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.

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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
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 Arucaria 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 northwest 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 δ18O record from Botuverá Cave (Cruz et al., 2006) and further adjusted to changes in summer insolation at 20°C 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 north-eastern (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 of the 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 (Waebroeck 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 Paráibó 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
Fig. 1. (a) Map showing the location of the study site (A) GeoB2107-3 (27.18° S, 46.45° W) at 1048 m water depth off southern Brazil (in this study), and other three marine records: (B) Core GL-1090, (C) GeoB3202-1 and (D) GeoB3229-2. Additionally, four continent pollen records (E) Colonia, (F) Volta Velha, (G) Serra do Tabuleiro, (H) Cambará do Sul, and two speleothem records (I) Santana Cave, (J) Botuverá Cave are also displayed on the map. The Brazil Current (BC), Malvinas Current (MC), Brazil-Malvinas Confluence (BMC) and Brazilian Coastal Current (BCC), which influence the study area are also indicated on the map. Color shading over the ocean represents annual mean sea surface salinity (Zweng et al., 2013), while over the continent it depicts topography. (b) Map showing the vegetation types according to RBMA (1999) for southern and southeastern Brazil. Blue and red circles indicate the location of the sites described above. The red ellipse indicates the catchment area of Rio Itajaí near the city of Florianópolis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
between 21 and 26 °C, and sea surface salinity (SSS) varies between ca. 34 and 36 psu (Practical Salinity Units). During austral winter, due to the decrease in water mass transport of the BC and the strength of the BCC (Matano, 1993), colder (ca. 11.5–21.1 °C) (Molina-Schiller et al., 2005) and less saline (ca. 29 and 33.5 psu) waters could be transported to the north (Piola et al., 2005).

2.2. Continental environmental setting including climate and vegetation

The continent in the study region is characterized by a narrow (50–200 km) strip of coastal lowland, followed by relatively steep slopes of the coastal mountain ranges of up to about 1800 m elevation, which is followed by the southern Brazilian highland between about 800 and 1400 m elevation decreasing further inland (Fig. 1a). Only small rivers are found draining the mountain slopes and the narrow lowland area. The only larger river in the study area is Rio Itajaí north of Florianópolis (Fig. 1b). The mean discharge of Rio Itajaí is 230 ± 280 m³ s⁻¹ since 1934 (Schettini, 2002). Further north and south of the study area, other larger rivers discharging in the western South Atlantic are Rio Paraíba do Sul and Rio Doce (to the north), Rio Uruguay and Rio Paraná that together form Rio de La Plata basin (to the south).

Precipitation over southeastern South America is related to two main atmospheric systems (Garreau et al., 2009). During austral summer, the South American Monsoon System circulation transports equatorial Atlantic moisture westward towards the Andes (Zhou and Lau, 1998). The warm and humid air masses are deflected southeasterwards by the Andes, through the South American low-level jet that transports moisture towards southern and southeastern South America, and contributes to the South Atlantic Convergence Zone (Carvalho et al., 2004; Marengo et al., 2004). The South Atlantic Convergence Zone, one of the main components of the South American Monsoon System, is an NW-SE oriented convective belt originating in the Amazon Basin and extending towards southeastern Brazil and the adjacent subtropical western South Atlantic.

During austral winter, incursions of mid-latitude air masses influence precipitation over southeastern South America (Vera et al., 2002). Advections of sub-Antarctic cold fronts cause strong rainfall when they meet tropical air masses. This occurs mainly over southern and southern southeastern Brazil. Therefore these regions have no pronounced annual dry season compared to northern part of southeastern Brazil (Nimer, 1989; Hastenrath, 1991). El Nino Southern Oscillation also plays a role in extreme climate events, particularly in southern Brazil, where is excess rainfall during El Nino years and drought during La Nina years (Grimm and Tedeschi, 2009).

Southern Brazil is a transition region, which is influenced both by tropical and subtropical climate. The climate in the study region is warm and humid without any or with only a short dry period. The annual precipitation ranges from 1250 to 2000 mm, and is even higher than 2000 mm in the mountains of the Serra do Mar. The average annual temperature ranges between 17 and 24 °C in the lowlands and 12–18 °C in the highlands. Frosts are rare or absent in the lowlands, but common in the highlands during the austral winter (Nimer, 1989).

