Sensitivity of Holocene East Antarctic productivity to subdecadal variability set by sea ice

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Antarctic sea-ice extent, primary productivity, and ocean circulation represent interconnected systems that form important components of the global carbon cycle. Subdecadal to centennial-scale variability can influence the characteristics and interactions of these systems, but observational records are too short to evaluate the impacts of this variability over longer timescales. Here, we use a 170-metre-long sediment core collected from Integrated Ocean Drilling Program (IODP) Site U1357B, offshore Adélie Land, East Antarctica to disentangle the impacts of sea ice and subdecadal climate variability on phytoplankton bloom frequency over the last ~11,400 years. We apply X-ray Computed Tomography, $IPSO_{25}$, diatom, physical property, and geochemical analyses to the core, which contains an annually-resolved, continuously laminated archive of phytoplankton bloom events. Bloom events occurred annually to biennially through most of the Holocene, but became less frequent (~2-7 years) at ~4.5ka when coastal sea ice intensified. We propose coastal sea-ice intensification subdued annual sea ice breakout, causing an increased sensitivity of sea ice dynamics to subdecadal climate modes, leading to a subdecadal frequency of bloom events. Our data suggest projected loss of coastal sea ice will impact the influence of subdecadal variability on Antarctic margin primary productivity, altering food webs and carbon-cycling processes at seasonal timescales.

Antarctica's marine margin is a complex biological and oceanographic system in which sea-ice growth, Antarctic Bottom Water (AABW) formation, and high primary productivity act as a significant CO_2 sink and ventilate the Southern Ocean[1,2]. High primary productivity occurs where nutrients are brought to the surface, including oceanographic fronts[3], polynyas[4], upwelling near the continental shelf break[5], and the marginal ice zone (MIZ)[6], all of which are influenced by Antarctic wind fields. High productivity and export events around Antarctica occur with changing insolation and stratification associated with sea-ice break up[7]. Large-scale subdecadal climate modes, specifically El Niño-Southern Oscillation (ENSO), the Southern

Annular Mode (SAM), and the Indian Ocean Dipole (IOD), are known to affect sea ice[8,9] and wind fields[10] around Antarctica. The teleconnection between ENSO (which varies at 2-7 year periods) and Antarctic sea-ice variability is largely driven by wind changes resulting from hemispheric-scale sea level pressure and 500 mBar height anomalies[8]. This teleconnection can be amplified or dampened by other subdecadal climate modes, such as the IOD and SAM[9–12]. Collectively, these subdecadal climate modes alter meridional and zonal wind flows[9,10] that regulate sea-ice break out[11] at 2-7 year periods, thus influencing primary productivity in Antarctica[13–15]. Clarifying how the annual cycle and subdecadal scale climate modes have impacted past Antarctic coastal systems will inform models used to project future system response[16].

We investigate a 170 m sediment core recovered from the Adélie Basin (IODP Site U1357B)[17] along the Wilkes Land Margin of East Antarctica (Figure 1). The Adélie Basin is a high primary productivity region near the MIZ. It also lies beneath and downstream of several large polynya systems, and the westward-flowing Antarctic Coastal Current. The drill site targeted a high-sedimentation (~1.5-2cm/year) drift deposit (Adélie Drift) dominated by pelagic biogenic deposition. It provides an ultra-high resolution Holocene record of climate and oceanographic variability adjacent to the Mertz Polynya system, one of the largest exporters of sea ice and AABW along the East Antarctic margin[2]. Previously collected Antarctic cores have significantly lower sedimentation rates, and alternate between massive (bioturbated) and laminated diatom ooze[18,19]. They cannot resolve high-frequency change at subdecadal scales. However, U1357B is continuously laminated, and high sedimentation rates afford an unprecedented opportunity to assess subdecadal and annual changes at the Antarctic oceanic margin.

An ultra-high-resolution record of marine biogenic blooms

The east-west elongated Adélie Drift deposit formed parallel to the wind-driven Antarctic Coastal Current[2,20]. This current influences both surface and deep waters on the continental shelf[2,20]. Consequently, the Mass Accumulation Rate (MAR) (methods) in this drift is thought to reflect current strength, and only partially reflects changes in biological productivity (Figure 2). Comparison of the covarying siliciclastic (detrital) and biogenic MAR[21] (Figure 3c), suggests detrital and biogenic sediments are advected to the site together, under the influence of wind-driven currents and focussed into the Adélie Basin by shelf bathymetry (Figure 2). Nearby core MD03-2601(Figure 1) shows covarying sedimentation rates with U1357B throughout the Holocene, indicating the sediment advection process is a regional signal (Figure 2; Extended Data Fig.1).

