The Scotia Sea: Reconstructing glacial climates from diatom assemblages

L. G. Collins,[1] C. Allen,[2] J. Pike,[3] and D. Hodgson[4]

[1]Geological Science Division, British Antarctic Survey, Cambridge, CB3 0ET, UK (lcol@bas.ac.uk)
[2]Geological Science Division, British Antarctic Survey, Cambridge, CB3 0ET, UK (csall@bas.ac.uk)
[3]Department of Earth, Ocean and Planetary Sciences, Cardiff University, Cardiff, CF10 3YE, UK (PikeJ@cardiff.ac.uk)
[4]Biological Science Division, British Antarctic Survey, Cambridge, CB3 0ET, UK (DHO@pcmail.nerc-bas.ac.uk)

Abstract We present the preliminary findings of a high-resolution palaeoceanographic record of high-frequency climate variability during the last glacial cycle (MIS 3 to MIS 2 transition). These results are based on the interpretation of diatom assemblages from a deep-sea sediment core located immediately south of the Polar Front in the north Scotia Sea. The Scotia Sea is a dynamic environment, where the juxtaposition of the globally mixed climatic signal carried by the Antarctic Circumpolar Current and the climatic influence of the Antarctic demonstrate the dramatic effects of ice on hydrography. High-frequency fluctuations in diatom concentration and assemblage composition allude to significant variations in oceanographic conditions. The diatom assemblage at the MIS 3 – MIS 2 transition reflects high-frequency variability within the sea-ice/open ocean dynamic. Fluctuating abundances of the sea-ice indicator group *Fragilariopsis curta/Fragilariopsis. cylindrus* indicate the persistent advance and retreat of sea-ice over the core site (5° north of the present average winter sea-ice limit). Synchronicity of the *Fragilariopsis curta/Fragilariopsis cylindrus* group peaks and troughs and those of *Chaetocerous* resting spores (CRS) is indicative of gradual spring melt back at the sea-ice edge. The occurrence of an anomalous productivity peak during the interstadial MIS 3, not associated with sea-ice presence, suggests the occurrence of oceanographic mechanisms other than those related to sea-ice. Ongoing research and statistical analyses should improve our understanding of these oceanographic relationships and aid in the completion of the first high-resolution reconstruction of the Southern Ocean glacial environment. Reconstructing the fluctuations of the late Quaternary climate of the Scotia Sea will aid in understanding the role played by the Southern Ocean during the glacial climate regime.

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Introduction

Late Quaternary climate was dominated by rapid millennial scale climate change, as revealed through myriad high-resolution terrestrial and marine palaeorecords (Huber, et al. 2006, Bond, et al. 1992, Bond, et al. 1993, Bond and Lotti 1995, Bond, et al. 1997, Raymo, et al. 1998, Chapman and Shackleton 2000). These millennial events are most pronounced during glacial regimes and are thought to be paced through the propagation of the thermohaline circulation. At present it is highly debated as to whether this rapid scale climate change was forced from the northern or southern hemisphere (Blunier, et al. 1998, Blunier and Brook 2001, Wunsch 2003, Huybers and Wunsch 2004, Brook, et al. 2005). Unfortunately, detailed reconstructions of southern hemispheric glacial ocean and climate variability are severely limited, impeding our understanding of southern hemispheric climate dynamics (Allen, et al. 2005). This project aims to help address this disparity and augment our knowledge of Antarctic and Southern Ocean glacial climatic regimes.

The Southern Ocean is dominated by the vigorous geostrophic flow of the Antarctic Circumpolar Current (ACC) and it's inherent meandering frontal systems (Orsi, et al. 1995). The convoluted nature of these fronts poses significant problems in objectively studying a 'typical' section of the Southern Ocean. We must therefore rely upon 'pinning points' where constrictive seafloor topography acts to reduce the lateral extent of the ACC and confine the Polar Front. One such location is Drake Passage, where the ACC is forced between South America and the Antarctic Peninsula into the relatively small marine basin of the Scotia Sea.

An additional characteristic of the Southern Ocean dictates that calcareous dissolution exceeds supply, resulting in a lack of carbonate sediments (Gersonde, et al. 2003). In the absence of carbonate sediments, siliceous ooze dominates the bed of the Southern Ocean, with the diatom microfossil group well preserved between the latitudes of 50-60°S (Leventer and Dunbar 1996). Their preferential preservation make diatoms an excellent proxy for the palaeoceonographic and palaeoenvironmental conditions of the Southern Ocean (Cunningham and Leventer 1998).

