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Marine Isotope Stage 11 in the Pacific sector of the Southern Ocean; a coccolithophore perspective

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A B S T R A C T

This work aims to provide new insights into environmental conditions during late Pleistocene Marine Isotope Stage 11 (MIS 11) in the Southern Ocean. We generated a multi-proxy coccolithophore dataset based on sediment core PS75/059-2. This core was retrieved at the western flank of the southern East Pacific Rise crest at ~3600 m water depth. Coccolithophore assemblage counts indicated that the coccolith fraction (CF; <20 μm) during MIS 11 was dominated by *Gephyrocapsa caribbeanica* and subsequently by small *Gephyrocapsa*. Coccolith accumulation rates, CF Sr/Ca data and temperature-corrected CF Sr/Ca records were consistent and showed a steep increase in coccolithophore productivity as well as apparent coccolith calcification during Termination V. Maximum values were reached during MIS 11. We explain this high coccolithophore production during MIS 11 by changes in sea surface temperature and nutrient regimes, due to a re-organisation of the surface circulation patterns and a southward migration of the frontal systems. Furthermore, the immense carbonate production of the coccolithophores may have contributed to increased atmospheric CO_2 contents, causing a drawdown of the carbonate saturation and an increase in dissolution at the seafloor. However the atmospheric CO_2 did not reach higher values probably due to the effective ballasting of organic matter by coccoliths.

1. Introduction

The study of past interglacial stages offers us the opportunity to understand the Earth's climatic history during warm periods in the absence of the anthropogenic influences. The comparison of these "base-scenarios" with the Anthropocene gives us the opportunity to quantify the human impact on the climate (e.g., Tzedakis et al., 2009). Amongst past interglacials, Marine Isotope Stage 11 (MIS 11; between ca. 424 and 374 kyr) is considered the best analogue of a human-free Holocene (e.g., Candy et al., 2014; Raynaud and Barnola, 2005) and appear to be unique in the Earth's climate history for several reasons. For example, the duration of warm interglacial conditions is longer during MIS 11 than for other interglacial stages of the past 500 kyr (e.g., Dickson et al., 2009; Droxler et al., 1999; Hodell et al., 2000; Howard, 1997; Melles et al., 2012; Prokopenko et al., 2010; Tarasov et al., 2011). The total and or partial collapse of the ice sheets at Greenland, West Antarctica and East Antarctica has been invoked as the most likely explanation for the higher than Holocene sea level (6–13 m; Hearty et al., 1999; Raymo and Mitrovica, 2012) during this interglacial. MIS 11 is also characterised by the unusual increase in the carbonate production at high latitudes, strong thermohaline circulation, coral reef expansion resulting in large accumulation of neritic carbonates and overall poor pelagic carbonate preservation (e.g., Barker, 2007; Barker et al., 2006). Unlike most other interglacials of the late Quaternary, MIS 11 cannot be explained and modeled just within the context of Milankovitch forcing mechanisms (the "MIS 11 problem"; e.g., Imbrie and Imbrie, 1980). Models forced with the relatively low 60° to 70°N insolation are unable to produce strong interglacial conditions (Droxler and Farrell, 2000; Droxler et al., 1999). Several theories have been suggested to address this problem. The warmth and the resulting overall higher than present eustatic sea level during MIS 11 could be explained by higher atmospheric CO_2 levels (Droxler and Farrell, 2000). These high CO_2 levels might be attributed to a rapid production-storage of carbonates along continental shelves and carbonate platforms at low

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latitudes together with an increase in carbonate production in the photic zones at high latitudes (Droxler and Farrell, 2000; Droxler et al., 1997; Hodell et al., 2000). This could have decreased the overall budget of carbonate in the oceans (together with the increasing atmospheric CO_2) producing a shoaling of the lysocline and enhancing deep pelagic carbonate dissolution (e.g., Farrell and Prell, 1989; Peterson and Prell, 1985). Despite evidence from oceanic carbonate records that point to drastic changes in the carbon cycle, ice core records suggest that the atmospheric CO_2 levels during MIS 11 were similar to the pre-industrial Holocene (Raynaud et al., 2005).

From a quantitative point of view, coccolithophores are one of the most important pelagic calcifying organisms (Westbroek et al., 1993). These unicellular phytoplanktonic algae impact the global carbon cycle through the emission and consumption of CO_2 during calcification and photosynthesis, respectively (Westbroek et al., 1993), modifying the alkalinity of the seawater (Denman and Peña, 1999). Therefore the net influence of coccolithophores on pCO_2 depends on the ballast of the plankton and the particulate inorganic: organic carbon ratio (e.g., Rickaby et al., 2007). The relatively small but highly calcified coccolithophore species *Gephyrocapsa caribbeanica* dominated during MIS 11 (e.g., Amore et al., 2012; Bollmann et al., 1998; Flores et al., 1999), accounting for instance for >80% of the total carbonate off SW Africa (Baumann and Freitag, 2004) and 60–90% in the NW Pacific Ocean (Bordiga et al., 2014). Such an increase in coccolith carbonate production could have led to increased dissolution at low latitudes in the Indian and Pacific Oceans (Baumann and Freitag, 2004) or even to global dissolution (Barker et al., 2006). Flores et al. (2003) observed that this increment in the abundance of *G. caribbeanica* was contemporaneous with enhanced dissolution in the Atlantic sector of the Southern Ocean (SO). Possible reasons for this world-wide micropaleontological event are still relatively speculative. Bollmann et al. (1998) concluded that evolutionary adaptation was the most likely process for the proliferation of this species, while Flores et al. (2012) linked its dominance to variations in the marine phosphorus availability due to changing oceanographic conditions.

