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Reappraisal of Antarctic seasonal sea-ice at the Last Glacial Maximum

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Abstract. We used modern analog technique applied to Antarctic diatoms to quantitatively reconstruct seasonal sea-ice extent at the Last Glacial Maximum. Winter maximum sea-ice limit occurred around 48°S in the Atlantic and western Indian sectors, around 55°S in the eastern Indian and western Pacific sectors, and around 58-60°S in the eastern Pacific sector of the Southern Ocean. Summer maximum sea-ice extents during the last ice age and today are similar, which contradicts CLIMAP's findings. This implies a reduced summer albedo feedback of the Southern Hemisphere and a greater transfer of heat and moisture from the ocean to the atmosphere than shown by previous qualitative studies.

Introduction

The determination of winter and summer sea ice limits in the Southern Ocean during the LGM is an important goal for paleoceanographers and climate modelers. Previous studies dealing with paleo sea-ice conditions were qualitative, remaining within the frame of sediment and ice-rafted-debris interpretation of deep-sea cores [Hays *et al.*, 1976; CLIMAP, 1981; Cooke and Hays, 1982]. However, few studies have been undertaken to assess past position of sea-ice using diatoms, with the exception of *Eucampia antarctica* abundances and ratios of its polar to subpolar variations [Burckle and Burak, 1988; Kaczmarzka *et al.*, 1993]. Yet, other diatom species are more closely linked to sea-ice and/or the sea-ice edge. The presence of such species and other species anti-correlated to the sea-ice presence in the Southern Ocean sediments, married with satellite observations of modern monthly sea-ice extent and concentration provide the first opportunity to quantitatively reconstruct past seasonal sea-ice conditions via transfer function approach.

Material and Methods

Diatom procedures follow that of Rathburn *et al.* [1997] whilst modern February and August sea-ice data are from the *Naval Oceanography Command Detachment* [1985]. This atlas provides bimonthly charts of sea-ice extent and concentration based on satellite measurements from 1973 through 1982. The charts present maximum, mean and minimum sea-ice limits for

each period, giving an indication of the interannual variability of sea-ice extent. To reconstruct such interannual variability, an index was associated to each extent (0 for the Open Ocean to 3 for the Minimum Extent). An index was also associated to each range of sea-ice concentration (0 for 0% to 4 for 80-100% of sea-water covered by sea-ice).

The modern data set is composed of 195 peri-antarctic surface sediments thought to be representative of the modern sedimentation. It covers the Atlantic and Indian sectors of the Southern Ocean from 38°S to the Antarctic Continent, plus the Ross Sea and the western part of the Antarctic Peninsula. Estimates of sea-ice conditions are given by the Modern Analog Technique (MAT) applied to 33 Antarctic diatom species related or anti-correlated to the sea-ice presence. Five modern analogs are requested. Hereafter, the modern database will be referred to as MAT_{5195/33}. Our study differs from Burckle [1984] qualitative investigation. Where he used preservational data and high factor loadings distributions (no parameter values associated to the modern data set) in both modern and fossil horizons to infer paleoceanographic conditions at the LGM, we showed the relationship between diatom assemblages and sea-ice environments and used a quantitative transfer function to reconstruct past sea-ice conditions.

The LGM data set is composed of 106 downcore samples dated around 18,000 years B.P. Of those, 89 are CLIMAP points [CLIMAP, 1976, 1981]; the 17 others are from R/V *Marion Dufresnes* cruises. This data set covers the Atlantic sector of the Southern Ocean between 40° and 60°S, the Indian sector between 35°S and the Antarctic Continent, and the eastern Pacific sector between 50° and 65°S. Exact locations of both data sets, datations and depths in the sediment of the LGM samples are developed in Crosta *et al.* [in-press].

Results and discussion

Relationship between species/assemblages and indexes

The diatom assemblages of the modern database have been subjected to Q-mode factor analysis [Imbrie and Kipp, 1971]. Four factors are resolved and explained 87% of the total variance. Factor 1 accounts for 35.5% of the total variance and is dominated by three sympagic species, *Fragilariopsis curta*, *Fragilariopsis obliquecostata* and *Fragilariopsis sublinearis*. It is referred to as an "Antarctic sea-ice zone" assemblage. Factor 2 represents 39.9% of the total variance and is dominated by *Fragilariopsis kerguelensis* and *Thalassiosira lentiginosa*. It is referred to as an "Antarctic Open-Ocean" assemblage. Factor 3 accounts for 8.3% of the total variance

