Regional validation of the use of diatoms in ice cores from the Antarctic Peninsula as a Southern Hemisphere Westerly Wind proxy

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Abstract. The Southern Hemisphere Westerly Winds are among the most important drivers of recently observed environmental changes in West Antarctica. However, the lack of long-term wind records in this region hinders our ability to assess the long-term context of these variations. Ice core proxy records yield valuable information about past environmental changes, although current proxies present limitations when aiming to reconstruct past winds. Here we present the first regional wind study based on the novel use of diatoms preserved in Antarctic ice cores. We assess the temporal variability in diatom abundance and its relation to regional environmental parameters spanning a 20-year period across three sites in the southern Antarctic Peninsula and Ellsworth Land, Antarctica. Correlation analyses reveal that the temporal variability of diatom abundance from high elevation ice core sites is driven by changes in wind strength over the core of the Southern Hemisphere Westerly Wind belt. Validating the use of diatoms preserved in ice cores from the Southern Antarctic Peninsula and Ellsworth Land as a proxy for reconstructing past variations in wind strength over the Pacific sector of the Southern Hemisphere Westerly Wind belt.

1 Introduction

Winds over the Southern Ocean (circumpolar westerlies) play a key role in driving the exchange of heat and carbon dioxide
20   between the ocean and atmosphere (Russell et al., 2006; Quéré et al., 2007; Hodgson and Sime, 2010; Landschutzer et al. 2015). In recent decades, the circumpolar wind belt has increased in strength and has shifted towards the Antarctic continent, constituting one of the strongest climatic trends in the Southern Hemisphere (Thompson and Solomon, 2002, Gille et al. 2008, Young et al. 2011). These atmospheric changes have been linked as drivers of the widespread warming observed in the Antarctic Peninsula (AP) (Thomas et al., 2009; Thomas and Tetzner, 2018; Turner et al., 2020) and West Antarctica (WA)
25   (Thomas et al. 2013) and as the mechanism behind the enhanced upwelling of deep and relatively warm, CO2-rich, oceanic water (Nakayama et al., 2018). The upwelling of circumpolar deep water has been shown to promote accelerated melting and thinning at the base of the ice shelves (Thoma et al., 2008; Jacobs et al., 2011; Pritchard et al., 2012; Steig et al., 2012; Wåhlin et al., 2013; Dutrieux et al., 2014; Favier et al., 2014; Gille et al., 2014; Joughin et al., 2014; Paolo et al., 2015; Holland et al., 2019), thus, threatening the stability of floating ice shelves along the coastline of the Amundsen-Bellingshausen Seas and

30 ultimately contributing to global sea-level rise (Pritchard et al., 2012). Changes in the circumpolar westerlies have also been linked to an observed pattern of increased snow accumulation in Antarctica over the 20th century, which has mitigated global mean sea level rise (Medley and Thomas., 2019). To assess the context of these recent wind changes, an extended record of wind strength is needed.

Direct meteorological observations in the AP region are sparse, relatively short-term and mostly constrained to coastal regions

35 (Oliva et al., 2017; Thomas and Tetzner, 2018). The scarcity of continuous long-term data can be partly addressed by using climate reanalyses datasets. These datasets comprise model outputs from simulations that are used to interpolate measured climate variables, providing accurate meteorological data in this region for the satellite-era (1979-present) (Tetzner et al., 2019), but are not viable for studying pre-satellite regional climate variability. Climate models can be used to extend the record back in time, however, model simulations from the fifth Coupled Model Intercomparison Project (CMIP5) exhibit strong biases

40 over the Southern Ocean compared with observations (Bracegirdle et al., 2013). Overall, the lack of long-term wind records in the region hinders the possibility to assess the long-term context of the recently observed changes.

Ice cores provide valuable climatic information over a range of timescales (Legrand and Mayewski, 1997). Insoluble mineral dust concentrations in Antarctic ice cores have been widely used to infer past variability in regional-to-hemispheric atmospheric circulation (Röthlisberger et al., 2002; Lambert et al., 2008; Koffman et al., 2014; Delmonte et al., 2020; Laluraj

45 et al., 2020). Geochemical tracers of mineral dust, such as the non-sea-salt component of soluble calcium (nssCa^{2+}) or potassium (nssK$^+$), have been used to track changes in the strength and position of the Southern Hemisphere Westerly Wind (SHWW) belt (Dixon et al., 2012; Mayewski et al., 2013). However, these traditional proxies typically originate from South America, Australia and New Zealand and are therefore potentially influenced by environmental changes in these distal source regions (McConnell et al., 2007; Lambert et al., 2008; Wolff et al., 2010; Bullard et al., 2016; Delmonte et al., 2017). Sea salt

50 sodium (ssNa$^+$) has been previously interpreted as a proxy of increased meridional transport from the Southern Ocean to ice core sites in Antarctica (Kreutz et al., 2000; Goodwin et al., 2004; Kaspari et al., 2005; Mayewski et al., 2013; Vance et al., 2013). However, the ssNa$^+$ signal is potentially influenced by inputs from blowing snow above sea ice (Frey et al., 2020) and by the production of ssNa$^+$ in 'frost-flowers', as well as by inputs from the open ocean (Huang and Jaeglé, 2017). As frost flowers are precipitated from the surface of freshly formed sea ice (Wagenbach et al., 1998; Rankin et al., 2000), and all these

55 sources are affected by sea ice extent, some studies have reflected on the potential of the ssNa$^+$ ice core record from Antarctic coastal sites as a proxy of seasonal sea ice extension (Rankin et al., 2002; Wolff et al., 2003; Wolff et al., 2006). These conflicting sources of ssNa$^+$ suggest that the variability of the ssNa$^+$ record is not entirely driven by changes in winds. The current limitations identified in conventional ice core wind proxies highlight the need to explore new species to reconstruct wind strength.

60 Marine diatoms entrained in Antarctic snow and ice have recently been proposed as an alternative source of information about winds (Allen et al., 2020). Diatoms are unicellular algae with siliceous cell walls that inhabit marine, brackish and freshwater environments throughout the world (Smol and Stoermer, 2010). Despite their aquatic habitats, several studies support that they can be airborne (Chalmers et al., 1996; Gayley et al., 1989; Lichti-Federovich, 1984; McKay et al., 2008; Wang et al., 2008;

Harper and Mackay, 2010; Spaulding et al., 2010; Hausmann et al., 2011; Budgeon et al., 2012; Papina et al., 2013; Fritz et
al., 2015). Marine diatoms can be effectively lifted from the sea-surface microlayer into the atmosphere by wind-induced
bubble-bursting and wave-breaking processes (Cipriano and Blanchard, 1981; Farmer et al., 1993). Once in the atmosphere,
they can be transported by winds over long distances (Gayley, 1989; McKay et al., 2008; Harper and McKay, 2010). Diatom
records have been evaluated at multiple ice core sites in the AP and Ellsworth Land (EL) regions (Tetzner et al., 2021a) to
reveal consistent spatial variations and increases in the diatom concentration during the past three decades. Despite the potential
the diatom record has shown to reconstruct past wind strength, this proxy requires evaluation against more established ice core
wind proxies.

In this study, we evaluate the potential for marine diatoms to reconstruct regional wind strength using an array of three shallow
depth ice cores drilled in the AP and EL regions. We investigate the relationship between diatom abundance and changes in
environmental parameters to assess the regional consistency of the diatom-based wind proxy. We expand these analyses by
comparing the diatom record to traditional ice core wind proxies based on major ions and dust.

