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Late Eocene to early Oligocene productivity events in the proto-Southern Ocean as drivers of global cooling and Antarctica glaciation

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Abstract. The Eocene-Oligocene transition (ca 40-33 Ma) marks a transformation from an ice free to an ice-house climate mode that is well recorded by oxygen stable isotopes and sea surface temperature proxies. Opening of the Southern Ocean gateways and decline in atmospheric carbon dioxide have been hypothesised as possible triggers of the major climate shift during the Cenozoic. However, the identification of the driving mechanisms remains controversial and it depends on a better understanding of how the different environmental changes correlate to each other. In this study, we investigate the spatio-temporal variation in export productivity using biogenic Ba (bio-Ba) from different Ocean Drilling Program (ODP) Sites in the Southern Ocean, focusing on possible mechanisms that controlled them as well as correlation of export productivity changes to changes in the global carbon cycle. We document two significant SO region high export productivity late-Eocene events (ca. 37 and 33.5 Ma) that are correlated to pronounced changes in global atmospheric pCO_2. We propose that paleoceanographic changes that followed Southern Ocean gateway openings, along with more variable increases in circulation driven by episodic expansion and decline of the Antarctic ice sheet, drove enhanced SO export production in the late Eocene through basal Oligocene. These factors may have driven the episodic reduction of atmospheric carbon dioxide and contributed to Antarctic glaciation during the Eocene-Oligocene transition.

1 Introduction

1.1 The late Eocene Events as Precursor to Antarctic Eocene/Oligocene Boundary Glaciation

The Eocene-Oligocene transition (EOT, ~ 40-33 Ma) is the most important climatic interval of the Cenozoic era (Kennett, 1977; Miller et al., 2009). This interval involves profound transformations in environmental conditions including the onset of continental-scale Antarctica glaciation at the Eocene-Oligocene boundary (Shackleton & Kennett, 1975, Zachos et al., 1996, Coxall et al., 2005), sea-level fall (Houben et al., 2012) and global cooling (Prothero and Berggren, 1992; Liu et al., 2009; Bohaty et al., 2012; Hutchinson et al., 2021) as evidenced by a global shift in oxygen isotope records from biogenic calcium carbonate (>1‰; Zachos et al. 2001; Coxall et al. 2005; Bohaty et al., 2012; Westerhold et al., 2020). A positive deep-sea carbon isotope excursion of up to 1‰ (Zachos et al., 2001, Coxall et al,. 2005; Coxall and Wilson, 2011; Westerhold et al., 2020) and a change from a shallow (~3.5 km) to a deeper (~4.5 km) calcite compensation depth (CCD) (Coxall et al., 2005; Rea and Lyle, 2005; Pälike et al., 2012; Dutkiewicz and Müller, 2021; Taylor et al., 2023) have also been observed and indicate that the carbon cycle played an important role in the

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changes observed during the transition, although the mechanisms that caused the carbon cycle perturbation are still unsolved.

Carbon cycling acts through a variety of feedback mechanisms. Even though it is well recognized that changes in atmospheric carbon dioxide (CO_2) impact the Earth's climate because of its large effect on temperature (Arrhenius, 1896; IPCC, 2021), the mechanisms controlling CO_2 over long timescales are still a matter of debate. The carbon cycle perturbation at the EOT provides an opportunity to understand climate-carbon cycle feedback (Zachos and Kump, 2005). The mechanisms proposed to explain such perturbations are processes operating gradually over long timescales, and thus likely to have had their origins around the middle to late Eocene.

Preceding the abrupt change at the E/O boundary, the late Eocene was a period of gradual cooling and progressive CO_2 decrease (Lauretano et al., 2021). The events associated with this time period may have had substantial importance to trigger the major climatic shift at the E/O boundary. The potential main drivers for the initiation of this global cooling and ice build-up in Antarctica are actively debated. Declining global atmospheric carbon dioxide concentrations, and the opening of Southern Hemisphere oceanic gateways, namely the Drake Passage (DP) and the Tasmanian Gateway (TG), are the two main proposed hypotheses to explain this transition (Coxall and Pearson, 2007; DeConto et al. 2008). The decline of carbon dioxide levels are an important factor in driving cooler temperatures, and have been suggested as the crucial factor in the EOT cooling and subsequent build-up of continental glaciers on Antarctica (DeConto and Pollard, 2003; Huber and Nof, 2006; Pagani et al., 2011). Atmospheric CO_2 partial pressure (pCO_2) decline has observational support during the E/O boundary by independent proxies, showing levels falling below 800 ppm (Pearson, 2009; Pagani et al. 2011; Zhang et al., 2013; Anagnostou et al. 2016), although data is sparse and thus details of the magnitude and timing are still unclear. Atmospheric pCO_2 has shown to decline through the Eocene, from ca 2000 ppm in the Middle Eocene (Bijl et al., 2010) to ca. 1000 ppm in the latest Eocene (Pearson et al., 2009). While pCO_2 reconstructions have advanced, there is marked variation between different proxies and the absence of tighter constraints on causative mechanisms requires further investigation of the carbon-climate interactions.

The tectonic opening of the Southern Ocean gateways is considered a trigger mechanism of the climatic shift because it allows the initiation of the Antarctic Circumpolar Current (ACC) (Kennett, 1977; Barker, 2001; Scher and Martin, 2006; Toumoulin et al. 2020). This intense eastward flowing current is proposed in this hypothesis to impact the regional and global climate by preventing tropical heat of low latitudes from reaching Antarctica, promoting the thermal isolation of Antarctica (Kennett and Shackleton, 1976). Numerous ocean circulation model studies of this hypothesis have yielded conflicting results (De Conto & Pollard, 2003; Goldner et al., 2014; Inglis et al., 2015; Ladant et al., 2014; Mikolajewicz et al., 1993; Najjar et al., 2002; Sijp et al., 2009) but most of these earlier works were limited by unrealistic boundary conditions or other issues (Toumoulin et al., 2020, Hutchinson et al., 2021). Recent modelling circulation studies (e.g. Toumoulin et al., 2020; Sauermilch, et al. 2021) demonstrate the importance of the Southern gateway openings and the proto-ACC on ocean cooling in the Southern Hemisphere. Additionally, glaciation has itself a strong influence both on the circulation of the Southern Ocean and on global climate, via increased albedo, colder temperatures and increased latitudinal temperature gradients, and stronger zonal winds (Goldner et al., 2014). There is increasing evidence for at least partial, if transient Antarctic continental glaciation within the late Eocene (Scher and Martin, 2014), and thus this also needs to be considered in understanding how climate and ocean change developed within this period.

Moreover, the ACC is associated with the development of fronts that contribute to upwelling-induced biological productivity (Chapman et al., 2020). Considering that the changes in the Southern Ocean circulation have the potential

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to affect export productivity and the role of export productivity in removing pCO_2 from the ocean-atmosphere system, the 'CO_2' hypothesis and the 'tectonic' hypothesis may be linked, via the influence that gateways may have had on Southern Ocean circulation, increasing export productivity enough to affect global pCO_2. Therefore, evaluating export productivity patterns in the Southern Ocean across the Eocene-Oligocene and its relationship with circulation and decline of atmospheric carbon dioxide during this time period provide important information about the climate feedback in this prominent climatic transition.

Many studies have shown variations in biological productivity at this time interval (Diester-Haass, 1995; Diester-Haass and Zahn, 1996; 2001, Salamy and Zachos, 1999; Diester-Haass and Zachos, 2003; Schumacher and Lazarus, 2004; Anderson and Delaney, 2005; Villa et al., 2014), pointing towards a productivity increase associated with ocean circulation changes that increased surface water nutrient availability (Diester-Haass 1992; Zachos et al 1996). However, existing studies have mostly focused on a single site, whose paleoceanographic history may reflect local rather than regional developments. A much broader spatial investigation is particularly important for understanding the influence of large-scale ocean circulation on this process. Moreover, the timing of productivity changes differs among the studies and different proxies, limiting our understanding of cause-and-effect relationship, therefore, highlighting the importance of constrained age models and consistent paleoproductivity proxy.

Here, we reconstruct the changes in export productivity across the late Eocene and early Oligocene, and evaluate how the changes observed may be linked to ocean circulation changes and contributed to the climate changes observed at this interval. We utilize biogenic barium (*bio*-Ba) accumulation rates to measure marine export productivity. *Bio*-Ba is defined as the fraction of total barium that not associated with terrigenous sources, sometimes referred as *excess*-Ba (Dymond et al., 1992), it has been applied in several studies in the Paleogene (eg. Nielsen et al., 2003; Anderson and Delaney, 2005; Faul and Delaney, 2010), and is considered a relatively reliable proxy to estimate changes in paleoproductivity in the Southern Ocean. Newly generated carbon and oxygen stable isotope records from the same samples of our *bio*-Ba data constrain the question of the causative mechanisms for the climatic shift at the EOT. We compare our export productivity proxy results to indicators of ocean circulation change, including how these changes correspond with gateways opening, paleoceanographic changes, ice sheet history, and their influence on marine biological productivity. We also compare our productivity records to proxies for the global carbon cycle, specifically pCO_2 and $\partial^{13}C$ of benthic deep sea foraminifera. Advancing our understanding of the cause of this event is crucial in identifying the mechanisms governing global climate change.

Although much of our understanding of the Eocene-Oligocene transition has been achieved through modelling studies as they provide means to compare several possible scenarios, this paper focuses on proxy evidence of the changes that occurred in this time interval. Our multiproxy approach and wide coverage allow us to test the hypotheses:

H1: Changes in ocean circulation patterns that took place during the late Eocene and early Oligocene (eg. development of ACC and strengthening of AMOC) contributed to the increase in biological productivity in the Southern Ocean.

H2: The magnitude of the export productivity increase during a time period that preceded the EOT may have been an important contribution to the drawdown of pCO_2.

First, we investigate the export productivity changes across the late Eocene to early Oligocene in two different regions in the Southern Ocean. Then we compare our results to the paleo-circulation changes that occurred at the same time period. We conclude by summarising the implications of the changes in ocean circulation and the possible climate driving mechanisms that led to the cooling of Earth.

1.2. Paleoceanographic Setting

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The Southern Ocean (SO) today is an important part of the global ocean circulation and climate system, interconnecting the Atlantic, Pacific and Indian Ocean basins, providing and thus inter-basin exchange of ocean properties and heat. There are strong latitudinal gradients and seasonal changes in ocean properties which affect surface water and export productivity, and thus this region's role in global carbon capture and sequestration. Low light levels and, in higher latitudes, extensive sea ice limit productivity during the winter months. Deep surface mixed layers over the large areas of the Southern Ocean, beyond the shallow stratification effects of meltwater near the sea ice edge, also tend to limit productivity in spring through fall as plankton is mixed below critical thresholds of light availability. The relationship between mixed layer thickness and productivity however is complex (Nelson and Smith, 1991; Li et al. 2021). Southern Ocean productivity is thus concentrated near the Antarctic Circumpolar Current (ACC), the dominant current in the region. This current is the longest and strongest ocean current on Earth. This complex circulation system is driven mainly by westerly winds, resulting in Ekman transport and favouring deep water upwelling. This flow pattern is possible in the absence of land barriers and is balanced by bottom topography friction (Rintoul et al., 2001; Carter et al., 2008), while the strength of the current is driven by the strength and location of the westerly winds, and thus, among other factors, the global latitudinal thermal gradient. The ACC is a key component of the 'ocean conveyor belt', playing a role in the global transport of heat (Katz, et al. 2011). Moreover, this circumpolar current influences the strength of meridional overturning circulation and several authors have proposed that this current is one of the main drivers of the Atlantic meridional overturning circulation (AMOC) (Toggweiler and Samuels, 1995; Toggweiler and Bjornsson, 2000; Scher and Martin, 2006, Kuhlbrodt et al., 2007, Scher et al., 2015, Sarkar et al., 2019).

The ACC is structured of multiple hydrological fronts, associated with specific water mass properties such as temperature and salinity (Sokolov and Rintoul, 2009). Orsi et al., 1995 were the first to propose the traditional view of Southern Ocean fronts. It consists of the Subantarctic Front (SAF), the Antarctic Polar Front (APF) and the Southern ACC Front (SACCF). Besides these main fronts, a Subtropical Frontal Zone (STFZ) can be found north of the ACC (Orsi et al., 1995; Palter et al. 2013; Chapman 2020). This frontal structure is fundamental to different processes that occur in the region, such as the distribution of important nutrients through the exchange between deep and surface ocean, and the exchange of tracers (Palter et al., 2013). Upwelling of Circumpolar Deep Water (CDW) brings nutrient-rich waters to the surface towards the Polar Front Zone (PFZ) where Antarctic Surface Waters (AASW) sink to form Antarctic Intermediate Water (AAIW), thereafter it extends into the Subantarctic Zone (SAZ) (Sarmiento et al., 2004) (Figure 1).

Wind-driven upwelling, that occurs within the Southern Ocean fronts, enhance biological productivity in these regions (De Baar et al., 1995; Moore et al., 1999). More recently, upwelling related to ACC bathymetry has been found as an important mechanism for establishing phytoplankton blooms in the SO (Sokolov and Rintoul, 2007). This complex structure involving ACC fronts, westerlies and the bottom topography, makes the Southern Ocean a highly productive region. Iron remobilisation has also been shown to occur due to latitudinal variations of the ACC (Kim et al., 2009), hence inducing a massive increase in productivity.

During the Cenozoic, the ACC structure began to develop with the opening of the pathways between South America and Antarctica and the following formation of the Drake Passage (DP) and, also between Australia and Antarctica that allows the Tasmanian Gateway (TG) opening. Removing these geographic barriers permitted the gradual development of circumpolar flow (Toggweiler and Bjornsoon, 2000). The TG opening to intermediate and deep waters occurred in the late Eocene, ca 35.5 Ma (Stickley et al., 2004). Tectonic reconstructions for the Drake Passage timing opening remain controversial, ranging from the late Eocene (ca 41 Ma; Scher and Martin, 2004, 2006) to the early Miocene (ca

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23 Ma, Barker 2001). Even if the timing of the deepening of the Drake Passage is less well constrained, a “proto-ACC” has been proposed as an earlier expression of the ACC and it is defined as a shallow-depth circumpolar current (Scher et al., 2015, Sarkar, et al., 2019). Cramer et al. 2009 suggested that “proto-ACC" would have played an important role in the ocean circulation changes that occurred in the Eocene.

