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Insolation forcing of coccolithophore productivity in the North Atlantic during the Middle Pleistocene

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ABSTRACT

Coccolithophores play a key role in the oceanic carbon cycle through the biological and carbonate pumps. Understanding controls on coccolithophore productivity is thus fundamental to quantify oceanic carbon cycling. We investigate changes in coccolithophore productivity over several Pleistocene glacial-interglacial cycles using a high-resolution coccolith Sr/Ca ratio record, which is an indicator of growth rate and thus a proxy for coccolithophore productivity. We use Middle Pleistocene sediments from the North Atlantic Integrated Ocean Drilling Program (IODP) Site U1313 (41.00′ N, 32.58’ W) spanning Marine Isotopic Stages 16 to 10 (638–356 kyr). The location of the record allows us to investigate processes affecting productivity in a mid-latitude setting and to unravel the effects of temperature and regional ocean circulation. Coccolithophore productivity shows a dominant glacial-interglacial cyclicity with higher productivity during glacials, which appears to reflect the southward migration of the North Atlantic high productivity zone currently located between 45° and 55° N. Spectral analysis of the productivity record reveals a suborbital variability consistent with forcing by insolation maxima superimposed on the front migration pattern. Similar to today, coccolithophore productivity during interglacials was enhanced when insolation was at its maximum in spring or in autumn, whereas during glacials, productivity was enhanced when summer/autumn insolation was at its maximum. We show that in the studied region, coccolithophore productivity was driven by processes reflecting regional insolation. Applying this information to model experiments is required to assess if coccolithophore productivity played a significant role in past changes of atmospheric CO_2.

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1. Introduction

Coccolithophores are the main primary producers in temperate regions of the open ocean (Brand, 1994) producing biogenic calcite (Bolton et al., 2016) and mediating cycling, sequestration and export of organic and inorganic carbon (Rost and Riebesell, 2004; Baumann et al., 2005). Coccoliths, the minute calcite plates that cover coccolithophore cell, are very abundant in seafloor sediments and have been extensively used as paleoenvironmental tracers providing information on paleoceanographic conditions and composition of the overlying photic zone's communities (e.g., Flores et al., 2003; Baumann et al., 2005; Marino et al., 2014; Emanuele et al., 2015; Maiorano et al., 2015). Enhanced coccolithophore calcification during glacials and terminations has been suggested to drive a decrease in the availability of the carbonate ion

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in the ocean and trigger the deglacial rise in atmospheric carbon dioxide (pCO_2) (Rickaby et al., 2010; Omta et al., 2013). Reconstructing past variations in the production and accumulation of sedimentary carbonate is thus important for understanding changes in pCO_2 (Sigman et al., 1998; Sigman and Boyle, 2000).

In well-preserved sediments, coccolithophore productivity has commonly been inferred from the total coccolith abundance (e.g., Emanuele et al., 2015) and the nannofossil accumulation rate (NAR) (e.g., Flores and Sierro, 2007; Cabarcos et al., 2014), but also from the relative abundance of small placoliths and *Florisphaera profunda* (e.g., Marino et al., 2008). In addition, other primary production indicators, such as alkenones (organic molecules mostly produced by certain species of coccolithophores) are also used (e.g., Villanueva et al., 2001; Emanuele et al., 2015). The accumulation of organic matter, including total organic carbon (TOC) and alkenones, represents the most direct record of general and coccolithophore productivity, respectively (Schoepfer et al., 2015). Both have been used as paleo-productivity proxies (e.g., Rühlemann et al., 1999; Stein et al., 2009) by assuming that changes in organic carbon content of sediment can be interpreted as changes in the surface productivity through time (Wefer et al., 1999). However, all of these proxies depend not only on supply but also on dilution (by minerals or other sediment constituents), sedimentation or accumulation rates, and preservation conditions (Rullkötter, 2006).

The coccolith fraction (CF) Sr/Ca ratio has been suggested as an alternative productivity proxy that is independent of accumulation rate. Coccolithophores construct coccoliths internally within their cell and several studies suggest that Sr/Ca of the coccolith is directly proportional to the coccolith calcification rate, which is a function of growth rate (e.g., Stoll and Schrag, 2000; Rickaby et al., 2007; Mejía et al., 2014). The faster coccolithophores grow, the faster they calcify and the more Sr is incorporated into the calcite lattice of their coccoliths (Stoll and Schrag, 2000; Stoll et al., 2002a).

The amount of Sr introduced into the calcite (Sr partitioning) varies among genera and species, with larger and more heavily calcified coccoliths generally having higher Sr content than smaller and lighter coccoliths (Stoll et al., 2007; Fink et al., 2010). Dissolution intensity and changes in coccolith assemblage appear to exert only a minor influence on CF Sr/Ca in the modern ocean (Stoll and Schrag, 2000). However, significant downcore changes in coccolith assemblages, including due to intensive or selective dissolution (Stoll et al., 2002b), should be evaluated when applying this proxy to the past.