2 Methods

2.1 Ice core records and age scales

Three ice cores from the southern AP and EL were included in this study (Figure 1) (Table 1). The Jurassic ice core (JUR, 140
m) was drilled in the vicinity of Jurassic Nunatak, using the BAS electromechanical drill during the austral summer 2012/2013.
The Sky-Blu ice core (SKBL, 21.8 m) from the vicinity of Sky-Blu Field Station, southern AP, and the Sherman Island ice
core (SHIC, 21.3 m) from Eights Coast, were drilled using a Kovacs hand-auger during the austral summer 2019/2020. For
JUR, SKBL and SHIC, an ice core chronology was established (Tetzner et al., 2021a) based on their hydrogen peroxide (H_2O_2)
annual cycle that is assumed to peak during the austral summer solstice and to exhibit its minimum during the austral winter
(Frey et al., 2006; Thomas et al., 2008). Ice core chronologies were corroborated using the annual cycle of the non-sea salt
component of major ions, such as non-sea salt sulphate ($nssSO_4^{2-}$) (Piel et al., 2006), that is assumed to peak between November
and January in this region (Pasteris et al., 2014; Thoen et al., 2018). Ice core chronologies were corroborated with the presence
of volcanic tephra in the 2001 CE ice core layer (Tetzner et al., 2021b). The top 15 m of SKBL included in this work and the
full SHIC core were dated back to 1999 CE, and the top 36.90 m of JUR included in this work dated back to 1992 CE. The
estimated dating error is ±3 months for each year and with no accumulated error.
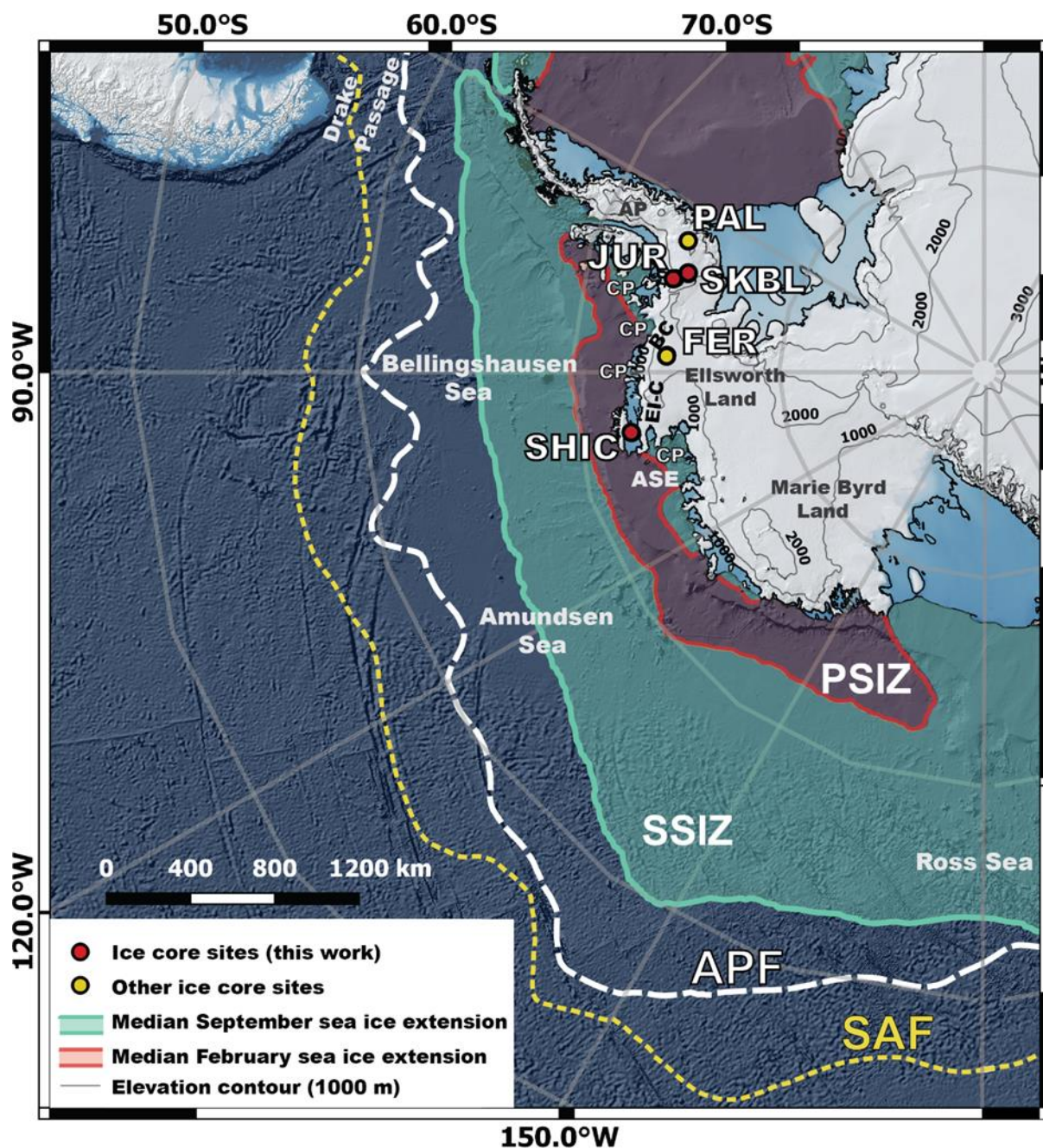
Figure 1. Map showing the location of the ice core sites and main oceanographic features considered in this study. The red circles show the locations of the three ice core sites. The pale green line shows the median September sea ice-extension between 1980-2010 CE and the pale green area represents the Seasonal Sea ice Zone (SSIZ). The red line shows the median February sea ice-extension between 1980-2010 CE, and the pale red area represents the Perennial Sea ice Zone (PSIZ). SAF= Sub-Antarctic Front. APF= Antarctic Polar Front. CP= Coastal Polynya. EI-C= Eights Coast. BC= Bryan Coast. ASE=Amundsen Sea Embayment. PAL= Palmer ice core site. FER= Ferrigno ice core site

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Table 1. Summary of each ice core geographical location and main features analysed in this study. SIE= Sea Ice Edge(*) - The distance from SIE reported corresponds to the median for years covering the data interval. September SIE values used for calculations were obtained as distance between the ice core site and the closest point in the northern limit of 15% sea ice cover.
100 **February SIE values used for calculations were obtained as the distance between the ice core site and the closest sea ice free region.**

Core name	Long	Lat	Elevation (m.a.s.l)	ANNUAL RECORD		Total depth used (m)	Distance from SIE (km)*	
				Years (CE)	# samples		Sept	Feb
JUR	-73.06	-74.33	1139	1992 - 2012	20	36.9	1045	140
SKBL	-71.59	-74.85	1419	1999 - 2019	20	15.0	1148	200
SHIC	-99.63	-72.67	474	1999 - 2019	20	21.3	753	130

2.2 Sample preparation and analyses

All ice cores included in this study were cut using a band-saw with a steel blade. Discrete ice core samples were cut at 5-cm resolution for ion chromatographic analyses using reagent-free Dionex ICS-2500 anion and IC 2000 cation systems in a class-100 cleanroom. Major ion concentrations were used to calculate the ionic contributions from marine and continental sources.

