Seasonal and subseasonal climate changes recorded in laminated diatom ooze sediments, Adélie Land, East Antarctica

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Abstract: A 40 m long sediment core covering the 1000–9600 years BP period was retrieved from the Dumont d’Urville Trough off Adélie Land, East Antarctica, during the MD 130–Images X-CADO cruise. This sedimentary sequence allows the documentation of changes in climate seasonality during the Holocene. Here we show preliminary results of diatom communities, lithic grain distribution and titanium content measured on two 30 cm long sequences of thin sections. The two sequences originate from two different climate regimes, the colder Neoglacial and the warmer Hypsithermal. Proxies were measured at microscale resolution on 25 laminations for the Neoglacial and 14 laminations for the Hypsithermal. The two sequences reveal alternating light-green and dark-green laminae. Light laminae result from low terrigenous input and high sea-ice edge diatom fluxes and are interpreted to represent the spring season. Dark laminae result from high terrigenous input mixed with a diversified open ocean diatom flora and are interpreted to represent the summer–autumn season. The two sequences therefore resolve annual couplets composed of one light plus one dark lamina. Variations in the relative thickness of laminations and annualcouplets, associated with diatom assemblage changes, are observed in each sequence and between the two sequences giving information on interannual to millennial changes in environmental conditions.

Key words: Adélie Land, Holocene, laminated sediments, diatom ooze, seasonality, sea ice, East Antarctica.

Introduction

Based on ice core records (Masson et al., 2000; NGICP members, 2004), the Holocene period was believed rather stable in comparison with the last glacial period. However recent palaeo-oceanographic investigations have revealed rapid and large amplitude variations in the North Atlantic (de Menocal et al., 2000; Bond et al., 2001) and in the Southern Ocean (Hodell et al., 2001; Nielsen et al., 2004). Sites of high sediment accumulation are therefore necessary to document these variations and to understand their frequency and origin. In that perspective, Antarctic inner shelf basins that present laminated sediments allow study of subseasonal reconstructions of Holocene oceanographic and climatic conditions, which may help to understand better both the interactions between Antarctic atmospheric–oceanic–cryospheric–sea-ice processes, deep ocean circulation and teleconnections between high and low latitudes. Most of the studies aimed at deciphering the signal recorded in laminations originate from the Antarctic Peninsula (eg, Pike et al., 2001; Leventer et al., 2002; Bahk et al., 2003; Maddison et al., 2005) and the Mac Robertson Shelf (Stickley et al., 2005). Nonetheless, evidence for strong Antarctic regional heterogeneous in recent climate changes (Jones et al., 1993; King et al., 2003) call for additional sedimentary records in order to provide a more comprehensive view of past climate dynamics at high southern latitudes. The Adélie Land region in the East Antarctic Margin (EAM) has received little attention so far, despite evidences for very high sediment accumulation (Leventer et al., 2006). Core MD03-2601 from the Dumont d’Urville Trough is a 40 m long sequence of laminated diatom ooze that covers the Holocene. Investigation of diatom communities, lithic grain distribution and titanium content at microscale resolution on two 30 cm long laminated sequences aimed to document (1) the nature of
the signal preserved in the laminations and (2) whether laminations may be used here to track climate change at the interannual timescale.