In southern and southeastern Brazilian tropical evergreen Atlantic rainforest occurs as a 50–200 km narrow zone along the Atlantic Ocean between the coast and the slopes of the Serra Geral and Serra do Mar coastal mountain ranges (Fig. 1b). The frost-sensitive tropical rainforests reach their limit in southern Brazil at ca. 28 to 29°S (Klein, 1978; Por, 1992). Coastal vegetation types occur in a small strip along the coast. Mangroves have been found with their distribution limits at Florianópolis (ca. 27.5°S). Subtropical vegetation occurs in the southern Brazilian highlands (Serra Geral plateau) and is formed by a mosaic of Araucaria forest and grassland (Campos). In the lowlands of southernmost Brazil, the vegetation change to the dominance of grassland (Campos) with gallery forests. Further south in Uruguay and northern Argentina, grassland (Pampa) is the main vegetation type (Seibert, 1996). Detailed information on vegetation and species composition can be found in Oliveira-Filho et al. (2015) and Santos et al. (2011).

In the continental area adjacent to our coring site, including Rio Itajaí catchment area (the distance of our coring site to the estuary of Rio Itajaí is about 200 km), vegetation is characterized by highly diverse Atlantic rainforest at elevations up to 800 m (Fig. 1b). The Atlantic rainforest is highly diverse in trees, shrubs, climbers, tree ferns such as Cyathea and epiphytes. The dominant trees are in the Euphorbiaceae (Alchornea), Areaceae (Euterpe), Myrtaceae, and Moraceae families. Araucaria forest with Araucaria angustifolia, Podocarpus, Ilex, Myrsine and the tree fern Dicksonia sellowiana is mainly found in highlands, but some of the trees grow also in the Atlantic rainforest. Araucaria forests often form a mosaic with the Campos. Campos is rich in species of the Poaceae family as well as Cyperaceae, Asteraceae, Apiaceae and Fabaceae (Klein, 1978).

3. Material and methods

3.1. Sampling and analysis methods

Sediment core GeoB2107-3 is 783 cm long and was collected during RV Meteor cruise M23/2. Additional information about the core is available in the cruise report (Bleil and cruise participants, 1993). In order to have an appropriate temporal resolution, the core was sampled in 10 and 20 cm intervals between 770 and 0 cm core depth, with about 2–4 g (wet weight) per sample for pollen and dinocyst analyses on the same sample. Sampling resolution in the deeper section of the core is lower than in the upper section, resulting in 51 dinocysts and 36 pollen samples (due to the low pollen concentration).

Pollen and dinocysts samples were prepared using standard preparation techniques (Faegri and Iversen, 1989), diluted in HCl (10%) and cold HF (40%) to remove the calcareous and siliceous content, respectively. Acetolysis was not applied on dinocyst samples to avoid damage to the cysts, but on samples of pollen and spores. To concentrate the dinocysts and pollen, all the samples were sieved by hand though a 1–1.5 µm nylon mesh after processing. Before processing the samples, exotic Lycopodium spores (one tablet containing 20,848 ± 1546 spores) were added to calculate the concentration (grains or cysts/g) and influx values (grains or cysts/cm²/yr) of the samples (Stockmarr, 1971).

The identification of the pollen and spores is based on the reference collections at the Department of Palynology and Climate Dynamics of the University of Göttingen and literature (Behling, 1993). We use the term “other” for pollen types which belong to a family but could not be identified to genus level. Pollen samples were counted to a minimum of 200, or 100 pollen grains in the case of samples with relatively low pollen concentration (mostly Holocene samples). The pollen sum, on which the percentage calculation is based, includes all pollen types but no fern and moss spores. The identified pollen and spore taxa were grouped into herbs, trees (including shrubs), tree ferns, ferns and mosses. Wetland and a few aquatic taxa are included in the pollen sum, as wetland taxa (i.e., Cyperaceae) occur also in the grassland (campos).

The identification of dinocysts is based on several published morphological descriptions (Zonneveld and Pospelova, 2015 and references therein). Each sample was counted up to 300 cysts. The total sum includes all the dinocysts counted per sample. Dinoflagellate are grouped into phototrophic and heterotrophic taxa.
regarding the different energy resources from photosynthetic process or zooplankton (Gaines and Elbrächter, 1987). Furthermore, dinocysts are also grouped regarding the ecological preference distribution of the living dinoflagellate in the ocean surface into cosmopolitan, eutrophic environmental and open sea taxa (Zonneveld et al., 2013).