Study location

The Scotia Sea is a small back-arc basin, located in the South Atlantic sector of the Southern Ocean (75 to 25ºW, 61 to 53ºS), sited immediately downstream of Drake Passage, through which flows the complex ACC (Barker 2001). The Scotia Sea region is characterised by its oceanic structure and origin and is banded on three sides by a series of seismic discontinuous ridges, the North Scotia Ridge, South Scotia Ridge and the South Sandwich Island volcanic arc. Together these ridges form the Scotia Arc. The geology of continental fragments currently forming the Scotia Arc betrays its origin as a segment of the once continuous continental connection between southernmost South America and the Antarctic Peninsula; the Andean continental link (Eagles, et al. 2005). The Scotia Sea is believed to have evolved from a close-knit community of continental fragments through back-arc extension, behind an eastward migrating arc and trench, feeding on the subduction of South Atlantic oceanic lithosphere belonging to the South American Plate (Barker, 2001). The resultant marine basin is a complex collage of marginal basins, littered with submerged blocks, relict continental fragments and ancient spreading centres (Brown, et al. 2006).

The Scotia Sea is a dynamic environment, a cauldron of oceanographic activity, exerting a profound influence on Southern Ocean oceanography. Its constrictive nature and undulating bathymetry spawns a complex oceanography, which is dominated by the ACC (Orsi, et al. 1995, Garabato, et al. 2002). As previously mentioned the ACC enters the Scotia Sea to the west, via the narrow confines of Drake Passage. Its frontal components follow a convoluted trajectory across the Scotia Sea, primarily regimented by marine topography, their exodus confined to clefts in the encompassing Scotia Ridge. These clefts act to pin the fronts in place, impeding their customary meanders, allowing an objective study of a frontal system. The Polar Front, the axis of the ACC, is pinned in place at Shag Rocks Passage (48ºW) in the North Scotia Ridge where its deep-water flow streams into the Falkland Trough (Allen *et al*., 2005). In addition to the ACC and its global climate signal the Scotia Sea is also subjected to the influence of the Antarctic climate to the south, this is manifest in the influx of Weddell Sea Deep and Bottom Waters via the South and East Scotia Ridges. The Scotia Basin is also exposed to the cyclic encroachment of sea-ice from the south (Locarnini, et al. 1993). The extent of this encroachment into the Scotia Sea can be effectively used as a gauge to measure the timing and magnitude of climatic events within the Southern Ocean.

It is the juxtaposition of these climatic signals that makes the Scotia Sea such an essential research location. Reconstructing the fluctuations of the glacial climate of the Scotia Sea will aid in understanding the role played by the Southern Ocean during the late Quaternary.

