Sedimentary response to sea-ice and atmospheric variability over the instrumental period off Adélie Land, East Antarctica

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Abstract

Diatoms account for a large proportion of primary productivity in Antarctic coastal and continental shelf zones. Diatoms, which have been used for a long time to infer past sea-surface conditions in the Southern Ocean, have recently been associated with diatom specific biomarkers (HBI). Our study is of the few sedimentary research projects on diatom ecology and associated biomarkers in the Antarctic seasonal sea-ice zone. To date, the Adélie Land region has received little attention, despite evidence for the presence of high accumulation of laminated sediment, allowing for finer climate reconstructions and sedimentary process studies. Here we provide a sequence of seasonally to annually laminated diatomaceous sediment from a 72,5 cm interface core retrieved on the continental shelf off Adélie Land, covering the 1970-2010 C.E. period. Investigations through statistical analyses of diatom

communities, diatom specific biomarkers and major element abundances document the relationships between these proxies at an unprecedented resolution. Additionally, comparison of sedimentary records to meteorological data monitored by automatic weather station and satellite derived sea-ice concentrations help to refine the relationships between our proxies and environmental conditionsover the last decades. Our results suggest a coupled interaction of the atmospheric and sea-surface variability on sea-ice seasonality, which acts as the proximal forcing of siliceous productivity at that scale.

1 Introduction

Diatoms have been long time used to infer past sea-surface conditions in the Southern Ocean on the basis of large-scale ecological studies from the plankton (e.g. Hasle, 1969) and surface sediments (DeFelice and Wise, 1981; Zielinski et al., 1997; Armand et al., 2005; Crosta et al., 2005). However, little is known about diatom ecology in the seasonal sea-ice zone and, especially, in the coastal and continental shelf zone (CCSZ) off East Antarctica. The Adélie Land region has especially received little attention despite evidence about high accumulation sites of laminated sediments (e.g. Escutia et al., 2010). A very limited number of ecological studies have been performed at the species or species group level in the plankton (Beans et al., 2008; Riaux-Gobin et al., 2013) or sediments (Leventer et al., 1992; Maddison et al., 2006, 2012; Denis et al., 2006), and even fewer studies have investigated their relationships with local or regional environmental conditions. As a result, diatom-based paleoenvironmental reconstructions for this area are derived from large scale studies and do not take into account the regional specificities. The Adélie Land region is of further particular interest due to the presence of coastal polynyas, in the vicinity of the Dumont d'Urville station (DDU) and the Mertz Glacier (MG), that are biologically very productive and where intense sea-ice formation during winter leads to a large volume of dense water production (Arrigo and van Dijken 2003; Sambrotto et al. 2003; Laccara et al., 2014) fueling the global circulation (Rintoul et al., 1998).

Investigations of diatom communities, diatom specific biomarkers and major element concentrations at high resolution along a 72.5 cm long interface core retrieved in the Dumont d'Urville Trough (DDUT) allowed documentation of the relationships between these proxies. Additionally, the comparison of our proxy records to meteorological data inferred from DDU automatic weather station and satellite derived sea-ice concentrations helped to determine the

relationships between environmental conditions and proxy data, and consequently, the sedimentary response to atmospheric and sea-surface changes. Here, we refine our knowledge of diatom ecology at the regional scale and propose a robust tool to infer past sea-surface conditions off Wilkes Land.

2 Environmental settings

2.1 Geographic features

The DDUT (Fig. 1b), located along the Adélie Land on the East Antarctic margin is composed of several glacial depressions. These topographic features, up to 1,000 meters deep, act as traps for sedimentary material (primary production and terrigenous particles) settling out from surface waters. The trough runs from the front of the Zélée and Astrolabe glaciers to the continental shelf break along a SE-NW orientation, and is bordered on its eastern side by the Dumont D'Urville Bank (DDU Bank; Fig. 1b), which culminates at 200 meters below sea level and limits exchanges with the Adélie Depression. On the western side, the DDUT is flanked by the Dibble Bank where the Dibble Ice Tongue perdures during summer as a seaward protrusion.

2.2 Water masses

The Adélie Land is influenced by several water masses and currents (Rintoul et al., 1998; Williams and Bindoff, 2003; Williams et al., 2008). The wind-driven East Wind Drift flows westward at the surface, and transports Antarctic Surface water that constitutes the summer sub-surface water mass on the continental shelf. The Circumpolar Deep Water upwells near the Antarctic Divergence and intrudes onto the plateau during summer. The High-Salinity Shelf Water originates from brine rejections during winter sea-ice formation and from the winter cooling of the Circumpolar Deep Water (Fig. 1). The High-Salinity Shelf Water flows northward at the sea-floor as part of the dense shelf waters, here Adélie Land Bottom Water, which represents a major contributor to Antarctic Bottom Water (Rintoul et al., 1998; Jacobs et al., 2004; Meredith et al., 2013).

2.3 Wind conditions

The Adélie Land coast experiences the windiest conditions ever recorded on Earth through the presence of intense katabatic winds (Périard and Pettré, 1993) that are funneled by narrow glacial valleys close to the shoreline (Wendler et al., 1997). Although relatively strong winds (>10 m/s) blow widely between 65° and 225° at DDU, the station is characterized by a dominant and recurrent katabatic wind from 140°-180° (SE) coinciding with maximum wind speeds (> 25 m/s) (Adolph and Wendler, 1995; Koning-Langlo et al., 1998). Such winds support the annual occurrence of polynyas in the region, such as the DDU Polynya (DDUP; 66.11°S–139.31°E), where important sea-ice production occurs (Adolphs and Wendler, 1995; Massom et al., 1998; Arrigo and van Dijken 2003).

2.4 Sea-ice conditions

In general, the sea-ice melts every year between November/December and reforms in February/March, with sea-ice concentrations greater than 80% in winter and dropping below 20% in summer (Arrigo and van Dijken, 2003). Both pack ice and fast ice are observed in the DDUT. Pack ice melts every year while fast ice may persist during summer months (Fig. 1a; Massom et al., 2003; 2009; Smith et al., 2011; Wang et al., 2014). At its maximum extent, fast ice develops ~100 km offshore between the Dibble Ice Tongue and the Adélie Bank (Fig. 1a; Massom et al., 2009; Smith et al., 2011). From the early spring to autumn, unstable fast-ice conditions, characterized by several fast ice breakouts and re-formations as a result of lack of anchor points, generally occur in the DDUT (Massom et al., 2009; Smith et al., 2011), whereas fast ice persists later in the season over the banks. A key factor of the formation, recurrence and persistence of these fast ice buttresses, are the numerous grounded small icebergs on the Adélie and Dibble Banks that trap the passing pack ice and act as anchor points for fast ice formation (Massom et al., 2001; Giles et al., 2008; Smith et al., 2011), growing two ice promontories on either side of the core site. The presence of fast ice buttresses is therefore closely associated to the intense sea-ice formation in the Mertz Glacier Polynya and westward advection within the EDW (Fig. 1b; Massom et al., 2009).