Oceanographic setting

The SE–NW oriented Dumont d’Urville Trough off Adélie Land is located on the EAM (Figure 1). It is composed of a succession of glacial depressions enclosed between the Dibble Bank to the west and Adélie Bank to the East. Core MD03-2601 (66°03.07’S; 138°33.43’E; 746 m water depth) was recovered from the slope of a small depression located ~60 km off the Adélie Land coast. This region is influenced by three water masses (Bindoff et al., 2001): the Antarctic Coastal Current (ACC), which flows westward at the surface (Figure 1); the Modified Circumpolar Deep Water (MCDW), which upwells at the Antarctic Divergence; and the High Salinity Shelf Water (HSSW) formed by brine-rejection during winter sea ice formation and cooling of the MCDW, which flows northward as part of the Antarctic Bottom Water (AABW) (Harris, 2000). The Adélie Land region is dissected by several small glaciers (Figure 1) injecting fresh water and terrigenous particles in the coastal area although these small glaciers have much less influence than the larger Mertz Glacier located few degrees to the East (Escutia et al., 2003). Sea ice is present ~9 months per year over the core site (Schweitzer, 1995) with more open marine conditions between the Dibble Bank to the west and Adélie Bank to the East. Core MD03-2601 (66°03.07’S; 138°33.43’E; 746 m water depth) was subsequently corrected by a marine reservoir age of 1300 years (Ingólfsson et al., 1998). The core covers the period from 9600 to 1000 yr BP. Diatom census counts and δ15N and δ13C investigations (Crosta et al., 2005) have shown that the Holocene period off Adélie Land can be divided into two different climatic phases: a colder Neoglacial (after 4000 yr BP), and a warm Hypsithermal (4000–9600 yr BP), which contains a cooling event (6350–8000 yr BP).

Material and methods

Material and core stratigraphy

Core MD03-2601 was collected using the MDII Calypso piston corer during the MD130-images X-CADO cruise in 2003. This 40.24 m long sequence of diatom ooze alternates between laminated and massive facies, and does not show any obvious visual disturbance. Stratigraphic control is based on five AMS 14C dates on humic acid (Crosta et al., 2005) that were subsequently corrected by a marine reservoir age of 1300 years. Sea ice is present ~9 months per year over the core site (Schweitzer, 1995) with more open marine conditions between April and March. Sea ice advances rapidly from April to June to reach its maximum extension between July and September, then retreats slowly during spring melting to attain its minimum extent during February. The Marginal Ice Zone is believed to be macro- and micronutrient rich, and ice melting produces a stratified stable environment favourable for diatom blooms (Leventer, 1992).

Laboratory procedures

Laboratory procedures involve preparations for macroscale investigations on half-core sections and for microscale analyses on thin sections.

Titanium content (Ti) expressed in counts per second (cps) was measured on half-core sections at 2 cm spacing along the entire core and at 2 mm spacing on the studied sections, on the Bremen University CORTEX XRF core-scanner following Jansen et al. (1998) method. Daily calibration of the XRF core-scanner precluded drift over time, thus ensuring low standard deviations of the data. Titanium is believed to be of terrigenous origin as this element does not participate in biological and diagenetic cycles, in contrast to iron and aluminium (Taylor and McLennan, 1985; Yarincik and Murray, 2000). Aluminium, which is actively uptaken and accumulated by diatoms, cannot be applied here to normalize Ti values (Van Bennekom et al., 1989; Moran and Moore, 1992).

Positive x-ray pictures of half-core sections were done using the SCOPIX image-processing tool (Migeon et al., 1999). Variations in grey levels indicate changes in the sediment density and thus composition. The light and dark laminations observed here correspond to sediment layers of low and high density, respectively.

Based on x-ray pictures, we determined the distribution and thickness of laminations along the entire core (Figure 2). We used a slightly modified technique from Francis et al. (2002), which involves drawing a suite of ellipses representative of each lamina and calculation of the distribution and thickness of laminae based on the ellipses in Scion Image®. This technique was applied to laminae only because sublaminae are difficult to distinguish on x-ray pictures. This approach helped us to sample two ~30 cm long sections of continuously laminated sediment. Section 5 (619–648.5 cm) originates from the Neoglacial while section 13 (1880.8–1910.7 cm) comes from the Hypsithermal.

Each lamina observed on x-ray pictures from sections 5 and 13 was sampled for diatom census counts and bulk isotopic ratios. Permanent slides were mounted following the procedure of Rathburn et al. (1997). This sampling strategy that takes the sediment over the entire thickness of the half-core sections cannot give access to diatom successions at the lamination scale because laminae are here inclined in both the horizontal and vertical plains. Such diatom census counts are, however, essential to interpret diatom assemblages at microscale on the thin sections.

Three thin sections (TS) were made for each period (TS 1, 2, 3 for core section 5 and TS 4, 5, 6 for core section 13) using the impregnating method detailed in Zaragosi et al. (2006).
The goal of this technique is to embed a large sediment volume into a permanent medium without disturbing the sediment structure. The resulting thin sections (TS) are used here to document variations in the biogenic and lithogenic content.