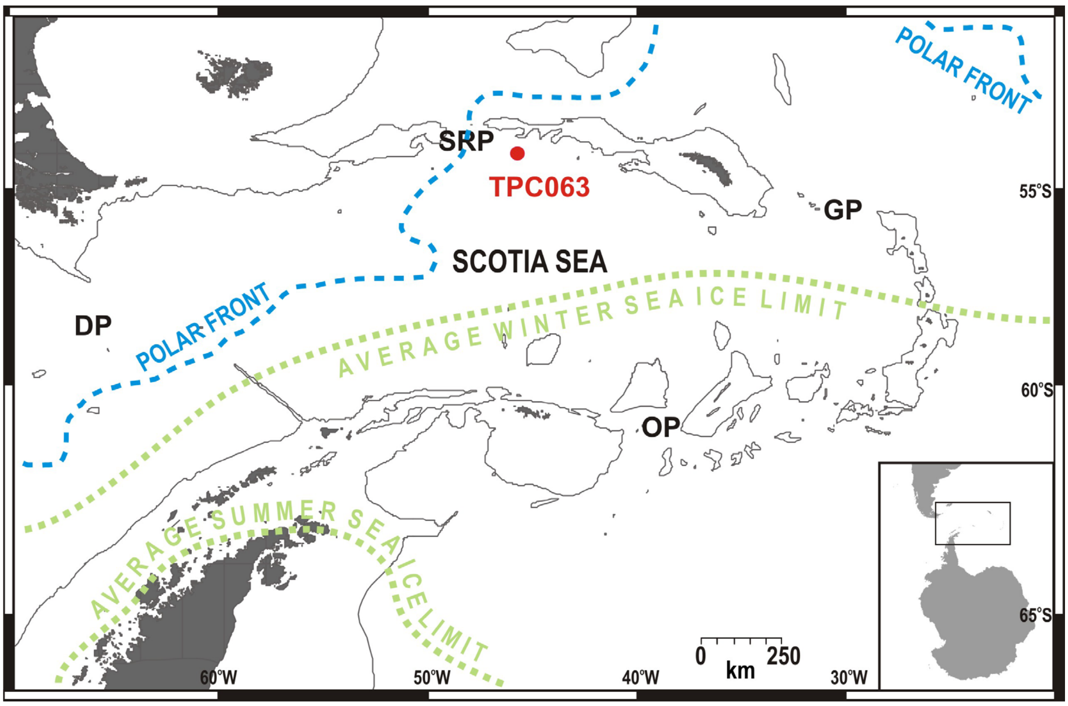

Figure 1. Map showing core location and bathymetric features mentioned in the text. The 2000m depth contour is marked. Abbreviations are DP, Drake Passage; SRP, Shag Rocks Passage; GP, Georgia Passage; OP, Orkney Passage. The Polar Front is marked with a dotted line, as are the average summer and winter sea-ice extents. Based on data from Allen et al., (2005) and Arhan et al., (2002).

Materials and methods

Samples representing the transition from MIS 3 to MIS 2 during the last glacial cycle are being examined from a deep-sea sediment core recovered from the Scotia Sea. Core PC063, a 6.5m long piston core, cored at a depth of 3956m was recovered from the north Scotia Sea in close proximity to the modern day Polar Front (53°56.0'S, 48°02.6'W) during cruise JCR04 with the *James Clark Ross.*

Sample treatment and preparation of quantitative slides for light microscopy is modified from Scherer (1994), and allows the calculation of quantitative diatom concentrations. A minimum of 400 valves per sample were counted with taxonomic identification conducted on an Olympus BH-2 light microscope at a magnification of x1000.

Winter sea-ice extent is determined through the presence of sea-ice indicator diatoms preserved in the sediments. The diatoms *Fragilariopsis curta and Fragilariopsis cylindrus* are widely accepted as species associated with sea-ice (Armand, et al. 2005). The combined species abundance pattern of this diatom group is considered to be indicative of the presence of the winter sea-ice edge and waters influenced by spring melt back. Gersonde and Zielinski (2000) determined that a relative abundance higher than 3% approximates a qualitative threshold between the presence of winter sea-ice and year round open waters.

Similarly, the proximity of the summer sea-ice limit can be inferred from the relative abundance of the heavily silicified cold water (<-1°C) taxon *Fragilariopsis obliquecostata*. This species has been shown to be an effective tracer of ice cover even in conditions of low sedimentation rates and enhanced opal dissolution (Gersonde and Zielinski 2000).

Stratigraphy

The extensive dissolution of calcareous biota south of the Polar Front Zone (PFZ), results in a deficiency of carbonate sediments and with it a lack of continuous benthic and planktic stable isotope records. Consequently it is difficult to construct accurate stratigraphic age models for late Pleistocene sediments. (Gersonde et al., 2003). We attempt to overcome this issue through a combination of magnetic-susceptibility curves and biostratigraphic reconstructions. The magnetic susceptibility acts as a proxy for the input of high terrigenous material (typical of glacials) vs high biogenic material (typical of interglacials) and as such is indicative of the cyclicity between glacial and interglacial regimes (Pudsey 2000). This allows us to qualitatively reconstruct Marine Isotope Stages throughout the glacial. These stages can then be reinforced through the use of the abundance patterns of specific diatom species. One such species is *Eucampia Antarctica*, a diatom indicative of glacial, or stadial regimes (Armand et al., 2005).

Unfortunately the highly variable sedimentation rates across the Southern Ocean prevent the use of the magnetic-susceptibility proxy for cross core correlation. However, by making use of the diatom species abundance patterns we can define unique diatom biofluctuation zones (BFZ), which we can then compare with sediment cores throughout the Southern Ocean.