The selective preservation of the organic-walled dinocysts in the marine environment needs to be considered while interpreting fossil dinocyst records (Kodrans-Nsiah, 2008). To test the preservation condition of dinocysts in the marine environment, the degradation constant of sensitive cysts \( k_t \) and the reaction time \( t \), in short \( k_t \), is calculated to reconstruct the primary production of dinocysts and to track the past content. The degradation of S-cysts expressed by “\( k_t \)” has been calculated assuming a first-order decay process \( k_t = \ln \left( \frac{X_i}{X_f} \right) \) with \( X_f \) = final cyst concentration (cysts/g) and \( X_i \) = initial cyst concentration (cysts/g) (Zonneveld et al., 2007, 2010).

The programs TILIA and TILIAGRAPH were used to plot the pollen diagrams; CONISS was used for cluster analysis of pollen and dinocyst data, and for the zonation of the diagrams (Grimm, 1987, 1993).

3.2. Age model

Chronological tie points for the upper 338 cm of core GeoB2107-3 are based on 14 accelerate mass spectrometry (AMS) radiocarbon ages (Heil, 2006) performed on the shallow dwelling planktonic foraminiferal species Globigerinoides sacculifer (Chiessi et al., 2007) at the Leibniz Laboratory for Radiometric Dating and Isotope Research at the University of Kiel, Germany (Table 1, Fig. 2a). The calibrated radiocarbon ages span back to ca. 46 cal kyr BP. For the lower part of the core (i.e., 338–770 cm), tie points were obtained by tuning the benthic foraminiferal \( \delta^{18}O \) record of GeoB2107-3 (Heil, 2006) to the \( \delta^{18}O \) foraminiferal SPECMAP stack (Table 1, Fig. 2b). The uncertainties related to the tuned tie-points were estimated as described in Santos et al. (2017). The calculated age of the core at 770 cm (lowermost sample) is about 73.5 cal kyr BP. The age-depth model has been already partly published in Hendry et al. (2012) and has been extended here with additional data from Heil (2006). The radiocarbon ages have been calibrated with the online version of Calib 7.1 (Stuiver and Reimer, 1993; Stuiver et al., 2017) using the Marine13 calibration curve (Reimer et al., 2013) and a \( \Delta R \) of 35 years (http://calib.org/marine/getref.php?RefNo=135, Stuiver et al., 2017) and calibrated ages are reported with 2 \( \sigma \) uncertainties (Table 1). The age-depth model was obtained by linear interpolation of all chronological tie points. Ages of the different pollen zones (PZ) and dinocyst zones (DZ) have been calculated based on

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Fig. 2. (a) Age-depth model and sedimentation rates for marine sediment core GeoB2107-3. (b) Tuning of the benthic oxygen isotope (U. peregrina) record of core GeoB2107-3 to the SPECMAP record beyond the radiocarbon dating range. The points are indicated by vertical arrows.
the age-depth model. The limits of the Marine Isotope Stages (MIS) and substages are based on Lisiecki and Raymo (2005).

4. Results

4.1. Pollen and spore assemblages

In total, 108 pollen and 26 spore taxa have been identified in 36 samples, excluding a few unknown pollen and spore types. The most frequent and important taxa are shown in the pollen diagrams (Figs. 3 and 4). According to the cluster analysis performed with CONISS, 4 PZs have been established. The pollen concentration (182–2237 grains/g) and influx values (1–48 grains/cm²/yr) are in general relatively low in core GeoB2107-3. Both are higher in PZ I and III, lower in PZ II and very low in PZ IV.

4.1.1. PZ I (73.5–55.8 cal kyr BP, 770–470 cm, 8 samples)

Herb pollen grains dominate in this zone (64–69%), in particular Cyperaceae, Poaceae, Asteraceae (other) and Amaranthaceae/Chenopodiaceae. Tree and shrub pollen values are less frequent (26–32%) than herb pollen. Most frequent taxa in this group are Araucaria angustifolia, Podocarpus, Alchornea, Moraceae, Urticaceae, Melastomataceae, Myrsine, Sebastiana commersoniana (0.5–3.5%), and Myrtaceae. Interestingly Araucaria angustifolia pollen is relatively frequent (6.5–7.5%) in the lower part of PZ I (until 690 cm core depth) and markedly less frequent in the upper part (1.5–3%, average 2.8%). Single pollen grains of the shrubs Ephedra tweediana and Ephedra (other) occur in this and the following PZ. Tree fern spores (1.5–5%) such as Cyathaea and Dicksonia sellowiana are rare. Among the fern group, monolete psilate spores are frequent and others are rare. Moss spores are rare.