105 The marine sea salt fraction of sodium (ssNa$^+$) and the non-sea salt fraction of calcium (nssCa^{2+}) were calculated using Equation (1) and Equation (2):

$$[ssNa^+] = [Na^+] - [nssCa^{2+}]/R_{crust} \tag{1}$$

$$[nssCa^{2+}] = [Ca^{2+}] - [ssNa^+]*R_{sea\ water\ Ca/Na} \tag{2}$$

Where R_{crust} and $R_{sea\ water\ Ca/Na}$ are the mean ratios (weight by weight - w/w) of Ca/Na in the Earth crust ($R_{crust\ Ca/Na}$= 1.78) and
110 in bulk sea water ($R_{sea\ water\ Ca/Na}$= 0.038), respectively (Bowen, 1979). The non-sea salt fraction of potassium (nssK$^+$) was calculated using the following Equation (3):

$$[nssK^+] = [K^+] - [ssNa^+]* R_{sea\ water\ K/Na} \tag{3}$$

Where $R_{sea\ water\ K/Na}$ is the mean ratio (weight by weight - w/w) of K/Na in bulk sea water ($R_{sea\ water\ K/Na}$= 0.036) (Piel et al., 2006).

115 Microparticle Concentration (MPC) was measured on each ice core using a flow-through Klotz Abakus laser particle counter connected to a continuous ice core melter system at the British Antarctic Survey (Grieman et al., 2021).

All diatom samples were extracted by filtration. Ice core meltwater was filtered through polycarbonate membrane filters (pore diameter 1.0 µm) and subsequently scanned in a scanning electron microscope (SEM) following the method presented in Tetzner et al. (2021c). Observations of diatom preservation were based on the visual identification of characteristic frustule
120 dissolution features and degradation described in Warnock and Scherer (2015). Diatom frustules and fragments less than 5 µm were excluded from counting and identification. Diatom counts per sample (n) included all diatom valves, partially obscured valves and diatom fragments identified in each sample. After processing, diatom counts per sample (n) were represented as their temporal equivalent, diatom abundance (n a^{-1}).

All correlations are based on detrended data and calculated using the Pearson's linear correlation (R). Time series linear
125 correlations were calculated over a 20-year period (1992-2012 CE for JUR and 1999–2019 CE for SHIC and SKBL). Seasons
are reported as austral summer (December to February, DJF), autumn (March to May, MAM), winter (June to August, JJA)
and spring (September to November, SON).

2.3 Climate reanalyses and sea ice extension data

Monthly reanalysis fields from the fifth generation of the European Center for Medium-Range Weather Forecasts (ECMWF),
130 ERA5 (Hersbach and Dee, 2016), were used to obtain spatial correlations between ice core records and environmental
parameters. Three fields were used to perform spatial correlation analyses: wind speed (10 m wind speed), precipitation and
sea ice cover. ERA5 datasets provide hourly data available at 0.25-degree resolution (~31 km) since 1979 CE.
Sea ice extension data were obtained from the Sea Ice Index, Version 3 dataset (Fetterer et al., 2017) from the National Snow
and Ice Data Centre (NSIDC), providing monthly sea ice concentrations at 25 km resolution from 1979 to 2021 CE. September
135 sea ice limits (defined as the median northerly extent of 15% sea ice cover) were considered the annual sea ice maximum and
February sea ice limits (defined as the median northerly extent of 15% sea ice cover) were considered the annual sea ice
minimum (Thomas et al., 2019).

2.4 Statistical analyses

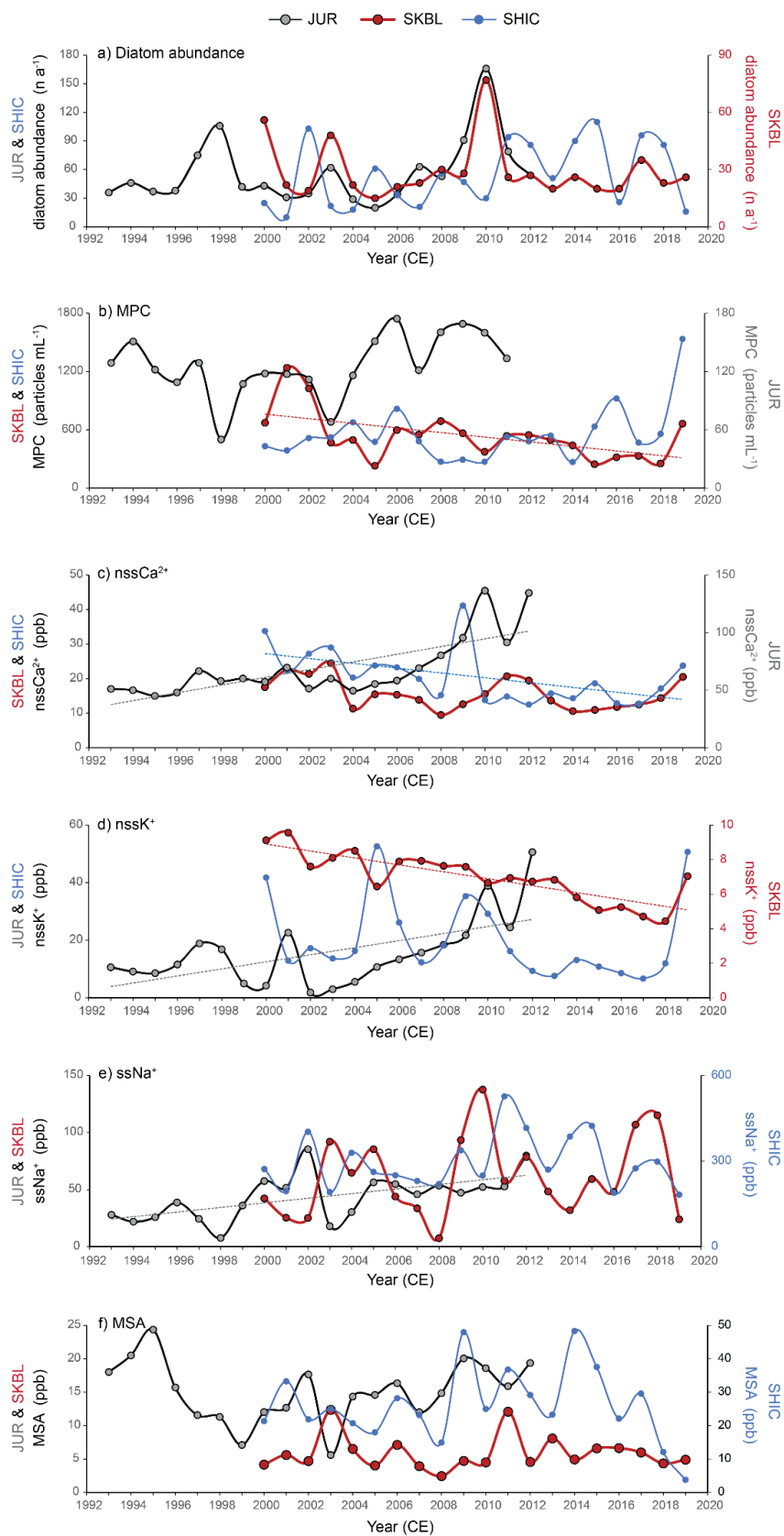
For each ice core site, the diatom abundance was compared to conventional ice core wind proxies ($ssNa^+$, $nssCa^{2+}$, $nssK^+$ and
140 MPC) and to records of methane sulphonic acid (MSA), a traditional sea ice proxy. All correlations were based on annual
averages. Spatial correlations were based on detrended data and calculated using the Pearson's linear correlation (R) over the
South Pacific sector, from 180°W to 60°W and 40°S to 90°S, selected based on air-mass pathways reaching the ice core sites
(Thomas and Bracegirdle, 2015). Based on the records of September sea ice cover between 1992-2020 CE (Fetterer et al.,
2017), spatial correlations for sea ice cover were calculated over a reduced region (between 180°W to 60°W and 55°S to 90°S).
145 All linear correlations were calculated over a 20-year period (1992-2012 CE for JUR and 1999–2019 CE for SHIC and SKBL).
Since diatom concentrations at SHIC peak during the austral summer (Tetzner et al., 2021a), spatial correlations for the SHIC
diatom record were also calculated over 6-month period covering the austral spring & summer season (September-February).