Preliminary results

Magnetic-susceptibility

As previously mentioned the anisotropy of magnetic susceptibility (MS) is a powerful tool in determining the phasing of climatic regimes. The down core trend demonstrated by PC063 seems to exhibit variability indicative of one stadial regime sandwiched between two interstadials. Low MS values dominate the upper 35cm before a steep decline over the subsequent 40cm. The MS values continue to decrease at a shallower rate, peaking at ~3m. Values then proceed to gradually increase for 150m prior to plateauing for the remainder of the record. This suggests a record extending through the past three Marine Isotope Stages, back to ~60ka.

Valve Concentration

Diatom counts were conducted at a spacing of 32cm for a precursory down core analysis (see figure 2a). Diatom valve concentration provides a good approximation for the sedimentation of biogenic opal, as such it should parallel the magnetic susceptibility trend, this is reflected throughout the core (see figure 2a). High concentrations of 1.20×10^{7} are observed in the upper 30cm, followed by a sharp decrease to values of 5.13×10^{6}. Concentrations between 4.66×10^{6} and 2.55×10^{6} are maintained throughout MIS 2, before a gradual increase to average values of 4.87×10^{6} during MIS 3. This synchronicity is interrupted only at the onset of MIS 3, where diatom concentration unexpectedly reaches highs of 1.38×10^{8}. Following further analysis it was determined that this anomaly was due to a *Chaetoceros* resting spore (CRS) peak.

Analysis of the low-resolution diatom species assemblage revealed a series of fluctuations in the sea-ice indicators, centred about a pronounced peak at ~400cm. This coincides with the proposed transition from the interstadial of MIS 3 to the peak glacial conditions of MIS 2. Considering the latitude of the core site and the proposed sensitivity of sea-ice to perturbations in the climate regime

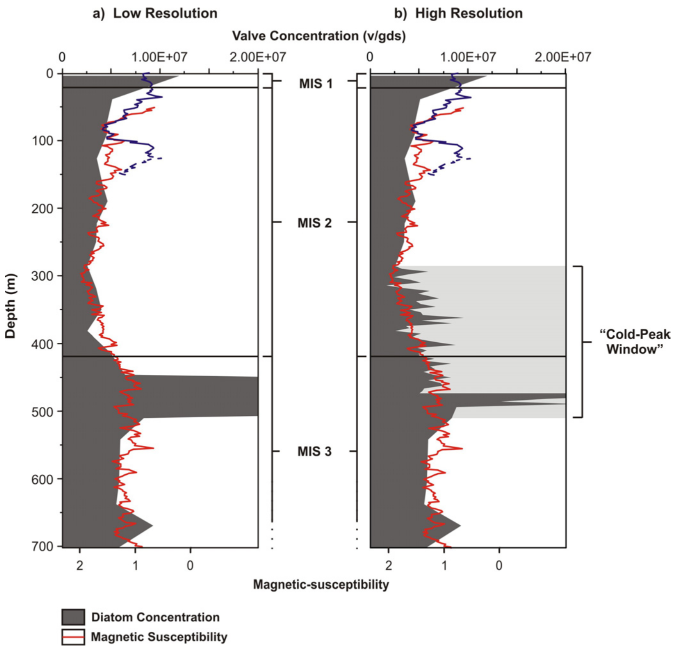

Figure 2. Plots showing diatom valve concentration versus magnetic susceptibility and the inference of Marine Isotope Stages (MIS). Plot a) Initial low-resolution (x32cm) diatom counts. Plot b) Superimposition of high-resolution (x4cm) "cold-peak window" counts onto low-resolution data.

it was determined that this "cold-peak window" warranted further attention. High-resolution counts at a spacing of 4cm were conducted between 286cm and 494cm (see figure 2b). The total diatom concentration trend revealed high-frequency oscillatory variability superimposed onto the glacial cooling trend exhibited by the low-resolution counts.

Analysis of the high-resolution "cold-peak window" diatom species assemblage revealed several interesting features potentially associated with the sea-ice dynamics within the Scotia Sea, one of which is the relationship between CRS and the *F. curta/F. cylindrus* group.