Many climate model studies have contributed with insights into the ocean structure and circulation of the late Eocene (e.g. Huber et al. 2004, Huber & Not 2006, Sipj et al., 2011, Sijp et al., 2016, Elsworth et al., 2017, Baasten et al, 2020, Toumoulin, et al., 2020). Although some of these experiments have shown that opening of gateways was not sufficient to have caused the global cooling recorded by proxies (DeConto & Pollard, 2003, Huber et al. 2004, Huber & Not 2006, Sipj et al., 2011, Baasten et al., 2020), they acknowledge that the circulation patterns have changed during the Eocene. A recent model circulation experiment has demonstrated the impact of the DP opening and its effects on ocean structure and dynamics even for shallow depths (Toumoulin et al., 2020).

The organisation of Southern Ocean proto-oceanic fronts may have occurred during the Eocene and formed poleward (proto-PF: <~70–60°S; proto-STF: 65–50°S) of their present-day positions, progressing to lower latitudes during the Oligocene and Miocene (Lazarus and Caulet, 1994; Nelson and Cooke, 2001; Cooke et al, 2002). This frontal zone migration likely played a role in major changes at that time period, including higher ocean productivity.

Evidence of significant events during the late Eocene highlights the importance of this period that preceded the permanent glaciation in Antarctica. Increasingly heavy global benthic oxygen isotope values in the late Eocene, at ca 37 Ma have been interpreted to reflect pre-EOT glaciation and cooling, this episode is referenced as PrOM event (Priabonian Oxygen isotope Maximum, Scher et al., 2014). Additional evidence for a prominent cooling episode has been found during this time period (Anderson et al., 2011, Douglas et al., 2014). Despite uncertainties about the nature and extent of the earliest ice in Antarctica, these changes imply that paleogeographic reconfiguration has affected the late Eocene Antarctic climate. It is clear that some combined processes favoured the development of permanent glaciation in Antarctica.

Given the importance of changes during the Eocene-Oligocene time interval, especially the ACC development and its frontal structure to the climate system and ecosystems, it is crucial to investigate the timing and magnitude of late Eocene paleoceanographic changes in the Southern Ocean, and equally important to expand our understanding of the implications of such changes on paleoproductivity and how these mechanisms are linked to a changing climate.

2 Materials and Methods

2.1 Site Descriptions

We investigated sediment samples from 3 Ocean Drilling Program (ODP) Sites in the Southern Ocean (Table 1). ODP Leg 177 Site 1090 on the southern flank of the Agulhas Ridge in the Southern Atlantic Ocean (42°54.8’S, 8°53.9’E, water depth 3,702m), ODP Leg 133 Site 689 on Maud Rise in the Southern Atlantic Ocean (64°31’S, 3°6’E, water depth 2,253m) and ODP Leg 120 Site 748 on Kerguelen Plateau in the Southern Indian Ocean (58°26.45’S, 78°58.89’E, water depth 1,290.9m). We selected samples from the middle Eocene through the E-O boundary, depending on the sample availability.

Currently, the sites studied are located in the Southern Ocean through the ACC. Sites 689 and 748 are located in the south of the Polar Front zone (PFZ) and Site 1090 in the Subantarctic zone, between the Subtropical front (STF) and the Subantarctic Front (SAF) (Figure 1). Across the Eocene-Oligocene transition, the sites were shallower (Table 1). Sites

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689 and 748 locations were similar to today and site 1090 was as much as 5° farther to the south (Gersonde et al., 1999) (Table 1).

The major lithology from the lower Eocene to the upper Oligocene at the Maud Rise is composed of calcareous and silicious oozes (Barker et al., 1988). Kerguelen Plateau site is composed mainly of nannofossil ooze and chert (Barron et al., 1989). Agulhas Ridge is predominantly composed of diatoms and nannofossil ooze, with $CaCO_3$ wt% highly variable, ranging from non-detectable to 69% of sediment throughout the study interval. (Gersonde et al., 1999) with rare occurrences and barren intervals of planktic and benthic foraminifera making it difficult to establish stable isotope records on this site.

Table 1. Position of the ODP Sites studied in the present-day and in the late-Eocene (~ 37 Ma). Paleocoordinates calculated based on Seton et al. (2012) rotation model.

Site	Geographic Setting	Latitude	Longitude	Water depth (m)	Paleodepths (m)	Paleo-latitude	Paleo-longitude
1090	Agulhas Ridge	42°54.8'S	8°53.9'E	3 702	ca. 3,000-3,300 (Pusz et al. 2011)	ca 47°33'S	ca 1°46.8' E
689	Maud Rise	64°31'S	3°6'E	2 253	ca. 1500 (Diester-Haass and Zahn, 1996)	ca 64°19.2'S	ca 2°43.2' E
748	Kerguelen Plateau	58°26.45'S	78°58.89'E	1 290.9	ca. 1200 (Wright et al., 2018)	ca 56°48.6'S	ca 75°36' E

2.2 Age Models, Linear Sedimentation Rates

Revised age models for the ODP Site 1090, ODP Site 689 and ODP Site 748 in this study were based on all magnetostratigraphic and biostratigraphic data available on the Neptune database via NSB system (Renaudie et al., 2020) (Figures S1-S4). All ages in our study are given in the Gradstein et al. (2012) GPTS scale, or have been remapped to this scale from prior studies.

ODP Site 177 1090 has an age model constructed from shipboard magnetostratigraphic data "U-channel", the records fit the geomagnetic polarity timescale (GPTS) (Channell et al., 2003). Nannofossil biostratigraphy has confirmed the Chron ages (Marino and Flores, 2002), as well as foraminiferal biostratigraphy (Galeotti et al. 2002), strontium isotopes (Channell et al., 2003) and oxygen and carbon isotope data from benthic foraminifera (Zachos et al., 2001, Billups et al., 2002). This integration of several age indicators and their consistency makes this a robust and very well constrained age model.

Magnetostratigraphic data for ODP 113 Site 689 is partially reinterpreted from the measurements originally made by Spiess, 1990. A new high-resolution study of Eocene-Oligocene "U-channel" samples from this site presents high correlation with the GPTS (Florindo and Roberts, 2005). Ocean calcareous nannofossil datums (Wei and Wise, 1992; Wei, 1992, Persico and Villa, 2002, 2004), planktonic foraminiferal datums (Kennett and Sott, 1990; Thomas, 1990; Berggren et al., 1995) and Argon-argon ($^{40}Ar/^{39}Ar$) dating (Glass et al., 1986; Vonhof et al., 2000) is used to re-calibrate ages for this site.

A high-resolution magnetostratigraphic study from ODP Site 748B was carried out by Roberts et al. 2003 in continuous "U-channel" samples, revising the shipboard analysis from Inokuchi and Heider, 1992. Calcareous nannofossils

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biostratigraphy (Aubry 1992), planktonic foraminiferal biostratigraphic datums (Berggren et al., 1995), diatom datums (Baldauf and Barron, 1991, Roberts et al., 2003) and strontium isotopes ages (Zachos et al., 1999; Roberts et al., 2003) were re-evaluated for a better age model.

Accumulation rate fluxes are obtained by calculating the product of linear sedimentation rates (LSR) and shipboard measured dry bulk densities (DBD), thus a robust age model is crucial for this calculation because it determines the linear sedimentation rates. We present data using a straightforward LSR calculation between age-depth control points based on magnetostratigraphic data, stable isotopes and biostratigraphic data. Mass accumulation rates (MARs, mol cm^{-2} kyr^{-1}) were calculated using LSR based on the above age models multiplied by DBD.

Since bio-Ba AR is a direct function of LSR, it is essential to evaluate any possible influence. Figure S5 shows a comparison of linear sedimentation rates and bio-Ba AR. This comparison showed a high amplitude peak at ODP Site 1090, with LSR of 4.11 cm kyr^{-1} at the late Eocene, this high rate is based on a very constrained model. The LSRs for ODP Site 689 varies from 0.1 cm kyr^{-1} during early Oligocene to up to 1.3 cm kyr^{-1} in the late Eocene, whereas ODP Site 748 has more uniform values during late Eocene. Small adjustments to LSRs may result in large changes in MARs, emphasising the importance of very well constrained age models. The available age data for our sites allow some variation in the placement of the line of correlation, and thus the precise timing and magnitude of sedimentation rate changes on the scale of ± ca.5 m.y. are not well constrained, patterns and calculated values over longer time scales are thought to be robust.

2.3 Stable Isotope Analyses

Stable isotopes of carbon and oxygen were measured both on the bulk fine fraction (<45µm) and benthic foraminifera. Bulk sediments were oven-dried and washed through different sieve sizes (125 and 45µm). Smear slides observations indicate that the main carbonate composition of the fine fraction is coccoliths, therefore stable isotopic compositions of bulk fine fraction (<45 µm) reflect primary nannofossil isotope signals. Contamination by non-coccolith carbonate such as fragments of foraminifera shells is minimal (Figure S5). Fifteen to twenty tests of benthic foraminifera (*Cibicidoides* spp.) were picked from the >125-µm-size fraction. Foraminiferal tests were ultrasonically cleaned using ethanol and oven-dried. Stable isotopic analyses were carried out at the Stable Isotope Laboratory of the Museum für Naturkunde (Berlin, Germany) on a Thermo Isotope Ratio Mass Spectrometer. All values are reported in the δ-notation in parts per mil (‰) relative to the Vienna Pee Dee Belemnite (VPDB). In this study, we applied an adjustment of +0.64‰ (Shackleton and Opdyke, 1973; Shackleton et al., 1984) to all $\delta^{18}O$ values of the benthic foraminifera *Cibicidoides* to account for disequilibrium effects.

2.4 Barium Analyses and Biogenic Barium as a Paleoproductivity Proxy

Barium (Ba) and aluminum (Al) were analysed by ICP OES, performed at the ElMiE Lab at the German Centre for Geosciences (GFZ, Potsdam, Germany) using a 5110 spectrometer (Agilent, USA). The analytical precision and repeatability were generally better than 2% and it is regularly tested by certified reference material and in-house standards. For preparation, 2g of each sample were grounded and dissolved with ultra-pure HCL. Intensity calibration was performed by external calibration using the same batch of solvent to ensure matrix matching. The analytical blank was negligible compared to the sample concentration.

Using barium as a paleoproductivity proxy requires some adjustments because other biogenic sources may contribute to the barium content in the sediment. Detrital aluminosilicate may affect the barium signal in Southern Ocean sediments.

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In order to solve this issue and reveal aluminosilicate contributions, the Biogenic Barium calculation was proposed by Dymond et al., 1992, following Eq (1):

Biogenic Barium (Bio Ba) = (Ba total) $_{\text{sample}}$ - (Ba/Al) $_{\text{bulk continental crust}}$ x Al $_{\text{sample}}$ (1)

This assumes that the aluminum (Al) concentration and the average continental crust abundance are representative of the detrital Ba component. The Ba/Al crust ratio of 0.0075 is the global average value from sedimentary rocks as suggested by Dymond et al. (1992). This value is based on various compilations of elemental abundances in crustal rocks. This normative calculation potentially introduces uncertainty in samples with high and variable detrital barium, but considering that clay assemblages and weathering regimes were relatively constant during the early Paleogene in the Southern Ocean, therefore, the crustal ratio probably did not vary much (Robert et al. 2002).

2.5 Data Compilation

2.5.1 Neodymium Isotope Data

Neodymium isotopes in seawater reflect the different weathering sources of neodymium that affects each water mass. The isotope values act as conservative elements during ocean mixing. They are therefore a robust water mass tracer, and further are faithfully archived in sediments (Piepgras and Wasserburg, 1982; Martin and Haley, 2000). Their behaviour in seawater and the conservation of the signal in sediments make them a valuable proxy for paleoceanographic studies and past ocean circulation reconstruction. Fossilised fish teeth is commonly used and are considered robust archives to extract Nd isotopic signature because they incorporate and preserve their Nd signature during very early diagenesis (Martin and Scher, 2004), and they can be found in deep-sea sediment samples all over the world and in many geologic time intervals. The Nd signal is given in εNd, where εNd is the ratio $^{143}Nd/^{144}Nd$ of a sample relative to the same of the bulk Earth, in parts per 10,000.

In this study, we compiled published Nd isotope data from fossil fish teeth, from the same Ocean Drilling Program (ODP) sites that we investigated in the Southern Ocean (ODP Site 1090 Agulhas Ridge, ODP Site 689 Maud Rise and ODP Site 748 Kerguelen Plateau) and explore the Nd isotope variability to examine the intrusion of waters from the Pacific to the Atlantic sector of the Southern Ocean. We then used these data and our records to explore the evolution of the Southern Ocean circulation and significant circulation changes across the Eocene-Oligocene transition. Sources of Nd isotope data are given in Table S1.