Optical observations were conducted on the TS using an Olympus BH2 light microscope at magnification of 250 × and 500 × to determine diatom community changes with a focus on the relative importance of dominant species. Diatom census counts along the entire core (Crosta et al., 2005) and within each lamina over the studied sections give us complementary insight on diatom assemblages and dominant species at decadal to subdecadal scales, which ascertains diatom identification on the TS.

Detrital material was similarly studied on the TS to determine (1) the mineral type via polarized light and (2) the distribution and number of lithics particles as grain number per square millimetre using an imagery system composed of a LEICA DM600B Digital microscope and Leica QWin 3.0 software. We conducted image analysis on 2.5–3.5 cm² TS areas, later referred to as Photomosaic (PM) (see Figure 4).

Because of the homogenous amorphous matrix of the diatom ooze sediment and of the impregnating Epoxy resin, the sediment matrix appeared darker than the clastic grains in the analysed polarized light. The picture processing method, detailed in Francus (1998), counts all the grains present in the area and estimates several characteristics as surface, width and length of the lithic grain. Two slides (TS2 and TS3) with very cottony texture did not allow coherent image acquisition and were not used in the calculations.

Results

General observations

Because of the sediment composition, laminations are almost invisible to the naked eye on half-core sections. They are, however, visualized on x-ray images as light and dark layers and on TS as light and brown layers. We will hereafter refer to light and dark laminae, which together form a couplet.

Mean thicknesses of light and dark laminations are 0.7 cm (n = 937, σ = 0.4) and 1.12 cm (n = 1018, σ = 1.22), respectively (Figure 2). Light and dark lamination thickness and lamination number reveals no obvious trend with depth but rather cyclic variations, whereas thickness of light laminations shows a slight decrease with depth.

Generally, x-ray images and TS show gradational colour contact between a light lamina and the overlying dark lamina and sharp colour contact from a dark to the overlying light lamina. Microscopic observations on TS reveal that light laminations are mainly composed of biogenic debris whereas dark laminations are composed of a mixture of biogenic and detrital debris, the latter being mainly clay and silt. Petrographic observations indicate that the clastic grains are mainly quartz. Only observable on TS, thin light laminae, called sublaminae, are found in dark laminations.

Section 5: Neoglacial period

Twenty-five laminations and four sublaminations are distinguished on TS 1, 2 and 3 that represent a ~30 cm long sequence of undisturbed sediment within section 5 (see Figure 4a for TS location). These laminations include 12 lights, 11 darks and 2 transitional laminae with average thicknesses of 1.1 cm (σ = 0.8), 0.8 cm (σ = 0.8) and 0.4 cm (σ = 0.03), respectively. The mean thickness of a couplet reaches 2.1 cm (n = 10, σ = 1.4).

Diatom assemblages

Diatom census counts performed between 608 cm and 670 cm (n = 50) show few dominant species among a highly diverse diatom community (~50 species), thus confirming results from lower resolution diatom counts (Crosta et al., 2005). In section 5, Fragilariopsis curta and Chaetoceros resting spores (CRS), mainly Hyalochaete Chaetoceros neglectus, represent the dominant species with 26% and 19%, respectively. They are accompanied by a set of subordinate species or species groups such as other cryophilic Fragilariopsis species (12%), F. rhombica (10%), F. kerguelensis (8%), large centric species thriving in cold waters (8%), Thalassiosira antarctica (6%), Phaeoceros vegetative cells (5%), Corethron permutatum + rhizosolenoid species (4%) and needle-like species mainly represented by Thalassiothrix antarctica (2%) (Figure 3a).

Qualitative examinations of diatom assemblages on the TS demonstrate the same dominant species as mentioned above. These investigations, however, show the fine distribution of the diatom species that was invisible in the stepwise sampling. As a general statement, diatom distribution follows the colour changes of the laminations with a gradational evolution in the assemblages from light to dark laminae and an abrupt change from dark to light laminae. A close investigation depicts the following five main diatom assemblages, labelled A-B for the ones occurring in the light laminae and D-E-F for the ones encountered in dark laminae (Figure 3a and see Figure 5).