Chaetoceros resting spores

The low-resolution down core trend of CRS generally displays low valve concentrations between 2.88×10^5 and 9.90×10^5 throughout MIS 3 with the exception of a large productivity event at 478cm, where values reach a maximum of 1.27×10^8. Low concentrations recommence following this event at the onset of MIS 2 prior to a sharp rise to higher values of 1.77×10^6 between 222cm and 190cm. Higher concentrations averaging at 1.73×10^6 are maintained throughout the remainder of the record.

High-resolution counts reveal a series of high-amplitude changes throughout the "cold-peak window", generally varying between values of 5.00×10^5 and 1.70×10^6, with a steady background concentration of 1.43×10^5. However, on 3 occasions during the transition from MIS 3 to MIS 2, at 478cm, 450cm and 362cm, concentrations of CRS pulse to values of 1.27×10^8, 4.77×10^6 and 5.78×10^6 respectively (see figure 3a). Several lower peaks are also observed throughout the window.

F. curta/F. cylindrus Group

The down core low-resolution trend in the absolute abundance of the *F. curta/F. cylindrus* group generally demonstrates low valve concentrations throughout the record, varying between values of 0 and 1.55×10^5, with no constant background concentrations (see figure 3b). This variability is superimposed onto a gradually decaying trend from MIS 3 through to MIS 1. The only exception to this trend is within the "cold-peak window" where slightly higher values are more consistent, with exceptionally high values of 2.86×10^6 occurring at 478cm, coincident with the high CRS productivity.