Iceberg rafted debris (IRD) is negligible (Extended Data Fig.2), aside from the very bottom of the core (>168 meters below sea floor; mbsf) suggesting direct sediment supply from icebergs is limited. The geometry and location of the drift is inconsistent with deposition as part of a glaciomarine fan system. Regional bathymetric highs are characterised by poorly sorted diamicts and muddy sands[22]. Grain size frequency distributions in those settings indicate the partial winnowing of the <125 μm component by bottom currents[22]. However, detrital siliciclastic material in the bathymetric troughs, including the Adélie Drift deposit, are consistently <125 μm with a well-defined silt-fine sand mode (Extended Data Fig.2). This is interpreted to represent suspension settling of winnowed muds derived from diamicts on the adjacent highs, suggesting the primary control on sedimentation is current strength and sediment advection (Figure 2). As suspended sediment winnowed from the banks is advected towards U1357, settling of sediment will occur where current slows as it passes over the deep bathymetric troughs[22]. Therefore, U1357 represents a sediment trap and changes in sediment grain size are a function of Antarctic Coastal Current strength, with larger grain sizes transported during stronger currents[22]. This is supported by the covariance of sand percent with MAR curves, whereby an increase in MAR and sand percent relate to increased current speed (Figure 3c, e; Extended Data Fig.3).

The site also traps biogenic material produced in the Dumont d'Urville polynya above[4], as well as biogenic material advected from the Mertz Polynya to the east. It is assumed that local biogenic material dominates[17]. Large phytoplankton bloom events along Antarctica's coastal margins are associated with a relatively fresh and stably stratified meltwater layer originating from seasonal sea-ice melt[4,6]. Seasonal sea-ice break up in this region is strongly affected by changes in katabatic and zonal wind intensity[23]. Diatom analysis from MD03-2597 in the Adélie Drift and nearby MD03-2601 interprets light laminae as biogenic bloom events, occurring during spring sea-ice retreat, which are rapidly exported to the seafloor[24,25].

To determine light laminae frequency, the top and bottom of each light lamina bloom event was manually determined using X-Ray Computed Tomography (CT) images and compared to greyscale timeseries extracted from raw CT data (methods; Extended Data Fig.4; Figure 3a). Comparisons of the greyscale curve to gamma ray attenuation (GRA) bulk density, Natural Gamma Radiation (NGR), XRF silica, XRF titanium indicate changes in the CT profile are primarily associated with changes in laminae composition (Extended Data Fig.5). This is assessed further by independent timeseries analysis of the greyscale and productivity indicators in the XRF data (Figure 4). $IPSO_{25}$ data from U1357B (methods), and diatom analysis from MD03-2601(ref.[26,27]) are used to assess the influence of sea-ice conditions on sedimentology and bloom frequency. $IPSO_{25}$ is interpreted as a proxy for fast ice[28], sea ice anchored to features along the continental margin, whereas increases in *Fragilariopsis curta* relative abundance indicate cooler temperatures and later spring sea-ice melting[27].

Subdecadal drivers of coastal Adélie Land bloom events

Applying the age model to the manual laminae counts, we find annual to biennial frequencies dominate prior to 4.5 ka. Subdecadal periodicities (2-7 years) dominate after 4.5 ka and are superimposed on distinct variations occurring at centennial to millennial timescales (Figure

3d). These annual to subdecadal frequencies, as well as the lower frequency shifts, are upheld by evolutionary spectral analysis of the raw CT-scan greyscale data and inferred XRF productivity ratio Si/Ti (methods; Figure 4). Comparison of these data with the MAR curve, $IPSO_{25}$, and diatom assemblage data indicate distinct climate states in the Holocene, noted in other Antarctic records (Figure 3)[16,29]. From 4.5 ka, a baseline shift occurs in coastal sea-ice proxies and sand percent, which correspond with less frequent bloom events relative to the overall record (Figure 3, Extended Data Fig.6). These laminae events occur at frequencies that are consistent with modern day ENSO frequencies of 2-7 years (Figure 3,4). However, this relationship is interrupted between 0.8-1.8 ka, when $IPSO_{25}$ is reduced, and bloom events are more frequent.

Although some records argue for a baseline shift in ENSO variability at 4-5 ka [30,31], others suggest it has been highly variable for the past 7 ka[32].Given a consistent pattern is not yet recognized in Holocene ENSO records[31,33], we remain cautious about correlating Antarctic timeseries with low-latitude records of Holocene ENSO variance[31,33]. Temporally limited proxy records of other subdecadal climate modes[34,35] (e.g. IOD, SAM), which amplify or dampen the ENSO response along Adélie Land[9–12], present a similar issue. This precludes us making a direct comparison of how variations in the intensity of these subdecadal climate modes have impacted Adélie Land. However, there is no evidence that ENSO frequencies have shifted out of the 2-7 year band into the 1-2 year band[30–33]. SAM and IOD modulate the amplitude of ENSO influence on winds[10] and coastal sea ice[9,11] – not the frequency. Below, we investigate how frequency of biological bloom events has shifted through the Holocene. We interpret our data primarily in the context of local productivity drivers. We also identify whether bloom frequencies are consistent with modern subdecadal climate modes, which regulate sea-ice break out[8–10] and induce bloom events[13,15], or the annual seasonal cycle.