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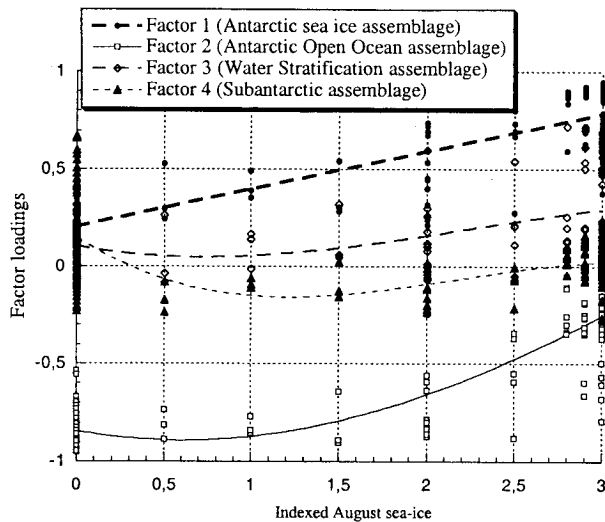


Figure 1. Relationship between the 4 factor resolved by the Q-mode factor analysis and the indexes of August sea-ice extent.

and is dominated by the *Chaetoceros* resting spores group. It is referred to as a "Water Stratification" assemblage. Factor 4 makes up 3.3% of the total variance and is dominated by warm water species, *Thalassionema nitzschioides* var. *parva*, *Roperia tessalata*, *Thalassiosira oestrupii*, *Hemidiscus cuneiformis* and *Fragilariopsis dololius*. It is referred to as a "Subantarctic" assemblage. More details on the results of the Q-mode factor analysis are given in *Crosta et al.* [in-press].

The relationship between species/assemblages and indexes is very similar whatever the parameter of this study. We therefore chose to show only the relationship with the August sea-ice extent (Figure 1). The relationship between factor 1 and indexes is linear. High factor loadings of the factor 1 are encountered between indexes 2 and 3. This assemblage is representative of an environment always covered by winter sea-ice. High negative factor loadings of factor 2 fall for low indexes (<1.5). This factor is representative of an environment with no or unusual winter sea-ice cover. Factor loadings of the factor 3 follow the distribution of factor 1 but with smaller values. High factor loadings of factor 4 are encountered for the index 0. This factor is representative of an environment free of winter sea-ice.

Factors 1 and 3 are the only factors directly related to the sea-ice indexes. Reconstruction of sea-ice conditions could be based solely on the species of these two factors. However, we think that the other factors are also important in constraining sea-ice edge and/or open-ocean conditions throughout the year.

Interdependence of the parameters

The factor analysis provides a correlation matrix table which measures the degree of interdependence between the parameters associated with the modern data set (Table 1). Values around 0.7 between February and August sea-ice parameters (both in extent and in concentration) show that summer sea-ice and winter sea-ice are independent variables. Hence, summer sea-ice conditions does not determine winter sea-ice conditions, and vice versa. Seasonal parameters can therefore be estimated separately.

In contrast, February sea-ice extent is correlated to February sea-ice concentration (0.93), and August sea-ice

Table 1. Correlation matrix table given by the Q-mode factor analysis

	Feb Ext	Aug Ext	Feb Conc	Aug Conc
Feb Ext	1	0.7	0.93	0.67
Aug Ext		1	0.76	0.99
Feb Conc			1	0.73
Aug Conc				1

Feb Ext, February sea-ice extent; Aug Ext, August sea-ice extent; Feb Conc, February sea-ice concentration; Aug Conc, August sea-ice concentration.

extent to August sea-ice concentration (0.99), showing that they are dependent parameters. They cannot be estimated separately, and therefore, sea-ice concentration closely follow sea-ice extent. Here, we chose to show the seasonal extent of the sea-ice. Anyway, we think that reconstruction of the sea-ice concentration will be useful for paleoclimate modeling.

Modern sea ice reconstructions

In a first step, we reconstructed the modern model of the distribution of the four parameters to test the accuracy of MAT_{5195/33}. Estimated values given by MAT were plotted against observed values, and a linear correlation line was calculated using a statistic program. Results are shown in Table 2. Correlation coefficients greater than 0.9, mean residuals and mean standard errors lesser than 0.2 for the summer and 0.25 for the winter respectively, indicate that the accuracy of this approach is very good. MAT_{5195/33} is a reliable technique to reconstruct modern sea-ice conditions and can therefore be used to reconstruct sea-ice environments in the past.

LGM sea ice reconstructions

The variability of the modern sea-ice cover is an important parameter since it is a constraint for the accuracy of the reconstructions. *Budd* [1975] and *Ackley* [1980] stated that typical interannual variations of 2° of latitude can be observed. Though important, this interannual variability may be unable to bias the MAT_{5195/33} reliability as the difference between present and LGM winter sea-ice extent is greater than 5° of latitude.