In most of the aforementioned studies, reconstructions were based on coccolith absolute numbers, accumulation rates and coccolith carbonate estimates. In addition to those micropalaeontological-based studies, a number of recent palaeoenvironmental reconstructions explored geochemical and isotope composition in coccoliths (e.g., Bolton et al., 2016; Bolton and Stoll, 2013; Fink et al., 2010; Mejía et al., 2014; Rickaby et al., 2002; Stoll and Ziveri, 2004; Stoll and Schrag, 2000; Stoll et al., 2007a; Ziveri et al., 2003). The Strontium-Calcium ratio (Sr/Ca) is a well-developed proxy, which reflects coccolithophore growth rates and therefore records variations in the coccolithophore production independent of any coccolith counting (Stoll et al., 2002). Positive relationships exist between coccolith Sr/Ca and nutrient-stimulated growth rate changes in culture, sediment core-top, and sediment trap studies, and also remains valid down-core through changes in surface ocean, pH, atmospheric CO_2 and temperature over glacial-interglacial transitions (e.g., Rickaby et al., 2002; Stoll and Schrag, 2000; Stoll et al., 2007a, 2007b). Several records from the Indian and Pacific oceans (Rickaby et al., 2007) as well as North Atlantic (Barker et al., 2006) showed that maximum coccolith Sr/Ca values were reached during MIS 11, coincident with the zenith in the production of *G. caribbeanica*. Rickaby et al. (2007) linked the secular coccolithophore production with the ~400 kyr eccentricity forcing and suggested that the production of coccolithophore bloom species is maximal at times of low eccentricity. Additionally, the enhanced production of coccolith carbonate (e.g., Baumann and Freitag, 2004; Rickaby et al., 2007) and the widespread carbonate dissolution (e.g., Flores et al., 2003, 2012) involve major changes in marine carbonate chemistry (e.g., a decrease in the saturation state) which might be expected to cause an increase in atmospheric CO_2, which has not been recorded (Barker et al., 2006; Raynaud et al., 2005). The reconstruction of coccolithophore productivity history during MIS 11 is crucial for defining past levels of pCO_2 (Rickaby et al., 2007), especially in relatively unexplored regions such as the SO. Based on the key role played by coccolithophores in the ocean biogeochemistry and ecosystem, this study presents a multiproxy coccolithophore dataset at Site PS75/059-2 for MIS 11, located in the Pacific sector of the SO. The aim of this study is to analyze the temporal trends in coccolithophore productivity variations and to link them to the regional palaeoclimate development during this period. In particular we discuss the role of the dominant species *G. caribbeanica* and also the possible coccolithophore contribution to atmospheric CO_2. For this purpose we chose the coccolith Sr/Ca as a proxy for coccolithophore productivity in combination with assemblage variations and coccolith relative and absolute numbers.

2. Regional setting

The present-day SO surface oceanography is characterised by the existence of different oceanographic fronts which have been traditionally defined as clear boundaries between different water masses. The Subtropical Front -STF- (Hofmann, 1985) marks the northernmost extent of Subantarctic waters. South of the Subtropical Front the Antarctic Circumpolar Current flows eastward connecting all major oceans (Orsi et al., 1995). This makes it an important component of the climate system as it can transmit signals from one region to another (Gille, 2002). There are two main Antarctic Circumpolar fronts, the Subantarctic and Polar Fronts (Emery, 1977; Whitworth, 1980). Detailed property indicators at each front can be found in Orsi et al. (1995). The distinct surface water mass regimes separated by the fronts have been called, from north to south (Whitworth, 1980) Subantarctic Zone (SAZ, between the STF and the Subantarctic Front -SAF-), Polar Frontal Zone (between the SAF and the Polar Front -PF-) and Antarctic Zone (south of the PF; Orsi et al., 1995, Fig. 1).

The present-day and recent distribution of extant coccolithophores in the Pacific sector of the SO is closely tied to the dynamics of the oceanographic fronts; e.g., increases in the numbers of coccospheres and coccoliths were found along the SAF and PF (Saavedra-Pellitero et al., 2014; Saavedra-Pellitero and Baumann, 2015). At the same time, the diversity and abundance of coccospheres and coccoliths decrease from the SAZ southward until almost a monospecific and sporadic record of *Emiliania huxleyi* in the Antarctic Zone, where primary production is dominated by diatoms (e.g., Ishikawa et al., 2002; Kemp et al., 2010; Tréguer et al., 1995).

Our study area is located in a high-nutrient low-chlorophyll region in which low to moderate primary production occurs with a net primary production of ca. 120 gC/m^2/yr according to the model of Longhurst et al. (1995). The average annual nutrient content at station PS75/059 showed fair values of 18.15 μmol/L (nitrate) and 1.31 μmol/L (phosphate) (World Ocean Atlas 2009; Garcia et al., 2009) while chlorophyll concentration reached values of 0.18 μg/L at 0 m water depth (Conkright and Boyer, 2002). Accordingly, the modern sea surface temperature (SST) and salinity retrieved from the World Ocean Database 2013 (WOD13, 0.25° grid; Boyer et al., 2013) at the closest point to station PS75/059 were 6.8 °C and 34.2 psu (annual average of the uppermost 50 m of the water column) and 7.3 °C and 34.2 psu (austral summer 50 m average). The in situ conductivity-temperature-depth (CTD) cast measurements available at station PS75/058 (54°12.87′S, 125°26.16′W) were 8.1 °C and 34.1 psu (50 m average).