Local deglaciation influenced bloom events (11.4-8 ka)

Sediments at in the lowermost ~0.7 m of U1357B are poorly sorted with IRD visible in the CT images (Extended Data Fig.7). Upcore, IRD is largely absent in the CT images and grainsize frequency distributions (Extended Data Fig.2). Bloom events occurred at an annual frequency around 11.4 ka, before trending towards biennial periods (5-7 laminae per 10 years) between 10.8-9 ka (Figure 3d). Bloom frequency was highest at ~8.2 ka, with one or multiple events occurring annually.

Prior to ~8.2 ka, frequent occurrences of laminae peaks are attributed to freshwater pulses from the final phase of local EAIS retreat[36,37]. Deglacial reconstructions suggest a calving bay re-entrant pattern, whereby ice retreated first in the bathymetric troughs, and later from the adjacent bathymetric highs[36,37]. This is supported by the decline in NGR and mean grain size, and gradual increased sorting of the detrital fraction upcore, representing a declining influence of glaciomarine sediment (Extended Data Fig.5b, 7). The low MAR during this period may indicate less lateral advection of sediments as bathymetric highs were still ice-covered, restricting sediment transport from the east.

In contrast, the sharp MAR increase at 8.2 ka likely indicates enhanced advection of material, initiated as the local bathymetric highs fully deglaciated (Figure 3c). A high proportion of *Chaetoceros (Hyalochaete)* resting spores in diatom assemblages from MD03-2601 indicate a more stratified and stabilized water column than in later parts of the Holocene, supporting the interpretation of enhanced glacial meltwater at this time[26,29]. Stratified and nutrient-rich glacial meltwater[38] likely created favourable conditions for bloom events.

The likely dominance of a local signal on sedimentation during the deglaciation suggests regional processes (i.e. meltwater stratification in an enclosed calving bay embayment) drove sea ice seasonality/break out and bloom events, not low-latitude teleconnections. A lack of fast ice, inferred from the $IPSO_{25}$ proxy, allowed regular bloom events to occur in most seasons, and any subdecadal climate mode influences appear to have subordinate control. In this context, evolutionary harmonic analysis (EHA) of the CT greyscale curve and XRF Si/Ti linescan data shows power throughout the 2-7-year frequency band. Laminae counts occasionally fall into this band as well, consistent with subdecadal climate mode influences (Figure 4). Although the annual sea-ice cycle appears to regulate bloom events during this period, we propose subdecadal climate modes were a background influence, potentially causing earlier or later breakout of seasonal sea ice.

Annual coastal sea-ice breakout modulated blooms (8-4.5 ka)

By ~8 ka, regional interpretations suggest glacial retreat was largely complete[29,36], and U1357B grain size values, MARs, and physical properties (e.g., NGR and CT density values) stabilise, albeit with millennial-scale variations (Figure 3, Extended Data Fig.5). Bloom events occur every ~1-2 years, and rarely fall into the 2-7 year subdecadal climate mode band (Figure 4).

Sea-ice reconstructions from *F. curta* in MD03-2601 (ref[26]) suggest reduced seasonal sea-ice duration, and $IPSO_{25}$ data from U1357B indicate reduced fast ice cover compared to later intervals (Figure 3f-g). Sand percent and MAR curves indicate stronger currents and high terrigenous sediment advection, inferring enhanced wind stress due to reduced ice cover (Figure 3c, e). A reduced duration of coastal ice in this region would increase the frequency of seasonal stratification from sea-ice meltwater and open water conditions. These conditions are currently observed to trigger diatom blooms in the Mertz Polynya[39]. Thus, during the relative warmth of the mid-Holocene[29], we propose the primary control on bloom events was the breakup and melting of seasonal sea ice. This is consistent with the observed shift towards annual to biennial laminae frequencies.

Although some studies suggest lower ENSO related variability from Eastern Pacific equatorial records prior to 4.5Ka [30,31], a shift to lower variability does not explain more frequent sea ice break out and bloom events (Figure 4). As with the preceding interval, spectral power in the 2-7 year band remains evident (Figure 4) and a subordinate influence could account for breakout events not occurring yearly. However, the annual cycle appears to be the dominant driver of coastal sea ice breakout events throughout this interval.

Increased coastal sea ice reduced productivity at 4.5 ka

Around 4.5 ka, a shift occurred in all records (Figure 3, Extended Data Fig.6), explained as a longer period of sea-ice cover most years. This is reconstructed by diatom assemblages and IPSO$_{25}$ proxies, and the decline in MARs and sand percent. Bloom events became less frequent and occurred ~2-7 years. EHA analysis of the greyscale curve and Si/Ti XRF variance indicates a similar shift to the 2-7 year band (Figure 3, Figure 4). Between 1.8-0.8 ka, there is an exception to this pattern. The IPSO$_{25}$ data show a drop in fast ice, sand percent increases and laminae frequency increases to near-annual to biennial events (5-8 laminae events per 10 years; Figure 4). Although it is qualitative measure of fast ice[28], we note a consistent pattern where IPSO$_{25}$ values are consistently low (e.g. $<0.2\mu g/g$) bloom events fall into the 1-2 year band (e.g. 1.8-0.8 ka). When fast ice increases, bloom events fall into the 2-7 year band.