2.5.2 $p\mathrm{CO_2}$ Data

A variety of geological proxies have been applied to reconstruct the partial pressure of atmospheric CO_2 ($p\mathrm{CO_2}$) during the Cenozoic Era (Pearson & Palmer, 2000; Pagani et al., 2005; Beerling & Royer 2011). Given the low sampling density through the critical Eocene-Oligocene interval, we compiled published $p\mathrm{CO_2}$ data from marine and terrestrial proxies that have been identified as reliable for reconstructing $p\mathrm{CO_2}$ in the Cenozoic. The marine geochemical proxies include alkenone-based estimations, carbon and boron isotope ($\delta^{11}B$) composition of well-preserved planktonic foraminifera calcite. Proxies from the terrestrial reservoir include paleosol carbon and stomatal density. Our atmospheric CO_2 compilation (Table S2) consists to our knowledge all the currently available proxy data on most recent Eocene and Oligocene $p\mathrm{CO_2}$ records. Such compilations are commonly used to estimate past $p\mathrm{CO_2}$, although it is known that there are limitations and variation among them (IPCC, 2021). Zhang et al. (2013) specifically argued that

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compositing limited, short time interval data from different proxies, and different localities may introduce substantial bias into the resulting fitted curve, and instead generated a 40 My long history of Cenozoic pCO_2 from a single section (Site 925 in the equatorial Atlantic). We consider this study's results to be the best single source of information on the history of atmospheric pCO_2. However, precisely because of the substantial amounts of between proxies and between locality variation, data using a single proxy, from a single site is also potentially not representative of global pCO_2 history. We thus use both the single site results of Zhang et al. (2013) and the full, multi-site and multi-proxy compilation (Supplementary material) in evaluating our own study's results.

3 Results

3.1 Biogenic Barium

Biogenic Barium accumulation rate (bio-Ba AR) records (Figure 2) show a pronounced rise in the late Eocene when the values were up to twice as high as in previous periods for all sites studied. At Kerguelen Plateau ODP Site 748, we also observe a previous and smaller increase around the middle Eocene Climatic Optimum (MECO, ca 40 Ma). At Maud Rise the increase began at ca 38.3 Ma and persisted for around 1.5 Myr. bio-Ba ARs show high value in the Agulhas Ridge at ca 36.8 Ma that is induced by a high sedimentation rate (Figure S5a). Although export productivity was higher (maximum values to about 16.8 µmol bio-Ba cm^{-2} ky^{-1}) at Maud Rise compared to the other sites -the Kerguelen Plateau reached maximum values of about 14.3 µmol cm^{-2} ky^{-1} and the Agulhas Ridge site 13.74 µmol cm^{-2} ky^{-1}, the records show a high degree of temporal correspondence in the late Eocene peak (ca 36.8 Ma). Bio-Ba values were low at all sites between ca 36 and 34.5 Ma. Between ca 34.5 Ma and ca 33.3 Ma, which includes the EOT interval, bio-Ba AR increased in both sites of the Atlantic Sector, but these increases were not very concurrent between the sites investigated. On the Agulhas Ridge, ODP Site 1090, the rise in bio-Ba (from 7.37 to 20.46 µmol cm-2 kyr^{-1}) is observed in the very latest Eocene (ca 34.3), just before the Oi-1 event. At Maud Rise, ODP Site 689, the increase is not observed until ca 1 Myr after, in the early Oligocene (maximum value 16.25 µmol cm^{-2} kyr^{-1} at ca 33.3 Ma). On the Kerguelen Plateau, ODP Site 748, the increase in export productivity registered by bio-Ba during the Oligocene is notably smaller than in the Atlantic sites, with values not higher than the low values observed during the Eocene.

Our bio-Ba results are in general concordant with the temporally more limited data obtained by prior studies of Southern Ocean sites (Anderson and Delaney, 2005, Site 1090; Diester-Haass and Faul 2019, Site 689) (Figure 2). However our results for Kerguelen Plateau Site 748 differ from those of Faul and Delaney, 2010 for nearby Site 738, where the latter estimate bio-Ba accumulation rates up to twice those obtained in our study of Site 748. The differences may be due to the different locations of the two sites, Site 738 is located several degrees further south, and in ca 1 km deeper water depth. The bio-Ba proxy is also very sensitive to sedimentation rates, and the differences may be due to the poor age control for Site 738 which in our studied time interval consists only of a few rather scattered biostratigraphic events (Figure S4a), which results in substantially different age models between our study, Faul and Delaney (2010), and other recent studies of this site, e.g. Huber and Quillevere (2005). In these studies the location and extent of hiatuses, and the uniformity of sedimentation rates varies considerably (SOM Figure S4b). The age model for Site 748 by contrast (Figure S3) is very well constrained by coherent biostratigraphic events from multiple groups of microfossils, Sr isotope stratigraphy and paleomagnetic stratigraphy, and we therefore accept the results from Site 748 as being more reliable.

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When the data for individual sites is composited together, the behaviour of the Southern Ocean region can be roughly estimated, even though our geographic coverage (lacking data from the Pacific/New Zealand sector) is incomplete and thus may not be entirely representative of the Southern Ocean as a whole. A lowess curve fit to the composited bio-Ba data shows that the key patterns noted in individual records are retained in the composite signal, and thus that Southern Ocean productivity can be characterised as having had two intervals of high values at around 37 and 34 Ma.

3.2 Oxygen and Carbon Isotopes

Our new oxygen (Figure 3C and E) and carbon (Figure 3D and F) stable isotope data allow us to identify previously noted trends and distinct events during the period studied. Benthic $\delta^{18}O$ values exhibit an overall increasing trend during the late Eocene indicating the overall decrease of oceanic bottom water temperatures. A sharp increase occurs at the Eocene-Oligocene transition (between 33.9 and 33.3 Ma) in both sites examined. This rapid shift has been observed in several sites in the Southern Ocean (e.g., Muza et al., 1983; Miller et al., 1987; Mackensen and Ehrmann, 1992; Zachos et al., 1996; Billups et al., 2002; Pusz et al., 2011) and it is well established as a global signal (Zachos et al., 2001). It is generally interpreted as a combination of deep ocean water cooling and major ice growth on the Antarctic continent (Zachos et al., 2001). At Site 689, the planktic $\delta^{18}O$ curve almost mimics the benthic one. The $\delta^{18}O$ values measured on fine fraction reveal a heavier trend more pronounced at ODP Site 748 (Kerguelen Plateau) compared to ODP Site 689 (Maud Rise). During the Eocene, heavier values are observed around 37 Ma in both Atlantic and Indian Sectors of SO. Both benthic and planktic foraminifera $\delta^{13}C$ records show fluctuations across the period studied, with low values across the Eocene-Oligocene boundary, followed by an increase that accompanied the $\delta^{18}O$ increase and low values again in the upper Oligocene. The benthic trend is also observed by previous data from the same sites (Mackensen and Ehrmann, 2002; Diester-Haass and Zahn, 1996; Bohaty et al., 2003). The fine fraction records show elevated $\delta^{13}C$ values between Late Eocene to Early Oligocene, followed by a decreasing trend during the Oligocene (from ca 33.2Ma). At Site 748, the fine fraction $\delta^{13}C$ curve shows less fluctuation than the benthic curves during the middle Late Eocene. A synchronous $\delta^{13}C$ increase (ca 0.6‰ shift) is observed at 36.5 Ma. Elevated fine fraction $\delta^{13}C$ values are observed from the late Eocene until the early Oligocene, coherent with previous studies (Bohaty et al., 2003), while the benthic values stay low during the same period (Figure 3D and F).

3.3 *p*CO_2 Proxies

As noted above, given the complexities and potential biases of compiling data from different proxies and different time intervals, we prefer to use the single site single proxy time series of *p*CO_2 from Zhang et al. (2013). This data (Figure 4) shows two peaks in the late Eocene, with a maximum for the entire study interval at ca 37 Ma and a smaller peak at ca 34.5 Ma, and a rapid drop of over 200 ppm from nearly 1000 to ca 750 ppm in the earliest Oligocene (ca 33.5 Ma). Despite the limitations of multi-proxy, multi-site compilations, the compiled data (Table S2; Figure S7) shows the same basic features, nor does the result appear to be sensitive to the precise choice of data to include in the analysis.

4 Discussion

4.1 Late Eocene Productivity Event and its Potential Impact

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The noticeable bio-Ba AR peak at ~ 36.8 Ma (Figure 2), suggests an important, ca 1 my long event of approximate doubling of export productivity during the late Eocene, preceding the significant cooling and the first formation of large Antarctic ice sheets at the Eocene-Oligocene boundary. The temporal synchronicity among different site locations in the Southern Ocean suggests that the process driving this enhanced export productivity in the late Eocene occurred throughout the Southern Ocean, requiring a mechanism that increased the delivery of nutrients to the surface ocean.

Our findings corroborate previous, more limited paleoproductivity studies that indicate an increase in export productivity in the Atlantic Sector of the Southern Ocean during this time period. Anderson and Delaney (2005) found several peaks in productivity indicators at the Agulhas Ridge during the same time interval, and benthic foraminiferal accumulation rates show an increase in paleo-primary productivity on Maud Rise (Diester-Haass & Faul, 2019) (Figure 2). A pronounced opal abundance peak is also documented by Diekman et al. (2004) between 37.5 and 33.5 Ma at the ODP Site 1090. The Kerguelen productivity record from Site 744 data shows a substantial peak around 37 Ma and an earlier one near 40 Ma. Our results thus show that the 37 Ma event extended at least as far as the Kerguelen Plateau in the Indian Ocean sector, thus affecting most of the Southern Ocean region.

The potential significance of this event for the development of late Eocene global climate depends on the extent to which the enhanced productivity contributed to enhanced carbon sequestration, and the magnitude of sequestration over the ca 1 my interval of enhancement. Our ability to estimate the impact of higher productivity on carbon sequestration is limited, as many of the factors that affect this in the modern ocean are poorly understood for Eocene oceans (export efficiency to the subsurface waters, rates of transport and degradation in the water column and upper sediment layers, organic carbon content of Southern Ocean Eocene pelagic sediments; as well as transport of organic carbon by subsurface water layers in the late Eocene oceans to lower latitude areas of productivity and sequestration). For simplicity we thus use values for the modern Southern Ocean, but conservatively ignore the (in the modern oceans) substantial transport of nutrients in the modern ocean to lower latitudes by Antarctic Intermediate Water (Sarmiento et al., 2004). The purpose of such a calculation is simply estimating if the magnitude of enhanced productivity, could, within the region studied, and over the 1 my interval of the event, at least potentially have sequestered a climatically significant amount of carbon. Using Hayes et al. (2021) data on the composition and flux of seafloor sediments in the Global Ocean, we compute the mean total organic carbon (TOC) exported to deep-sea sediments per cm2 per year in the Southern Ocean (SO, area below the polar front and above the Antarctic continent), the Polar Frontal Zone (PFZ, based on Park et al. 2019 coordinates for the subantarctic and polar fronts) and, as a subset of the SO total, just the Atlantic sector of the Southern Ocean. We thus estimate the total amount of organic carbon currently exported to the deep sea per year in these areas. Finally, given the approximate doubling of productivity during the 1 my interval, we compute the amount of excess exported carbon over 1 Myr, and translate it into the corresponding amount of atmospheric CO_2 in ppm (using Clark 1982 equivalency) to roughly estimate the order of magnitude of how much carbon the biological carbon pump could have buried in the sediments of the area of interest. The results (Table 2) suggest that enhanced carbon sequestration in the late Eocene SO, even if restricted only to the Atlantic sector, could have indeed been sufficient to have affected global pCO_2 (hypothesis 2 as stated in the introduction). If the enhanced productivity affected most, or all of the circumpolar region, and if indirect carbon sequestration via intermediate water transport also played a role the impact could have been dramatic.

Table 2. Potential impact of doubling modern Southern Ocean export productivity/carbon sequestration for a 1 my time interval. See text for definitions of areas and calculations.

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Region	Area (km2)	Mean TOC ($gC\ cm^{-2} yr^{-1}$)	Exported carbon ($PgC\ Myr^{-1}$)	Equivalent pCO_2 (ppm)
Southern Ocean	35 882 985	0.004882	1 751.856	882.5
PFZ	10 290 123	0.004326	445.108	209.0
Atlantic Sector of SO	11 561 803	0.005047	583.518	274.0

4.2 Surface Water Changes in Physical Conditions in the Late Eocene

The late Eocene is generally accepted as a time interval of gradual cooling of Southern Ocean waters. Indeed, biomarker-based temperature estimates reveal substantial (3-5 °C) high latitude sea surface temperatures (SST) cooling within the late Eocene (Liu et al., 2009, O'Brien et al., 2020). Our fine fraction stable oxygen isotopes confirm this cooling trend following MECO, with a distinct peak at 37 Ma during the Eocene, matching the peak cooling reported by O'Brien et al. (2020). This interval of maximum $\delta^{18}O$ values occurred during the same interval in which export productivity increased (Figure 2). In this interval the difference in the $\delta^{18}O$ gradient between benthic foraminifera and fine fraction (nannofossil) carbonate is less pronounced. This increase in similarity can either be caused by a decrease in water column stratification or by enhanced vertical mixing. In other words, either the (temperature) conditions during deposition were identical across larger areas and depths, or water masses were mixed more frequently.

This change in export productivity in the late Eocene is coeval with a change towards increasing variability carbon stable isotopes ($\delta^{13}C$) of benthic foraminifera (Figure 4). Benthic foraminiferal $\delta^{13}C$ provides a powerful tracer for the reconstruction of bottom water circulation patterns, nonetheless, should be carefully interpreted because the signal can be overprinted by multiple effects such as the global carbon cycle or local dissolved nutrient contents. Comparing our local stable carbon isotope records to a global compilation shows that the local $\delta^{13}C$ curves fit reasonably well within the global records (Figure 3B, D and F). In the global context, a shift towards more positive values in the $\delta^{13}C$ at 37 Ma demonstrates a carbon cycle perturbation. The subsequent decrease towards more positive values in the late-Eocene is coeval with the global trend and also coincides with the productivity changes. One possible explanation is that the marine organic carbon burial is increased, preferentially scavenging the light 12C from the carbon pool.

This adds evidence to an event of high productivity during the late-Eocene. However, in the Indian Sector and afterwards in the Atlantic Sector of the Southern paleo Ocean, the local $\delta^{13}C$ does not follow the secular trend. This argues that ocean circulation also changes along with productivity.

4.3 Oceanographic Circulation Drivers of the Late Eocene Productivity Change

We propose that the main cause for the productivity increase observed in the late Eocene is upwelling of nutrient-rich deep waters. Understanding however the physical oceanographic mechanisms that led to increased upwelling throughout the Southern Ocean requires examining links between the different processes that occurred at that time period. Changes in paleoceanography during the Paleogene were significantly mediated through tectonic re-organisation, such as the Southern Ocean gateways opening (i.e., the Drake Passage and the Tasman Gateway), changes in the Atlantic-Arctic gateway and in the Tethys Seaway.