Assemblage type A is characterized by a co-dominance of F. curta plus other cryophilic Fragilariopsis species and CRS...
plus vegetative *Phaeoceros* sp. and *C. pennatum*. *Chaetoceros* RS relative abundance increases progressively toward the top of the laminae while cryophilic *Fragilariopsis* species dominance decreases (Figure 3a). We counted 11 light laminae in the three TS of section 5, from which three laminae are characterized by assemblage type A, five laminae by assemblage type B and four laminae by a slow transition from assemblage type A to assemblage type B. The third and the ninth light laminae contained more CRS.

Assemblage type D shows a mixed flora composed of *F. kerguelensis*, CRS, *T. antarctica*, large centric species, and needle-like species. Dominant species of each assemblage within laminae:

- **A** = *F. curta*, CRS, *C. pennatum* and *Phaeoceros* sp.
- **B** = Idem A with more *Phaeoceros* sp. and *C. pennatum* + rhizosolenoids
- **C** = *F. rhombica*, *F. kerguelensis*, CRS, *C. pennatum* and *Phaeoceros* sp.
- **D** = very complex assemblage with *F. kerguelensis*, large centric species, *T. antarctica*, CRS and *Phaeoceros* sp.
- **E** = Idem D with more *T. antarctica*
- **F** = Idem D + needle-like species

Notes:
- **Rh**: rhizosolenoids
- **Ta**: *T. antarctica*
- **P**: pulsed bloom with assemblage type D
- **Bi**: bi-specific species
- **HS**: High degree of silicification
- **CRS**: very abundant CRS

**Figure 3** Schematic log of lamination and sub-lamination distribution in section 5 (a) and in section 13 (b). Location of the centimetric scale thin sections, and number of annual couplets are reported on the left side. Pie-charts illustrate the relative abundance of the various diatom groups from centimetric-scale diatom census counts in section 5 (a) and 13 (b).
Phaeoceros sp. and C. pennatum. Assemblage type E is similar to assemblage type D but with greater presence of T. antarctica. Assemblage type F also resembles assemblage type D but with a greater dominance of needle-like species (Figure 3a). We counted 11 dark laminations, from which seven are composed of the assemblage type D. The other dark laminations display a succession of assemblage types. Four laminations show a slow evolution from assemblage type E to assemblage type F, one lamination from assemblage type D to assemblage type F, and one lamination from assemblage type D to assemblage type E to assemblage type F (Figure 3a). Diatoms at the top of the dark laminations generally show a higher degree of silicification (see Figure 5). Complex dark laminations are encountered in couplets five to ten in which light laminations also demonstrate a more complex structure. Transitional laminations between the light and the overlying dark laminations and showing a mixture of assemblage types A, B and D characteristics are also present here.

Detrital content
Titanium content is correlated to density changes visualized by x-ray photography with lower Ti content in light laminations than in dark laminations with mean values of 11.6 and 13.7 cps respectively (Figure 4a). Titanium content is similarly correlated to TS colour changes even though some variability is encountered within each lamina. We used the Wilcoxon-Mann-Whitney (WMW) test to determine whether the Ti content is significantly different in light and dark laminations. Briefly, the WMW is a non-parametric variance analysis test adapted for small data sets ($n_{light}/n_{dark}$, here) (Saporta, 1990). This test determines whether Ti values are randomly distributed or organized according to different populations (light and dark laminations). At the 1% confidence level, the WMW test yields a $H_{Ti}$ content value of 4.32 that is superior to the rejection threshold of 2.58. This demonstrates that different Ti content indeed prevails in light and dark laminations and that intracouplet differences are greater than homochromic intercouplet differences.