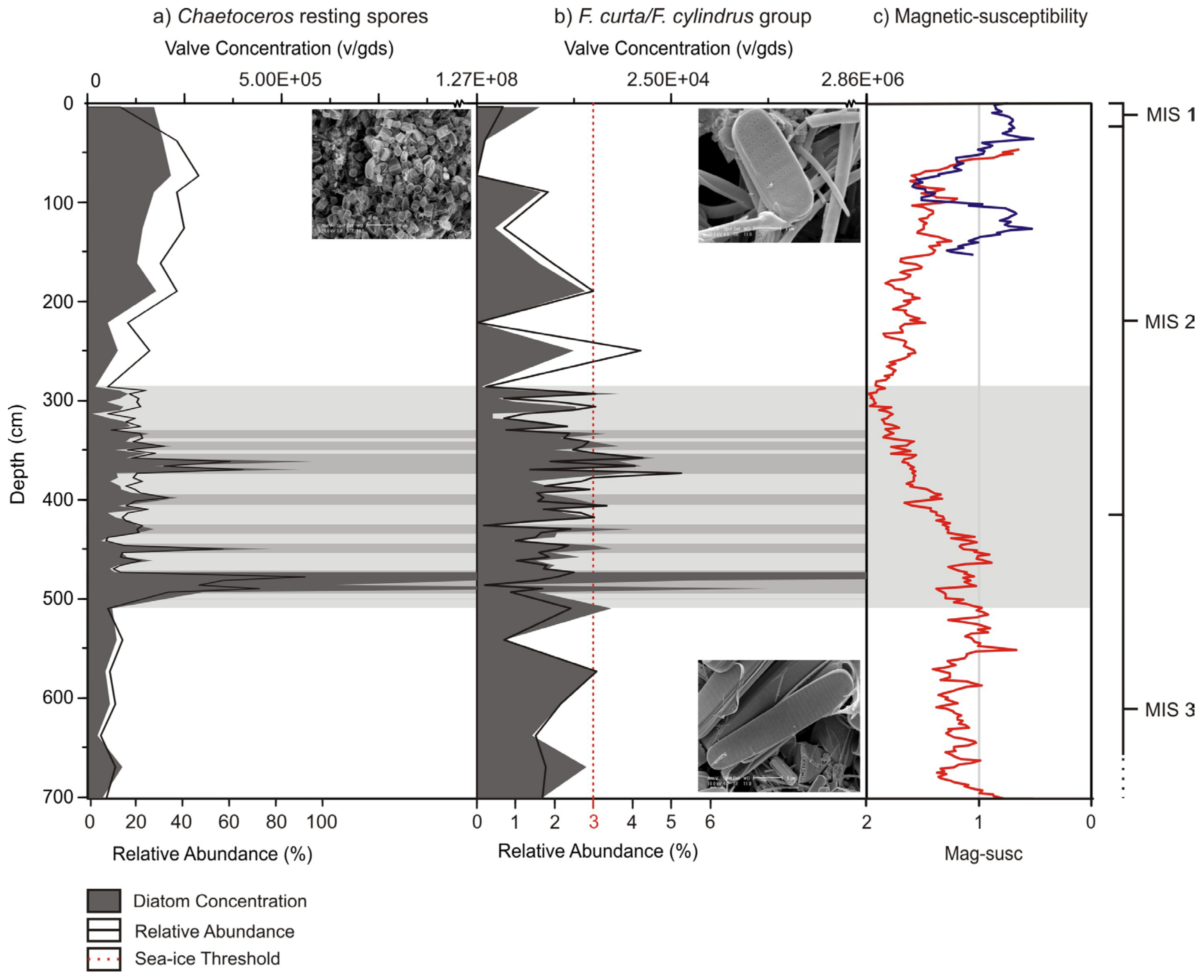

Figure 3. Plots the down-core relationship between CRS (a) and the sea-ice indicator group *F. curta/F. cylindrus* (b) with reference to the inferred marine isotope stages (c). The grey banding highlights the synchronicity of the high-amplitude variability, while the light-grey block denotes the "cold-peak window".

Within the “cold-peak window” high-resolution analysis reveals a great deal of variability (see figure 3b). The peak in valve concentrations at 478cm is proven to be robust, mirroring the fluctuations identified in the CRS. With distance up-core the trend oscillates rapidly between higher and lower values, with peaks apparently synchronous with those in the CRS record (see figures 3a and 3b). As the record enters MIS 2 the trend adopts more structure, with values gradually building to a robust peak of $2.30x10^5$ at 358cm, before declining again. This second peak coincides with the third CRS pulse noted above. The valve concentrations of the *F. curta/F. cylindrus* group revert back to high-frequency variability for the remainder of the “cold-peak window”.

Discussion

Chaetoceros are an opportunistic genus, which exploit conditions in the Marginal Ice Zone (MIZ) during spring melt back. As sea-ice retreats the influx of fresh water stratifies the water column confining the diatoms and high concentrations of nutrients in the photic zone. As nutrients are exhausted and/or stratification decays the *Chaetoceros* vegetative cells produce blooms of resting spores (Crosta, et al. 1997).

In addition to the MIZ CRS demonstrate high abundances along the coast of the Antarctic Peninsula and within the Ross Sea where high nutrient concentrations and freshwater outflow from the continent produce optimal conditions. In contrast to this, abundances within the permanently open ocean zone have been shown to be significantly lower (Dierssen, et al. 2002).

Site PC063 is located in the north Scotia Sea, an open ocean environment in the PFZ, a region of ocean not known for high abundances of CRS. Therefore the presence of several CRS peaks within the down core diatom species assemblage warrants further investigation. Due to CRS association with the MIZ, the occurrence of these peaks possibly alludes to more complex workings within the sea-ice/open ocean dynamic. Investigating the correlation between CRS and the sea-ice indicator group *F. curta/F. cylilndrus* should determine the robustness of the association between CRS peaks and the presence of sea-ice.

It is well established that both *F. curta* and *F. cylindrus* occupy sea-ice covered environments. With highest reported abundances around the Antarctic Coast, southward of the maximum winter sea-ice limit. Both species are closely associated with both land-fast and pack sea-ice and have also been observed in exceptionally high abundances in the water column at the melting sea-ice edge (Armand et al., 2005). It is proposed that as sea-ice retreats these sea-ice taxa are ‘seeded’ in the water column, within the stratified lens produced during spring melt back. Under these optimal conditions they bloom before descending through the water column to be preserved in the sediments below (Crosta *et al*., 1997). This allows their existence within Southern Ocean sediments to be used as a proxy for the winter sea-ice edge. The occurrence of this indicator group, in sufficient quantities, in the sediments of PC063, would suggest that winter sea-ice, during the last glacial cycle, extended to the position of the modern-day Polar Front, possibly providing a mechanism for the CRS peaks observed in the diatom assemblage.