In this context, the Southern Ocean circulation during this time period is still debated due to uncertainties concerning the opening of the gateways that led to the development of the Antarctic Circumpolar Current (ACC). Estimates for the onset of the modern-like ACC have not reached a consensus yet and vary from as early as middle Eocene (ca 41 Ma,

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Scher & Martin, 2006; ca 35.5 Ma, Stickley et al. 2004) to middle Oligocene (ca 23Ma; Pfuhl and McCave, 2005). This inconsistency suggests that the onset of ACC could have been a gradual or an intermittent change. Further, local proxy records cannot distinguish between regionally developed fronts and true circumpolar, i.e. ACC flow.

In addition to $\delta^{18}O$ and $\delta^{13}C$, εNd has been used to identify circulation changes and water masses exchange through the Eocene (Scher and Martin, 2004, 2008; Scher et al., 2014; Huck et al., 2017; Wright et al., 2018). Nd isotopes are one of the most robust tracers of water mass origin (Frank, 2002). The residence time of Nd in oceans is much shorter (300 - 1000 years) than ocean mixing time and is thus distinct at a given location. Further, the isotope composition of the Nd ocean budget is solely determined by terrigenous contribution. The latter is balanced by Nd sinks that remove Nd quantitatively, yet this only influences the net budget and thus the magnitude and/or swiftness of changes to the εNd composition. However, mixing of water masses, e.g. through lateral or vertical mixing, can also cause changes as long as they occur more rapidly than the residence times.

In the late Eocene, starting at 37 Ma, Scher and Martin (2004) found a dramatic positive shift in ε-Nd values in the Atlantic sector of the SO that they interpreted as the influx of Pacific deep waters, due to its characteristic of more radiogenic (positive) waters, not previously observed in the Atlantic Ocean. Recently published Nd isotope records from the Kerguelen Plateau (Wright et al., 2018) revealed a long-term negative trend during the late Eocene, which also suggests that the water mass mixing between the Pacific and Atlantic preceded 36 Ma. εNd (t) records from the Kerguelen Plateau in fact showed values comparable to modern CDW during the Oligocene, inferring water mass composition similar to the present day. Thus, Nd isotope data support at least partial opening of Drake Passage by the late Eocene (before 36 Ma), consistent with plate tectonic reconstructions (Livermore et al., 2005, 2007). Regardless of the depth, Neodymium isotope evidence for late Eocene opening of the Drake Passage suggests that increased fetch for surface flow and changing deep water composition could have had changes in the surface water conditions in the South Atlantic sector of the late Eocene Southern Ocean.

This has been explicitly demonstrated in a recent modelling study conducted by Toumoulin et al. (2020). They demonstrate that the Drake Passage opening, even at shallow depth, notably connects prior regional frontal systems together, thereby allowing the formation of a proto-ACC; and has a strong effect on the Southern Ocean Eocene water mass structure, inducing ocean cooling in most of the Southern Hemisphere. These temperature changes are not linear and differ from one region to another, with DP opening causing changes in the mixed layer depths and provoking different responses in the Atlantic and Indian Sectors of the SO. In the Atlantic and Indian Ocean sectors in particular, very deep seasonal mixing (several hundred meters) over broad areas of the entire region is replaced by more moderate levels of mixing (generally ca 200 m or less), except near the proto-polar front region, where seasonal mixing of 300-400 m still occurs. Vila et al. 2014 have found nannofossil assemblages characteristic of cool sea surface waters in the late-Eocene in Kerguelen Plateau samples Cooler temperatures are coeval with the paleoceanographic re-organization and intensified upwelling that we infer for this time period, while differences in the depth of the mixed layers between ocean basins may explain the different magnitude of export productivity observed in the Atlantic and Indian sectors of the SO.

The wind-driven eastward flow and the characteristic fronts of the modern ACC support the upwelling of nutrient-rich water to the surface and consequently high levels of productivity. On the balance of evidence, it seems that the export productivity seen in our data in the late Eocene is likely to have occurred in response to a proto-ACC front's development and its associated upwelling. The inferred onset of a proto-ACC in the late Eocene and our finding of increased upwelling fits the hypothesis that ACC type circulation itself helps drive the AMOC circulation (Toggweiler

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and Bjornsson, 2000; Katz et al., 2011; Sarkar et al., 2019). A proto-ACC causes SO upwelling, and thus provides support for increasing AMOC-like circulation in the late Eocene as an additional cause of increased upwelling as a causative mechanism of the export productivity event. Temperature asymmetry between Northern and Southern Hemisphere and comparisons between benthic $\delta^{13}C$ records provide evidence for the strengthening of the AMOC in the late Eocene (Elsworth et al., 2017).

4.4 Eocene-Oligocene Boundary Productivity Changes

The earliest Oligocene, following the EOT, has been suggested as a period of a significant rise in biological productivity in high southern latitudes (Diester-Haass, 1995, 1996; Diester-Haass and Zahn, 1996, 2001). However, in contrast to the late Eocene event, the export productivity changes across the Eocene-Oligocene boundary observed in our study were not always concurrent between the sites investigated (Figure 2). In the Atlantic sites, export productivity increases and decreases several times from the late Eocene to early Oligocene. We thus argue that the fluctuations in export productivity that occurred in the Southern Ocean during this global climatic re-organization are more strongly modulated by local parameters, whereas the late Eocene productivity event is more uniform and reflects the global re-organization of ocean circulation. If the trends observed in export productivity across the EOT were regulated only by global, or at least regional temperature and circulation changes, then we would observe significant changes also in the Indian sector of the Southern Ocean. It seems however that productivity increase was more pronounced in the Atlantic sector of the Southern Ocean.

Today, the Southern Ocean (SO) has a frontal system that strongly impacts circulation, primary productivity and the entire climate system (Chapman et al., 2020). The Antarctic Polar Front (APF) is particularly important for controlling nutrient distribution. Latitudinal variations of the APF for example have been shown to alter regional productivity over the glacial cycles (Kim et al., 2014, Thole et al., 2019). The causes of the lack of significant export productivity changes in the Indian sector of the Southern Ocean during the early Oligocene after the Eocene-Oligocene boundary are unclear. The Kerguelen Plateau may not have been located in a position favourable to nutrient-rich upwelling. In addition, the regional frontal migration may have been more intense in the Atlantic sector compared to the Indian sector of the SO.

4.5 A Scenario for Southern Ocean Productivity and Circulation Change in the Late Eocene

The patterns of productivity change seen in our study can be placed in an (admittedly speculative) scenario, which is at least compatible with prior studies and modelling of conditions in the late Eocene austral ocean region and Antarctica. In the earliest interval covered in our study (ca 40-38 Ma) productivity was in most sites fairly low (Figure 5a). At this time there is little evidence for significant influx of Pacific waters into the Atlantic, and the Drake Passage is thus assumed to be effectively closed to ocean circulation.

During the 38-36 Ma interval, evidence summarised by Scher et al. (2014) suggests that a significant, if transient, glaciation event occurred on the Antarctic continent - the Priabonian oxygen maximum, or PriOM. If sufficient in magnitude this would have significantly affected circulation throughout the austral ocean region, with strengthened temperature gradients, stronger circumpolar circulation, and increased upwelling (Goldner et al, 2014). This would account both for the substantial increase in productivity, and the broad geographic extent of the increase seen in our data (Figure 5b). The cause of this glaciation event is unknown, but may be related in part to the trend in the late Eocene towards lower atmospheric pCO_2 interacting with orbital fluctuations in polar insulation as explored in model simulations by Van Breedam et al. (2022).

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With the end of transient glaciation, atmospheric forcing of ocean circulation would have declined, and with it the high levels of productivity seen in our data (Figure 5c). However, by this time (ca 36-34 Ma) the Nd isotope data suggests that a significant influx of Pacific water was reaching the South Atlantic sector of the austral ocean (Scher and Martin, 2004), and consequently, the Drake Passage must have been at least partially open. This would have resulted in, if not as strong as during the PriOM, nonetheless stronger circumpolar circulation in a proto-ACC, increased upwelling, and increased nutrient availability from Pacific-sourced deep waters. The locus of high productivity would have become however more cantered near the proto-ACC, which at that time, according to the model results of Toumoulin et al. (2020) was located a few degrees north of the current location of the ACC. The high productivity and accumulation of biogenic opal seen at Site 1090, fortuitously located at this time in this region can be thus be explained, as can the lower relative productivity of Site 689, located much further to the south and thus outside the region primarily influenced by the proto-ACC system.

Lastly, at the E/O boundary itself (Figure 5d), the well known major shifts in oxygen isotopes signal the formation of a full continental ice-sheet, which would have in turn driven a renewed increase in circumpolar ocean circulation - a full, if early form of the ACC, and dramatically increased levels of productivity, again however primarily near the ACC region.

4.6 Possible Implications to the EOT Global Cooling

Our pCO_2 compilation shows that carbon dioxide levels declined gradually from ca 1200 ppm in the late Eocene to ca 750 ppm across the EOT (Figure 4 and Figure S7). There are different processes involved in the oceanic uptake of CO_2. The solubility pump is a physic-chemical process that promotes gas transfer between atmosphere and sea water in order to achieve chemical equilibrium. This process depends on temperature, in which the solubility increases as temperature decreases. Evidence for cooling of surface waters observed in the Southern Ocean (Liu et al., 2009; Hutchinson et al., 2021) could have favoured the ability to dissolve atmospheric CO_2, thus being an important contributor to the drawdown of pCO_2 during the late-Eocene.

Silicate weathering has been suggested to play an essential role in regulating CO_2 across the EOT (Zachos and Kump, 2005). On geologic time scales, chemical silicate weathering is considered to modulate atmospheric CO_2 levels through a negative feedback mechanism (Berner et al.,1983). Weathering of silicate rocks is a source of alkalinity to the oceans and thus a sink for atmospheric CO_2, thereby influencing global climate. Increasing silicate weathering increases primary productivity through the delivery of nutrients to the ocean. Intensified weathering is supported by Os isotope records, showing an anomaly before the EOT, at ca 35.5Ma (Dalai et al., 2006).

The potential effects of enhanced export productivity could have modulated these changes in CO_2 because it removes organic carbon from the surface ocean and transport it into the deep ocean, and thus via sequestration is a mechanism that contributes to the decline of atmospheric carbon dioxide and intensifies the cooling trend. Therefore, enhanced productivity in the late-Eocene and at Eocene-Oligocene transition recorded in our study is a potential candidate that may have provided important positive feedback to the pCO_2 decline.

Despite some modelling studies showing that circulation changes were not the main factor in driving the cooling and glaciation on Antarctica (e.g. Huber et al., 2004; Huber and Not 2006; Sijp et al., 2011), sea surface temperature decreased affecting the atmosphere-ocean CO_2 equilibrium. A succession of events may have contributed to the evolution of climate: thermal isolation of Antarctica, glaciers formation, increasing intensity of silicate weathering, together with upwelling of nutrient rich and cold deep waters, leading to higher solubility pump and high biological productivity, then declining pCO_2. Moreover, because the Atlantic Meridional Overturning Circulation (AMOC) affects the distribution of tracers such as temperature, dissolved inorganic carbon (DIC), alkalinity and nutrients (Boot et al., 2021), the strengthening of AMOC could explain the further decrease in atmospheric CO_2 via biological export productivity. Elsworth et al., (2017), for example, suggest that enhanced weathering is driven by intensified AMOC in the latest Eocene due to increasing AMOC causing differential global distribution and increase of surface temperatures and precipitation over land areas. These factors together suggest that E-O changes in AMOC also may play an important role as a driver of CO_2 decline.

Taken together, the above processes indicate that a variety of positive feedbacks contributed to Antarctic glaciation from about 37 Ma onwards. Recent evidence suggests that continental-scale Antarctic glaciation initiated in the late Eocene (Scher et al., 2014; Carter et al., 2017). Our results indicate that significant changes in Southern Ocean export productivity preceded the E/O boundary by approximately 3 million years. These trends are likely to be a response to the combination of the intensified processes that had been in place since the late Eocene, and suggest that biological productivity played an important role in the drawdown of pCO_2 levels. The CO_2 fixation by phytoplankton and carbon export to the seafloor increased via biological pump may have contributed to decrease atmospheric CO_2 through a positive feedback and, thus boosting the cooling trend. The establishment of Antarctic glaciation may have been influenced significantly by enhanced productivity. What remains unclear is the biological drivers (plankton) of this productivity change and their role in the long-term evolution of global climate change.

4.7 Limitations and Future Directions

Our study has numerous limitations. Our data on paleoproductivity does not cover the full time interval in all of the sites studied, and our geographic coverage is still incomplete. In particular, we have not examined sections from the Pacific sector, or the influence of the Tasman gateway. Most of our interpretations are based on a single productivity proxy - biogenic Barium. While this proxy is well established and gives coherent results in our study, productivity proxies are known to have complex behaviours, and results using different proxies might be at least somewhat different. Our estimates of how much elevated late Eocene Southern Ocean productivity might have affected global carbon sequestration is only a rough estimate of potential magnitude and much more detailed study of both actual sequestration values in sediment, and the impact on atmospheric pCO_2 are still needed. Our interpretative scenario attributing productivity changes to a combination of Drake Passage opening and continental scale glaciation on Antarctica are purely qualitative and need further study. Despite these limitations, our study sheds new light on the late Eocene oceanic precursors of the Eocene-Oligocene glaciation event - the most dramatic climate change of the Cenozoic.

5 Conclusions

Our bio-Ba data provide important records of the Southern Ocean productivity history across the EOT. These data show that export productivity increased significantly in the late Eocene in the Southern Ocean and was affected by ocean circulation changes. The development of a regionally varying circumpolar polar flow (proto-ACC) and the associated frontal system is likely to have contributed to the enhanced productivity in the Southern Ocean through the intensification of upwelling (H1).

