. We still need to know more about specific diatom tolerances and niches in the ice community, the succession of diatom species against the annual cycle of sea-ice growth and decay, and the transport to and preservation within the sea floor of sea-ice diatoms. Some scientists are critical of the amount of information truly portrayed by sea-ice diatoms in the sedimentary record. They suggest that only defining a maximum sea-ice edge is possible. The future of sea-ice estimation depends on careful micropaleontological research and a better understanding of the environment, biology, and oceanographical processes that diversify the prolific micro-siliceous algae—otherwise known as diatoms.

ACKNOWLEDGMENTS

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