3 Results

3.1 Jurassic ice core (JUR)

150 ### 3.1.1 Chemistry, MPC and diatom abundance annual records

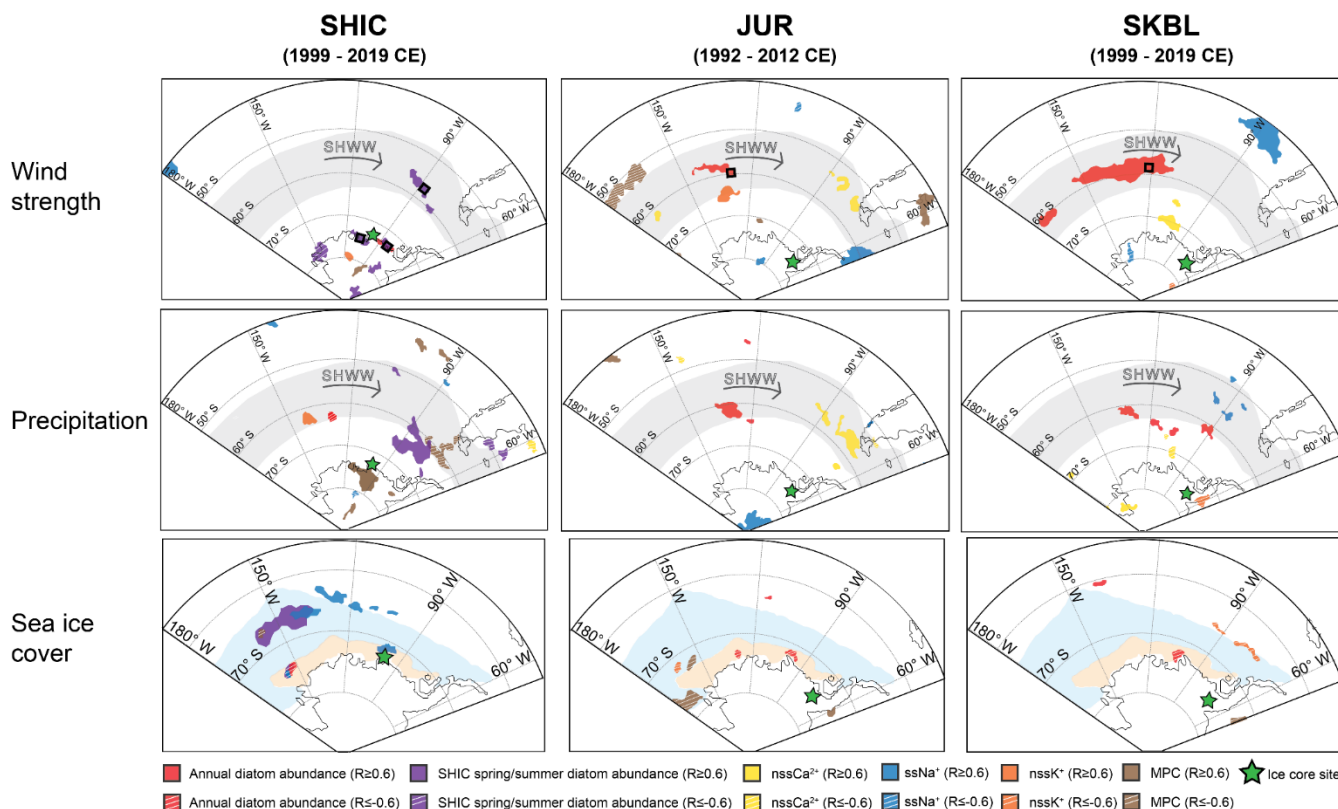
The JUR chemical, MPC and diatom abundance records are characterized by positive trends during the 1992-2012 CE period
(Figure 2). Of them, only $nssCa^{2+}$, $nssK^+$ and $ssNa^+$ were statistically significant ($p<0.05$) (Appendix A - Table A1). The

nssCa^{2+} shows a steady increase after 2005 CE, reaching a maximum (136.46 ppb) between 2009-2010 CE. The nssK$^+$ shows a similar pattern with values increasing steadily after 2001 CE, and doubling by 2011-2012 CE. The ssNa$^+$ has a consistent positive trend (2.01 ppb y^{-1}, $p<0.05$) from 1992 to 2012 CE, with a single major increase in 2001 CE. The MSA displays an overall decrease between 1992-2002 CE, followed by a general increase during 2002-2012 CE. Similarly, the MPC exhibits an increase during 1992-2012 CE with its lowest values during 1997 CE. The diatom abundance is moderately variable between 1992-2004 CE, followed by a marked increase after 2004 CE, reaching its highest value during 2009-2010 CE (Figure 2).

160   **Figure 2. Time series of chemical species, MPC and diatom abundance for each ice core site. Data points represent the annual austral winter-to-winter average and were plotted over the correspondent austral summer. Colour-coded dashed lines show statistically significant linear trends (p<0.05). MPC record from JUR covers the interval 1992-2011 CE.**

3.1.2 Environmental correlations

All records (excluding MSA) presented strong and significant correlations with wind strength (R≤-0.6 & R≥0.6, p<0.05)

165   (Figure 3). Diatom abundance is positively correlated with wind strength (0.6≤R≤0.67, p<0.05) over a latitudinal band at the northern limit of the Amundsen Sea (~60°S), and negatively correlated with the sea ice cover north of the SHIC ice core drilling site (-0.6≥R≥-0.69, p<0.05). The MPC is positively correlated with wind strength over the east coast of Argentina (0.6≤R≤0.73, p<0.05). The nssCa^{2+} exhibits a positive correlation with wind strength (0.6≤R≤0.62, p<0.05), and with precipitation (0.6≤R≤0.77, p<0.05), off the western coast of southern South America. The nssK$^+$ shows a positive correlation

170   with wind strength (0.6≤R≤0.66, p<0.05) over the Amundsen Sea. The ssNa$^+$ is positively correlated with wind strength over the Drake Passage (0.6≤R≤0.7, p<0.05) and over Ellsworth Land (0.6≤R≤0.63, p<0.05). No significant correlations were identified with wind strength or precipitation at, or near, the JUR ice core drilling site. No strong correlations (R≥0.6 or R≤-0.6) between the MSA record and sea ice cover were identified in the region.