Determiner of grain distribution and characteristics was only possible on TS1 within two study zones: PM 1 and 2 (Figure 4a). The digital approach recognizes grains with diameter greater than 5 µm. In this population, silts are dominant with an unimodal histogram frequency centred at ~10 µm of diameter. In agreement with the Ti content data,
Figure 5 Various diatom assemblage types. Photographs 1–3 and 5–6 show, respectively, typical light/biogenic laminae and dark/terrigenous laminae assemblages. Photograph 7 illustrates two types of sublaminae. Photographs 4 and 8 compare two different degrees of silicification on two diatom species.
the number of lithic grains (GN) is generally lower in light ($n_{\text{light}} = 4$) than in dark laminae ($n_{\text{dark}} = 5$) with mean values of 303 and 548 grains/mm$^2$, respectively (Figure 4a). We ascertained the significance of different grain populations in light versus dark laminae through the WMW statistic test. At the 1% confidence level, the WMW test yields a $H_{\text{GN}}$ value of 2.84 superior to the rejection threshold of 2.58 ($n_{\text{light}} = 23$, $n_{\text{dark}} = 43$). Different GN thus prevails in light and dark laminae, indicating that intracouplet differences are greater than intercouplet differences between laminae of the same colour.

**Section 13: Hypsithermal period**

Fourteen laminae and 26 sublaminae were observed in section 13 (TS 4, 5, 6) (see Figure 4b for TS location). The laminae divide up into five lights, six darks and three transitional laminae with respective thicknesses of 0.7 cm ($\sigma = 0.1$ cm), 3.6 cm ($\sigma = 1.8$ cm) and 0.6 cm ($\sigma = 0.2$ cm), yielding an average thickness of 4.6 cm ($\sigma = 1.6$) for the couplets. Thickness of sublaminae varies between 0.1 and 2.1 mm ($n = 26$, mean = 1 mm, $\sigma = 0.6$ mm).

**Diatom assemblages**

Diatom census counts performed between 1858 cm and 1919 cm ($n = 62$) evidence the same diatom species as in section 5 but with an important shift in dominance. *Chaetoceros* resting spores (22%), *F. kerguелиensis* (19%), *F. rhombica* (15%) and *T. antarctica* (11%) are more abundant and are accompanied by a suite of subordinate species such as large centric diatoms (9%), *F. curta* (9%), other cryophilic *Fragilariopsis* diatoms (8%), *Phaeoceros* vegetative cells (4%), needle-like species (2%) and *C. pennatum* and rhizosolenoids (1%) (Figure 3b).

Qualitative examinations of diatom assemblages on the TS demonstrate the same dominant species as mentioned above with a gradational evolution of the assemblages from light to dark laminae and an abrupt change from dark to light laminae. Three main assemblages are documented: assemblages type C in the light laminae and assemblages type E and F in the dark laminae (Figure 5).

Assemblage type C is mainly composed of *F. rhombica* associated with cryophilic *Fragilariopsis* sp., *F. kerguелиensis* and CRS. The relative occurrence of CRS increases from bottom to top of the laminae. Out of five light laminations analysed on the TS taken from section 13, four are composed of assemblage type C. The last lamination is represented by the bi-specific assemblage type B defined before (Figure 3b).

Dark laminae are characterized by the above-described assemblage types E and F. Of six dark laminae, five are characterized by assemblage type E while the last lamination is composed of assemblage type F. We noted the presence of three transitional laminae, showing a mixture of assemblage types C, B and D in the lower part of the TS sequence (Figure 3b). We also noted that dark laminations numbers 1 and 4 present greater relative abundances of CRS and higher frustule silicification (Figure 5).

Twenty-six sublaminae appear as thin light laminae within dark laminae with upper and lower sharp contacts. Diatom examinations evidence three diatom assemblage types. Two are near monospecific assemblages, composed of *T. antarctica* ($n = 8$) or rhizosolenoids ($n = 3$) and referred to Ta and Rh, respectively (Figure 5). The last one, named P for pulsed event, is similar to assemblage type D ($n = 15$) (Figure 3b). The Rh sublaminae appear at the bottom of dark laminales while the Ta sublaminae generally occur at the top of dark laminales. P sublaminae are scattered throughout dark laminales. Ta, Rh and P display mean thicknesses of 371 $\mu$m ($\sigma = 289$ $\mu$m), 860 $\mu$m ($\sigma = 470$ $\mu$m) and 1300 $\mu$m ($\sigma = 460$ $\mu$m), respectively. These sublaminae cannot be interpreted as light laminales because of their specific diatom assemblages and reduced thickness. They conversely represent abrupt events during deposition of the dark laminares.