Our results show that increasing Southern Ocean productivity in the late Eocene to earliest Oligocene is correlated to global changes in atmospheric pCO_2 and carbon isotope proxies for organic carbon extraction. This finding points toward a potential positive climate system feedback, involving ocean circulation changes, enhanced export productivity

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and drawdown of atmospheric CO_2. Although studies have the inclination to point to a dominant mechanism (ocean gateway opening vs pCO_2 decline) for causing the initiation of Antarctica glaciation, each mechanism plays a different role and has associated complex feedbacks.. Our study points toward a climate feedback system involving ocean circulation, thermal isolation and biological productivity, where several mechanisms are interconnected and cannot be considered separately. Openings of gateways led to the development of a circumpolar flow, promoting cooling and increased upwelling that contributed to ocean carbon pumps and promotes the decline of atmospheric carbon dioxide.

Data Availability

The supplementary information related to this article is available in the Supplement, the raw data will be available upon publication in an open-access database (PANGAEA: https://www.pangaea.de).

Author Contributions

The manuscript was designed and written by GRF in collaboration with DL. DL updated age models. GRF prepared all the samples for geochemical analyses. JS run barium and aluminum analyses. US generated carbon and oxygen stable isotope data. pCO_2 data and neodymium isotopes data were compiled by GRF. Biogenic barium was calculated by GRF. All authors contributed to editing the manuscript.

Competing Interests

The authors declare that they have no conflict of interest.

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References

Anagnostou, E., John, E. H., Edgar, K. M., Foster, G. L., Ridgwell, A., Inglis, G. N., Pancost, R. D., Lunt, D. J., and Pearson, P. N. Changing atmospheric CO2 concentration was the primary driver of early Cenozoic climate: Nature, v. 533, pp. 380-384. https://doi.org/10.1038/nature17423, 2016.

Anagnostou, E., John, E. H., Babila, T.L., Sexton, P. F., Ridgwell, A., Lunt, D.J., Pearson, P.N., Chalk, T.B., Pancost, R.D. and Foster, G.L. Proxy evidence for state-dependence of climate sensitivity in the Eocene greenhouse. *Nature Communications,*11, 4436 (2020). https://doi.org/10.1038/s41467-020-17887-x, 2020.

Anderson, L.D. & Delaney, M.L. Middle Eocene to early Oligocene paleoceanography from Agulhas Ridge, Southern Ocean (Ocean Drilling Program Leg 177, Site 1090). Paleoceanography and Paleoclimatology, 20, 1. https://doi.org/10.1029/2004PA001043, 2005.

Anderson, J.B., Warny, S., R.A. Askin, J.S. Wellner, S.M. Bohaty, A.E. Kirshner, D.N. Livsey, A.R. Simms, T.R. Smith, W. Ehrmann, L.A. Lawver, D. Barbeau, S.W. Wise, D.K. Kulhanek, F.M. Weaver, W. Majewski. Progressive Cenozoic cooling and the demise of Antarctica's last refugium PNAS, 108, pp. 11356-11360, 2011.

Arrhenius, S. On the influence of carbonic acid in the air upon the temperature of the ground. Philosophical Magazine and Journal of Science, 5, v.41, 237-276, 1986.

Aubry, M.P. Late Paleogene Calcareous nannoplankton evolution: a tale of climatic deterioration In: Prothero, D.R., Berggren, W.A. (Eds.), Eocene/Oligocene Climatic and Biotic Evolution, Princeton University Press, Princeton, NJ, pp.272-309, 1992.

Baldauf, J. G., & Barron, J. A. 29. Diatom Biostratigraphy: Kerguelen Plateau and Prydz Bay regions of the Southern Ocean. In: Barron, J., Larsen, B. et al. (1991) Proceedings of the Ocean Drilling Program, Scientific Results, v 119, 1991

Barker, P.E, Kennett, J.P., et al. Proc. ODP, Init. Repts., 113: College Station, TX (Ocean Drilling Program). doi:10.2973/odp.proc.ir.113.1988.

Barker, P.F. Scotia Sea regional tectonic evolution: implications for mantle flow and palaeocirculation. Earth-Science Reviews, 55, 1-39 https://doi.org/10.1016/S0012-8252(01)00055-1, 2001

Barron, J., Larsen, B., et al. Proc. ODP, Init. Repts., 119: College Station, TX (Ocean Drilling Program). doi:10.2973/odp.proc.ir.119.1989.

Beerling, D., Royer, D. Convergent Cenozoic CO_2 history. Nature Geoscience, 4, 418–420 https://doi.org/10.1038/ngeo1186, 2011.

Berggren, W.A., Kent, D.V., Swisher, C.C., III, and Aubry, M.P. A revised Cenozoic geochronology and chronostratigraphy, in Berggren, W.A., et al., eds., Geochronology, time scales and global stratigraphic correlation: Framework for an historical geology: SEPM (Society for Sedimentary Geology) Special Publication 54, p. 129–212, 1995.

Berner, R. A., Lasaga, A. C. & Garrels, R. M. The carbonate-silicate geochemical cycle and its effect on atmospheric carbon dioxide over the past 100 million years. Am. J. Sci. 283, 641–683, 1983.

Billups, K., Channell, J.E.T. and Zachos, J. Late Oligocene to early Miocene geo- chronology and paleoceanography from the subantarctic South Atlantic, Paleoceanography, 17(1), 1004. doi:10.1029/2000PA000568, 2002.

Bijl, P.K., Houben, A. J. P., Schouten, S., Bohaty, S. M., Sluijs, A., Reichart, G.-J., Sinninghe Damste, J.S., and Brinkhuis, H. Transient Middle Eocene atmospheric CO_2 and temperature variations, Science, 330, 819-821, 2010.

Bohaty, S. M. and Zachos, J. C. Significant Southern Ocean warming event in the late middle Eocene, Geology, 31, 1017–1020, https://doi.org/10.1130/G19800.1, 2003.

Bohaty, S. M., Zachos, J.C., and Delaney, M.L. Foraminiferal Mg/Ca evidence for Southern Ocean cooling across the Eocene-Oligocene transition, Earth Planet. Sci. Lett., 317–318, 251–261, 2012.

Boot, D., Von Der Heydt, A.S., and Dijkstra, H.A. Effect of the Atlantic Meridional Overturning Circulation on Atmospheric pCO_2 variations. Earth System Dynamics, , https://doi.org/10.5194/esd-13-1041-2022, 2022

Carter, L., McCave, I.N., Williams, M.J.M.Chapter 4 Circulation and Water Masses of the Southern Ocean: A Review, Developments in Earth and Environmental Sciences, Elsevier, v. 8, 85-114, https://doi.org/10.1016/S1571-9197(08)00004-9, 2008.

Carter, A., Riley, T.R., Hillenbrand, C.D., Rittner, M. Widespread Antarctic glaciation during the Late Eocene, Earth and Planetary Science Letters, 458, 49-57, https://doi.org/10.1016/j.epsl.2016.10.045, 2017.

Channell, J. E. T., Galeotti, S., Martin, E.E., Billups, K., Scher, H.D., and Stoner, J.S. Eocene to Miocene magnetostratigraphy, biostratigraphy and chemostratigraphy at ODP Site 1090 (sub-Antarctic South Atlantic), Geol. Soc. Am. Bull., 115, 607–623, 2003.

Chapman, C.C., Lea, MA., Meyer, A. Defining Southern Ocean fronts and their influence on biological and physical processes in a changing climate. Nature Climate Change, 10, 209–219, https://doi.org/10.1038/s41558-020-0705-4, 2020.

Clark, W. C. (ed.). Carbon Dioxide Review: 1982, p. 468, Oxford University Press, New York, 1982.

Cooke, P.J., Nelson, C.S., Crundwell, M.P., Spiegler, D.Bolboforma as monitors of Cenozoic palaeoceanographic changes in the Southern Ocean, Palaeogeography, Palaeoclimatology, Palaeoecology, Volume 188, Issues 1–2, 73-100, https://doi.org/10.1016/S0031-0182(02)00531-X, 2002.

Coxall, H.K., Wilson, P.A., Pälike, H., Lear, C.H., Backman, J. Rapid stepwise onset of Antarctic glaciation and deeper calcite compensation in the Pacific Ocean. Nature 433, 53–57. https://doi.org/10.1038/nature03135, 2005.

Coxall, H., Pearson, P.N. The Eocene-Oligocene transition, In: Williams, M., Haywood, A.M., Gregory, F.J., Schmidt, D.N. (Eds.), Deep-Time Perspectives on Climate Change: Marrying the Signal from Computer Models and Biological Proxies. pp. 351–387, 2007.

Coxall, H. K., & Wilson, P. A. Early Oligocene glaciation and productivity in the eastern equatorial Pacific: Insights into global carbon cycling, Paleoceanography, 26. PA2221, https://doi.org/10.1029/2010PA002021, 2011.

Coxall, H.K., Huck, C.E., Huber, M. Export of nutrient rich Northern Component Water preceded early Oligocene Antarctic glaciation. Nature Geoscience 11, 190–196, 2018.

Cramer, B. S., J. R. Toggweiler, J. D. Wright, M. E. Katz, and K. G. Miller. Ocean overturning since the Late Cretaceous: Inferences from a new benthic foraminiferal isotope compilation, Paleoceanography, 24, PA4216, doi:10.1029/2008PA001683, 2009.

Dalai, T.K. et al. The Late Eocene $^{187}Os/^{188}Os$ excursion: Chemostratigraphy, cosmic dust flux and the Early Oligocene glaciation. Earth and Planetary Science Letters, 241(3-4), 477-492, https://doi.org/10.1016/j.epsl.2005.11.035, 2006.

De Baar, H., de Jong, J., Bakker, D. et al. Importance of iron for plankton blooms and carbon dioxide drawdown in the Southern Ocean. Nature 373, 412–415 https://doi.org/10.1038/373412a0, 1995.

https://doi.org/10.5194/egusphere-2023-1276
Preprint. Discussion started: 25 July 2023

DeConto, R. & Pollard, D. Rapid Cenozoic glaciation of Antarctica induced by declining atmospheric CO2. Nature 421, 245–249. https://doi.org/10.1038/nature01290, 2003.

DeConto RM, Pollard D, Wilson PA, Palike H, Lear CH, Pagani M. Thresholds for Cenozoic bipolar glaciation. doi:10.1038/nature07337, 2008.

Diekmann, B., Kuhn, G., Gersonde, R., Mackensen, A.Middle Eocene to early Miocene environmental changes in the sub-Antarctic Southern Ocean: evidence from biogenic and terrigenous depositional patterns at ODP Site 1090, Global and Planetary Change, Volume 40, Issues 3–4, Pages 295-313, https://doi.org/10.1016/j.gloplacha.2003.09.001, 2004.

Diester-Haass, L. Late Eocene-Oligocene sedimentation in the Antarctic Ocean, Atlantic Sector (Maud Rise, ODP leg 113, Site 689), Development of surface and bottom water circulation, in The Antarctic Paleoenvironment: A Perspective on Global Change, Part 1, Antarct. Res. Ser., vol. 56, edited by J. P. Kennett, and D. A. Warnke, pp. 185– 202, AGU, Washington, D. C, 1992.

Diester-Haass, L. Middle Eocene to early Oligocene Paleoceanography of the Antarctic Ocean (Maud Rise, ODP Leg 113, Site 689): change from a low to a high productivity ocean. Paleogeography, Paleoclimatology, Paleoecology, 113, 311-334. https://doi.org/10.1016/0031-0182(95)00067-V, 1995.

Diester-Haass, L. Late Eocene-Oligocene paleoceanography in the southern Indian Ocean (ODP Site 744). Marine Geology 130, 99-119, 1996.

Diester-Haass, L & Zahn, R. Eocene-Oligocene transition in the Southern Ocean: History of water mass circulation and biological productivity, Geology, 24, 163–166. 1996.

Diester-Haass, L & Zahn, R. Paleoproductivity increase at the Eocene-Oligocene climatic transition: ODP/DSDP Sites 763 and 592. Paleogeography, Paleoclimatology, Paleoecology, 172, 153-170. https://doi.org/10.1016/S0031-0182(01)00280-2, 2001.

Diester-Haass, L. & Zachos, J. The Eocene-Oligocene transition in the Equatorial Atlantic (ODP Site 925); paleoproductivity increase and positive d13C excursion. In Prothero, D.R; Ivany, L. C; Nesbitt, E. A. (eds) From greenhouse to icehouse; the marine Eocene-Oligocene transition, Columbia University Press, New York, NY, United States (USA), 2003.

Diester-Haass, L., & Faul, K. Paleoproductivity reconstructions for the Paleogene Southern Ocean: A direct comparison of geochemical and micropaleontological proxies. Paleoceanography and Paleoclimatology, 34(1), 79– 97. https://doi.org/10.1029/2018PA003384, 2019.

Douglas, P.M.J., Affek, H.P., Ivany, L.C., Houben, A.J.P., Sijp, W.P., Sluijs, A., Schouten, S., Pagani, M. Pronounced zonal heterogeneity in Eocene southern high-latitude sea surface temperatures. PNAS, 111 (18) 6582-6587 https://doi.org/10.1073/pnas.1321441111, 2014.

Dutkiewicz, A., Müller, R.D. The carbonate compensation depth in the South Atlantic Ocean since the Late Cretaceous. Geology, 49 (7): 873–878. https://doi.org/10.1130/G48404.1, 2021.

Dymond, J., Suess, E. and Lyle, M. Barium in Deep-Sea Sediment: A Geochemical Proxy for Paleoproductivity. Paleoceanography and Paloclimatology, 7(2), 163-181. https://doi.org/10.1029/92PA00181, 1992.

Elsworth, G., Galbraith, E., Halverson, G.et al. Enhanced weathering and CO2 drawdown caused by latest Eocene strengthening of the Atlantic meridional overturning circulation. Nature Geoscience 10, 213–216). https://doi.org/10.1038/ngeo2888, 2017.