3 Material and Methods

3.1 Core description and ^{210}Pb chronology

A 72.5 cm long interface core, DTCI2010, was retrieved aboard the R/V Astrolabe (66°24.68' S; 140°26.67' E; 1010 m water depth) during the 2010 ALBION-HOLOCLIP cruise. Positive X-ray images performed on the SCOPIX image-processing tool (Migeon et al., 1999) gave detailed information about sediment density and structure. SCOPIX images revealed laminations along the entire sedimentary section. The core was sampled continuously at 0.5 cm resolution and its chronological framework was determined based on ^{210}Pb excess ($^{210}Pb_{xs}$; T1/2 = 22.3 years). The activities of ^{210}Pb and ^{226}Ra were measured on dried sediments by non-destructive gamma spectrometry using a well-type, high efficiency low background detector equipped with a Cryo-cycle (CANBERRA) (Schmidt and De Deckker, 2015). Activities are expressed in mBq g-1 and errors are based on 1 standard-deviation counting statistics. $^{210}Pb_{xs}$ was determined by subtracting the activity supported by its parent isotope, 226Ra, from the total ^{210}Pb activity in the sediment. In the interface core DTCI2010, there is a general downcore trend in decreasing $^{210}Pb_{xs}$ activities, from 242 to 74 mBq g-1, as expected due to the decay of the unsupported ^{210}Pb (Fig. 2). However, the observation of a layer where activities decrease slowly between 10 and 40 cm led us to retain the Constant Initial Concentration model (CIC; Robbins and Edgington, 1975) to calculate the age (t) of each measured horizon as: $t= (1/\lambda) \ln (A0/Az)$ where t and Az are the age of the sediment and the excess ^{210}Pb activity at the depth z, A0 is the activity at the surface and λ is the decay constant of ^{210}Pb. This choice is supported by the almost constant activities measured in the uppermost sediments of cores collected in 2003 (240 ± 13 mBq g-1; Massé et al, 2011) and 2011 (253 ± 13 mBq g-1 in DTCI2011; Schmidt S., unpublished data). A second-order polynomial function was calculated from the 11 ^{210}Pb-dates obtained over the entire core to build the age model (Fig. 2).

3.2 Sedimentary analyses

3.2.1 Diatoms

Micropaleontological analyses were performed according to the methodology described in Rathburn et al. (1997) at a ~0.25 year resolution (every 0.5 cm) in core DTCI2010. Counts

were performed under a microscope Olympus BH-2 at a magnification of x1000. For each sample, 300-350 diatom valves were counted and data are presented as species relative abundances. Diatom identification was performed to the species or species group level following the taxonomical references detailed in Crosta et al. (2004) and the counting rules described in Crosta and Koç (2007). Sixty-two diatom species were identified in down-core assemblages, from which twenty-four presented abundances higher than 2% of the total diatom assemblages (Table S1).

3.2.2 Biomarker

Few marine and freshwater diatoms belonging to *Haslea, Navicula, Pleurosigma* and *Rhizosolenia* genera were recently found to be synthesizing Highly Branched Isoprenoids (HBI) (Sinninghé Damsté et al., 2004; Massé et al., 2011). Recent studies have proposed the use of HBIs to reconstruct variations of Holocene Antarctic sea-ice duration as a complementary approach to diatom counts (Collins et al., 2013; Campagne et al., 2015; Smik et al., 2016). Biomarker analysis followed the technique described by Massé et al. (2011) and were also performed at a ~0.25 year resolution (every 0.5 cm) in core DTCI2010.

3.2.3 XRF

X Ray fluorescence (XRF) measurements were conducted on slab sections at a 2 mm resolution along the entire core using an AAVATECH XRF core-scannerat two different tube voltages (10 and 30 keV) allowing for the determination of major elements associated with the detrital (Rubidium [Rb]) and terrigenous fractions (Zirconium [Zr] and Titanium [Ti]). More details about the protocole can be found in Fleury et al. (2015).

3.3 Instrumental data

3.3.1 Atmospheric data

Daily measurements of wind direction (from 0 to 360°), velocity (m/s) and temperature (°C) for the time period 1956-2011 were obtained from the METEO France publithèque. The dataset is based on Automatic Weather Station at the DDU French station (66.7° S, 140° E; Wendler et al., 1997), 30 km from the core site. The dataset provides monthly statistics based on 6-hourly in-situ observations at 10 meters. Wendler et al. (1997) showed that from Penguin

Point (east of the Mertz Glacier) to DDU stations, meteorological parameters displayed similar variations, leading to the conclusion that measurements from automatic weather station were relatively robust. Wind direction represents the origin of the wind over 360°. East/South/North/West -erly wind components indicate the number of days between November and March during which the wind blows between 45°-135°/135°-225°/315°-45°/225°-315° respectively. A ratio between easterly and southerly wind components (hereafter noted E/S), and a ratio between northerly and westerly wind components (hereafter noted N/W), were calculated and used to account respectively of the dominant and the secondary wind directions in the region according litteratures and observations (Note S2). Monthly anomalies are expressed relative to the mean value calculated for each month over the 1979-2009 period.

3.3.2 Sea-ice data

Daily sea-ice concentrations (SIC) for the time period 1978-2012 were obtained from the National Snow and Ice Data Center data repository. The dataset is based on passive microwave observations from the Nimbus-7 SSMR (1978-1987) and DMSP SSM/I (1987-2007) and SSMIS (2007-2012) radiometers processed with the NASA Team algorithm (Cavalieri et al., 1995) at a spatial resolution of 25x25 km. Averaged sea-ice concentrations (SIC) were calculated over the core site in the central part of the DDUT (Fig. S1). The sea-ice retreat date was determined arbitrarily as the Julian day when the SIC (7-day average) dropped below 40%, while the sea-ice advance corresponds to the day when SIC increased to above 40%. The duration of the ice-free season corresponds to the number of days per year during which SIC<40 %. Monthly anomalies are expressed relative to the mean value calculated for each month over the 1979-2009 period.

3.4 Statistical analyses

Statistical analyses were run using the statistical software XLStat (Addinsoft). Principal Component Analyses (PCA) and Pearson correlation tests (significance level α=0.05) were performed on all sixty-two diatom species including the species accounting for less than 1% of the total diatom assemblage (Table S1), two diatom specific biomarkers along with their associated ratio, three major elements including a ratio to, first (1) determine the relationships between species and identify potential diatom cluster (in order to increase the statistical

weight of minor species) and (2) investigate the relationships between the different proxies in our study. Complete statistical analyses are presented in Note S1 (Fig. S2; Table S2), and allowed to identify the sedimentary proxies that are significant in our study area (presented in Section 4), in terms of abundances and ecological preferences. Additionally in Note S2 (Fig. S3; Table S3), PCA and the Pearson correlation test were performed on seasonally averaged meteorological and satellite data to support the few previous oceanographic and atmospheric observations about climate forcing and their environmental response in the area. This work constituted a basis to afinal PCA (presented in Section 5) between annually averaged meteorological data and significant sedimentary proxies interpolated at one year, to determine, through the sedimentary response, how the preserved signal respond to local environmental parameters. Although the standardization of our data partially hide the variability of our sedimentary signals (Fig. S4), the main characteristics are preserved and allow for interannual comparisons.