Focusing on the “cold-peak window” looking down core it is evident that several, if not all, of the CRS peaks are mirrored in the *F. curta/F. cylindrus* group record (see figure 3), supporting the hypothesis that sea-ice is the dominant mechanism responsible for CRS productivity in the area. However, if we introduce an additional component, the relative abundance curve of the *F. curta/F. cylindrus* group (see figure 3b), it becomes apparent that this is not the case across the full range of the record. The *F. curta/F. cylindrus* group relative abundance curve is the documented indicator of the winter sea-ice edge (Gersonde & Zielinski, 2000). According to Gersonde & Zielinski (2000), a quantity of >3% is indicative of the presence of the winter sea-ice edge. Throughout the majority of the “cold-peak window” this condition is satisfied. However, it is clear that the largest event, the productivity peak apparent in the low-resolution records, does not occur concurrently with sea-ice coverage. On closer inspection this productivity pulse appears as a twin peak and is replicated in *F. curta/F. cylindrus* group absolute abundances. The parallel between the valve concentrations of both groups alludes to a shared origin, potentially a sedimentation event or variability within regional upwelling.

Conclusions

- The synchronicity of the magnetic susceptibility curve and down core diatom concentration supports the use of diatoms as a climate proxy and indicates a stable sedimentary environment
- Consistently high valve concentrations (absolute abundances) across a spectrum of sea-ice and cold-water diatom taxa are indicative of a cold-peak climatic window spanning the MIS 3 – MIS 2 transition.
- High-resolution analysis of the cold-peak window reveals the superimposition of high-frequency variability onto the cooling climatic trend.
- The relationship between the sea-ice indicator group *Fragilariopsis curta/Fragilariopsis cylindrus* and *Chaetoceros* resting spores indicates episodic melt back of the winter sea-ice edge at the position of the modern day polar front during the climate shift from MIS 3 to MIS 2.
- A large productivity event at 478cm is inconsistent with the cyclicity of the winter sea-ice edge alluding to a separate oceanographic mechanism. Possibly variability in the sedimentation regime or a strengthening of regional upwelling.

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References

Allen, C. S., Pike, J., Pudsey, C. J. and Leventer, A. 2005. Submillennial variations in ocean conditions during deglaciation based on diatom assemblages from the southwest Atlantic. - Paleoceanography 20: art. no.-PA2012.

Arhan, M., Garabato, A. C. N., Heywood, K. J. and Stevens, D. P. 2002. The Antarctic Circumpolar Current between the Falkland Islands and South Georgia. - Journal of Physical Oceanography 32: 1914-1931.

Armand, L. K., Crosta, X., Romero, O. and Pichon, J.-J. 2005. The biogeography of major diatom taxa in Southern Ocean sediments: 1. Sea ice related species. - Palaeogeography, Palaeoclimatology, Palaeoecology 223: 93-126.

Barker, P. F. 2001. Scotia Sea regional tectonic evolution: implications for mantle flow and palaeocirculation. - Earth-Science Reviews 55: 1-39.

Blunier, T., Chappellaz, J., Schwander, J., Dallenbach, A., Stauffer, B., Stocker, T. F., Raynaud, D., Jouzel, J., Clausens, H. B., Hammer, C. U. and Johnsen, S. J. 1998. Asynchrony of Antarctic and Greenland climate change during the last glacial period. - Nature 394: 739-743.

Blunier, T. and Brook, E. J. 2001. Timing of millennial-scale climate change in Antarctica and Greenland during the last glacial period. - Science 291: 109-112.

Bond, G., Heinrich, H., Broecker, W., Labeyrie, L., McManus, J., Andrews, J., Huon, S., Jantschik, R., Clasen, S., Simet, C., Tedesco, K., Klas, M., Bonani, G. and Ivy, S. 1992. Evidence for massive discharges of icebergs into the north-Atlantic Ocean during the last glacial period. - Nature 360: 245-249.

Bond, G., Broecker, W., Johnsen, S., McManus, J., Labeyrie, L., Jouzel, J. and Bonani, G. 1993. Correlations between Climate Records from North-Atlantic Sediments and Greenland Ice. - Nature 365: 143-147.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I. and Bonani, G. 1997. A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates. - Science 278: 1257-1266.

Bond, G. C. and Lotti, R. 1995. Iceberg discharges into the north-Atlantic on millenial time scales during the last glaciation. - Science 267: 1005-1010.