4.1.2. PZ II (55.8–38.5 cal kyr BP, 470–235 cm, 6 samples)

In this PZ the amount of herb (60–76%) and slightly higher tree pollen (21–35%), remain at similar levels as in the previous zone. Cyperaceae and Amaranthaceae/Chenopodiaceae values are slightly higher at the beginning of this zone around 55 cal kyr BP, Amaranthaceae/Chenopodiaceae decrease in the upper part of the PZ. Asteraceae (other) increase slightly. The representation of different tree pollen is similar to the previous PZ with small fluctuations. Tree ferns (3–9%) and ferns, in particular monolete psilate spores are slightly higher in the lower part of the zone. Moss spores are rare, but increase slightly.

4.1.3. PZ III (38.5–13.0 cal kyr BP, 235–75 cm, 14 samples)

The PZ is characterized by an increase of herb pollen (59–80%), in particular in the middle part of the PZ, while the representation of tree pollen (17–34%) shows the opposite trend. Poaceae and Cyperaceae show a marked higher representation whereas other herb pollen values are stable compared to the previous zone. The representation of almost all tree pollen taxa decrease in this zone. Interestingly, several single Nothofagus pollen grains (up to 1.5%) occur in this zone only. Ephedra tweediana pollen grains are slightly more frequent. Tree ferns (1.5–8%) and ferns are lower than in the previous zone. Moss spores are rare, but with a slightly higher representation of Phaeoceros leavis.

4.1.4. PZ IV (13.0–0 cal kyr BP, 75–0 cm, 8 samples)

This zone is marked by a strong decrease of all herb pollen taxa (54–43%) while almost all tree pollen taxa increase (34–48%). Borreria and Eryngium pollen grains are now absent. Tree pollen grains are mainly represented by Araucaria angustifolia (1.9–11%), Alchornea (4–7%), Moraceae-Urticaceae (4–12%), Melastomataceae (2–6%), Podocarpus (1–4%), Araucaria angustifolia pollen grains reach its highest value in the uppermost sample with 11%. Tree ferns spores (18–37%) such as Cyathaea, Cyathaea schanschins type and Dicksonia sellowiana are frequent. Fern spores increase by the high representation of the trilete psilate spore types. Moss spores are still rare.

4.2. Dinoflagellate cyst assemblages

In total 31 dinocyst taxa were distinguished in 51 samples. The most frequent taxa are displayed in the dinocyst percentage and group diagrams (Figs. 5 and 6). According to the cluster analysis performed with CONISS, 4 DZs can be recognized. The dinocyst concentration (512–15139 cysts/g) and influx values (4.8–160 cysts/cm²/yr) are in general lower in core GeoB2107-3. Values are higher in DZ I and III, but lower in DZ II and IV. The calculated kr values for the whole record are between 3 and 7 with little fluctuations. Slightly lower values are found in the lower and middle part of DZ I and slightly higher values are found in the uppermost part of DZ IV.

Throughout the whole record, dinoflagellate cysts produced by phototrophic taxa dominate the association, whereas cysts produced by heterotrophic taxa are rare. Regarding their modern geographical distribution in sea surface waters, cyst species with a cosmopolitan distribution and those that have their highest relative abundances in eutrophic environments such as coastal embayments and river plumes, are dominant and fluctuate strongly. Species that have nowadays their highest relative abundances in sediment deposits of the central ocean are relatively rare.

4.2.1. DZ I (73.5–53.9 cal kyr BP, 770–440 cm, 17 samples)

This zone is characterized by the dominance of eutrophic environmental taxa such as Spinifertites mirabilis, Lingulodinium machaerophorum, Tuberculodinium vancampoae and Spinifertites ramosus. However, we have to consider that Spinifertites mirabilis is not a typical eutrophic taxon, but can react on high nutrient environments (Zonneveld et al., 2013). As this taxon responds similar as other eutrophic taxa, therefore we consider Spinifertites mirabilis for this site as an indicator of eutrophic conditions. These eutrophic environmental taxa show in this zone the highest percentages of the whole record. Contrastingly, the cosmopolitan taxon Operculodinium centrocarpum shows the lowest values in this zone. Open sea taxa are rare in the record, but relatively frequent in this zone. The heterotrophic dinocysts are low, but somewhat higher in this zone compared to the other zones. The group of cysts formed by heterotrophic species is dominated by Brigantedinium spp.