175   **Figure 3. Regional maps showing spatial correlations between environmental parameters and chemical species, MPC and diatom abundance. Colour-coded polygons in the maps indicate highly correlated regions (R≥0.6 or R≤-0.6). All polygons plotted are statistically significant (p<0.05). Pale grey latitudinal band indicates the core of the Southern Hemisphere Westerly Wind (SHWW)**

belt. **Pale blue polygons indicate the region covered by seasonal sea ice. Pale orange polygons indicate the region covered by perennial sea ice. Black squares represent a 1°x1° quadrant around the point of highest correlation (QHC) between wind strength and diatom abundance. Spatial correlations between MSA and environmental parameters were excluded because they were below the threshold (R<0.6, R>-0.6 or p>0.05). Regional maps only present areas of spatial correlation larger than 1°x1°.**

3.2 Sky-Blu ice core (SKBL)

3.2.1 Chemistry, MPC and diatom abundance annual records

The SKBL chemical, MPC and diatom abundance records are characterized by negative trends during the 1999-2019 CE period (Figure 2) (Appendix A – Table A1), with the exception of $ssNa^+$ which exhibits a positive trend. Among these trends, only MPC and $nssK^+$ exhibited linear trends that were statistically significant ($p<0.05$). The diatom abundance is characterized by moderate interannual variability and single major increases during 1999-2000, 2002-2003 and 2009-2010 CE. The later presenting the absolute highest value (77 n a^{-1}). Major increases in MSA were also registered during 2002 CE and 2010 CE. (Figure 2).

3.2.2 Environmental correlations

The diatom abundance, chemical and MPC records from SKBL were compared to environmental parameters over the 1999-2019 CE period (Figure 3). Two records are highly correlated with wind strength, the diatom abundance and $ssNa^+$. Diatom abundance exhibits a positive correlation with wind strength ($0.6 \leq R \leq 0.78$, $p<0.05$) over a latitudinal band (~60°S) extending from the Ross Sea to the Amundsen Sea and a negative correlation with the sea ice cover ($-0.6 \geq R \geq -0.71$, $p<0.05$) over the Amundsen Sea Embayment. The $ssNa^+$ is positively correlated with wind strength ($0.6 \leq R \leq 0.75$, $p<0.05$) off the west coast of South America at ~45°S. No correlations were identified between the ice core records and wind strength or precipitation over the SKBL ice core drilling site. No strong correlations ($R \geq 0.6$ or $R \leq -0.6$) between the MSA record and sea ice cover were identified in the region.

3.3 Sherman Island ice core (SHIC)

3.3.1 Chemistry, MPC and diatom abundance annual records

The SHIC chemical, MPC and diatom abundance records present contrasting features over the 1999-2019 CE period (Figure 2) (Appendix A – Table A1). Negative linear trends are observed in $nssCa^{2+}$ (-0.7 ppb y^{-1}, $p<0.05$) and $nssK^+$ (-0.48 ppb y^{-1}, $p>0.05$). The $ssNa^+$ exhibits a positive trend (1.61 ppb y^{-1}, $p>0.05$) with values reaching an absolute maximum during 2011-2012 CE. The MSA was relatively constant over the 1999-2014 CE period. After 2014 CE, MSA decreases, reaching its absolute minimum between 2018-2019 CE. The MPC shows a steady increase after 2008-2009 CE, reaching its highest value in 2018-2019 CE. The diatom abundance exhibits a positive trend (2.16 n a^{-1}, $p>0.05$) with a strong interannual variability which describes a semi-periodic 3-year pattern (Figure 2).

3.3.2 Environmental correlations

The diatom abundance, chemical and MPC records from SHIC were compared to environmental parameters over the 1999-
2019 CE period (Figure 3). Diatom abundance, MPC and ssNa$^+$ are highly correlated with wind strength over the 1999-2019
CE period. Annual diatom abundance is positively correlated with wind strength ($0.6 \leq R \leq 0.61$, $p<0.05$) over the Bryan Coast
sector. The spring/summer diatom abundance is positively correlated with wind strength over a latitudinal band at the northern
limit of the Bellingshausen Sea (~60°S) ($0.6 \leq R \leq 0.64$, $p<0.05$), over the Bryan Coast ($0.6 \leq R \leq 0.64$, $p<0.05$) and over the
Amundsen Sea Embayment ($0.6 \leq R \leq 0.71$, $p<0.05$). In parallel, the spring/summer diatom abundance is positively correlated
with the sea ice cover over the Amundsen Sea ($0.6 \leq R \leq 0.81$, $p<0.05$). MPC is positively correlated with precipitation
($0.6 \leq R \leq 0.66$, $p<0.05$) over the SHIC drilling site. Conversely, MPC is negatively correlated with precipitation off the southern
coast of South America ($-0.6 \geq R \geq -0.65$, $p<0.05$). The ssNa$^+$ is positively corelated with sea ice ($0.6 \leq R \leq 0.7$, $p<0.05$) to the west
and north-west of the SHIC drilling site. No clear correlations were identified with the nssCa^{2+} and nssK$^+$ records. No strong
correlations ($R \geq 0.6$ or $R \leq -0.6$) between the MSA record and sea ice cover were identified for the SHIC site.

3.4 Correlation of ice core records

Linear correlations were calculated between the annual chemical, MPC and diatom abundance records across all ice core sites
(Supplementary material – Table S1). Strong positive and statistically significant ($p<0.05$) correlations were identified between
nssCa^{2+} and nssK$^+$ in SHIC and JUR (R=0.54 and R=0.88, respectively) and between MPC and MSA in SHIC and JUR (R=-
0.55 and R=0.65, respectively). Diatom abundance and ssNa$^+$ were the only components to exhibit strong and significant
correlations ($p<0.05$) across all the ice core sites (R=0.78, R=-0.46 and R=0.52, for SHIC, JUR and SKBL, respectively). The
only statistically significant correlation in the same proxy across the sites was between diatom abundance in the JUR and
SKBL cores (R=0.84, $p<0.05$). No clear or consistent pattern was identified when comparing chemical proxies from different
ice core sites.

4 Discussion

4.1 Temporal variability of the diatom record

The diatom abundance preserved in ice cores reveals a strong interannual variability across the AP and EL regions from 1992-
2019 CE. The relationship between diatom abundance and environmental parameters at the ice core drilling sites are weak and
not statistically significant. Indicating that conditions at the ice core site are not drivers of the diatom temporal variability, in
agreement with previous studies concluding that ice core diatom records are not dependent on annual snow accumulation or
local wind conditions (Allen et al., 2020; Tetzner et al., 2021a).

Spatial correlations of annual wind strength and the annual diatom abundance preserved in ice cores reveal regions of
significant positive correlations ($0.6 \leq R \leq 0.78$, $p<0.05$) (Figure 3). These regions match well with the oceanographic zones

indicated by the ecology of the dominant marine diatom taxa (Tetzner et al., 2021a). Furthermore, the neighbouring ice core sites of JUR and SKBL share similar regions of spatial correlation ($0.67{\leq}R{\leq}0.78$, $p<0.05$) (Figure 3). Numerous studies have

240   highlighted the relationship between wind strength and sea-spray production (Blanchard, 1963; Schlichting, 1974; Monahan et al., 1983; Callaghan et al., 2007; Löndahl, 2014; Tesson et al., 2016; Wiśniewska et al., 2019; Marks et al., 2019). Stronger winds have been shown to enhance the production of sea-spray aerosols, including microalgae, which implies an increased transfer of diatoms from the sea-surface microlayer into the atmosphere (Marks et al., 2019). Studies on regional atmospheric circulation confirm that air masses from these regions are effectively transported to ice core sites (Thomas and Bracegirdle,

245   2009; Abram et al., 2010; Thomas and Bracegirdle, 2015; Allen et al., 2020), therefore establishing an efficient transport pathway from the identified source regions to the ice core sites.