**Detrital content**

Ti relative concentrations are lower in light laminae than in dark laminae both at the x-ray and TS scale, with mean values of 13 and 14 cps, respectively (Figure 4b). Digital analysis of grains larger than 5 $\mu$m indicates dominance of the silt fraction with a unimodal histogram frequency centred at ~10 $\mu$m diameter. The number of grains (GN) calculated on 5 PM (Figure 4b) follows the same pattern as Ti content with mean values of 152 grains/mm$^2$ in light laminations and 264 grains/mm$^2$ in dark laminares. At the 1% confidence level, the WMW test yields a $H_{\text{Ti content}}$ value of 1.72, greater than the rejection threshold of 1.64, and a $H_{\text{GN}}$ value of 5.61, also superior to the rejection threshold of 2.58 ($n_{\text{light}} = 25$, $n_{\text{dark}} = 111$ for Ti content; $n_{\text{light}} = 58$, $n_{\text{dark}} = 94$ for GN). This demonstrates that different detrital populations prevail in light and dark laminares of the sequence studied here and that the intracouplet differences in Ti content and GN are greater than intercouplet differences of the same colour type lamination.

**Discussion**

The presence of well-preserved frustules of needle-like species and of the easily dissolved species *C. pennatum* (Beucher et al., 2004) indicates that buried diatom communities are barely influenced by differential preservation and, thus, accurately record surfuce environment changes. We hereafter use data on detrital content as well as the ecological preferences of dominant species to determine the significance of lamination types and to link their succession to environmental conditions.

**Seasonal and subseasonal signals**

**Light/biogenic laminae**

Light laminae are characterized by low density, low Ti content and low GN. They are therefore mainly composed of biogenic material, i.e., diatoms. Light laminae are characterized by assemblage types A and C in which cryophilic *Fragilariopsis* species (mainly *F. curta* in section 5 and *F. rhombica* in section 13) and CRS are the co-dominant species groups, with subordinate presence of *C. pennatum* and vegetative *Phaeoceros* sp.

*Fragilariopsis curta* and CRS show a preference for stable, stratified waters and sea ice proximity (Leventer, 1991; McMinn and Hodgson, 1993; Crosta et al., 1997) that seeds the surrounding surface water as it melts. This seems also true for *F. rhombica*, with the difference that this species thrives in waters slightly warmer than *F. curta* (Armand et al., 2005). These conditions are encountered in spring and, when associated with sufficient light and nutrients levels, promote intense diatom blooms. Blooms may eventually deplete the nutrient pool thus leading to CRS formation (Leventer, 1991). We therefore interpret the light/biogenic laminae to represent the spring season. Spring laminae evidence here, however, depart from previous studies in other cores from the EAM (Stickley et al., 2005) and the Antarctic Peninsula (Leventer et al., 2002; Bahk et al., 2003; Madsion et al., 2005) in which the spring season is characterized by greater abundances of CRS (60%). Low CRS occurrence is confirmed by diatom census counts all core long (Crosta et al., 2005) and may result from more oceanic conditions prevailing at the core location.
Indeed, presence of *Phaeoceros* vegetative cells suggests an oceanic influence (Maddison, 2005) and *Ch. neglectus* has not been reported to be seeded from sea ice (Garrison et al., 1987; Riaux-Gobin et al., 2003).

Assemblage type A may be followed by the predominance of migrant species such as *C. pennatuum* and rhizosolenoids that characterize the diatom assemblage type B. These species thrive normally in open water with little sea ice during the growing season (Fryxell and Hasle, 1971) and display positive buoyancy (Crawford, 1995; Leventer et al., 2002; Bahk et al., 2003). Out of Antarctica, these species groups were shown to be part of the shade flora that reaches very high biomass at the pycnocline (Kemp et al., 1999). Their record in the sediment was interpreted as an event of rapid sedimentation when the pycnocline weakened (Kemp et al., 2000). Increasing occurrence of *C. pennatuum* and rhizosolenoids throughout the light laminae suggest here a strengthening of the pycnocline during the spring season, thus conducting to increasing biomass accumulation and export after cell senescence. This assemblage therefore may be an indicator of warmer, more oligotrophic, open-water intrusion (Stickley et al., 2005) or reduced wind stress.