A reduction in primary productivity, and therefore bloom events, is expected with an overall increase in seasonal duration of sea-ice cover, due to reduced light availability and shorter growing season[26]. Extensive multiyear fast ice along George V Land[23], to the east of U1357, significantly influences this region today. A regional increase in multiyear ice would reduce the occurrence of bloom events. Larger-scale seasonal sea-ice breakup would occur less frequently, thereby reducing the frequency of stratification events adjacent to the Mertz and Dumont d'Urville polynyas. The mechanism for increased sea-ice duration at 4.5 ka is not a focus of this paper. It is noted around much of the Antarctic margin, and previously interpreted as a consequence of reduced local insolation forcing and enhanced ocean-ice shelf interactions[21]. Decreases in sand percent and MAR indicate an associated drop in current speed (Figure 3c, e;

Extended Data Fig.3). This is likely due to expanded sea-ice coverage, which reduced wind stress on the ocean surface and the vigour of the coastal current. A slowdown in sedimentation rate is also observed at MD03-2601, indicating a regional slowdown in wind driven current and sediment advection (Extended Data Fig.1). These lines of evidence indicate the shift in productivity and reduced laminae frequency was due to increased presence and duration of coastal sea ice.

Sea ice sets system sensitivity to subdecadal climate modes

Although synoptic and katabatic winds are essential for opening and maintaining the Mertz Polynya, fast ice distributions are also important. Increased fast ice extent to the west and east restrict sea-ice export and "back-fill" the polynya, thereby limiting its size[40]. Greater fast ice extent over Site U1357, which lies west of the Mertz Polynya (Figure 1), would increase the probability of "back-fill" events, limiting bloom events. However, greater fast ice extent could also increase stratification during favourable conditions for sea-ice breakout.

Our Adélie Land record shows frequency of mass biogenic bloom events in coastal polynyas of Adélie Land, East Antarctica is strongly modulated by coastal sea ice. Two-to-seven-year variability in bloom events, consistent with subdecadal climate mode forcing, increased after 4.5 ka. This agrees with other Antarctic Holocene records which suggest increased impacts of subdecadal climate modes on westerly winds and surface temperatures in the late Holocene[19,41]. Changing seasonality and distribution of coastal sea ice, and shifts in zonal winds are modulated by subdecadal climate modes under modern conditions[8–10,14]. We propose the increased extent of coastal ice at 4.5 ka accentuated the impact of subdecadal climate modes on sea-ice breakout. This caused biogenic blooms to shift from annual/biennial events to subdecadal-scale modulation.

This is relevant to projections of Antarctic coastal change, as Adélie Land climate anomalies associated with climate modes differ among reanalysis studies[9,42–44]. Climate models also struggle to capture recent sea-ice trends, due to the complexities of ocean and atmospheric feedbacks in the Antarctic[45]. Thus, critical processes appear to be underrepresented in models which project the future response of Antarctic coastal systems to increased tropical and southern mid-latitude variability.

Our data highlight the importance of sea-ice dynamics in regulating the sensitivity of biological productivity to subdecadal scale climate modes (e.g. ENSO, SAM and IOD) along the Adélie Land margin. If future warming trends result in reduction or loss of coastal sea ice, as occurred during the mid-Holocene at Adélie Land, our work suggests more frequent bloom events will result, independent of background shifts in subdecadal scale climate modes. This has implications for future food webs in the Antarctic, and carbon cycling processes within this globally important region of Antarctic Bottom Water formation.

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Author Contributions:

K.M.J, R.M.M, and N.A.N.B designed the study and wrote the paper with input from all authors. K.M.J, R.M.M, and H.J.H analysed the X-ray Computed Tomography data. R.M.M and A.A. conducted the grain size analyses. J.E. produced the HBI data. F.J.J.E analysed the XRF geochemical data. C.R.R. conducted the opal (%BSi) measurements. M.Y. and Y.Y. analysed and provided the compound specific ^{14}C ages. R.B. and C.E. were lead proponents of the ancillary IODP expedition 318 proposal to core IODP Site 1357. All authors contributed to the interpretations of data and finalisation of the manuscript.

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Figure Captions:

Figure 1: Area of study and example bloom event after sea ice breakout. (a) Map[46-48] of Adélie Land and site locations of U1357B (orange circle), MD03-2601 (black circle), MD03-2597 (pink circle) and Dumont d'Urville (DDU) station (black square). Primary bathymetric features[48], wind directions, and current locations indicated. X-Y (black) indicates approximate location of seismic profile[17] in Figure 2 (b) MODIS true color (bands 1,4,3) satellite imagery capturing sea ice breakout on December 12th, 2008. (c) MODIS true color (bands 1,4,3) satellite imagery overlain with chlorophyll-a concentrations[49,50] from phytoplankton bloom event on January 15th, 2009, following sea ice breakout. (b,c) Site U1357B is indicated by orange circle. Antarctic Polarstereographic projection (EPSG: 3031). MODIS true color satellite images from NASA Worldview.