Two oceanographic zones were highlighted in the spatial correlation analyses for their strong link between changes in wind strength and changes in diatom abundance; the seasonal sea ice zone (SSIZ) and permanently open ocean zone (POOZ). The JUR and SKBL diatom records were correlated exclusively with winds in the POOZ (northern Amundsen Sea) and the SHIC

250   spring/summer diatom record was correlated with regions from both the SSIZ (Bryan Coast sector & Amundsen Sea Embayment) and POOZ (northern Bellingshausen Sea) (Figure 3). It is important to note that these regions of spatial correlation agree with the oceanographic affiliations of the diatom assemblages for the respective ice cores (coastal vs inland sites) reported by Tetzner et al. (2021a). Despite the correlation between the SHIC spring/summer diatom record and winds in the POOZ, the diatom assemblages for SHIC support a stronger link with the SSIZ (Tetzner et al. 2021a). Therefore, discussion

255   for the SHIC diatom record will be focused on environmental changes within the SSIZ.

4.1.1 SSIZ controls on diatom variability at a coastal site (SHIC)

The SSIZ is identified as the dominant source region by both the spatial correlation analyses and the ecological associations of the SHIC diatom record (Tetzner et al., 2021a). Wind strength and sea ice dynamics play an important role in driving the primary productivity in diatom source regions within the SSIZ (Arrigo et al., 2008; Arrigo et al., 2012). In the Bryan Coast

260   and Amundsen Sea Embayment, winds drive sea ice northward producing large ice-free areas (polynyas) near the coast (Arrigo et al., 2012; Holland and Kwok, 2012). These coastal polynyas have been identified as among the most productive regions in the Southern Ocean (Arrigo et al., 2008; Soppa et al., 2016). The stronger link to wind strength during the austral spring and summer (Figure 3), and strong seasonality identified in the sub-annual diatom record reflect the enhanced austral spring/summer primary productivity in these regions (Arrigo et al., 2008; Soppa et al., 2016; Tetzner et al., 2021a). This

265   suggests that the interannual diatom variability at this site is not exclusively driven by wind strength, but also dependent on sea ice dynamics and/or primary productivity. Previous studies have identified recent reductions in the ice-covered days (sea ice concentration) during the austral summer (Stammerjohn et al., 2012) and the development of coastal polynyas (Eltanin Polynya, Pine Island Polynya and Amundsen Sea Polynya) within the regions identified as the SHIC diatom sources (Arrigo and van Dijken, 2003; Arrigo et al., 2012). Both lead to prolonged and increased biogenic primary productivity near the ice

270   core site. Greater sea ice breakup and more open water in summer often result in larger phytoplankton blooms (Soppa et al.,

2016). A prolonged ice-free diatom source and/or recently enhanced primary productivity will increase the availability of diatoms on the ocean surface, favouring potentially larger entrainments of diatoms by strong winds. This is consistent with the recent large decadal increases seen in the SHIC diatom concentration (Tetzner et al., 2021a).

The clear link identified between the seasonality of the diatom record and sea ice primary productivity is complemented by

275   the strong relationship between the austral spring/summer diatom abundance and sea ice cover over the Amundsen Sea. However, no direct relationship was observed between the diatom abundance and the sea ice cover directly in the vicinities of SHIC (Figure 3). This is consistent with the lack of correlation between MSA and sea ice at this site, despite previous studies observing a positive relationship between MSA and sea ice extent in this region (Abram et al., 2010; Thomas and Abram, 2016). These findings suggest that diatom (and MSA) variability at SHIC is not exclusively driven by either marine primary

280   productivity or changes in sea ice cover. This can be explained by the effect of a bi-directional pattern of winds at SHIC, drawing air masses from both the east (Bryan Coast) and the west (Amundsen Sea Embayment) (Tetzner et al., 2019) resulting in two distinct sources of aerosols to the ice core site. Additionally, the onset of the sea ice breakup and duration of ice-free conditions at the Bryan Coast, Eights Coast and the Amundsen Sea Embayment does not follow a clear pattern. Some years present these regions completely ice-free, while others present either one or more regions ice-covered (Arrigo et al., 2008).

285   The development of coastal polynyas near SHIC (See Figure 1) will contribute to the increased availability of diatoms in some years (Arrigo and van Dijken, 2003; Arrigo et al., 2015). The potential input of diatoms from sources from opposite directions, along with the variability in the distribution and duration of the sea ice cover and the occasional development of coastal polynyas adds an additional and non-negligible source of variability to the diatom record at SHIC.

4.1.2 POOZ controls on diatom variability at inland sites (JUR and SKBL)

290   The diatom source region identified by the spatial correlation analyses and diatom ecological affiliations for JUR and SKBL is in the northern Amundsen Sea within the POOZ (Figure 1 and Figure 3). This oceanographic zone is characterized by the lowest seasonal and interannual variability in primary productivity for the whole SO (Arrigo et al., 2008; Soppa et al., 2016). The absence of sea ice in the POOZ reduces the seasonal extremes in primary productivity evident within the SSIZ (Tetzner et al., 2021a). The diatom availability in northern Amundsen Sea POOZ presents a low variability year-round (Arrigo et al.,

295   2008; Soppa et al., 2016), limiting the impact of interannual changes in primary productivity on the diatom record and upholding that temporal variability in the JUR and SKBL diatom records is derived mainly from changes in wind strength at the source. The marine source region supplying diatoms to JUR and SKBL is in the core of the SHWW belt. The significant positive correlation between wind strength and annual diatom abundance ($0.6 \leq R \leq 0.78$, $p < 0.05$) demonstrate the diatom records from these sites can be used as a proxy for interannual changes in the strength of the SHWWs. However, changes in ocean

300   primary productivity may contribute to diatom variability over longer time-scales.

Results presented here are consistent with the relationship identified between SHWWs strength and diatoms in an EL ice core (Allen et al., 2020). Specifically, our results show a close agreement with the location (50-60°S, 140°W) and magnitude of the strongest correlation (R=0.61, $p < 0.05$) between annual SHWW anomalies and calibrated diatom flux at the Ferrigno ice core

site (Figure 1) (Allen et al., 2020). Unlike JUR and SKBL, the Ferrigno diatom assemblage was characterised by the absence

305   of sea ice diatoms. This can be explained by the more north-westerly location of the Ferrigno diatom source (compared to the

JUR and SKBL source region) that is less likely to receive inputs from the SSIZ. Additionally, the absence of sea ice diatoms

at Ferrigno supports the conclusion that inland sites have limited influence from low-elevation airmasses in contact with the

SSIZ (Tetzner et al., 2021a).

4.1.3 Recent regional environmental changes and the diatom record

310   Ice core diatom records have the potential to capture regional environmental changes. The correlation between the annual

diatom abundance variability at JUR and SKBL with changes in the wind strength in the SHWW belt (Figure 3) (Figure 4a

and 4b) strongly suggests that the recent increase in diatoms at these ice core sites (Tetzner et al., 2021a) is driven by a

strengthening of the SHWW belt during the satellite-era (Mayewski et al., 2013; Young and Ribal, 2019; Goyal et al., 2021).

This link is further supported by sea-spray production experiments showing that a ~10% increase in wind strength (U_{10}>5 m

315   s^{-1}) has the potential to double the production of spume drops and sea-spray aerosol, including microalgae (Monahan et al.,

1986; Wu, 1993; Anguelova et al., 1999). Increasing the entrainment of aerosols into the atmosphere would likely increase the

supply of diatoms to the ice core sites and therefore the number of diatoms contained in the ice. Despite SHIC exhibiting a

similar increase in annual diatom abundance, the intrinsic relationship between the SHIC diatom record, the sea ice cover in

SSIZ, and winds over the SSIZ prevents establishing a direct link between the increases in annual diatom abundance at SHIC

320   and the strengthening of the SHWW belt (Figure 4c).