The diatom succession from cryophilic *Fragilariopsis* species to CRS and finally to migrant species observed here indicates a transition from a cold-stratified environment with extensive sea ice cover at the beginning of the spring season to more open water as temperatures rise, with increasing seasonal insolation coupled to a decrease of the nutrient pool. Sea ice persistence implies low terrigenous input from the continent, which is additionally diluted by the intense diatom fluxes to the sea floor.

*Dark/terrigenous laminae*

Dark laminae are characterized by higher density, higher Ti content and higher GN. They are composed of a mixture of biogenic and terrigenous material. Dark laminae are characterized by more diverse diatom assemblages dominated by *F. kerguelensis*, *T. antarctica* and large centric species. These species preferentially thrive in open ocean water and do not support sea ice presence during the growing season (Armand et al., 2005; Crosta et al., 2005). They also exhibit lower nutrient requirements and lower growth rates than bloom-related species (Leventer and Dunbar, 1987; Zielinski and Gersonde, 1997). We interpret these assemblages as representative of summer production in open water when sea ice has melted (Fryxell and Hasle, 1971) and display positive buoyancy (Crawford, 1995; Leventer et al., 2002; Bahk et al., 2003). Out of Antarctica, these species groups were shown to be part of the shade flora that reaches very high biomass at the pycnocline (Kemp et al., 1999). Their record in the sediment was interpreted as an event of rapid sedimentation when the pycnocline weakened (Kemp et al., 2000). Increasing occurrence of *C. pennatuum* and rhizosolenoids throughout the light laminae suggest here a strengthening of the pycnocline during the spring season, thus conducting to increasing biomass accumulation and export after cell senescence. This assemblage therefore may be an indicator of warmer, more oligotrophic, open-water intrusion (Stickley et al., 2005) or reduced wind stress.

The three above-described sublaminae types record spring/summer transition (Rh), punctual intense summer blooms (P) and autumn/winter transition (Ta). The distribution of the sublaminae may provide information on atmospheric and oceanic shifts and on sea ice seasonality at the annual scale.

**A model of lamina deposition**

We developed a schematic model to explain the climatic and oceanic conditions leading to the deposition of the laminae (Figure 6). At the beginning of spring, sea ice starts to melt but a large extent still limits continental input to the water column.
Sea ice melting creates strong water column stratification while supplying diatoms and macro- and micronutrients to the surface waters. The beginning of spring is also a time of decrease in the wind regime, of increase in light levels and of high nutrient content in response to the winter overturning. These factors create a favourable environment supporting an intense bloom of cryophilic pennate diatoms and Chaeetoceros species. As spring advances, the reduction of sea ice influence and the intense nutrient uptake eventually cause CRS formation. Meanwhile, C. pennatum and rhizosolenoids slowly build up high biomass at the well-defined pycnocline. They eventually settle after cell senescence or after episodic pycnocline breakdown. In the Antarctic Peninsula, similar laminations have been interpreted to represent autumn mass sedimentation of diatoms that have grown during the period of summer stratification. Summer stratification is promoted by reduced wind activity and the local ‘island effect’ (Amos, 1987; Huntley et al., 1987). In our study area, more oceanic and more chaotic atmospheric conditions (King and Turner, 1997) conducting to less stable surface water layer, explain episodic export events early in the season. High spring primary production in the form of successive diatom blooms and low detrital supply produces thick biogenic spring laminae.