Table 2. Reconstruction of the modern model given by MAT_{5195/33}

	Feb Ext	Aug Ext	Feb Conc	Aug Conc
R	0.92	0.96	0.93	0.96
MRES	0.12	0.19	0.19	0.18
MSEE	0.15	0.24	0.21	0.25

Feb Ext, February sea-ice extent; Aug Ext, August sea-ice extent; Feb Conc, February sea-ice concentration; Aug Conc, August sea-ice concentration; R, correlation coefficient; MRES; Mean residuals (the residual is the absolute value of the difference between the observed value and the estimate); MSEE, Mean standard error.

Compared with the modern ice cover, LGM winter sea-ice was greatly expanded (Figure 2). Maximum limits occurred around 48°S in the Atlantic and western Indian sectors, around 55°S in the eastern Indian and western Pacific sectors, and around 58–60°S in the eastern Pacific sector, i.e., 5°–10° farther to the north. Winter sea-ice concentration at the LGM (not shown here) showed the same increase in sea-ice cover with an extension of the compacted sea-ice zone (80–100% of sea-ice). The unconsolidated sea-ice part remained stable, ranging from 5° to 10° south of the sea-ice margin, the same situation being observed today [Burckle et al., 1982; Comiso and Gordon, 1996].

Hays et al. [1976] and Cooke and Hays [1982] related the boundary between silty diatomaceous clay and diatom ooze in surface sediments to present-day summer sea-ice cover, and used this criterion to draw the position of LGM summer sea-ice. However, Burckle et al. [1982] and Burckle [1984] demonstrated that this boundary marks the mean spring sea-ice position and that the true summer sea-ice limit was farther to the south. Our results indicate that maximum summer sea-ice extent occurred south of 60°S in the Atlantic and the Indian sectors of the Southern Ocean, and south of 65°S in the Pacific sector, i.e., well south of previous limit qualitative estimations (Figure 3). Summer sea-ice concentration at the LGM (not shown here) confirms the distribution of summer sea-ice extent as only southernmost control points display low quantitative values typical from the ice margin. Our results are of necessity preliminary as the lack of southernmost LGM samples does not permit a more accurate determination of summer sea-ice distribution, particularly in the embayment areas (Weddell and Ross Seas). Nevertheless, our results strongly indicate that LGM summer sea-ice extent was not very different than today.

Since winter sea-ice extended farther north than today, greater melting than today must have happened during the

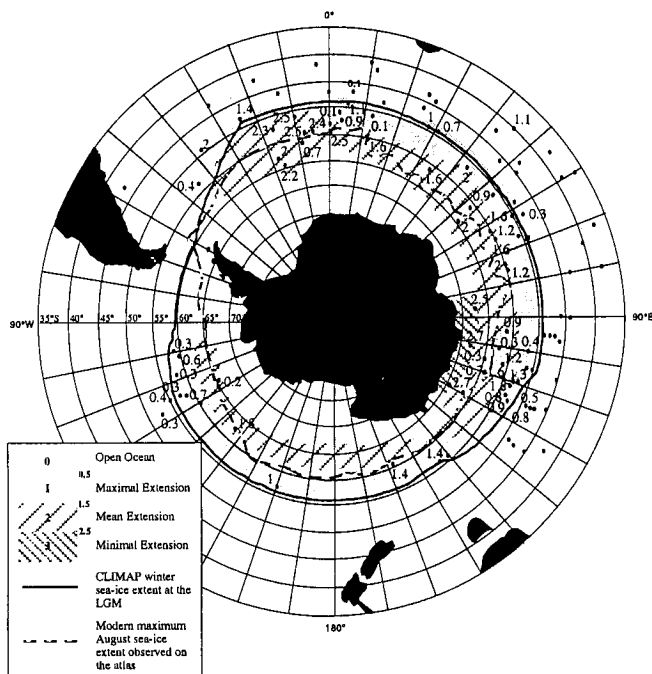


Figure 2. August (winter) sea-ice extent at the LGM. Dots represent LGM control points. Values are quantitative estimates of the indexes estimated by MAT_{5195/33}. Points with no associated values display the estimate 0.