Faul K. L., Delaney, M. L. A comparison of early Paleogene export productivity and organic carbon burial flux for Maud Rise, Weddell Sea, and Kerguelen Plateau, south Indian Ocean. Paleoceanography, v.25, 3214, 2010.

Falkowski P., Scholes R.J., Boyle E., Canadell J., Canfield D., Elser J., Gruber N., Hibbard K., Högberg P., Linder S., Mackenzie F.T., Moore III B., Pedersen T., Rosenthal Y., Seitzinger S., Smetacek V., Steffen W. The global carbon cycle: a test of our knowledge of earth as a system. Science, 290, 291–296. doi: 10.1126/science.290.5490.291. PMID: 11030643, 2000.

Florindo, F. and Roberts, A. P. Eocene-Oligocene magnetobiochronology of ODP Sites 689 and 690, Maud Rise, Weddell Sea, Antarctica. Geological Society of America Bulletin, 117(1), 46–. doi:10.1130/b25541.1, 2005

Foster, G.; Royer, D. and Lunt, D. Future climate forcing potentially without precedent in the last 420 million years. Nature Communications, 8, 14845. https://doi.org/10.1038/ncomms14845, 2017.

Frank, M. Radiogenic isotopes: tracers of past ocean circulation and erosionalinput. Rev. Geophys. 40, 1001. doi:10.1029/2000RG000094, 2002.

Galeotti, S., Coccioni, R., Gersonde, R.Middle Eocene–Early Pliocene Subantarctic planktic foraminiferal biostratigraphy of Site 1090, Agulhas Ridge, Marine Micropaleontology, 45, 3–4, 357-381, https://doi.org/10.1016/S0377-8398(02)00035-X., 2002.

Gersonde, R., Hodell, B.A., Blum, P., and Shipboard Scientific Party. Leg 177 summary, Proc. Ocean Drill. Program, Initial Rep., 177, 1–67, 1999.

Glass, B.P., Hall, C.M., and York, D. 40Ar/39Ar laser probe dating of North American tektite fragments from Barbados and the age of the Eocene-Oligocene boundary: Chemical Geology, v. 59, p. 181–186., 1996.

Goldner, A., Herold, N. and Huber, M. Antarctic glaciation caused ocean circulation changes at the Eocene-Oligocene transition, Nature, 511(7511), 574–577, doi:10.1038/nature13597, 2014.

https://doi.org/10.5194/egusphere-2023-1276
Preprint. Discussion started: 25 July 2023

Gradstein, F. M., Ogg, J. G., Schmitz, M., & Ogg, G. The Geological Time Scale 2012 (pp. 1176). Oxford, UK: Elsevier, 2012.

Gruber, N., Landschützer, P., Lovenduski, N.S. The Variable Southern Ocean Carbon Sink. Annual Review of Marine Science, 11, 159-186. https://doi.org/10.1146/annurev-marine-121916-063407, 2019.

Hayes, C.T.; Costa, K.M.; Anderson, R.F.; Calvo, E.; Chase, Z.; Demina, L.L.; Dutay, J.; German, C.R.; Heimbürger-Boavida, L.; Jaccard, S.L.; et al. Global Ocean Sediment Composition and Burial Flux in the Deep Sea. Global Biogeochem. Cycles 35, 2021.

Henehan, M.; Edgar, K.M.; Foster, G.L., Penman, D.E.; Hull, P.M.; Greenop, R.; Anagnostou, E.; Pearson, P.N. Revisiting the Middle Eocene Climatic Optimum "Carbon Cycle Conundrum" with New Estimates of Atmospheric pCO_2 from Boron Isotopes. Paleoceanography and Paleoclimatology. 35(6). https://doi.org/10.1029/2019PA003713, 2020.

Houben, A.J.P., van Mourik, C.A., Montanari, A., Coccioni, R., Brinkhuis, H. The Eocene–Oligocene transition: Changes in sea level, temperature or both? Palaeogeography, Palaeoclimatology, Palaeoecology. 335–336,p 75-83 https://doi.org/10.1016/j.palaeo.2011.04.008, 2012.

Huber, B.T. and Quillevere, F. Revised Paleogene Planktonic Foraminiferal biozonation for the Austral realm. Journal of Foraminiferal Research, 35(4), 299-314., 2005.

Huber, M., Brinkhuis, H., Stickley, C.E., Döös, K., Sluijs, A., Warner, J., Schellenberg, S.A. and Williams, G.L. Eocene circulation of the Southern Ocean: Was Antarctica kept warm by subtropical waters? Paleoceanography 19, doi:10.1029/2004PA001014, 2004.

Huber, M. and Nof, D. The ocean circulation in the southern hemisphere and its climatic impacts in the Eocene. Palaeogeography, Palaeoclimatology, Palaeoecology 231, 9-28, 2006.

Huck, C. E., van de Flierdt, T., Bohaty, S. M. and Hammond, S. J. Antarctic climate, Southern Ocean circulation patterns, and deep-water formation during the Eocene. Paleoceanography, 32, 674– 691. https://doi.org/10.1002/2017PA003135, 2017.

Hutchinson, D.K., Coxall, H.K., Lunt, D.J., Steinthorsdottir, M., de Boer, A.M. et al. The Eocene-Oligocene transition: A review of marine and terrestrial proxy data, models and model-data comparisons. Climate of the Past 17(1), 269-315, 2021.

Inglis, G. N., Farnsworth, A., Lunt, D., Foster, G. L., Hollis, C. J., Pagani, M., Jardine, P. E., Pearson, P. N., Markwick, P., Galsworthy, A. M. J., Raynham, L., Taylor, K. W. R. and Pancost, R. D. Descent toward the Icehouse: Eocene sea surface cooling inferred from GDGT distributions, Paleoceanography, 30(7), 1000–1020, doi:10.1002/2014PA002723, 2015.

Inokuchi, H; Heider, F. Paleolatitude of the southern Kerguelen Plateau inferred from the paleomagnetic study of late Cretaceous basalts. In: Wise, SW; Schlich, R; et al. (eds.), Proceedings of the Ocean Drilling Program, Scientific Results, College Station, TX (Ocean Drilling Program), 120, 89-96, https://doi.org/10.2973/odp.proc.sr.120.129.1992

IPCC. Climate Change 2021: The Physical Science Basis. Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391pp, 2021.

Katz, M.E., Cramer, B.S., Toggweiler, J.R., Esmay, G., Liu, C., Miller, K.G., Rosenthal, Y., Wade, B.S., Wright J.D. Impact of Antarctic Circumpolar Current Development on Late Paleogene Ocean Structure. Science, 332, 1076-1079, 2011.

Kennet, J.P. Cenozoic evolution of Antarctic glaciation, the circum-Antarctic Ocean, and their impact on global paleoceanography. J. Geophys. Res., 82, 3843-3860, 1977.

Kennett, J.P. and Stott, L.D. Proteus and Proto- Oceanus: ancestral Paleogene oceans as revealed from antarctic stable isotopic results: ODP Leg 113. In: Leg 113. ODP Sci. Res., pp. 865-880, 1990.

Kim J.H., Crosta, X., Michel, E., Schouten, S., Duprat, J., Damsté, J.S.S. Impact of lateral transport on organic proxies in the Southern Ocean, Quaternary Research, 71(2), 246-250. https://doi.org/10.1016/j.yqres.2008.10.005, 2009.

Kim, Yong Sun, Orsi, Alejandro H. On the Variability of Antarctic Circumpolar Current Fronts Inferred from 1992–2011 Altimetry. Journal of Physical Oceanography 3054–3071. https://doi.org/10.1175/JPO-D-13-0217.1, 2014.

Kuhlbrodt, T., Griesel, A., Montoya, M., Levermann, A., Hofmann, M., Rahmstorf, S. On the driving processes of the Atlantic meridional overturning circulation. Rev. Geophys.,45, RG2001, doi:10.1029/2004RG000166, 2007.

Ladant, J.-B., Donnadieu, Y. and Dumas, C. Links between CO2, glaciation and water flow: reconciling the Cenozoic history 1680 of the Antarctic Circumpolar Current, Clim. Past, 10(6), 1957–1966, doi:10.5194/cp-10-1957-2014, 2014.

Lauretano, V., Kennedy-Asser, A.T., Korasidis, V.A., Wallace, M.W., Valdes, P.J., Lunt, D.J., Pancost, R.D. and naafs, B.D.A. Eocene to Oligocene terrestrial Southern Hemisphere cooling caused by declining pCO2.Nature Geoscience 14, 659–664. https://doi.org/10.1038/s41561-021-00788-z, 2021.

Lazarus, D. and Caulet J.P. Cenozoic Southern Ocean reconstructions from sedimentologic, radiolarian, and other microfossil data. In: J.P. Kennett and D.A. Warnke, Eds., The Antarctic Paleoenvironment: A perspective on global change. Pt. 2. Antarctic Research Series, 60: 145-174, 1994.

Li, Z., Lozier, M.S., Cassar, N. Linking Southern Ocean Mixed□Layer Dynamics to Net Community Production on Various Timescales. JGR Oceans 126. https://doi.org/10.1029/2021JC017537, 2021.

https://doi.org/10.5194/egusphere-2023-1276
Preprint. Discussion started: 25 July 2023

Liu, Z., M., Pagani, D., Zinniker, R., DeConto, M., Huber, H., Brinkhuis, S. R., Shah, R. M. Leckie, and Pearson, A. Global cooling during the Eocene – Oligocene climate transition, Science, 323, 1187–1190, 2009.

Livermore, R., Nankivell, Eagles, G. and Morris, P. Paleogene opening of Drake Passage, Earth Planet. Sci. Lett., 236, 459–470, 2005.

Livermore, R., Hillenbrand, C., Meredith, M., and Eagles, G. Drake Passage and Cenozoic climate: an open and shut case?, Geochem. Geophy. Geosy., 8, Q01005, https://doi.org/10.1029/2005GC001224, 2007.

Mackensen, A., and Ehrmann, W.U. Middle Eocene through Early Oligocene climate history and paleoceanography in the Southern Ocean: Stable oxygen and carbon isotopes from ODP Sites on Maud Rise and Kerguelen Plateau, Mar. Geol., 108, 1–27, 1992.

Marino, M. and Flores, J.A. Middle Eocene to early Oligocene calcareous nannofossil stratigraphy at Leg 177 Site 1090, Mar. Micropaleontol., 45, 383–398, 2002.

Martin, E.E. and Haley, B.A.Fossil fish teeth as proxies for seawater Sr and Nd isotopes. Geochimica et Cosmochimica Acta, 64 (5), 835-847, doi:10.1016/S0016-7037(99)00376-2, 2000.

Martin, E.E. and Scher, H.D.Preservation of seawater Sr and Nd isotopes in fossil fish teeth: bad news and good news. Earth and Planetary Science Letters, 220(1-2), 25-39, https://doi.org/10.1016/S0012-821X(04)00030-5, 2004.

Mazloff, M.R., Heimbach, P., Wunsch, C. An eddy-permitting Southern Ocean state estimate. J. Phys. Oceanogr. 40, 880–899, 2010.

Mikolajewicz, U., Maier-Reimer, E., Crowley, T. J. and Kim, K.-Y. Effect of Drake and Panamanian Gateways on the circulation of an ocean model, Paleoceanography, 8(4), 409–426, doi:10.1029/93PA00893, 1993.

Miller, K.G. Janecek, T.R., Katz, M.E., Keil, D.J. Abyssal circulation and benthic foraminiferal changes near the Paleocene/Eocene boundary. Paleoceanography, 2(6), 741-761, https://doi.org/10.1029/PA002i006p00741, 1987.

Miller, K.G., Wright, J.D., Katz, M.E., Wade, B., Browning, J.V., Cramer, B.S., and Rosenthal, Y. Climate threshold at the Eocene-Oligocene transition: Antarctic ice sheet influence on ocean circulation, in Koeberl, C., and Montanari, A., ed., The Late Eocene Earth Hot house, Icehouse, and Impacts: Geological Society of America Special Paper 452, p. 169–178, doi:10.1130 /2009.2452 (11), 2009.

Moore, J. K., M. R. Abbott, J. G. Richman, W. O. Smith, T. J. Cowles, K. H. Coale, W. D. Gardner, and R. T. Barber. SeaWiFS satellite ocean color data from the Southern Ocean, Geophys. Res. Lett., 26, 1465–1468, 1999.

Muza, J.P., Williams, D.F., Wise, S.W. Paleogene oxygen record for Deep Sea Drilling Project Sites 511 and 512, subantarctic South Atlantic Ocean: Paleotemperatures, paleoceanographic changes, and the Eocene/Oligocene boundary event. In: Ludwig, WJ; Krasheninnikov, VA; et al. (Eds.), Initial Reports of the Deep-Sea Drilling Project (U.S. Govt. Printing Office),71, 409-422,https://doi.org/10.2973/dsdp.proc.71.117.1983, 1983.

Najjar, R.G., Nong, G.T., Seidov, D., Peterson, W.H. Modeling geographic impacts on early Eocene ocean temperature, Geophys. Res. Lett., 29 (15), 401-404. https://doi.org/10.1029/2001GL014438, 2002.

Nelson, D.M. & Smith, W. Sverdrup revisited: Critical depths, maximum chlorophyll levels, and the control of Southern Ocean productivity by the irradiance-mixing regime. Limnol. Oceanogr. 36, 1650–1661. https://doi.org/10.4319/lo.1991.36.8.1650, 1991.

Nielsen, E.B., Anderson, L.D., Delaney, M.L. Paleoproductivity, nutrient burial, climate change and the carbon cycle in the western equatorial Atlantic across the Eocene/Oligocene boundary. Paleoceanography, v 18, n. 3, 1057, doi:10.1029/2002PA000804, 2003.

O'Brien, C. L., Huber, M., Thomas, E., Pagani, M., Super, J. R., Elder, L. E., Hull, P. M. The enigma of Oligocene climate and global surface temperature evolution. Proceedings of the National Academy of Sciences Oct 2020, 117 (41) 25302-25309; DOI:10.1073/pnas.2003914117, 2020.