Figure 2: Simplified Sediment Deposition Model for U1357B
(a) Simplified deposition model of Adélie Drift during weaker winds (katabatic/zonal; blue arrows), more sea ice, and subsequent weaker coastal current (yellow arrows). Biogenic and winnowed terrigenous material are selectively deposited (white arrows) into drift as water slows over basin. Light and dark laminae indicated by brown and green lines. Pink line indicates approximate location of U1357. Relative strength of winds and currents indicated by arrow size. Characteristics of this mode are reduced grain size, reduced MAR, reduced laminae thickness, and increased laminae per meter. X, Y marks seismic profile direction as seen in Figure 1. (b) same as (a), but for stronger winds (katabatic/zonal) less sea ice, and stronger current.

Figure 3: Holocene proxy records in Adélie Land. (a) Raw CT greyscale data (b) Raw XRF linescan data of productivity ratio Si/Ti (c) Mass Accumulation Rates (MAR) from U1357B. Green is biogenic silica MAR, brown is terrigenous[21] (d) Laminae frequency per 10 years smoothed in a 5 point moving mean, while the bold curve is an rlowess smoothing, using a 5% span of the data (e) Sand percentage of the light laminae, which is representative of current speed (f) $IPSO_{25}$ concentration from U1357B, a proxy for fast ice conditions (g) Percentage of *F. curta* from MD03-2601 (ref.[27]), a diatom species indicative of later spring sea-ice melt. Missing data in (a,b) represent intervals with no core recovery.

Figure 4: Evolutive Harmonic Analysis (EHA) of the greyscale data and XRF Si/Ti productivity proxies. (a) greyscale data (b) XRF Si/Ti. Both plots are overlain with laminae frequency per 10 years curves in white and black (same as in 3d). Normalized power is similar across both proxies, showing a distinct shift to fewer bloom events and reduced productivity at 4.5 ka. Manual laminae counts binned at 10-year intervals are consistent with the EHA. The white curve is the 10-year binned record smoothed in a 5-point moving mean, while the black curve is a rlowess smoothing, using a 5% span of the unsmoothed 10-year binned record. The black boxes indicate intervals with no core recovery. The 2-7-year subdecadal climate mode band is indicated by the vertical black dotted lines (i.e., 5 laminae per 10 years is a 2-year frequency).

Data availability:

The raw greyscale data, light laminae depths, light laminae sand percent, XRF Silicon, XRF Titanium, and HBI diene data can be found at https://doi.pangaea.de/10.1594/PANGAEA.933380.

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Methods

Age Model:

The age model was developed from 87 ^{14}C dates from acid-insoluble bulk sedimentary organic carbon to constrain the ages of the sediment between ~11.4 ka BP and modern day[51] (Extended Data Fig.1). The age model only resolves ages to 11.4 ka as ages older than this are anomalously old and assumed to incorporate reworked carbon of pre-Last Glacial Maximum age. This was also indicated by a larger terrestrial contribution observed at the lowest section of the core according to XRF data[52]. Ages younger than 11.4 ka are less likely to be affected by reworked carbon at the Adélie Drift site, as lack of Ice Rafted Debris suggests direct glacial influences were negligible. The consistent stratigraphic order of the 87 radiocarbon ages and sedimentation rates through the Holocene support this interpretation. Very few Antarctic marine sediment core records presently have age models of this resolution and with this level of stratigraphic integrity. A reservoir correction age of 1200+/-100 was applied to the depth to age conversion calculated by BACON, that uses a Bayesian iteration scheme that invokes memory from dates above any given horizon and produces a weighted mean and median age-depth curve[53]. This correction is consistent with the uncalibrated age of the upper most sample of 1310 years.

Since C_{16} fatty acids decompose rapidly in the water column and sediment[54,55], compound-specific (CS) ages in Antarctic sediments that contain relict carbon from glacial reworked sediments often show younger ages than bulk ages[56,57]. Yamane *et al*. (2014) reported the age model based on CS ^{14}C ages using C_{16} fatty acids from core U1357A and ages were reported with 1-sigma uncertainty. In this study, the background level of the study was rigorously re-examined using the latest background evaluation method for small-scale ^{14}C analysis developed at the Atmosphere and Ocean Research Institute, the University of Tokyo[58]. The modern carbon contamination (MCC) was evaluated from ^{14}C value of IAEA-C4 (wood: $\Delta^{14}C$ = –998.0 to –995.6 ‰) which was processed and measured by AMS in the same batch as other unknown samples (Figure S1a). The background correction was carried out differently depending on sample size using the relationship between sample size and background (Figure S1b). To externaly evaluate the reliability of the MCC, we estimated the core top CS ^{14}C value using the mean sedimentation rate of lithostratigraphic unit I (0 – 170.25 m below seafloor). Based on the revised CS ^{14}C ages, it is estimated that the $\Delta^{14}C$ value of core-top sediment is about –147 ‰. This $\Delta^{14}C$ value is in agreement with the pre-bomb dissolved inorganic carbon (DIC) $\Delta^{14}C$ value of the Southern Ocean (–149.8 ± 10.4 ‰; ref.[59]), hence validating the CS ^{14}C. The values are co-plotted with bulk ages with 2-sigma uncertainties and show that CS and bulk organic ^{14}C ages are consistent (Extended Data Fig.1). This is the case for earlier values (i.e. ref.[52]) if we plotted values with 2-sigma uncertainties, thus all ages are consistent within statistical uncertainties. Consequently, these revised compound specific radiocarbon assessments support our inference that contamination of reworked carbon in these rapidly deposited biogenic rich samples are minimal