4 Results

4.1 Sedimentary signals

The main diatom species and species groups identified in core DTCI2010 (Note S1) are *Fragilariopsis cylindrus*, *Thalassiosira antartica*, *Porosira glacialis* and *Porosira pseudodenticulata* (hereafter noted *Porosira* gp; Note S1), *Fragilariopsis kerguelensis*, large centric species (noted Open Water gp; Note S1), *Rhizosolenia* species (noted *Rhizosolenia* gp) and *Chaetoceros Hyalochaete* resting spores (noted CRS). These diatom groups are presented along with di-unsaturated HBI isomers [HBI:2], tri-unsaturated HBI isomers [HBI:3], and their respective ratio, Titanium (Ti) contents and Zirconium *versus* Rubidium (Zr/Rb) that constitute the main relevant geochemical proxies identified in our study area (Note S1). Other diatom proxies such as the *Banquisia* gp, *Fragilariopsis obliquecostata*, *Fragilariopsis curta*, *Eucampia antarctica*, the *Fragilariopsis* summer gp, the *Thalassiothrix* gp, *Fragilariopsis rhombica*, *Chaetoceros Phaeoceros*, and the Benthic gp sometime used in the literature to infer past sea-ice conditions are here not significant in term of population and/or relevant in term of statistical relationships to other proxies and environmental parameters. They are discussed in Note S1.

Highest abundances of *F. cylindrus* in sediments are observed during the ~1972-1979 C.E., 1983-1984 C.E., 1996-1998 C.E. and 2002-2003 C.E. periods. [HBI:2] concentrations present a similar pluri-decadal pattern to *F. cylindrus*. However, pluri-annual variations appear opposite with higher concentrations in 1971-1978 C.E., ~1982 C.E., 1985-1986 C.E., ~1989 C.E., 1995-2002 C.E., and since 2006 C.E. (Fig. 3a). The CRS and Zr/Rb exhibit contrasting trends during the 1970s to the mid 1980s, with decreasing CRS relative abudances and increasing Zr/Rb values during the 1973-1976 C.E. and ~1977-1978 C.E. periods. They are then relatively in phase with concomitant increasing values in 1984/1985-1987 C.E., and in 1989-1995 C.E. The Open Water gp and *F. kerguelensis* records display similar patterns, increasing in 1972-1977 C.E., 1980-1986 C.E., 1995-2001 C.E. and ~2007 C.E. In the same way, the Ti contents increase in 1975-1978 C.E., 1985-1987 C.E., 1996-2001 C.E. and ~2008-2010 C.E.[HBI:3] and the *Rhizosolenia* gp exhibit similar pattern with high values in ~1973-1975 C.E., moderate values in ~1978-1980 C.E., 1983-1985 C.E., and 1995-2001 C.E. *Thalassiosira antarctica* increased slightly over the 1976-1978 C.E., 1982-1985 C.E. and reached highest values between 2000-2010 C.E. The *Porosira* gp increased slightly over the 1980-1986 C.E. and large increases occured around the ~2000 C.E. and 2007 C.E. periods.

4.2 Environmental parameters

Atmospheric data indicate the increasing occurrence of easterly winds from spring to autumn (Fig. 3b) during the 1970-1975 C.E., 1983-1984 C.E., and between 1997-2007 C.E. periods (Fig. 3b). At the opposite, southerly winds dominate during the 1976-1982 C.E., 1985-1996 C.E. periods and since 2008 C.E. (Fig. 3b). The increasing occurrence of northerly winds from spring to autumn characterises the 1971-1975 C.E., 1979-1980 C.E., 1984 and 1992 C.E. and in the 1996-2001 C.E. periods, and more westerly winds occur between 1975-1979 C.E., 1981-1982 C.E., 1985-1991 C.E., 1993-1996 C.E., 2000 C.E. and since 2002 C.E. (Fig. 3b). Analysis of the satellite data reveals the presence of heavier sea-ice conditions in the area during spring, summer and autumn in the 1979-1981 C.E., 1990-1998 C.E. and 2001-2004 C.E. periods (Fig. 3b), that coincide with delayed sea-ice retreat in spring-summer.At the opposite earlier open conditions in spring occur between ~1981-1988C.E.,~1994 C.E., ~1998-2001 C.E. and ~2005-2007 C.E. (Fig. 3b). Delayed sea-ice advance in autumn characterises the 1980s and the 2002 C.E. periods, while earlier sea-ice closing occur between 1989-2001 C.E. and since 2003 C.E. (Fig. 3b).

5 Discussion

Below, we first discuss the significance, behavior and relationships between the relevant proxies at the DDUT site over the last 40 years. Secondly, we statistically confront 40 years of instrumental records to our sedimentary signals, that are commonly used for paleoclimate reconstructions, to refine our understanding of their ecological preferences or environmental significance in the CCSZ at the regional scale of Adélie Land .

5.1 Sedimentary signals off Adélie Land over the instrumental period

- **Sea-ice proxies**

High occurrences of *F. cylindrus* populations and [HBI:2] in high-southern latitude water column and sediments,including our study area, characterize spring sea-ice occurrence (Kang and Fryxell, 1992; Armand et al., 2005; Massé et al., 2011; Smik et al., 2016; Table 1; Note S1). High abundances of these proxies were used in Holocene sediments to track consolidated sea-ice conditions lasting in summer (Leventer et al., 1993; Campagne et al., 2015). Our results indicate that intervals characterised by heavier sea-ice conditions in the area during spring to autumn (Fig. 3b) broadly coincide with those characterized by higher abundances of *F. cylindrus* (Fig. 3a). However, changes in sea ice concentration do not satisfactorily explain *F. cylindrus* variability during the last 40 years. Additionally, *F. cylindrus* abundances present a weak agreement with the timing of the sea-ice retreat (Fig. 3). Conversely, a relation is observed between *F. cylindrus* abundances and wind origin, where by increasing occurrences of relatively weak northerly winds coincide with higher abundances of the species (Fig. 3). As observed for *F. cylindrus*, changes in [HBI:2] concentration over the last 40 years do not closely follow SIC variations norseasonal sea-ice dynamics (Fig. 3). Rather, high concentrations of this biomarker co-occur with more westerly winds (Fig. 3).

Thalassiosira antarctica and the *Porosira* gp were found to share similar seasonal occurrence in autumn, although it has been suggested that *P. glacialis* prefers slightly colder and icier conditions (Pike et al., 2009; Table 1; Note S1). *Thalassiosira antarctica* and the *Porosira* gp have thus been interpreted in Holocene sediments to indicate a late summer/autumn rapid deposition, linked to early sea-ice return (Denis et al., 2006; Maddison et al., 2006, 2012). As

already observed for previous sea-ice related proxies, the distribution of autumnal bloom species does not closely follow SIC variations in our study area (Fig. 3). However, our results suggest that the occurrence *T. antarctica* and the *Porosira* gp should be linked to sea-ice dynamics and wind variability, as large increase of *T. antarctica* and *Porosira* gp over the 2000s coincides with the earliest sea-ice advance in the last 30 years and the prevalence of easterly winds (Fig. 3).

- **Open ocean proxies**

Along with the Open Water gp, *F. kerguelensis* was found to dominate the summer-autumn laminae off East Antarctica and record a lengthening of the open water season and a warming of sea-surface waters in summer (Denis et al., 2006; Maddison et al., 2006; Table 1; Note S1). In our data, open ocean proxies seem to follow regional sea-ice conditions relatively well, regardless the sea-ice origin, structure and nature. Indeed, the Open Water gp and *F. kerguelensis* present highestrelative abundaces (Fig. 3a) during periods of low SIC, earlier sea-ice retreat and enhanced ice free season (Fig. 3b) and lowest values during periods of heavier sea-ice conditions.