Orsi, A.H.,Whitworth, T., Nowlin, W.D. On the meridional extent and fronts of the Antarctic Circumpolar Current, Deep Sea Research Part I: Oceanographic Research Papers, v 42, 5, 641-673, https://doi.org/10.1016/0967-0637(95)00021-W, 1995.

Pagani, M., Zachos, J. C., Freeman, K. H., Tipple, B., and Bohaty, S. Marked decline in atmospheric carbon dioxide concentrations during the Paleogene.Science, 309 600–603. DOI: 10.1126/science.111006, 2005

Pagani, M., Huber, M., Liu, Z., Bohaty, S.M., Henderiks, J., Sijp, W., Krishnan, S. & DeConto, R.M. The role of carbon dioxide during the onset of Antarctic glaciation. Science, 334, 1261-1264. DOI: 10.1126/science.1203909, 2011.

Pälike, H., Lyle, M.W., Nishi, H., Raffi, I., Ridgwell, A., Gamage, K., Klaus, A., Acton, G., Anderson, L., Backman, J., Baldauf, J., Beltran, C., Bohaty, S.M., Bown, P., Busch, W., Channell, J.E.T., Chun, C.O.J., Delaney, M., Dewangan, P., Dunkley Jones, T., Edgar, K.M., Evans, H., Fitch, P., Foster, G.L., Gussone, N., Hasegawa, H., Hathorne, E.C., Hayashi, H., Herrle, J.O., Holbourn, A., Hovan, S., Hyeong, K., Iijima, K., Ito, T., Kamikuri, S., Kimoto, K., Kuroda, J., Leon-Rodriguez, L., Malinverno, A., Moore, T.C., Murphy, B.H., Murphy, D.P., Nakamura, H., Ogane, K., Ohneiser, C., Richter, C., Robinson, R., Rohling, E.J., Romero, O., Sawada, K., Scher, H., Schneider, L., Sluijs, A., Takata, H., Tian, J., Tsujimoto, A., Wade, B.S., Westerhold, T., Wilkens, R., Williams, T., Wilson, P.A., Yamamoto, Y., Yamamoto, S., Yamazaki, T., Zeebe, R.E. A Cenozoic record of the equatorial Pacific carbonate compensation depth, Nature 488 (7413), 609-615, doi:10.1038/nature11360, 2012.

Palter, J. B., Sarmiento, J. L., Marinov, I. & Gruber, N. In Chemical Oceanography of Frontal Zones (ed. Belkin, I. M.) https://doi.org/10.1007/698_2013_241 (Springer), 2013.

https://doi.org/10.5194/egusphere-2023-1276
Preprint. Discussion started: 25 July 2023

Park Y. H., Park T., Kim T.W., Lee S.H., Hong C.S., Lee J.H., Rio M.H., Pujol M.I., Ballarotta M., Durand I., Provost C. Observations of the Antarctic Circumpolar Current over the Udintsev Fracture Zone, the narrowest choke point in the Southern Ocean. Journal of Geophysical Research: Oceans, -. https://doi.org/10.1029/2019JC015024, 2019.

Pearson, P. & Palmer, M.R. Atmospheric carbon dioxide concentrations over the past 60 million years. Nature, 206, 695-699, 2000.

Pearson, P., Foster, G. and Wade, B. Atmospheric carbon dioxide through the Eocene–Oligocene climate transition. Nature, 461, 1110–1113. https://doi.org/10.1038/nature08447, 2009.

Persico, D., and Villa, G. High-resolution calcareous nannofossil biostratigraphy and palaeoecology from Eocene-Oligocene sediments, Maud Rise, Weddell Sea, and Kerguelen Plateau, Antarctica: University of Parma, Italy, Abstract 9th International Nannoplankton Association Conference, 8th−14th September 2002.

Persico, D., and Villa, G. Eocene-Oligocene calcareous nannofossils from Maud Rise and Kerguelen Plateau (Antarctica): Palaeoecological and palaeoceanographic implications: Marine Micropaleontology, v. 52, p. 153–179, doi: 10.1016/j.marmicro.2004.05.002, 2004.

Piepgras D.J., Wasserburg G.J. Isotopic composition of neodymium in waters from the drake passage. Science Jul 16;217(4556):207-14. doi:10.1126/science.217.4556.207, 1992.

Pfuhl, H. A. & McCave, I. N. Evidence for late Oligocene establishment of the Antarctic Circumpolar Current. Earth and Planetary Science Letters, 235, 715–728, 2005.

Prothero, D.R. & Berggren, W.A. Eocene-Oligocene Climatic and Biotic Evolution. Princeton Univ. Press, Princeton, NJ, 1992.

Pusz, A. E., Thunell, R.C. and Miller, K.G. Deep water temperature, carbonate ion, and ice volume changes across the Eocene-Oligocene climate transition, Paleoceanography, 26, PA2205, doi:10.1029/2010PA001950, 2011.

Renaudie, J., Lazarus, D. and Diver, P. NSB (Neptune Sandbox Berlin): An expanded and improved database of marine planktonic microfossil data and deep-sea stratigraphy. Palaeontologia Electronica,23(1):a11 https://doi.org/10.26879/1032, 2020.

Rintoul, S.R., Hughes, C.W., Olbers, D. Chapter 4.6 The antarctic circumpolar current system, Editor(s): Gerold Siedler, John Church, John Gould, International Geophysics, Academic Press, v.77, 271-XXXVI, 2001.

Robert, C., Diester Haass, L. and Chamley, H. (2002). Late Eocene Oligocene oceanographic development at southern high latitudes, from terrigenous and biogenic particles: A comparison of Kerguelen Plateau and Maud Rise, ODP Sites 744 and 689, Mar. Geol., 191, 37–54, doi:10.1016/S0025-3227(02)00508-X, 2002.

Roberts, A.P., Bicknell, S.J., Byatt, J., Bohaty, S.M., Florindo, F., and Harwood, D.M. Magnetostratigraphic calibration of Southern Ocean diatom datums from the Eocene-Oligocene of Kerguelen Plateau (Ocean Drilling Program Sites 744 and 748): Palaeogeography, Palaeoclimatology, Palaeoecology, v. 198, p. 145–168, doi: 10.1016/S0031-0182(03)00397-3, 2003.

Salamy, K.A & Zachos, J.C. Latest Eocene-Early Oligocene climate change and Southern Ocean fertility: inferences from sediment accumulation and stable isotope data. Paleogeography, Paleoclimatology, Paleoecology, 145, 61-77. https://doi.org/10.1016/S0031-0182(98)00093-5, 1992.

Sarkar, S., Basak, C., Frank, M. Late Eocene onset of the Proto-Antarctic Circumpolar Current. Science Reports, 9, 10125, 2019.

Sarmiento, J.L., Gruber, N., Brzezinski, M.A., Dunne, J.P. High-latitude controls of thermocline nutrients and low latitude biological productivity. Nature 247, 56–60, 2004.

Sauermilch, I., Whittaker, J.M., Klocker, A. et al. Gateway-driven weakening of ocean gyres leads to Southern Ocean cooling. Nat Commun 12, 6465. https://doi.org/10.1038/s41467-021-26658-1, 2021.

Shackleton, N.J. and Opdyke, N.D. Oxygen isotope and paleomagnetic stratigraphy of equatorial Pacific core V28-238: Oxygen isotope temperatures and ice volumes on a 105 year and 106 year scale. Quat. Res., 3(1), 39-55, doi::10.1016/0033-5894(73)90052-5, 1973.

Shackleton, N. J., and Kennett, P. Paleotemperature history of the Cenozoic and the initiation of Antarctic glaciation: Oxygen and carbon isotope analysis in DSDP Sites 277, 279 and 281, Initial Rep. Deep Sea Drill. Proj., 29, 881–884, 1975.

Shackleton, N.J., Hall, M.A., Boersma, A.Oxygen and carbon isotope data from Leg 74 foraminifers. Init. Rep. Deep Sea Drilling Proj., 74, pp. 599-612, 1984.

Scher, H.D., Martin, E.E. Circulation in the Southern Ocean during the Paleogene inferred from neodymium isotopes. Earth Planet. Sci. Lett. 228, 391–405. https:// doi.org/10.1016/J.EPSL.2004.10.016, 2004.

Scher, H. D. and Martin, E. E. Timing and climatic consequences of the opening of Drake Passage. Science, 312, 428–430. DOI: 10.1126/science.1120044, 2006.

Scher, H.D., Bohaty, S.M., Smith, B.W., Munn, G.H. Isotopic interrogation of a suspected late Eocene glaciation. Paleoceanography 29, 628–644. https://doi.org/ 10.1002/2014PA002648, 2014.

Scher, H., Whittaker, J., Williams, S. et al. Onset of Antarctic Circumpolar Current 30 million years ago as Tasmanian Gateway aligned with westerlies. Nature 523 580–583. https://doi.org/10.1038/nature14598, 2015.

https://doi.org/10.5194/egusphere-2023-1276
Preprint. Discussion started: 25 July 2023

Schumacher, S. and Lazarus, D. Regional differences in pelagic productivity in the late Eocene to early Oligocene—a comparison of southern high latitudes and lower latitudes. Paleogeography, Paleoclimatology, Paleoecology, 214, 243-263. https://doi.org/10.1016/j.palaeo.2004.06.018, 2004.

Seton, M., Müller, R., Zahirovic, S., Gaina, C., Torsvik, T., Shephard, G., Talsma, A., Gurnis, M., Turner, M., Maus, S., and Chandler, M. Global continental and ocean basin reconstructions since 200Ma. Earth-Science Reviews, 113:212-270. https://doi.org/10.1016/ j.earscirev.2012.03.002, 2012.

Sijp, W. P., England, M. H. and Toggweiler, J. R. Effect of Ocean Gateway Changes under Greenhouse Warmth, J. Clim., 22(24), 6639–6652, doi:10.1175/2009JCLI3003.1, 2009.

Sijp, W. P., England, M.H., and Huber, M. Effect of the deepening of the Tasman Gateway on the global ocean. Paleoceanography, 26, doi:10.1029/2011PA002143, 2011.

Sokolov, S., Rintoul, S.R. On the relationship between fronts of the Antarctic Circumpolar Current and surface chlorophyll concentrations in the Southern Ocean. J. Geophys. Res. 112, 2007.

Sokolov, S. Rintoul, S.R. Circumpolar structure and distribution of the Antarctic Circumpolar Current fronts: 1. Mean circumpolar paths. J. Geophys. Res. 114, 2009.

Spiess, V. (1990) Cenozoic magnetostratigraphy of Leg 113 drill sites, Maud Rise, Weddell Sea, Antarctica, In: Barker, P. F., et al., (eds). Proceedings of the Ocean Drilling Program: College Station, Texas, Scientific Results, v. 113, p. 261–318.

Stickley, C.E., Brinkhuis, H., Schellenberg, S.A., Sluijs, A., Röhl, U., Fuller, M., Grauert, M., Huber, M., Warnaar, J., Williams, G.L. Timing and nature of the deepening of the Tasmanian Gateway. Paleoceanography, 19 (4). https://doi.org/10.1029/2004PA001022, 2004.

Taylor, V. E., Westerhold, T., Bohaty, S.M., Backman, J., Dunkley Jones, T., Edgar, K. M.. Egan, K. E., Lyle, M., Pälike, H., Röhl, U., Zachos, J., Wilson, P. A. Transient Shoaling, Over-Deepening and Settling of the Calcite Compensation Depth at the Eocene-Oligocene Transition. Paleoceanography and Paloclimatology, 38(6), https://doi.org/10.1029/2022PA004493, 2023

Thole, L.M., Amsler, H.E., Moretti, S., Auderset, A., Gilgannon, J., Lippold, J., Vogel, H., Crosta, X., Mazaud, A., Michel, E., Martínez-García, A., Jaccard, S.L. Glacial- nterglacial dust and export production records from the Southern Indian Ocean. Earth Planet. Sci. Lett. 525, 115716. https://doi.org/10.1016/j.epsl.2019.115716, 2019.

Thomas, E. Late Cretaceous through Neogene deep-sea benthic foraminifera (Maud Rise, Weddell Sea, Antarctica). Proc. Ocean Drill. Program Sci. Results 113, 571–594, 1990.

Toggweiler, J. R. and Samuels, B. Effect of Drake Passage on the global thermohaline circulation. Deep-Sea Res. I 42, 477–500, 1995.

Toggweiller, J.R. and Bjornsoon, H. Drake Passage and paleoclimate. Journal of Quaternary Science, 15 (4) 319-328.

Toumoulin, A., Donnadieu, Y., Ladant, J., Batenburg, S.J., Poblete, F. and Dupont-Nivet, G. (2020). Quantifying the Effect of the Drake Passage Opening on the Eocene Ocean. Paleoceanography and Paloclimatology, 35(8) https://doi.org/10.1029/2020PA003889, 2000.

Van Breedam, J., Huybrechts, P., Crucifix, M. Modelling evidence for late Eocene Antarctic glaciations, Earth and Planetary Science Letters, 586, 117532, ISSN 0012-821X, https://doi.org/10.1016/j.epsl.2022.117532, 2022.

Vonhof, H.B., Smit, J., Brinkhuis, H., Montanari, A., and Nederbragt, A.J. Global cooling accelerated by early late Eocene impacts: Geology, v. 28, p. 687–690, doi: 10.1130/0091-7613(2000)0282.3.CO;2, 2000.

Villa, G., Fiorini, C., Persico, D., Roberts, A.P. Florindo, F. Middle Eocene to Late Oligocene Antarctic glaciation/deglaciation and Southern Ocean productivity. Paleoceanography and Paloclimatology, 29, 223-237. https://doi.org/10.1002/2013PA002518, 2014.

Wei, W. Paleogene chronology of Southern Ocean drill holes: An update, in Kennett, J.P., and Warnke, D.A., eds., The Antarctic paleoenvironment: A perspective on global change: Antarctic Research Series, v. 56, p. 75–96, 1992.