As summer approaches, light increases and sea ice disappears, driving a transitional diatom assemblage characterized by the appearance of the open water species F. kerguelensis and of centric species, mixed with cold water species. At the beginning of summer, punctual pycnocline disruption leads to pulsed exports of rhizosolenoids, imprinted by thin sublami- nae. Dilution of sea ice meltwater reduces water column stratification and increases the depth of the pycnocline. The summer light levels are maximum and nutrient content is maintained via MCDW upwelling. These conditions lead to the development of mixed diatom communities primarily dominated by F. kerguelensis, while centric species that present a slower growth rate may become co-dominant as the summer develops. A slower but longer diatom growth during summer than during spring is inferred from the higher silicification degree of C. pennatum, vegetative Phaeoceros sp. and Fragilaripopsis specimens. The biogenic sedimentation is, however, lower than during spring which, coupled with increased glacial runoff, enables the concomitant settling of terrigenous particles from overflow glacial plumes (Leventer et al., 2002; Finocchiaro et al., 2005). Events of high productivity during summer dilute the terrigenous supply and are recorded as P sublaminae. During autumn, light level decreases, storm activity increases and sea ice returns, thus stimulating the formation of T. antarctica that may even lead to Ta sublaminae when the export is rapid.

**Interannual variability**

While TSs represent snapshots of only a few years that may be lost in the centennial to millennial climate variability, it is attractive to compare the two sequences in term of diatom assemblages. The difference in terrigenous content between the two sections is not conclusive. Section 5 from the Neoglacial period shows expanded spring laminations, dominated by F. curta, and reduced summer laminations (Figure 3a). Section 13 from the Hypsithermal period shows reduced spring laminations, dominated by F. rhombica, and expanded summer laminations (Figure 3b). These findings demonstrate cooler conditions during the period covered by TS 1–3 than during the period covered by TS 4–6, with late sea ice break up and early sea ice return during the Neoglacial.

Superimposed on the climatic trends, a strong variability in lamination thickness and diatom composition is encountered within each sequence of TS. In section 5, spring laminations of years 1–5 appear much thicker than spring laminations of years 6–11 (Figure 3a) indicating greater diatom productivity in relation to more stable and favourable environmental conditions. This is further confirmed by the recurrence of transitional laminae at the spring/summer transition in years 7–10, which possibly depicts enhanced wind activity during this period. The occurrence of assemblage type B at the beginning of the spring season instead of assemblage type A (Figure 3a) may result from more important injection of oligotrophic warmer water (Stickley et al., 2005) may be resulting in earlier sea ice waning. In section 13, diatom assemblages and succession are more complex during years 1–3 than during years 4–5. Annual sedimentation rate is also reduced, especially because of thinner summer laminations, and many sublaminae are present during years 1–3 (Figure 3b). These findings again argue for less stable conditions during this period that reduced the overall diatom productivity. Lower productivity may also be related to lower nutrient input, as shown by events of greater CRS occurrence and higher silicification degree, may be in relation...
to iron limitation (Hutchins and Brueland, 1998), or to earlier return of sea ice in late summer as shown by the Ta sublamineae (Figure 3b).

While TSs represent snapshots of a few years in ‘cold’ and ‘warm’ periods, they argue for strong environmental changes in nutrient supply and sea ice cover with a period of 3–5 years. At these latitudes, sea ice seasonal waning and waxing is strongly dependent upon the Antarctic Circumpolar Trough position (Enomoto and Ohmura, 1990). It is therefore attractive to link the observed changes in environmental conditions to the Antarctic Dipole that present a similar 4–5 years cyclicity (Yuan, 2004). Investigation of longer sequences of sediment fabric may help to confirm or refute this hypothesis.

Conclusions

Preliminary investigation of core MD06-2301 from the Adélie Trough illustrates the presence of laminated sedimentary layers that record seasonal and subseasonal diatom productivity and lithic input. Light laminae are mainly biogenic layers with co-dominance of cryophilic Fragilariaopsis species and CRS. Light laminae correspond to the spring season. Dark laminations show a mixture between terrigenous particles and complex diatom assemblages dominated by *F. kerguelensis* and large centric species. Dark laminae represent the summer/autumn season. Variations in lamination thickness and in diatom assemblage types reveal a strong interannual variability that results from the interplay of sea ice, glacial runoff and oceanic currents in response to interactions between the atmosphere, ocean and cryosphere. These local to regional changes are possibly connected to the global sea ice cycle around Antarctica via the Antarctic Dipole. Further investigations of longer sections will provide a unique tool to document local to global Antarctic climate variability and cyclicity during the Holocene period at the seasonal resolution.

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