(Table S1). Below, we independently assess the reliability of the bulk organic carbon age model by comparison to age models from nearby core MD03-2601 (Extended Data Fig.1).

The BACON methodology was applied to the ^{14}C dates from MD03-2601[60,61] to recalibrate the MD03-2601 age model[51]. The model shown in this paper is different from the one used previously[62], which used an inferred meteorite impact at ~15m to determine an age of 4ka at that depth. The old age model also removed two ^{14}C dates at 4.4 and 5.6 ka years due to the assumption that these ages were anomalously old relative to the meteorite impact. However, the meteorite age-depth correlation cannot provide absolute age control and the new age model presented here indicates the impact occurred around 5.4 ka. Comparison between the U1357B and new MD03-2601 age model show strong covariance in sedimentation rates and suggest a regional sedimentation advection process (Extended Data Fig.1).

Depth Scales:

Core recovery from each 9.5 m piston core run often exceeded 100% due to expansion as the core is decompressed during recovery. Data derived from these initial core lengths is termed the csf-a depth scale. The standard IODP procedure to correct for expansion is to apply a linear compression algorithm to scale recovery back to 100% and create a new scale (csf-b), as it is assumed expansion is uniform in the core. However, in U1357, expansion due to biogenic gas was particularly high and resulted in discrete sections of core being pushed apart creating voids in the depth scale that did not represent real gaps in the stratigraphy. To account for this, the voids are numerically removed, and the depth scale adjusted, prior to linear compression being applied (if recovery still exceeds 100%). In this paper, we term this the csf-d scale (noting it is not an official IODP depth scale term). Although cap expansion gaps (voids) are removed within individual core runs, the csf-d scale still contains sections with no core recovery at the base of some runs where there was less than 100% after voids within the cores were numerically removed. The sections with no core recovery are as follows: 48.82-50.0m; 58-

59.5m; 66.19-69.0m; 76.81-78.5m; 86.5 88.0m; 95.66-97.5m; 105.16-107.0m; 115.72-116.5m; 124.38-126.0m; 134.41-135.5m; 144.23-145m; 153.85-154.5m; 163.94-164.0. Slight differences in these depths could have occurred in core storage prior to CT and XRF scans.

Composite Core:

Three holes (U1357 A, B, and C) were drilled in the Adélie Basin as part of IODP Expedition 318[63]. Drilling multiple holes is standard IODP procedure for sites with paleoceanographic focus to address core breaks and other intervals of incomplete recovery; a complete and continuous stratigraphy can usually be constructed by splicing sections from individual holes into a stratigraphic composite section. This is usually achieved in IODP cores by using physical core properties to guide placement of the least disturbed, highest recovery intervals in the spliced sections. However, cores from Site U1357 are problematic in this context as extremely high biogenic and gaseous content precluded many physical property measurements, such as magnetic susceptibility, from being registered beyond typical noise levels. This made construction of a composite core at subcentennial-scale precision extremely difficult. Given the difficulties in creating a spliced record, hole U1357B was selected as the best core for this analysis because it had less gas-related disturbances than hole A, and a more complete record than hole C, which was a shorter core. Additionally, it also has a higher resolution age model.

Linear Sedimentation Rates:

The linear sedimentation rates were calculated for every centimetre using the age-depth model above. These were then binned every 10 cm.

Mass Accumulation Rates:

Terrigenous and Biogenic mass accumulation rates (MARs) were calculated using the formula below:

$$MAR = \%X * (LSR * BD)$$

MAR=mass accumulation rate (g/cm^2/yr)
LSR=linear sedimentation rate (cm/yr)
X=the percent abundance of the component of interest (i.e. terrigenous or biogenic)
BD=bulk density (g/cm^3)

Shipboard bulk density measurements were not collected on U1357B, which was preserved as whole-round sections until the post-expedition sampling party several months after collection. Moisture and density (MAD) bulk densities from core U1357A cores (collected at the same site location) were used instead, with a linear fit taken though these data to derive a downhole estimate of bulk density[63]. The associated depths of these discrete samples were converted to age using the U1357A age-depth model. This model uses 36 bulk organic carbon dates and demonstrates the age vs depth relationship using the same Bayesian approach used in the U1357B age model. A linear fit between the age and density measurements of U1357A was interpolated to the U1357B age scale to determine the densities for U1357B. Biogenic silica and terrigenous percentage were determined using alkaline extraction spectrophotometric methods[64].