In laboratory cultures, coccolith Sr/Ca also correlates with temperature. Stoll et al. (2002a) cultured different coccolithophore species strains at different temperatures, with results for several strains of *Gephyrocapsa oceanica* indicating that increasing temperature can increase Sr partitioning. This suggests that there is a temperature-controlled change in Sr partitioning coefficients (D_{Sr}) in calcite, analogous to that observed in abiogenic dolomite-calcite and aragonite-calcite transformation experiments (Malone and Baker, 1999). If this interpretation is correct, then the temperature effect should be removed from coccolith Sr/Ca records to identify the component of variation due to growth rate. If the temperature effect on D_{Sr} is the dominant source of temperature dependence on coccolith Sr/Ca in culture experiments (Stoll et al., 2002a; Müller et al., 2014), then the relationship from cultures coupled with an independent temperature measurement (e.g., Mg/Ca-based sea-surface temperature (SST) from foraminifers) can be used to correct for this effect, as has been done in previous studies (e.g., Mejía et al., 2014). With temperature and assemblage effects considered, the SST corrected CF Sr/Ca curve should mostly reflect qualitatively coccolithophore growth rate and therefore their productivity (Stoll et al., 2002a; Müller et al., 2014). The validity of the CF Sr/Ca productivity proxy has been established in previous studies in oceanographic regions where SST variations over glacial-interglacial cycles were relatively small (~4 - 6 °C) (Mejía et al., 2014; Tangunan et al., 2017) as well as in the Southern Ocean where SSTs are significantly lower (varying between 6 °C - 12 °C) (Saavedra-Pellitero et al., 2017).

Here, we reconstruct the paleoproductivity of coccolithophores, the most significant component of the phytoplankton community in the central North Atlantic, based on the CF Sr/Ca ratio. We used a carbonate-rich sediment archive that contains well-preserved coccolithophores from the mid-latitude North Atlantic (IODP Site U1313), spanning the mid-Brunhes dissolution interval and the *Gephyrocapsa caribbeanica* acme (e.g., Baumann and Freitag, 2004; Barker et al., 2006). The location of IODP Site U1313 (Fig. 1) allows the assessment of coccolithophore productivity changes in a transitional productivity area particularly sensitive to basin-scale forcing changes, such as changes in temperature and circulation (Barton et al., 2003).

The key motivation for this study is to understand the climate drivers of North Atlantic coccolithophore production dynamics across Pleistocene glacial/interglacial cycles. We investigate how atmospheric and hydrographic changes influence coccolithophore productivity, at both orbital and suborbital time scales. We emphasize that our research focuses on the qualitative characteristics of the paleoproductivity record, namely the inherent orbital and suborbital periodicities, rather than quantitatively estimating the coccolithophore productivity. Thus, we reconstruct the CF Sr/Ca component of coccolithophore productivity and not quantitative production.

We analyze changes in the ocean surface circulation and its relationship to nutrient availability, as well as changes in the insolation as a potential forcing mechanism. To do this we reconstructed coccolithophore productivity qualitatively based on the CF Sr/Ca at IODP Site U1313 over the interval between 638 and 356 ka. This is the first time that the Sr/Ca proxy has been used in a temperate region that experienced significant SST oscillations associated with glacial ice-rafting events (Stein et al., 2009; Naafs et al., 2011) and we address potential caveats accordingly. The studied interval covers a wide range of climatic conditions from Marine Isotopic Stages (MIS) 15 to MIS 11, including the late and early phases of MIS 16 and MIS 10, respectively. MIS 11 is acknowledged as an analogue for the present interglacial (e.g., Loutre and Berger, 2003) and MIS 12 was one of the harshest glacials of the last one million years (e.g., Jansen et al., 1986). On the other hand, MIS 15 and MIS 13, on the other hand, were relatively milder interglacial stages than MIS 11 (Jouzel et al., 2007).

It is worth noting that coccolithophore communities evolved and changed throughout this interval (e.g. Bollmann et al., 1998). Our 300 kyr-long sedimentary record falls mostly within the *Gephyrocapsa caribbeanica* acme between MIS 14/MIS 13 and MIS 8 when this species dominated (≥50%) coccolithophore communities worldwide. The interval also includes the extinction of *Pseudoemiliania lacunosa* in MIS 12 (Raffi et al., 2006). Neither species are found in modern assemblages and their behavior cannot be assessed through cultured studies. Additionally, our mid-Brunhes record precedes the first occurrence of *Emiliania huxleyi* (290 ka; Raffi et al., 2006), the cosmopolitan and dominating species in the modern ocean.

2. Regional setting

2.1. Hydrography

The North Atlantic constitutes a vigorous overturning circulation of the modern ocean (Toggweiler, 2009). It is characterized by the central anticyclonic subtropical gyre, the northern cyclonic

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