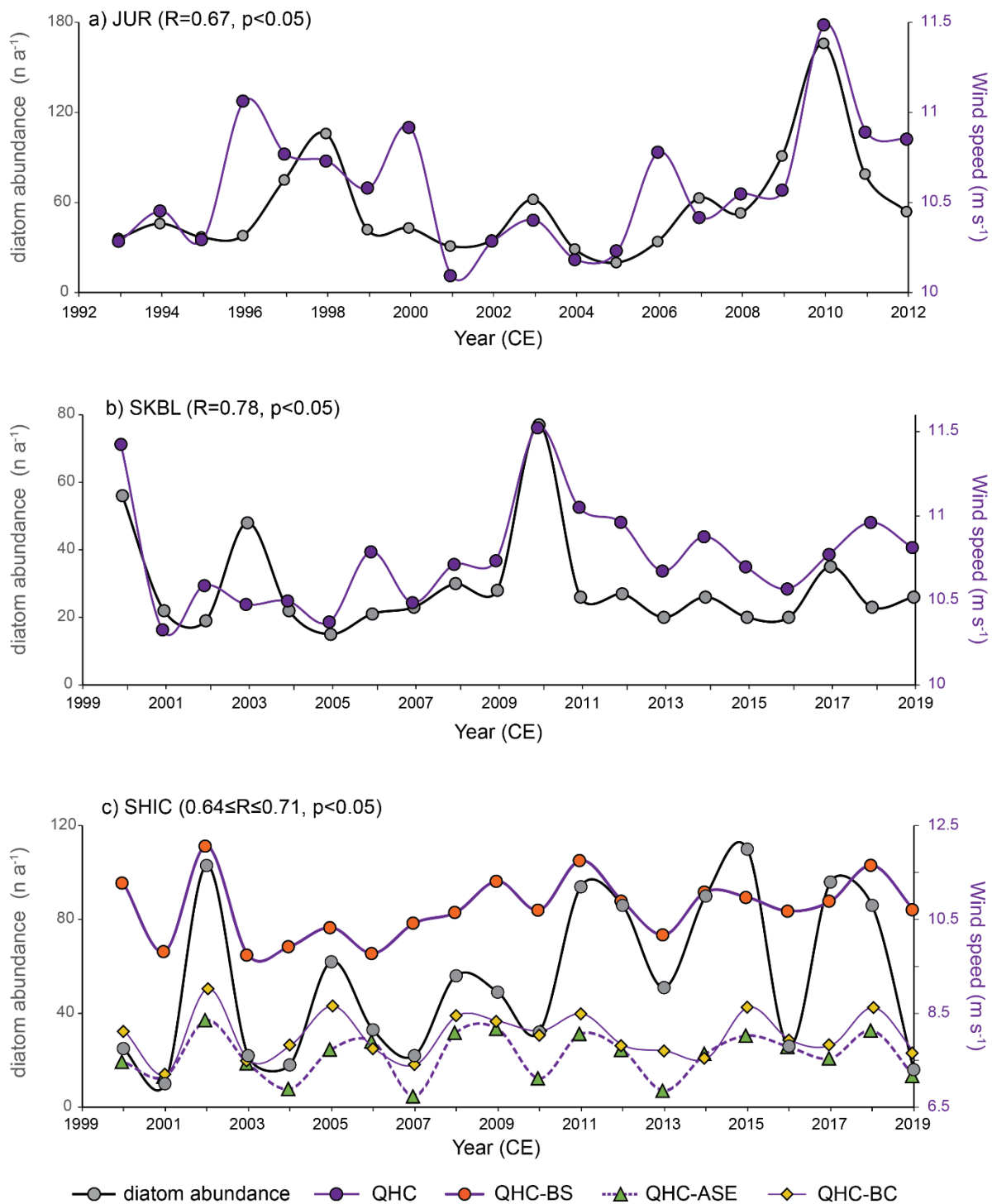



Figure 4. Time series of diatom abundance and mean wind speed inside the quadrants of highest correlation (QHC) for each ice core site highlighted in Figure 3. Data points represent the annual austral winter-to-winter average and were plotted over the correspondent austral summer. Colour-coded symbols for SHIC ice core represent the time series of wind speed on each of the QHC

325   **identified for that site. QHC-BS= Quadrant of high correlation over the Bellingshausen Sea. QHC-ASE= Quadrant of high correlation over the Amundsen Sea Embayment. QHC-BC= Quadrant of high correlation over the Bryan Coast.**

4.2 The diatom wind proxy and the traditional ice core wind proxies

We have demonstrated that the annual diatom abundance shows promise as a wind proxy of SHWW at multiple sites. To assess the full scope and validity of this novel proxy, we compared the new diatom records with established ice core wind proxies.

330   MPC, $nssCa^{2+}$, $ssNa^+$ and $nssK^+$ have been used to infer past variability in regional-to-hemispheric atmospheric circulation from annual to millennial timescales. Our results reveal the limitations in these traditional proxies, which fail to reproduce the interannual variability of wind strength upwind from the ice core sites. Instead, they provide only sporadic spatial correlations with annual wind strength that are scattered across the southern mid-latitudes (Figure 3). Even though many of these records show a strong link with wind strength, their region of correlation did not fit with their expected sources and were not consistent

335   between sites. This refutes a direct link between wind strength and their in-situ aerosol production. For example, there are strong correlations between continental-ions ($nssK^+$ and $nssCa^{2+}$) and wind strength over regions in the middle of the ocean, where it is not feasible to entrain continental-ions (JUR $nssK^+$ record). Similarly, some records are strongly linked to other environmental parameters such as precipitation, suggesting that source (JUR $nssCa^{2+}$ record) or site conditions (MPC record at SHIC), rather than wind strength, dominate the variability of these species. Some proxies (MPC at JUR and $ssNa^+$ at SKBL)

340   were strongly linked to wind strength over regions north (~40-45°S) of the core of the SHWW belt (Figure 3). This result suggests that these records could indicate changes in wind strength over continental or marine regions far from the core of the SHWW belt. Overall, these results call into question the validity of established wind proxies in the AP and EL ice cores and highlight the need for a thorough site and proxy evaluation before using these chemical and MPC species to reconstruct wind changes through time.

345   The $ssNa^+$ was the only record with a regionally consistent relationship with the diatom abundance (yellow cells in Supplementary material - Table S1). Despite the strong correlations at each ice core site, they presented opposite signs (R<0 for JUR & R>0 for SHIC and SKBL). Suggesting that the interannual variability of diatom abundance and $ssNa^+$ is not driven exclusively by the same environmental parameters across the AP and EL region.

Correlation analyses of ice core proxies between sites confirm that diatom abundance is the only record with a consistent,

350   statistically significant and strong correlation (JUR vs SKBL, R=0.84, p<0.05) (grey cell in Supplementary material - Table S1), supporting the regional validity of the diatom-based wind proxy at the high elevation sites. The $nssCa^{2+}$ record at JUR exhibits significant correlations with winds in the SHWW belt, although not in the same sector as the diatom record. Thus, the significant correlation between these two proxies at JUR (R=0.64, p<0.05) provides evidence to support diatoms as a wind proxy. However, the $nssCa^{2+}$ pattern is not reproduced at the nearby SKBL site, suggesting $nssCa^{2+}$ may not be a reliable proxy

355   throughout the AP-EL region.