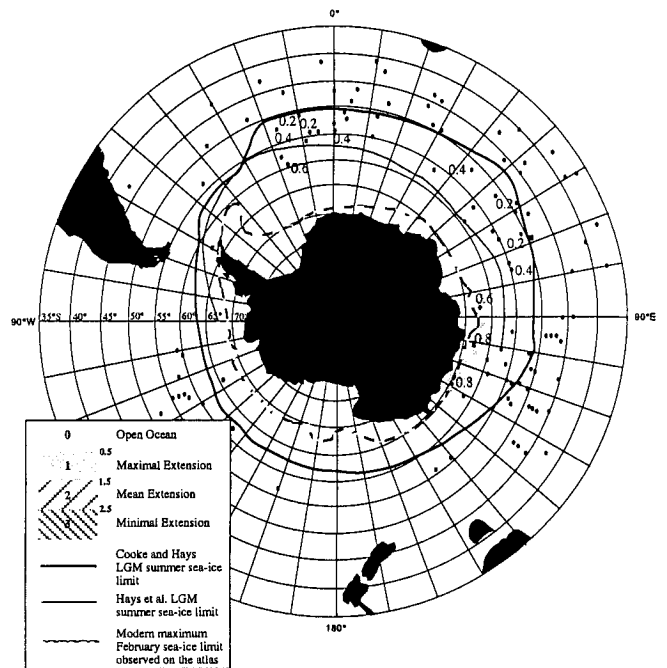


Figure 3. February (summer) sea-ice extent at the LGM. Dots represent LGM control points. Values are quantitative estimates of the indexes estimated by MAT_{5195/33}. Points with no associated values display the estimate 0.

short spring/summer months in order to reduce the sea-ice to summer levels comparable to today. The atmosphere to ocean heat flux is insufficient to account for present-day rapid spring/summer decrease in sea-ice. It accounts for 50% of the necessary heat flux [Gordon, 1981] whilst the remainder is supplied by upwelling of relatively warm Circumpolar Deep Water (CDW) at the Antarctic Divergence (AAD). Hence, the AAD may play a role in determining the northern limit of summer sea-ice [Comiso and Gordon, 1996] since the generation of open water provides a heat source to accelerate melting of the surrounding pack [Ackley, 1979]. During the LGM, increased winter sea-ice cover should be related to lower temperatures and increased atmospheric circulation. The very low difference in global insolation between the LGM and present cannot account for such variations, but the reduction of NADW during the LGM may be the reason for lower sea-surface temperatures in the Southern Ocean [Broecker et al., 1985; CLIMAP, 1981]. This smaller amount of heat and salt to the Southern Ocean via upwelling of deep water at the AAD participated in sea ice decay and may have been sufficient to restrict summer ice margin to locations similar to today. Hence, the AAD during the LGM must have been located at the same position as today where it is somehow constrained, perhaps by bottom topography, even though atmospheric circulation was intensified [Petit et al., 1990].

Presence of open-ocean species such as *Fragilariopsis kerguelensis* and *Thalassiosira lentiginosa* in high percentages in all LGM samples (>60%) implies a ice-free summer season of the whole studied area. However, because of a shorter sea-ice free period, the diatom growing season may have been shorter than it is today, leading to the silty diatomaceous clays found south of 55–60°S. There, diatom assemblages present greater relative abundances of sea-ice related species than today. Last Glacial Maximum samples also show greater percentages of *Eucampia antarctica*, but as

this species is not introduced in the modern database the MAT approach does not take this increase into account.

CLIMAP [1981], and Cooke and Hays [1982] estimated a permanent sea-ice cover reaching 50°S in the Atlantic and Indian sectors of the Southern Ocean, and 60°S in the Pacific sector. In contrast, changes in Antarctic continental ice were small. Such a sea-ice cover would have greatly reduced the amount of heat and moisture from the ocean to the atmosphere, and greatly increased the global Earth's albedo. An increase in planetary albedo plus CO₂ effect would have significantly contributed to the cooling during glacials. Our study shows that Southern Ocean summer sea-ice extent was quite similar at the last ice age to today, except in the embayment systems. What is the effect of such a reduced summer sea-ice cover in comparison to previous studies? This new scenario has great implications for the exchange of heat and moisture at the ocean-atmosphere interface and for the albedo feedback. Indeed, CLIMAP [1981] stated that the albedo feedback brought by changes in ice cover was substantially greater in the Southern than in the Northern Hemisphere. As the albedo effect of the ice depends on its surface, not volume, our data imply that the Southern Hemisphere feedback was greatly smaller than previously thought; and may have been not very different than the modern situation. A permanent sea-ice cover acts as an insulator between the relatively warm ocean and the cold overlying air. Our results imply that heat and moisture transfer from the ocean to the atmosphere was greater than previously thought. Ice free ocean regions close to the Antarctic Continent may have served as significant moisture supply for the ice sheets through evaporation processes. Implications resulting from these data should assist others in estimating Southern Ocean atmosphere-ocean-cryosphere changes.

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