Ti content in sediment is an indicator of open water conditions (Table 1; Note S1), mainly reflecting variaitons in terrigenous delivery by glacial melting (Presti et al., 2003; Escutia et al., 2003). In our records, the Ti pattern is relatively coherent with the Open Ocean gp and *F. kerguelensis* records (Fig. 3a). Highest values generally occur during low SIC periods, long ice free seasons and high temperatures such as during the 1980s. However, some discrepancies occur as highest sedimentary Ti values in 1970-1972 C.E. are concomitant to only a slight increase of open ocean proxies and no particular warming event in monitored temperatures (Fig. 3). This suggests that Ti content can be impacted by rapid deposition events that are independent of the length or the warmth of the ice-free season. Therefore, downcore differences between Ti and open ocean proxies may help identifying episodic processes such as local glacial discharge or ice rafted material derived from the Mertz Glacier Tongue basal melting (Maddison et al., 2006; Dinniman et al., 2012; Campagne et al., 2015).

[HBI:3] have been identified in water column phytoplankton (Massé et al., 2011; Table 1; Note S1), synthesized by the Rhizosolenoids (Sinninghé Damsté et al., 2004). The latter diatom group is generally associated to late summer season production and to long diatom

productivity season, linked with turbulent open ocean conditions (Armand et al. 2005; Crosta et al. 2005; Beans et al., 2008; Note S1). In core DTCI2010, [HBI:3] and the *Rhizosolenia* gp display similar patterns, and present a strong relation with ice-free conditions (Fig. 3b). The maximum occurrence of [HBI:3] between the mid 1970s to the mid 1980s coincides well with positive temperature anomalies and lower wind speed anomalies at that time (Fig. 3b), arguing for a strong relationship between the biomarker development and surface conditions forced by atmospheric variability.

- **Polynya activity proxies**

High percentages of CRS in Holocene sediments from AGVL have been associated to strong siliceous productivity supported by melting ice-induced stratified surface waters and strong intermittent surface mixing conditions (Maddison et al., 2006; Table 1; Note S1). Off Adélie Land, vertical mixing along with variations in bottom current velocities were associated to enhanced polynya activity (Campagne et al., 2015; Table 1; Note S1), and were estimated from changes in sediment grain size inferred the Zr/Rb ratio relative abundances. In core DTCI2010, CRS and Zr/Rb exhibit contrasting trends during the 1970s to the mid 1980s, but are then relatively in phase over the last 20 years (Fig. 3a). Zr/Rb follows SIC variations relatively well whereas CRS relative abundances seem to follow spring sea-ice dynamics (Fig. 3). Interestingly, a relationship is observed between CRS abundances and Zr/Rb with wind pattern, as both proxies coincide well with the prevalence of southerly winds in our study area, e.g. between 1983-1996 C.E. (Fig. 3), arguing for a strong relationship between the polynya activity and atmospheric pattern variability.

5.2 The coupled role of wind pattern and sea-ice variability on sea surface productivity in Adélie Land

PCA between seasonal atmospheric forcing and sea-ice conditions over the core site (Note S2; Fig. S3) argues that wind conditions, and particularly wind direction, exert a strong impact on sea-surface conditions off Adélie Land, in agreement with several studies at larger spatial scales (Massom et al., 2003; 2009; Smith et al., 2011; Wang et al., 2014; Campagne et al., 2015). Based on PCA analyses between our proxy records and instrumental data , we document the sedimentary response to changes in environmental conditions with a special

emphasis on wind fields and wind induced sea-ice variability and, therefore, we refine proxies validation at the regional scale (Note S2; Fig. S3; Table S3). Results are summarized and presented in Table 1.

Here, environmental parameters were averaged over the ice-free season (from November to March) to allow a direct comparison of the impact of atmospheric and sea-surface conditions on the sedimentary response, and by inference, on the biological surface response. F1 axis, which accounts the highest variance of 18.09 % (Fig. S5), represents sea-ice conditions from November to March, as driven by SIC, the length of the sea-ice free season and the sea-ice dynamics (Fig. 4). The easterly wind direction is significant on F1+ while the southerly wind component is significantly located on F1- (Fig. 4; Table S4), indicating that sea-ice conditions and dynamics off Adélie Land are strongly impacted by the dominant wind field. F2 axis accounts for 16 % of the total variance (Fig. S5). Westerly and northerly wind directions are significantly located on F2- and F2+, respectively, with very low scores on F1 (Fig. 4; Table S4). Increasing wind direction (southerly to westerly winds) or weak onshore (northerly winds) circulation is of cyclonic origin in our study area (Heil et al., 2006; Parish and Bromwich, 2007; Wang et al., 2014). This result suggests that storm forcing on sea-ice conditions are represented by the F2 axis. We herafter present the sedimentary response to the four cases of mean wind fields and wind-induced sea-ice conditions identified by our PCA analyses (Note S2; Fig. S3).

- **Westerly winds increase spring sea-ice conditions**

A dominant westerly wind component originating from enhanced cyclone activity conducts to lower temperatures and wind speed in our data (Heil et al., 2006; Parish and Bromwich, 2007; Massom et al., 2003; 2009; Wang et al., 2014; Note S2). Westerly winds have been observed to decrease the open water fraction, promote pack ice or thinner sea ice lasting longer in spring and delayed sea-ice advance in autumn in our study area (Massom et al., 2003; Heil et al., 2006; Smith et al., 2011; Wang et al., 2014; Zhai et al., 2015; Note S2). Under such conditions, the sedimentary response shown by the PCA indicates increased content of the [HBI:2]/[HBI:3] ratio, which is significantly correlated with westerly winds (0.398; Table S4) and presents a strong negative relationship with low temperature in our data (Fig. 4). Similar relationships are observed for [HBI:2] (Fig. 4). Our observations agree with the environmental interpretation these proxies as sea-ice and cold environment indicators (Table

1; Note S1). Indeed, it has been suggested recently that relatively high [HBI:2] in surface samples from East Antarctica might be a good indicator of extended (into summer) seasonal sea-ice cover, whereas melt-water stratified marginal sea-ice environments should be associated with lower [HBI:2] (Smik et al., 2016). Therefore, the occurrence of [HBI:2] in sediments might attest the presence of overlying heavy pack-ice conditions or episodic fast ice presence, in spring to summer time in our study area (Table 1).

- **Northerly winds increase spring sea-ice conditions**

At the Antarctic scale, northerly winds promote early spring sea-ice retreat and late autumn sea-ice advance (Stammerjohn, et al., 2008). However, northerly winds in our study area have been observed to decrease northward transport of sea ice and increases sea-ice duration (Holland et al., 2012; Wang et al., 2014). Our PCA results (Fig. 4) indicate that the northerly wind component is associated with lower wind speeds conducive to delayed sea-ice advance at the core site (Note S2), but relationships with SIC and sea-ice retreat date are not clear in our data. We here propose that northerly winds have two opposite impacts on sea-ice conditions off Adélie Land. First, they tend to increase spring sea-ice presence in the area, likely by pushing the offshore pack ice toward the coast or limiting its northward transport. Secondly, they contribute to increase summer melting and delay ice regrowth in autumn by transporting warm air from the north and by enhancing the swell. Under such environmental conditions, the sedimentary response shown by the PCA indicates increasing abundances of the *Rhizosolenia* gp, [HBI:3] and *F. cylindrus,* that have high scores on F2+ (Fig. 4). The concomitant presence of sea-ice related proxies and open ocean proxies indicate a marked seasonal cycle. *Fragilariopsis cylindrus* displays a strong association with high temperature in our study area, but present a non-significant positive relationship with SIC (Table S4). Our results may thus indicate that *F. cylindrus* respond to pack-ice presence in spring and subsequent rapid melting (Table 1) as previously evidenced elsewhere (Gersonde and Zielinski, 2000; Armand et al., 2005).