Previous studies have proposed MPC as a proxy for winds in the AP and EL region (Mosley-Thompson et al., 1990; Mosley-Thompson et al., 1991; Thompson et al., 1994), suggesting that the MPC record is indicative of long-term regional

environmental changes. However, low background concentrations reported in those studies suggest the MPC annual record from the AP and EL region could be biased by the occurrence of sporadic major dust events reaching the high southern

360   latitudes. Our results are in close agreement, showing that the regional MPC record preserved in ice cores from the AP and EL is not a robust indicator of interannual wind strength variability. In contrast, the WAIS Divide ice core in neighbouring Marie Byrd Land, revealed a link between the coarse particle percentage (analogous to MPC) and interannual zonal wind strength variability at both 700hPa and 850hPa over the satellite-era (R=0.3-0.5, p<0.01) (Koffman et al., 2014). This contrasting behaviour can be partly explained by the diametrically opposed continental regions supplying mineral dust to Antarctica

365   (Sudarchikova et al., 2014; Neff and Bertler, 2015). Similarly, differences in transport pathways and the role of local meteorology have also been used to explain the different behaviour observed in sea ice proxies (MSA) around Antarctica (Abram et al., 2013; Thomas et al., 2019). Our findings provide further evidence that ice core proxies perform differently depending on the geographical region and the temporal resolution over which they are assessed.

The temporal variability of chemical tracers ($nssCa^{2+}$, $nssK^+$, $ssNa^+$) in a network of ice cores across Marie Byrd Land (ITASE)

370   have been proposed as tracers of long-term (multi-year) changes in atmospheric circulation (Dixon et al., 2012; Mayewski et al., 2013). However, only $nssCa^{+2}$ proved reliable in capturing interannual variability in atmospheric circulation patterns over the satellite-era ($0.37 \leq R \leq 0.59$, p<0.01), although not directly related to wind strength, but to northerly air mass incursions (Dixon et al., 2012). Thus, there is clearly a need for a reliable proxy for past wind strength in this important region of Antarctica. Based on our results, we propose that diatoms show the most promise as a tool to reconstruct the interannual

375   variability of SHWW strength.

4.3 Recommendations

Our findings demonstrate that marine diatoms show the most promise as a proxy for past wind strength in AP and EL ice cores when compared with a range of traditional chemical and MPC records. At inland sites, diatom abundance is most strongly dependent on annual changes in the strength of the SHWWs and has excellent potential as a proxy to reconstruct past changes

380   in the strength of the SHWWs over the northern Amundsen Sea.

Based on our results, we propose three candidate ice core sites across the AP and EL region where multi-decadal to centennial scale reconstructions of winds could be achieved: the Jurassic, Ferrigno and Palmer ice cores (Thomas and Bracegirdle, 2015) (See Figure 1). Evaluations have already confirmed the suitability of the JUR site (this study) and the Ferrigno site (Allen et al., 2020) in reproducing recent changes in the SHWW strength. Previous studies on the Ferrigno ice core have confirmed that

385   this ice core covers the last three centuries (Thomas et al., 2015; Thomas and Abram, 2016), making it a good candidate for extending a SHWW reconstruction back to the core of the Little Ice Age (~1700 CE), while the JUR site has the potential to capture changes over the last two centuries. The diatom record from the Palmer ice core has not yet been explored, however, this high elevation, low snow accumulation site (Thomas and Bracegirdle, 2015) has the potential to hold one of the longest records in the region. An annually-resolved wind strength reconstruction from any of these three ice cores will establish if the

recent intensification of the SHWW belt is unprecedented over the last few centuries and will clearly identify the timing of onset (Abram et al., 2013; Koffman et al., 2014; Turney et al., 2016; Perren et al., 2020).

Despite the consistency of the observations presented in this work, it must be acknowledged that they are from a particular region in Antarctica. Antarctica is a vast continent with contrasting environmental conditions in different sectors (Jones et al., 2016; Stenni et al., 2017; Thomas et al., 2017; Thomas et al., 2019). Thus, we recommend conducting a detailed assessment of the diatom proxy outside the AP-EL regions.

5 Conclusions

Ice cores capture changes in past wind strength and atmospheric variability, with several chemical and microparticles suggested as potential proxies. In this study, we propose an exciting new wind proxy, based on marine diatoms, that performs better than traditional ice core wind proxies in ice cores from the Southern Antarctic Peninsula and Ellsworth Land. A set of ice cores from this region have been analysed to demonstrate that the temporal variability of the diatom record preserved in inland ice cores is exclusively driven by changes in the wind strength within the core of the Southern Hemisphere Westerly Wind belt. While the temporal variability of the diatoms preserved in coastal ice cores is driven by a combination of wind strength and sea ice dynamics within the seasonal sea ice zone.

The lack of coherence between ice core chemical and dust proxies at sites from the same region suggest that these proxies should be used with caution. For these proxies, both the production at the source and the deposition at the ice core sites drive the variability, making it hard to resolve the signal of wind strength. These findings demonstrate the importance of a thorough site evaluation before extending environmental interpretations back in time, with no single proxy suitable for reconstructions across all of Antarctica.

We propose the marine diatom record preserved in ice cores from the Antarctic Peninsula and Ellsworth Land regions is the optimal proxy for reconstructing the interannual wind strength variability in the Pacific sector of the Southern Hemisphere Westerly Wind belt. Further research should be focused on expanding the study of the diatom record and its potential as a wind proxy in other regions of Antarctica and over longer timescales.

Appendix A

Table A1. Basic statistics for the diatom abundance (n a^{-1}), chemical species (ppb) and MPC (particles mL^{-1}) annual records from each ice core. Bold numbers indicate statistically significant linear trend values (p<0.05). (*) MPC record from JUR covers the interval 1992-2011 CE due to missing data.

	Mean	Stdv	Max	Min	Linear trend
SHIC (1999-2019 CE)					
Diatom abundance	54.4	33.7	110	10	2.16

MPC	554.80	287.44	1536.12	269.04	18.63
nssCa^{2+}	20.62	7.67	41.17	12.51	**-0.7**
nssK$^+$	20.56	14.13	52.65	6.71	-0.48
ssNa$^+$	295.38	94.38	526.82	182.34	1.61
MSA	26.09	10.96	48.3	3.76	-0.09
JUR (1992-2012 CE)					
Diatom abundance	57.0	34.0	166	20	2.07
MPC*	126.33	31.72	174.55	50.16	2.26
nssCa^{2+}	69.41	26.45	136.46	45.08	**3.35**
nssK$^+$	15.6	12.16	50.62	1.83	**1.23**
ssNa$^+$	43.30	19.84	85.36	7.64	**2.01**
MSA	15.12	4.56	24.36	5.58	0.02
SKBL (1999-2019 CE)					
Diatom abundance	29.2	14.9	77	15	-0.41
MPC	537.60	250.19	1239.19	230.46	**-23.74**
nssCa^{2+}	15.71	4.43	24.52	9,48	-0.28
nssK$^+$	7.00	1.41	9.57	4.44	**-0.2**
ssNa$^+$	61.04	34.94	137.62	7.44	1.31
MSA	5.91	2.52	12.35	2.44	-0.01

Data availability

Datasets original to this work will be available at the UK Polar Data Center (https://www.bas.ac.uk/data/uk-pdc/).

Author contribution

DT did the initial conceptualization. DT and MG were in charge of data curation. DT, ET and CA conducted the formal analysis. DT was in charge of the Investigation. DT, ET and CA designed the Methodology. DT prepared the original manuscript. ET, CA and MG contributed to the reviewing and editing of the original manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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