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Long-term vegetation, climate and ocean dynamics inferred from a 73,500 years old marine sediment core (GeoB2107-3) off southern Brazil

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ABSTRACT

Long-term changes in vegetation and climate of southern Brazil, as well as ocean dynamics of the adjacent South Atlantic, were studied by analyses of pollen, spores and organic-walled dinoflagellate cysts (dinocysts) in marine sediment core GeoB2107-3 collected offshore southern Brazil covering the last 73.5 cal kyr BP. The pollen record indicates that grasslands were much more frequent in the landscapes of southern Brazil during the last glacial period if compared to the late Holocene, reflecting relatively colder and/or less humid climatic conditions. Patches of forest occurred in the lowlands and probably also on the exposed continental shelf that was mainly covered by salt marshes. Interestingly, drought-susceptible *Araucaria* trees were frequent in the highlands (with a similar abundance as during the late Holocene) until 65 cal kyr BP, but were rare during the following glacial period. Atlantic rainforest was present in the northern lowlands of southern Brazil during the recorded last glacial period, but was strongly reduced from 38.5 until 13.0 cal kyr BP. The reduction was probably controlled by colder and/or less humid climatic conditions. Atlantic rainforest expanded to the south since the Lateglacial period, while *Araucaria* forests advanced in the highlands only during the late Holocene. Dinocysts data indicate that the Brazil Current (BC) with its warm, salty and nutrient-poor waters influenced the study area throughout the investigated period. However, variations in the proportion of dinocyst taxa indicating an eutrophic environment reflect the input of nutrients transported mainly by the Brazilian Coastal Current (BCC) and partly discharged by the Rio Itajaí (the major river closest to the core site). This was strongly related to changes in sea level. A stronger influence of the BCC with nutrient rich waters occurred during Marine Isotope Stage (MIS) 4 and in particular during the late MIS 3 and MIS 2 under low sea level. Evidence of *Nothofagus* pollen grains from the southern Andes during late MIS 3 and MIS 2 suggests an efficient transport by the southern westerlies and Argentinean rivers, then by the Malvinas Current and finally by the BCC to the study site. Major changes in the pollen/spore and dinocyst assemblages occur with similar pacing, indicating strongly interlinked continental and marine environmental changes. Proxy comparisons suggest that the changes were driven by similar overarching factors, of which the most important was orbital obliquity.

1. Introduction

The comprehensive knowledge of past environmental changes is valuable for an in-depth understanding of modern and future environmental dynamics under global climate change. In particular, land-ocean interactions may play a crucial role in determining past environmental changes (Ramesh et al., 2015). Studying terrestrial and marine records in the same environmental archive (e.g., marine sediment core) allows a direct comparison of terrestrial and marine environmental changes without the uncertainties commonly

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associated with the synchronization of different archives. Past environmental changes in southeastern South America, such as long-term vegetation, climate and ocean dynamics can provide important information about the Atlantic rainforest, a biodiversity hotspot (Carnaval et al., 2009; Butchart et al., 2010). Furthermore, models of past Atlantic rainforest distribution in southeastern South America (Carnaval and Moritz, 2008), as well as its spreading over the exposed continental shelf during glacial times (Leite et al., 2016), can be evaluated by long marine pollen records.

Several terrestrial pollen archives from southeastern South America have been previously studied. Records from southern Brazil, e.g., Cambará do Sul and Serra do Tabuleiro (Fig. 1b) which date back to 42 cal kyr BP (calibrated kiloyears before the present; the present is set to 1950 by definition), indicate that the southern Brazilian highlands were almost treeless and covered by grassland during glacial times (Behling et al., 2004; Jeske-Pieruschka et al., 2013). The present-day *Araucaria* forest was probably restricted to small populations in protected deep valleys with sufficient moisture (Behling et al., 2004). A pollen record from the Atlantic coastal lowland in southern Brazil at Volta Velha (Fig. 1b) indicates that a mosaic of grassland and subtropical forest occurred in the area of the modern Atlantic rainforest in particular during the Last Glacial Maximum (LGM) (Behling and Negrelle, 2001). This indicates a marked northward retreat of the Atlantic rainforest of at least 750 km compared to today (Behling, 2002).

In southeastern Brazil, a strong reduction of forests is also found in different records from the highlands and mountains (e.g. Behling and Lichte, 1997). However, a long terrestrial record covering the last ca. 130 cal kyr BP from the highlands at Colônia (Fig. 1), southeastern Brazil (Ledru et al., 2005, 2009), indicates oscillations in the amount of arboreal pollen that were related to changes in insolation, more specifically precession. It is noteworthy, however, that the age model of the core beyond ca. 37 cal kyr BP was tuned to other records (i.e., the arboreal pollen record from Colônia was tuned to the $\delta^{18}O$ record from Botuverá Cave (Cruz et al., 2006) and further adjusted to changes in summer insolation at 20°S) and not independently dated. The Atlantic rainforest in the lowlands expanded to southern Brazil during the Lateglacial (Behling and Negrelle, 2001), while on the southern Brazilian highlands *Araucaria* forest expanded significantly only after 4 cal kyr BP and, in particular, during the last 1 cal kyr BP reducing the area covered by grasslands (Behling et al., 2004).