Our results suggest that both *F. cylindrus* and [HBI:2] are associated with longer sea-ice duration in spring/summer in our study area (Table 1). They however respond to different sea-ice conditions whereby sea-ice dwelling diatoms synthesizing the [HBI:2] have greater affinities with heavy pack-ice or fast-ice conditions under more westerly winds (colder sea ice) while *F. cylindrus* develops at the pack-ice edge and within sea-ice meltwater conditions

under weak northerly winds (warmer sea ice) (Table 1). This dichotomy may explain that the biomarker record lags the diatom record by ~2 years in core DTCI2010 (Fig. 3a). However, time series studies on the formation, export and burial of HBIs and diatoms are necessary to fully understand this decoupling. We note that [HBI:2] and *F. cylindrus* present similar trends at decadal to pluri-decadal scales, supporting their use as complementary sea-ice indicators for paleoclimate studies (e.g. Campagne et al., 2015). Regarding the productivity associated to summer time, the presence of [HBI:3], a marker of open water related productivity, along with *Rhizosolenia* gp, an indicator of warmer conditions and of a long diatom productivity season (Note S1), would support the presence of stable sea-surface conditions due to low wind speed during summer and of enhanced open water conditions in autumn (Table 1).

- **Easterly winds induce open conditions**

A dominant easterly wind component yields to earlier sea-ice retreat and earlier sea-ice advance, lower SIC from November to March and, in some extent, to a longer ice-free season in the study area (Fig. 4; Note S2). Easterly winds tend to increase ice advection and icebergs in the area and contribute to building a fast-ice buttress over the banks (Massom et al., 2009). Persistence of fast-ice promontories during the summer over the Dibble and the DDU banks, can in turn acts as a barrier to westward sea-ice advection and leads to the establishment of open water conditions over the DDUT, as observed in several locations off East Antarctica (e.g. MGP and Terra Nova Bay polynyas) (Arrigo and van Dijken, 2003; Massom et al., 2001; 2009; Campagne et al., 2015). Similarly in autumn, easterly winds tend to increase ice advection and icebergs in the area, providing favourable conditions for the formation of thick fast ice and buttress earlier in the autumn (Heil et al., 2006). Under such environmental conditions, the PCA indicates that the sedimentary response consists of higher abundances of several proxies strongly inter-correlated on F1+, *T. antarctica*, the *Porosira* gp, *F. kerguelensis*, [HBI:3] and Ti (red shaded area on Fig. 4; Table S4). The Ti signal is also linked to the northerly wind component (Table S4), suggesting that this proxy is tied to onshore wind circulation and probably responds to longer ice free season. *Thalassiosira antarctica*, *Porosira* gp, *F. kerguelensis* and Ti are strongly linked to low SIC over the ice-free season in our study area (Table S4). Similarly, [HBI:3], the *Porosira* gp (-0.431; Table S4), *F. kerguelensis* (-0.360) and *T. antarctica* are strongly associated with earlier open water conditions, and *F. kerguelensis* is linked to a longer ice-free season. We conclude that the

Open Water gp, *F. kerguelensis,* Ti and [HBI:3] are associated with long ice-free seasons associated to easterly winds, suggesting that these species develop under oligotrophic and stable environments (Table 1). The *Porosira* gp and *T. antarctica* are associated with an earlier sea-ice advance in autumn and lower temperature (Table 1; Fig.4; Table S4). These results agree well with ecological preferences of those diatoms, which are considered as biological indicators of early sea-ice freezing in autumn (Table 1; Note S1). However, in our study the *Porosira* gp is linked to a longer ice-free season than *T. antarctica* is (Fig.4; Table S4). These results contradict paleoecological inferences on these species whereby *P. glacialis* has been associated with slightly longer annual sea-ice cover relative to *T. antarctica* (Pike et al., 2009), maybe because these studies did not separate the two varieties of *T. antarctica*.

Our observations support the use of the Open Water gp, *F. kerguelensis,* Ti and [HBI:3] as indicators of the lengthening of ice free conditions in paleoclimate studies (Table 1). Our resuts are generally in line with the known environmental conditions of these proxies occurence (Table 1; Note S1), as along with *Porosira* gp and *T. antarctica*, these proxies have been attributed to more open conditions in the Mertz Glacier Polynya area during periods with reinforced easterly wind conditions (Campagne et al., 2015). The lengthening of the ice free season results from early sea-ice retreat, probably due to the development of the DDU polynya (Arrigo et al. 2003) during the early spring-summer period. Indeed, the concomitant presence of the *Porosira* gp and *T. antarctica* indicate early sea-ice regrowth as a response to an easterly wind field (Table 1) that has been shown to weaken the northward transport of sea ice in the region, thus increasing sea-ice conditions in autumn (Massom et al., 2003; 2009). This suggests that *T. antarctica* and the *Porosira* gp are good indicators for autumnal sea-ice dynamics forced by atmospheric variability.

- **Katabatic winds and coastal polynya**

Southerly winds are of katabatic origin in our study area (Wendler et al., 1997; Note S2). A dominant southerly wind component is conducive to a delayed spring sea-ice retreat and late autumn freezing, higher SIC from November to March, and to some extent, a shortened ice-free season in the study area (Note S2). Indeed, strong katabatic winds break the fast ice along the coast, leading to enhanced open water conditions and to the formation of a coastal polynya constrained to the coastline (Vaillancourt et al., 2003; Massom et al., 2009; Riaux Gobin et al., 2013). However at the core site, the pack ice would be present due to a reduced fast-ice

buttress and the increasing northward transport of the pack ice under strong southerly winds (Massom et al., 2009). Under such environmental conditions, the sedimentary response shown by the PCA indicates increasing abundances of the CRS gp and Zr/Rb that are strongly linked to F1- (Fig. 4). Their response to katabatic wind events is probably through the opening of a coastal polynya (Note S2). In addition, although the CRS gp shows no relation with SIC parameters, this group is associated to a strong wind speed (0,364; Table S4) over the ice-free season, in agreement with the environmental interpretation of the species (Note S1). In contrast, Zr/Rb is closely associated with increasing SIC over the ice-free season in addition to a delayed sea-ice retreat (Table S4).

Enhanced polynya activity along the coast has been shown to coincide with a deep mixed layer and high Chl a levels (Vaillancourt et al., 2003; Riaux Gobin et al., 2013). Stronger vertical mixing may increase nutrient availability, favouring the rapid development of the *Chaetoceros Hyalochaete* spp. Spore formation may occur through deep mixing of vegetative cells under the photic zone or nutrient depletion when winds weaken. Northward lateral advection of surface production from the coast to the study area may explain the occurrence of CRS gp along with more sea ice at the core site. Continuous sea-ice formation in the coastal polynya may favour brine production and subsequently, stronger bottom currents, leading to the observed Zr/Rb high values. However changes in the phase relationship between relative abundances of the CRS gp and Zr/RB content over the last 40 years argue for periodic decoupling between polynya activity and katabatic winds. We propose that CRS are strongly linked to katabatic wind pulses and rapid stratification/mixing events while Zr/Rb is more directly linked to polynya activity (and bottom water velocity) that responds to windy conditions (Table 1). Under southerly winds both high values CRS and Zr/Rb are expected while under strong south to easterly winds lower CRS abundances but still high ZR/Rb values are expected (Table 1).