Wei, W., and Wise, S.W. Jr. Eocene-Oligocene calcareous nannofossil magnetobiochronology of the Southern Ocean: Newsletters on Stratigraphy, v. 26, p. 119–132, 1992.

Westerhold.T., Marwan, N., Drury, A.J., Liebrand, D., Agnini, C., Anagnostou, E., Barnet, J.S.K., Bohaty, S.M., Vleeschouwer, Florindo, F., Frederichs, T., Hodell, D.A., Holbourn, A.E., Kroon, D., Lauretano, V., Littler, K., Lourens, L.J., Lyle, M., Pålike, H., Röhl, U., Tian, J., Wilkens, R.H., Wilson, P.A. and Zachos, J.C. An astronomically dated record of Earth's climate and ist predictability over the last 66 million years. Science, 369, 6509, 1383-1387. DOI: 10.1126/science.aba6853, 2020.

Wright, N.M., Scher, H.D., Seton, M., Huck, C.E., Duggan, B.D. No change in Southern Ocean Circulation in the Indian Ocean from the Eocene through Late Oligocene. Paleoceanography, Paleoclimatology, 33, 152–167. https://doi.org/10.1002/ 2017PA003238, 2018.

Zachos, C. J., T. M. Quinn, and K. A. Salamy. High-resolution (104 years) deep-sea foraminiferal stable isotope records of the Eocene-Oligocene climate transition, Paleoceanography, 11, 251–266, 1996.

Zachos, C. J., B. N. Opdyke, T. M. Quinn, C. E. Jones, and A. N. Halliday. Early Cenozoic glaciation, Antarctic weathering, and seawater 87Sr/86Sr: Is there a link? Chem. Geol., 161, 165–180, 1999.

Zachos, J., Pagani, M., Sloan, L., Thomas, E., Billups, K. Trends, rhythms and aberrations in global climate 65 Ma to present. Science, 292, 686-693. https://doi.org/10.1126/science.1059412, 2001.

Zachos, J., Kump, L. Carbon cycle feedbacks and the initiation of Antarctic glaciation in the earliest Oligocene. Global and Planetary Change, 47 (1). 51-66 doi:10.1016/j.gloplacha.2005.01.001, 2005.
Zhang, Y. G., Pagani, M., Liu, Z., Bohaty, S. M., and DeConto, R. A 40-million-year history of atmospheric CO2. Philosophical Transactions of the Royal Society A, v. 371, https://doi.org/10.1098/rsta.2013.0096, 2013.

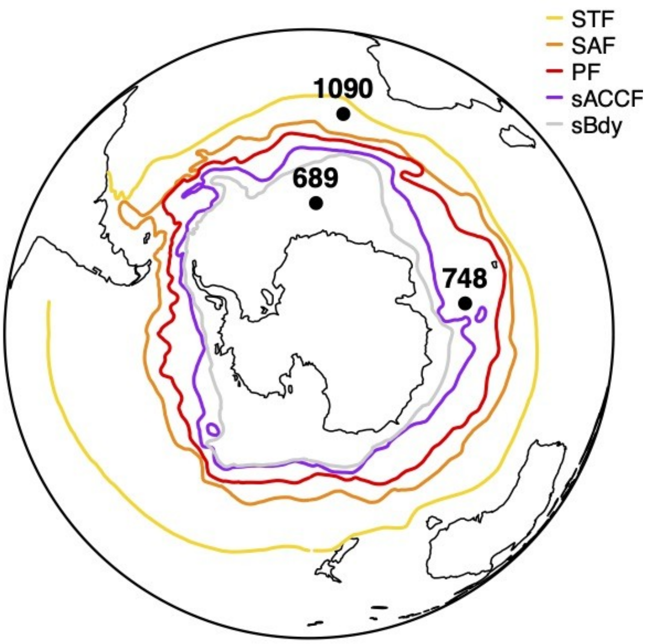

Figure 1: Schematic Antarctic Circumpolar Current (ACC) and Southern Ocean fronts as determined by Orsi et al., 1995, named from north to south, STF: Subtropical front, SAF: Subantarctic Front; PF: Polar Front and SACCF: Southern Antarctic Circumpolar Current Front, and sBdy: Southern Boundary front. Modern location of ODP sites (1090, Agulhas Ridge; 689, Maud Rise and 748, Kerguelen Plateau) used for reconstructions in this study. ODP = Ocean Drilling Program.

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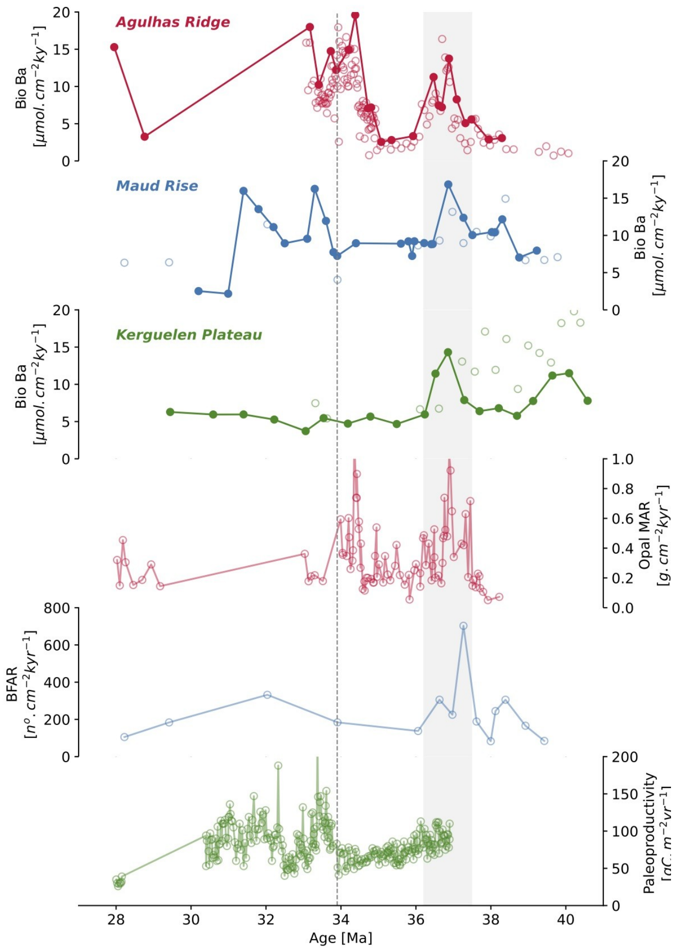

Figure 2: Paleoproductivity proxies vs Age (Ma) for Agulhas Ridge (ODP Site 1090, in red), Maud Rise (ODP Site 689, in blue) and Kerguelen Plateau (ODP Sites 748, 744 and 738, in green). Solid circles are new biogenic barium accumulation rate (bio-Ba, µmol cm^{-2} kyr^{-1}) data of this study, open circles from prior literature (Agulhas Ridge data from Anderson and Delaney, 2005; Maud Rise data from Diester-Haass and Faul 2019; Kerguelen Plateau data from Faul et al., 2010). Site 1090 opal MAR data are from Diekmann et al., 2004. Site 689 BFAR data are from Diester-Haass and Zahn 1996. Kerguelen Plateau Site 744 paleoproductivity data from Diester-Haass (1996). Vertical bar identifies the E/O boundary (at ca 33.8 Ma). Shaded area encompasses the late-Eocene productivity event.

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Preprint. Discussion started: 25 July 2023

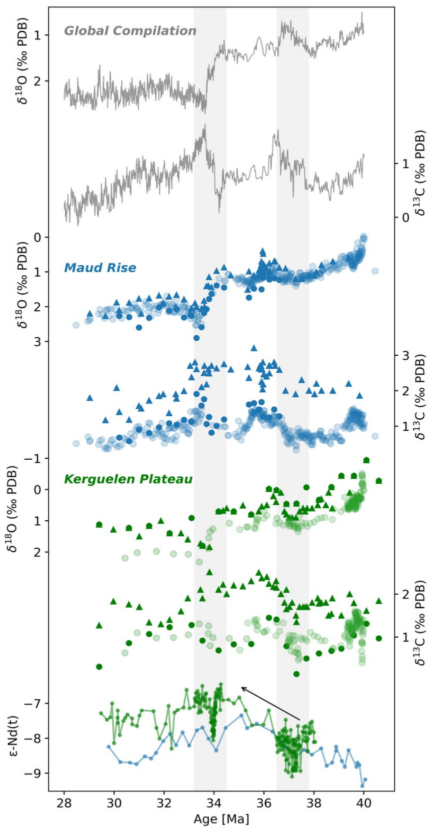

Figure 3: Multiproxy records from the late Eocene and early Oligocene. Global compilation of oxygen and carbon stable isotopes (from Westerhold et al., 2020). New generated oxygen and carbon benthic foraminiferal isotopes data (solid circles) and fine fraction (<45µm) (solid triangles), and previously published oxygen and carbon stable isotopes (shaded circles, from Mackensen and Ehrmann, 1992; Diester-Haass and Zahn, 1996; Bohaty et al., 2003) from Atlantic Southern Ocean (Maud Rise) ODP Site 689 (in blue) and Indian Southern Ocean (Kerguelen Plateau) ODP Site 748 (in green). PDB is PeeDee Belemnite carbonate reference. Compilation of εNd data obtained from fossil fish teeth for the Atlantic Sector of SO (Maud Rise - in blue, site 689), and for the Indian sector of SO (Kerguelen Plateau - in green, sites 738 and 748) (Scher and Martin, 2004, 2006; Scher et al., 2014; Wright et al. 2018). Shaded area identifies E/O boundary at ca 33.8 Ma and the changes in ocean circulation. Note inverted y-axis scales for oxygen and Nd isotopes.

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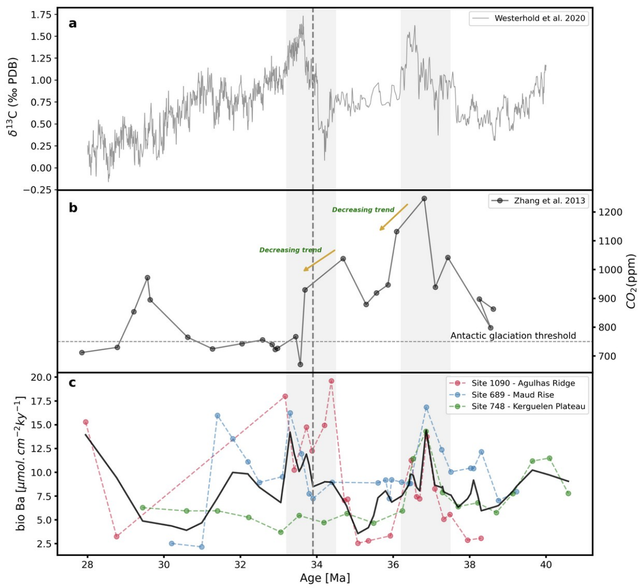

1016 **Figure 4: Comparison between (a) a global compilation of carbon stable isotopes (from Westerhold et al., 2020),**
1017 **(b) alkenone-based atmospheric *p*CO_2 record (from Zhang et al., 2013) and (c) biogenic Barium (bio-Ba) export**
1018 **productivity proxy. Antarctic glaciation thresholds (approx. 750 ppm) (from climate model, DeConto et al. 2008)**
1019 **is marked by a dashed line. Shaded areas encompass the late-Eocene and early-Oligocene high productivity**
1020 **intervals.**

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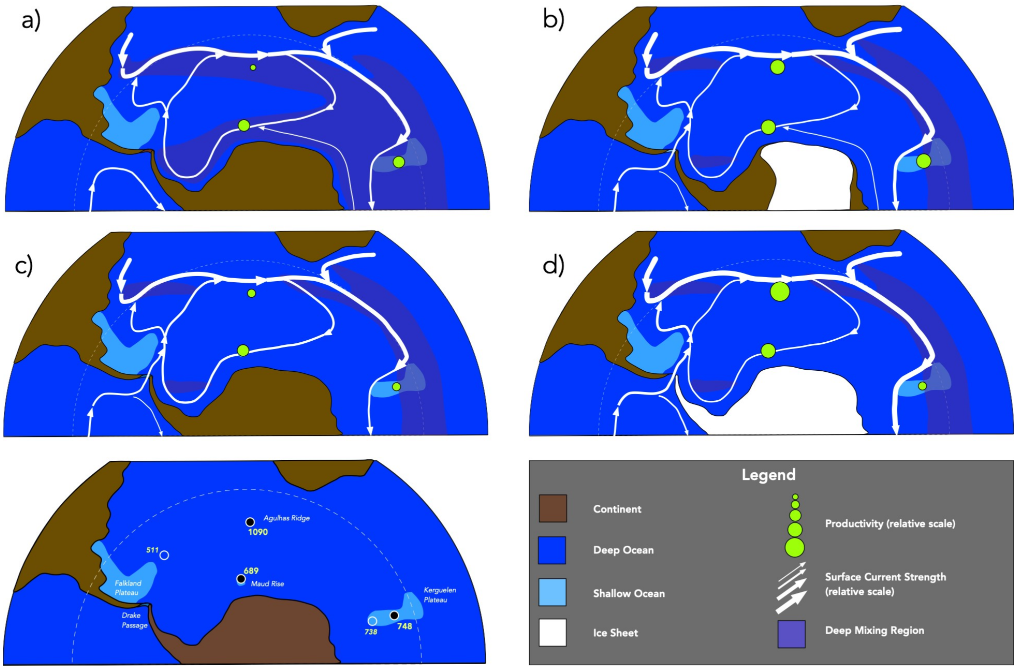

Figure 5: Interpretive scenario of paleoceanographic change in the late Eocene to earliest Oligocene Southern Ocean. Base map, circulation patterns and extent of deep mixing regions largely after Toumoulin et al. (2020), ice sheet extent at 38 Ma after models in Van Breedam (2022).Productivity values based on results of this study, shown in relative scale. Note general trend towards higher productivity values, and within this, higher productivity, focussed near proto-ACC, during intervals with inferred ice sheets.