A high-resolution and accurately dated speleothem stable oxygen isotope record from Botuverá Cave in southern Brazil (Fig. 1a) spanning the last 116 cal kyr BP, indicates that regional changes in atmospheric circulation and convective intensity was primarily driven by oscillations in austral summer insolation strongly controlled by orbital precession (Cruz et al., 2005). Periods of high (low) austral summer insolation were characterized by lower (higher) stable oxygen isotope ratios (for details see Fig. 7) and were interpreted as periods of enhanced moisture inflow from the Amazon basin (subtropical western South Atlantic). In turn, periods of strengthened moisture inflow from the Amazon basin (subtropical western South Atlantic) would be related to a strong austral summer monsoon (austral winter cyclonic activity) (Cruz et al., 2005, 2006).

Marine pollen records have the advantage of integrating environmental signals from larger continental areas if compared to continental records (e.g. Dupont and Leroy, 1995). Marine pollen records from the eastern Atlantic, for instance, have been successfully used to reconstruct changes in western African vegetation (e.g. Bouimetarhan et al., 2009; Hooghiemstra et al., 2006; Urrego et al., 2015), but little is known from the western South Atlantic. So far only a few marine pollen records are available off northeastern (Behling et al., 2000; Jennerjahn et al., 2004; Dupont et al., 2010) and southeastern Brazil (Fig. 1; Behling et al., 2002). The latter study gives evidence of a relatively high proportion of Atlantic rainforest in the southeastern Brazilian lowlands during the recorded last glacial, but during the LGM the geographical extension of rainforest was reduced.

Here we provide the first record off southern Brazil which addresses long-term vegetation and climate dynamics in that region, and the possible interactions between southeastern South America and the subtropical western South Atlantic. Additionally, this is the first long dinocyst record for the entire western South Atlantic and provides important insights into oceanic environmental changes during the last 73.5 cal kyr BP. With these records, we addressed four main research questions: What were the long-term environmental changes in southern Brazil and the adjacent ocean? Were there correlations between continental and oceanic environmental changes? How does the new pollen and dinocyst records relate to previously published records from southeastern South America and the adjacent ocean? What were the main factors controlling past environmental changes over long time periods?

2. Study area

2.1. Oceanic environmental setting

Marine sediment core GeoB2107-3 (27.18°S, 46.45°W) was retrieved during RV Meteor cruise M23/2 (Bleil and cruise participants, 1993) from the continental slope off southern Brazil in the western South Atlantic (Fig. 1a) at 1048 m water depth. The coring site is bathed by Antarctic Intermediate Water (AAIW) at a position not far from the boundary between AAIW and North Atlantic Deep Water (NADW), where oxygen-rich waters (AAIW) change to oxygen-poor waters (NADW) (Stramma and England, 1999; Garcia et al., 2014). The distance of the coring site to the coast north of the city of Florianópolis (ca. 27.5°S, Fig. 1b) is nowadays of about 200 km. According to the bathymetry of the study region (Mahiques et al., 2010; Mohriak et al., 2010), large areas of the continental shelf were exposed during glacial times when sea level was about 60–130 m lower than today (Waelbroeck et al., 2002). During these times the coastline was located about 130 km closer to the coring site and accordingly, the Atlantic coastal lowland area was much larger, ranging from about 50 to 120 km (http://www.earth.google.com).

The Brazil Current (BC) dominates the upper water column of the study area (Fig. 1a) (Peterson and Stramma, 1991). The BC flows southwards along the continental margin, transporting warm and saline waters from the tropical South Atlantic (Fig. 1a). Due to the main influence of the BC and low-level atmospheric circulation, sediments delivered by the Rio Doce (20°S) and Rio Paraíba do Sul (21°S), both about 900–1000 km to the north, as well as productivity signals of the upwelling area of Cabo Frio (23°S, about 700 km to the north), might be transported to the core locality (Razik et al., 2015; Marta-Almeida et al., 2016). The Malvinas Current (MC) flows northwards along the continental margin off Argentina and transports cold and low salinity waters to the study site (Peterson and Stramma, 1991). Both currents meet and form the Brazil-Malvinas Confluence (BMC) which is about 1200 km to the south of the coring site. Furthermore, on the continental shelf off Uruguay and southern Brazil, the Brazilian Coastal Current (BCC) (Fig. 1a) flows northwards and transports to the study site with low salinity waters as well as terrigenous material from the La Plata River drainage basin (Souza and Robinson, 2004; Piola et al., 2005; Razik et al., 2015).

In the studied western subtropical South Atlantic, seasonality also plays an important role (Matano et al., 1993; Boyer et al., 2013). Due to the influence of warm and saline tropical water masses during austral summer, sea surface temperature (SST) range