6 Conclusion

Investigation of annual to interannual relationships between diatom communities, diatom specific biomarkers and major element abundances in connection with meteorological parameters shows that the relevance and use of some proxies (1) may be characteristic of the study area (e.g. CRS gp assemblage), or (2) differ slightly from previous long-term studies (e.g. *F. cylindrus*). Indeed, at such a fine scale, the distribution of the sea-ice related proxies

in sediments highlights complex relationships between the biota and sea-ice concentration, dynamics, cover structure and origin, constrained by the wind pattern. Our results therefore attest for the importance of the origin and nature of the sea-ice in the sedimentary distribution of sea-ice proxies. A clear and unambiguous distinction of sea-ice type through a finer satellite study in the region (e.g. MODIS satellite imagery) would greatly help to assess and better constrain such relationships. However, we note that the complex inter-relations between winds and sea ice should be alleviated at longer time scales when large atmospheric and ocean temperatures changes become preponderant. On the other hand, in our study area, open ocean related proxies seem to be primarily connected to the length of the growing season thus agreeing well with previously published regional to-large scale studies. Polynya activity may be inferred from variations in the Zr/Rb ratio values. Monitoring the sedimentary signal formation in surface water, its export throughout the water column and burial in deep-sea sediments are necessary to understand the regional behaviour of the proxies commonly constrained via synoptic studies. Other high-resolution and longer timescale reconstructions are required to refine our understanding of the ice-ocean-atmosphere interactions and system feedbacks.

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Author contributions

X. C. & G. M. designed the study and P.C. carried it out. O.T. performed diatom extraction and XRF analyses; P.C. performed diatom census counts and PCA analyses; M-N. H.

extracted daily sea-ice concentrations; S. S. performed ^{210}Pb analyses and developed the age model of the core; P.C. prepared themanuscript with contributions from all co-authors.

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559 Table 1. Summary of the relationships between sedimentary proxies and
560 environmental conditions.

PROXY/GROUP IDENTIFIED IN CORE DTCI2010	**KNOWN ECOLOGY (LITERATURE)**	**ENVIRONMENTALRELATIONSHIPS OFF ADÉLIE LAND**
F. cylindrus	Spring sea-ice covered/sea-ice stratified waters	Compacted pack ice in spring by northerly winds ("warm" sea ice), sea-ice stratified waters
[HBI:2], [HBI:2]/[HBI:3]	Spring sea-ice environment	Compacted pack ice or fast ice in spring by westerly winds (cold sea ice)
Banquisia gp(*N. directa N. glaciei, Synedra* spp, *Ephemera* spp)	Spring sea-ice conditions	No clear pattern
F. obliquecostata	Surface melt pools, sea-ice covered waters in summer	No clear pattern
E. antarctica	Ubiquist, open conditions, melting glacial ice	Onshore winds increase spring-summer sea ice (short ice free season, delayed sea-ice retreat)
Fragilariopsis summer gp (*F. ritscheri, F. sublinearis*)	Summer sea-ice edge environment, melted waters	No clear pattern
T. antarctica	Open water conditions in summer-autumn, slush and wave-exposed shore ice environment	Summer open water conditions but icy autumn conditions (early sea-ice advance) induced by easterly winds
Porosira gp (*P. glacialis, P. pseudodenticulata*)	Relative open water conditions in summer, slush and wave-exposed shore ice environment, icy autumn and early sea-ice advance	Summer open water conditions but icy autumn conditions (early sea-ice advance) induced by easterly winds
F. kerguelensis	Open water, ice free conditions during summer	Summer open water conditions (early sea-ice retreat, long ice free

		season) induced by easterly winds
Open water gp (*T. lentiginosa, T. oliverana, T. trifulta, T. gracilis, T. tumida, Coscinodiscus* spp, *A. actinochilus, S. microtrias*)	Open water, ice free conditions during summer	Summer open water conditions (early sea-ice retreat, long ice free season) induced by easterly winds
[HBI:3]	Marginal Ice Zone, open water, ice-free conditions during summer	Summer open water conditions (early sea-ice retreat) induced by easterly to northerly winds
Rhizosolenia gp (*Rhizolenia* spp, *R. antennata semispina*, *Proboscia* spp, *P. truncata* and *P. inermis*)	Open conditions in summer/autumn, stratified oligotrophic waters	No clear trend with sea-ice conditions, stable summer surface waters induced by northerly winds
Thalassiotrix gp (*Tx. antarctica,T. reinboldii*)	Open conditions in autumn, highly stable and nutrient poor water column	Summer open water conditions (early sea-ice retreat, long ice free season) induced by easterly winds
F. rhombica	Unconsolidated sea ice in spring, ice-free summer	Warm conditions in spring-summer, delayed ice free season (late sea-ice retreat and late sea-ice advance)
Ti	Summer open conditions favoring glacial melting	Rapid sea-ice melting in spring, warm open-water conditions in summer induced by northerly winds
Zr/Rb	Polynya environment	Coastal polynya activity under intense southerly to souht-easterly winds
CRS GP (*Chaetoceros Hyalochaetes* spp)	Rapid changes in stratification, decreasing nutrient levels	Stratification disruption at the MIZ or within polynyas by katabatic wind pulses (high wind speed)
Phaeoceros gp (*C. Phaeoceros* spp, *C. atlantica, C. dichaeta*)	Open water environment	No clear pattern

Benthic gp (*Cocconeis* spp, *Grammatophora* spp, *Trachyneis* spp, *Licmophora* spp, *Melosira solenia*, *Achnantes brevipes*, *Amphora* spp, *Diploneis* spp, *Melosira adelia*, *Pseudogomphonema* spp, *O. weissflogii*)	Spring wind (storm) induced mixing conditions	No clear pattern
Corethron gp (*C. criophilum*, *C. pennatum*)	Open ocean conditions, surface mixed waters	No clear pattern