Brook, E. J., White, J. W. C., Schilla, A. S. M., Bender, M. L., Barnett, B., Severinghaus, J. P., Taylor, K. C., Alley, R. B. and Steig, E. J. 2005. Timing of millennial-scale climate change at Siple Dome, West Antarctica, during the last glacial period. - Quaternary Science Reviews 24: 1333-1343.

Brown, B., Gaina, C. and Muller, R. D. 2006. Circum-Antarctic palaeobathymetry: Illustrated examples from Cenozoic to recent times. - Palaeogeography, Palaeoclimatology, Palaeoecology 231: 158-168.

Chapman, M. R. and Shackleton, N. J. 2000. Evidence of 550-year and 1000-year cyclicities in North Atlantic circulation patterns during the Holocene. - Holocene 10: 287-291.

Crosta, X., Pichon, J.-J. and Labracherie, M. 1997. Distribution of Chaetoceros resting spores in modern peri-Antarctic sediments. - Marine Micropaleontology 29: 283-299.

Cunningham, W. L. and Leventer, A. 1998. Diatom assemblages in surface sediments of the Ross Sea: Relationship to present oceanographic conditions. - Antarctic Science 10: 134-146.

Dierssen, H. M., Smith, R. C. and Vernet, M. 2002. Glacial meltwater dynamics in coastal waters west of the Antarctic peninsula. - Proceedings of the National Academy of Science of the United States of America 99: 1790-1795.

Eagles, G., Livermore, R. A., Fairhead, J. D. and Morris, P. 2005. Tectonic evolution of the west Scotia Sea. - Journal of Geophysical Research 110.

Garabato, A. C. N., Heywood, K. J. and Stevens, D. P. 2002. Modification and pathways of Southern Ocean Deep Waters in the Scotia Sea. - Deep-Sea Research Part I-Oceanographic Research Papers 49: 681-705.

Gersonde, R. and Zielinski, U. 2000. The reconstruction of late Quaternary Antarctic sea-ice distribution--the use of diatoms as a proxy for sea-ice. - Palaeogeography, Palaeoclimatology, Palaeoecology 162: 263-286.

Gersonde, R., Abelmann, A., U., B., Becquey, S., Bianchi, C., Cortese, G., Grobe, H., Kuhn, G., Niebler, H.-S., Segl, M., Sieger, R., Zielinski, U. and Futterer, D. K. 2003. Last glacial sea surface temperatures and sea-ice extent in the Southern Ocean (Atlantic-Indian sector): A multiproxy approach. - Paleoceanography 18.

Huber, C., Leuenberger, M., Spahni, R., Fluckiger, J., Schwander, J., Stocker, T. F., Johnsen, S., Landais, A. and Jouzel, J. 2006. Isotope calibrated Greenland temperature recrods over Marine Isotope Stage 3 and its relation to CH_4. - Earth and Planetary Science Letters 243: 504-519.

Huybers, P. and Wunsch, C. 2004. A depth-derived Pleistocene age model: Uncertainty estimates, sedimentation variability, and nonlinear climate change. - Paleoceanography 19: art. no.-PA1028.

Leventer, A. and Dunbar, R. B. 1996. Factors influencing the distribution of diatoms and other algae in the Ross Sea. - Journal of Geophysical Research 101: 18489-18500.

Locarnini, R. A., Whitworth III, T. and Nowlin, W. D. 1993. The importance of the Scotia Sea on the outflow of Weddell Sea Deep Water. - Journal of Marine Research 51: 135-153.

Orsi, A. H., Whitworth III, T. and Nowlin Jr, W. D. 1995. On the meridional extent and fronts of the Antarctic Circumpolar Current. - Deep-Sea Research I 42: 641-673.

Pudsey, C. J. 2000. Sedimentation on the continental rise west of the Antarctic Peninsula over the last three glacial cycles. - Marine Geology 167: 313-338.

Raymo, M. E., Ganley, K., Carter, S., Oppo, D. W. and McManus, J. 1998. Millennial-scale climate instability during the early Pleistocene epoch (vol 392, pg 699, 1998). - Nature 394: 809.

Scherer, R. P. 1994. A new method for the determination for the absolute abundance of diatoms and other silt-sized sedimentary particles - Journal of Paleolimnology 12: 171-179.

Wunsch, C. 2003. Determining paleoceanographic circulations, with emphasis on the Last Glacial Maximum. - Quaternary Science Reviews 22: 371-385.