Grain size analysis:

Grain size analysis was performed on 341 samples. Samples were treated twice with a 1M sodium hydroxide (NaOH) solution in an 80°C water bath for 24 hours to remove biogenic opal, and then treated with hydrogen peroxide (H_2O_2) to remove organic material. As terrigenous material formed a minor component of the bulk sediment, post treatment sample mass varied from ~0.035-0.8 g. Samples were measured on a Beckman Coulter LS 13 320 Laser Diffraction Particle Size Analyser (LPSA). Eighty-four sub-samples were taken after chemical treatment with NaOH and H_2O_2 to assess for reproducibility. Twelve samples were split into two subsamples and chemical treatment was performed on each subsample to test for biases relating to subsampling and chemical dissolution. Correlations calculated using a least squares regression between the original and repeat measurements were r^2=0.74 for the post chemical treatment replicates and r^2=0.75 for the pre-chemical treatment replicates.

Computed Tomography Scans

X-ray Computed Tomography (CT) scanners quantify the amount of X-ray energy absorbed (attenuated) by a particular object and display the resulting attenuation coefficients in a greyscale image[65]. Pixel values within these images are expressed as greyscale values or Hounsfield units (HU) (also known as CT number) which are calculated by comparing the sample attenuation coefficient to that of water[15].

X-ray attenuation is a function of density, porosity, chemical composition, and grain size of the sample[66]. Brighter areas in the image represent higher attenuation, while darker areas represent lower attenuation. CT scans were completed on Core U1357B using a Toshiba Aquilion TXL CT scanner at the Department of Petroleum Engineering at Texas A&M University. Axial scans were completed at 135 kVp and 200mA, and coronal slices were created in open-source HOROS software[67]. The resolution averages 1.3 pixels per mm, and each core was exported as its own DICOM image stack which contained 512 images. From there, the best image (e.g. accounting for cracks and other spaces in the core) from each stack was selected and exported to another CT processing software, FIJI[68], for greyscale analysis and laminae counting.

HBI/Isoprenoid/$IPSO_{25}$ Data:

$IPSO_{25}$ (for Ice Proxy for the Southern Ocean with 25 carbon atoms) is another name for the Highly Branched Isoprenoid (HBI) lipid biomarker (diene II). The C_{25}-highly branched isoprenoids (HBI) alkenes, in particular the di-unsaturated C_{25}-HBI with a double bond, also referred to as diene, were extracted at Laboratoire d'Océanographie et du Climat:

Experimentations et Approches Numériques (LOCEAN), using a mixture of 9mL CH_2Cl_2/MeOH (2:1, v:v) to which internal standards (7 hexyl nonadecane, 9 octyl heptadecene and androstanol) were added; several sonication and centrifugation steps were applied in order to properly extract the selected compounds[69]. After drying with N_2 at 35°C, the total lipid extract was fractionated over a silica column into an apolar and polar fraction using 3 mL hexane and 6 mL CH_2Cl_2/MeOH (1:1, v:v), respectively. HBIs were obtained from the apolar fraction by the fractionation over a silica column using hexane as eluent following the procedures reported by refs.[70,71]. After removing the solvent with N_2 at 35°C, elemental sulfur was removed using the TBA (Tetrabutylammonium) sulfite method[72,73]. The obtained hydrocarbon fraction was analysed within an Agilent 7890A gas chromatograph (GC) fitted with 30m fused silica Agilent J&C GC column (0.25 mm i.d., 0.25 μm film thickness), coupled to an Agilent 5975C Series mass selective detector (MSD). Spectra were collected using the Agilent MS-Chemstation software. Individual HBIs were identified on the basis of comparison between their GC retention times and mass spectra with those of previously authenticated HBIs (e.g. ref [74]) using the Mass Hunter software.

IMAGE ANALYSIS

Greyscale Curve

Any pixel value less than zero was converted to non-values (NaNs) by thresholding the images in FIJI[68]. This eliminated noise from pervasive sub-mm to mm-scale cracks resulting from expansion due to biogenic gas in the cores (Extended Data Fig.4).

A single greyscale curve was created by taking a line profile of the greyscale image for each core. The line profile was 4 pixels wide, with the pixel value of each row being the average of these four pixels. The profile was chosen to minimize core disruptions. Many CT-studies choose to average all rows along the whole width of the image, but this was not possible due to the middle of this core having previously been sampled using U-Channel methods, and due to dipping of the laminae along the core liner. These image curves were then corrected for any depth offset introduced by the core liner and CT machine, and concatenated into a final data set.