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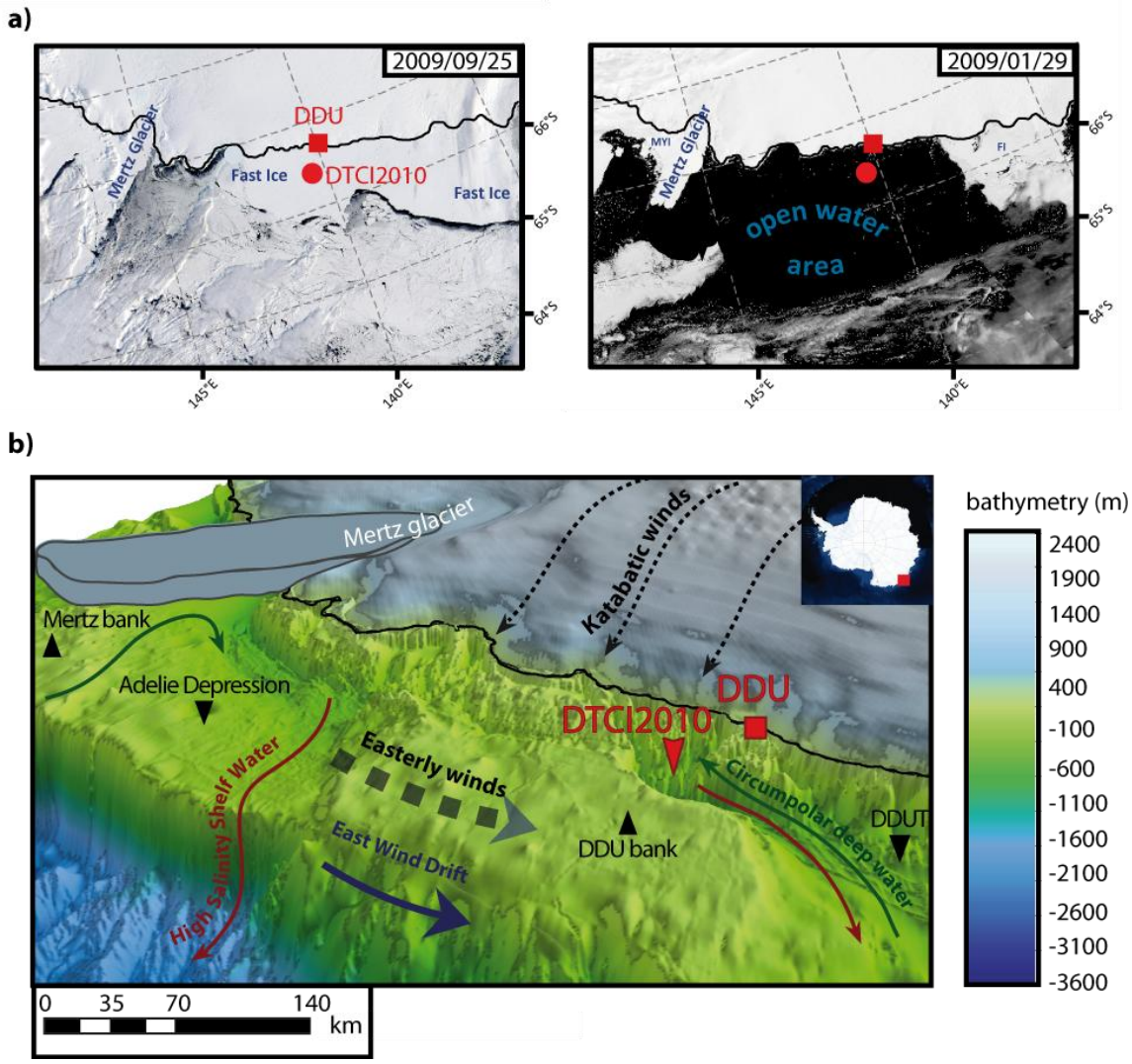

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564 Figure 1. Study area. **a)** Modis satellite images of Adélie Land, showing mean sea-ice
565 conditions from early spring to summer in the region, the location of sediment core
566 DTCI2010 and the French research station Dumont D'Urville (DDU). **b)** Map of the study
567 area showing the location of sediment core DTCI2010 in the Dumont D'Urville Trough
568 (DDUT), the main glacial and topographic features, the principal water masses (solid lines)
569 and the main wind streams (dahsed lines).

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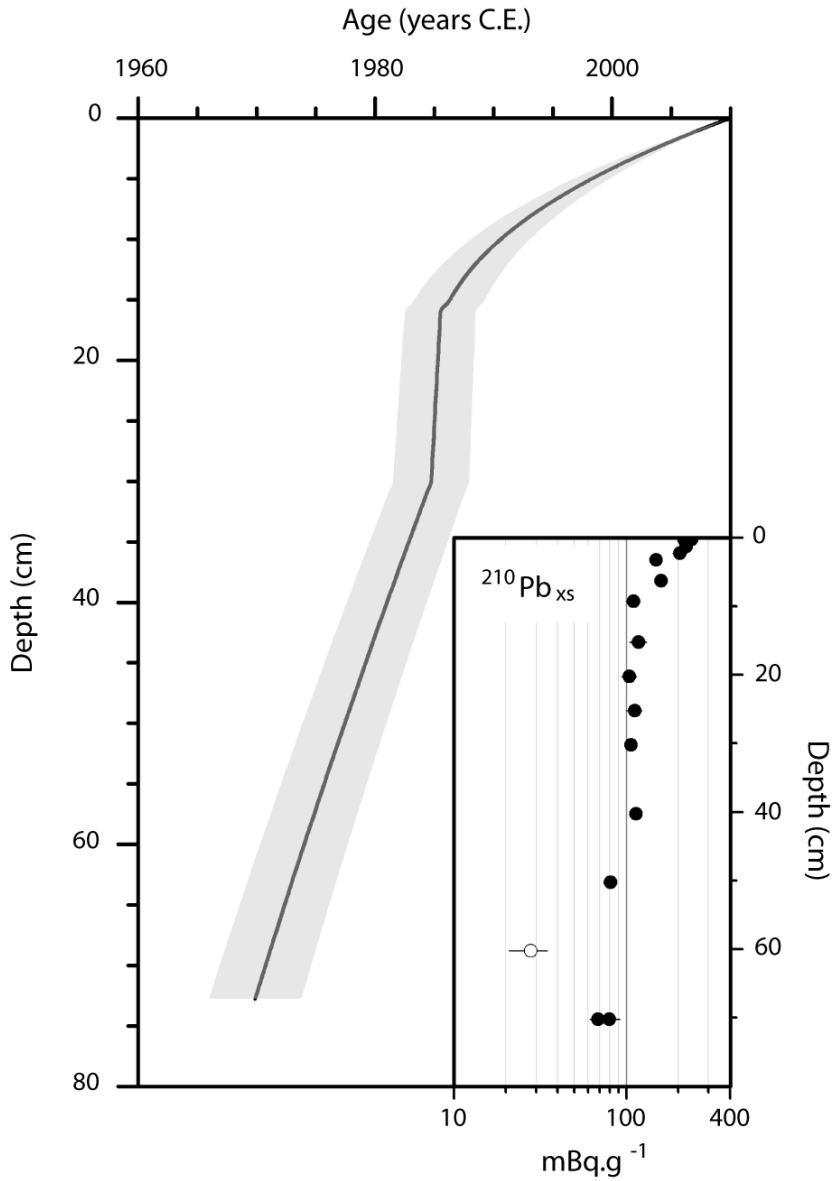

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572 Figure 2. DTCI2010 chronology, based on ^{210}Pb excess ($^{210}Pb_{xs}$) and associated age-model
573 errors (grey area). The inset corresponds to the downcore profile of $^{210}Pb_{xs}$ (error bars
574 correspond to 1 SD).

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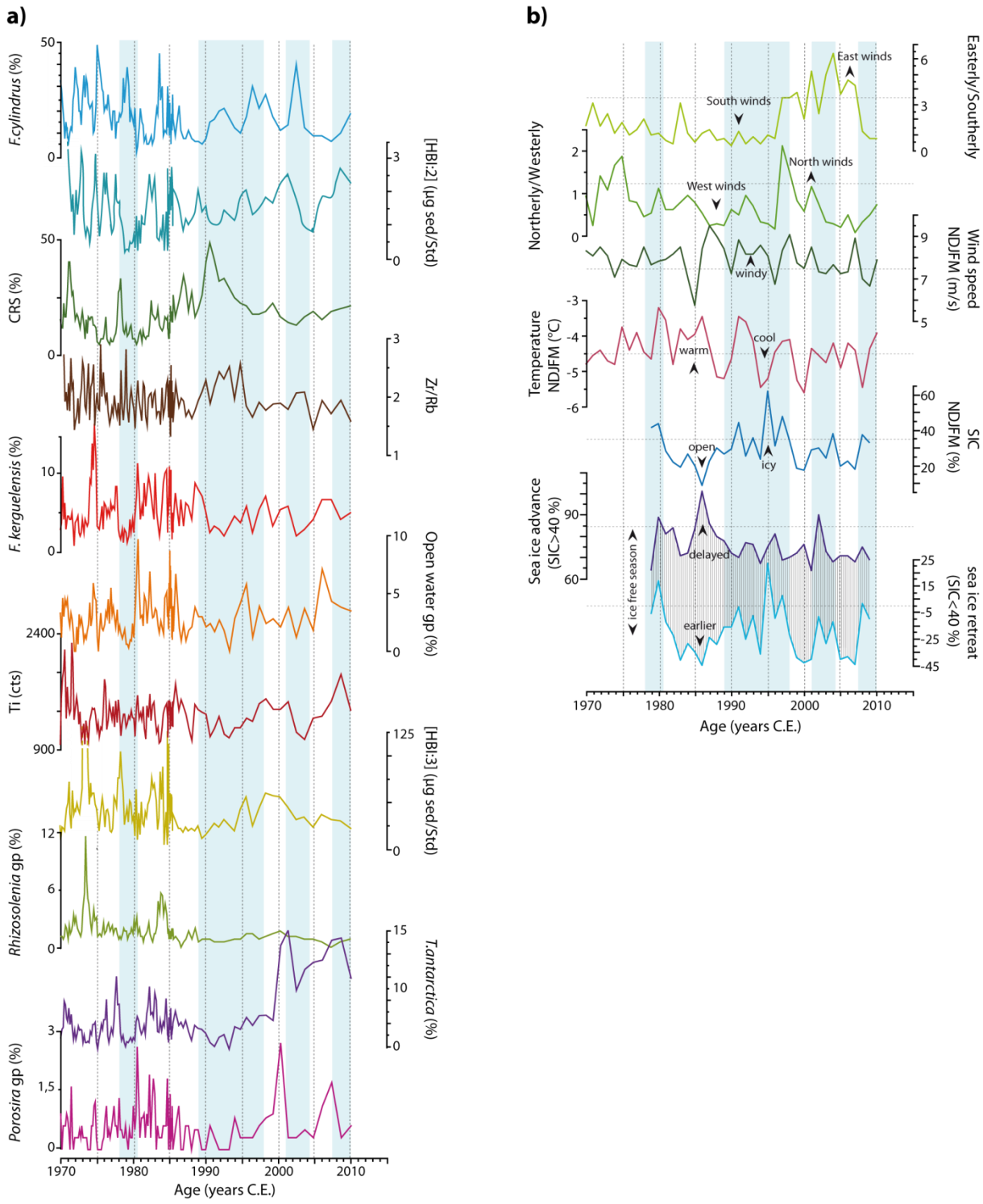

Figure 3. **Part a)** Raw sedimentary records from DTCI2010 interface core over the 1970-2010 period. The blue shading indicates periods marked by increasing monitored sea-ice concentration at the core site. **Part b)** Meteorological parameters and climate index over the 1970-2010 period. Daily meteorological parameters were averaged over the November to March period. Blue shaded areas mark increases of SIC.

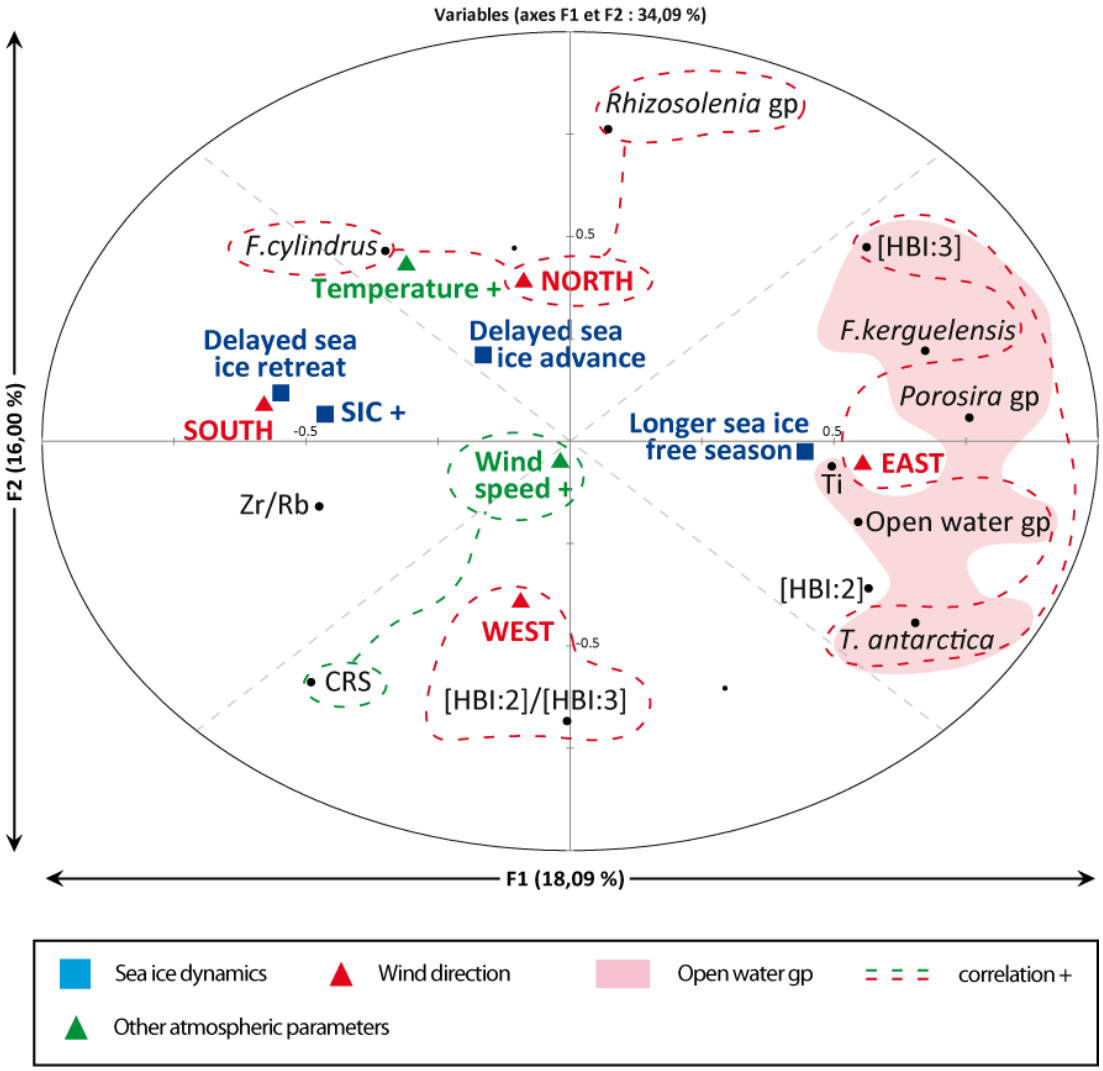

Figure 4. PCA applied to standardized sedimentary data from the DTCI2010 core and meteorological parameters. The yearly standardized sedimentary data represent the ice-free season of the related year. Weather forecast/satellite data were averaged between November and March. F1 axis represents the sea-ice conditions linked to the predominant Easterly and Southerly winds. F2 axis represents the secondary wind directions in the study area, Northerly and Westerly winds.