Laminae Counts

The top and bottom of bright laminae were picked manually throughout the entire core. Some laminae had sharp divisions between bright and dark pixels, while others had a gradual transition. In addition, some bright laminae were interspersed among a slightly lighter background, making it difficult to distinguish between multiple laminae and single events. We counted such intervals as a single lamina, and suggest these could represent seasons when there were multiple blooms or prolonged bloom events. Visual picking of the laminae can be subjective, but was preferred over automated methods due to noise produced by gas expansion cracks, which varied core-to-core. To assess this subjective aspect, laminae picks were visually overlain on the greyscale curve to evaluate consistency throughout the length of the core (Extended Data Fig. 4). Some laminae were disrupted by cracks. We manually removed the laminae disrupted by several centimetres or more, but these accounted for less than 0.1% of laminae. Laminae were binned into 10-year intervals (Figure 3, Figure 4). For bins that contained a missing interval, i.e. the base of a 9.5 m core run where recovery was <100%, the binned laminae amounts were scaled to represent the actual number of years per bin. For the scaled 10-year bins, seven data points were removed because the bins contained fewer than 2 years of data. Comparison of the manually-picked laminae with evolutionary spectra of the raw greyscale curve and Si/Ti values from XRF linescan data was conducted to independently verify the frequencies identified (Figure 4).

Evolutionary Spectral Analysis

Prior to analysis, the greyscale data was interpolated to 0.1 year (from an average spacing of 0.041 year) and the XRF data were interpolated to 0.4 years (from an average timestep of 0.44

years), using a piecewise linear interpolation. Evolutive Harmonic Analysis (EHA) using the Thomson Multitaper method to determine power spectra was performed in the R package Astrochron[75] using both the XRF and CT greyscale data. Outliers were removed from the series using the 'Trim' function in Astrochron which uses a boxplot algorithm with a coefficient of 1.5 to identify values greater than or less than 1.5 times the interquartile range from quartile 3 and quartile 1, respectively. For EHA on the CT greyscale data, an MTM time-bandwidth product of 4, window width 100 years, and step size of 20 years was used. For the lower resolution XRF data, an MTM time-bandwidth product of 3, window width of 70 years, and step size of 10 year was used. Resulting spectra were seen to be relatively insensitive to window width and step size and time series analysis on other XRF productivity proxies (Ba/Ti, Si/Al) yielded similar results. In all datasets analysed, power was normalized so that maximum power in each window is unity.

The manual laminae counts, binned into 10-year intervals were then overlain on the EHA results and show consistent centennial-scale shifts in the power of the 2-7 years frequency bands. This indicates binned laminae frequencies are representative of the EHA results and are able to capture higher frequency variations in bloom events.

X-ray Fluorescence

X-ray Fluorescence data were measured using an AVAATECH XRF core scanner at the JRSO XRF facility, located at the Gulf Coast Repository at Texas A&M University Research Park. Measurements were undertaken at a 0.5 cm resolution (where possible) with a 5mm slit size using generator settings of 10 kV and currents of 0.8 mA. The sampling time was set at 45 s and scanning took place directly at the split core surface of the archive half. The split core surface was covered with a 4-micron thin SPEXCerti Prep Ultralene1 foil to avoid contamination of the XRF measurement unit and desiccation of the sediment.

Biogenic silica concentration in sediments (%BSi) are commonly used as an indicator of past diatom and radiolarian productivity in high latitude marine sediments (e.g. refs.[76,77]). Silicon (Si) is the main component of biogenic opal and Si-based ratios are commonly used as %BSi proxies[78]. Estimating %BSi from Si content or Si-based ratios obtained by XRF-Scanner require site-specific calibration, but comparison with the Si/Ti ratio shows almost parallel distribution with %BSi records as function of depth (e.g., ref.[78]). Nevertheless, use of Si as productivity proxy should be applied with caution, because Si can also be controlled by siliciclastic material during low productivity periods, even in polar regions[79] and light elements, such as Si or Al, have low detectability by XRF-scanner measurements when present in low concentrations[80].

Site U1357B is a laminated diatom ooze. Diatom content estimated from smear slides have a mean of 91% (ref.[63]). %BSi content in this study ranges from 30 to 63% with an average of 48 %BSi for the late Holocene. Si detection by the XRF-Scanner is not an issue, as the average Si peak area is ~200,000 counts. In any case, the high opal content masks Si input related to siliciclastic material. To correct dilution effect and obtain a first-order discrimination between biogenic and detrital Si we normalized Si to Ti. This normalization assumes that Ti is a conservative element associated only with the terrigenous fraction and Si/Ti ratio of the terrigenous matter remains almost constant over the period studied. We use the obtained Si/Ti ratio as a semi-quantitative record of the siliceous productivity in agreement with previous studies that use Si/Ti or equivalent ratios as a productivity proxy both in marine[81,82] and lacustrine records[83,84].

Correlation analysis between Laminae counts, Biogenic MAR and Sand Percent

Laminae counts, Biogenic MAR, and sand percent were linearly interpolated to a common 100-year step. Regression statistics were calculated from10,050 BP onwards, as the glaciated environment prior to this time is not representative of current relationships.

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