4.2.2. DZ II (53.9–35.0 cal kyr BP, 440–205 cm, 13 samples)

The cosmopolitan taxon Operculodinium centrocarpum is frequent compared to the previous zone. The eutrophic environmental taxa Spinifertites mirabilis, Lingulodinium machaerophorum, Tuberculodinium vancampoae and Spinifertites ramosus show low values relatively to the other DZ. This zone is also marked by the lowest values of the heterotrophic dinocyst Brigantedinium spp. in the whole record.

4.2.3. DZ III (35.0–14.0 cal kyr BP, 205–85 cm, 12 samples)

The dinocyst assemblages are characterized by high values of eutrophic environmental taxa Spinifertites mirabilis, Lingulodinium machaerophorum and Tuberculodinium vancampoae, in particular in the lower part of the zone. Oppositely, the cosmopolitan taxon Operculodinium centrocarpum decrease in the lower part of the zone and end up with similar values as in the beginning of this zone. This zone is characterized by the rare but more frequent occurrence of several taxa of Impigidium that nowadays have their maximal distribution in open ocean sediments. Heterotrophic taxa are now more frequent, starting increase already at the end of the previous DZ.
Fig. 3. Pollen percentage diagram showing the most frequent pollen and spore taxa from core GeoB2107-3 grouped into herbs, trees, tree ferns, ferns and mosses. The diagram also includes the age model and pollen zones (PZ) for the record.
4.2.4. DZ IV (14.0–0 cal kyr BP, 85–0 cm, 9 samples)

This zone is marked by a strong and continuous increase of the cosmopolitan taxon *Operculodinium centrocarpum* to the end of this zone. The eutrophic environmental taxa such as *Spinifertites mirabilis*, *Lingulodinium machaerophorum* and *Tuberculodinium vancampoae* either decrease or become rare. And the heterotrophic taxa, in particular *Brigantedinium* spp. are decrease as well.

5. Environmental reconstruction and discussion

5.1. Preconditions for the interpretation of the pollen and spore data

Winds, rivers and marine currents can transport pollen and spores. In the study area, the eolian transport can be considered of minor relevance, as there are no strong winds blowing from southeastern South America to the subtropical western South Atlantic throughout the year (Garreaud et al., 2009). Rivers in southeastern South America, draining from the coastal mountains to the Atlantic coastal lowland, are rather small except for Rio Itajaí, which discharges its sediment load in the region of the coring site. Therefore, this river may have been important for the input of pollen and spores originating from the coastal, lowland, highland, and mountain vegetation although it has a relatively small catchment area compared to other rivers in southeastern South America that drain into the Rio de La Plata.

The BC may transport pollen and spores from the north (discharged by the Rio Paraliba do Sul and Rio Doce) to the study area, as well as the BCC may transport pollen and spores from the south (discharged by the Rio Uruguay and Rio Paraná, that together form Rio de La Plata, Fig. 1a) to the study area (Razik et al., 2015). Importantly, based on surface samples, Razik et al. (2015) showed that terrigenous material could be transported by the BCC from the mouth of the Rio de La Plata along the southeastern South American margin to the north up to ca. 24° S. However, it can be assumed that the amount of pollen and spores transported from distant sources (i.e., Rio de La Plata, Rio Paraliba do Sul and Rio Doce) is low, because the pollen spectra in the uppermost samples (see section PZ IV: 13.0–0 cal kyr BP – MIS 1 (14–0 cal kyr BP), below) reflect more closely the modern vegetation of the adjacent continent in southern Brazil, as recorded in terrestrial pollen records for the late Holocene (e.g. Behling, 1993; Behling et al., 2004), than the one from Rio de La Plata catchment area, or the one from southeastern Brazil. This indicates that most of the pollen and spores come from the nearby continent.

5.2. Continental palaeoenvironmental reconstruction

5.2.1. PZ I: 73.5–55.8 cal kyr BP ~ MIS 4 (71–57 cal kyr BP)

High amount of herb pollen values indicate that the nearby continental area was dominated by grassland on the highlands and probably also on the lowlands including coastal areas, mainly represented by Cyperaceae, Poaceae, Asteraceae, Amaranthaceae-Chenopodiaceae and others (Figs. 3 and 4). The high abundance of Cyperaceae, which is in general higher than the proportion of Poaceae and Cyperaceae in the grasslands of the highlands (Behling et al., 2004), suggests that wetlands such as salt marches occurred also on the exposed continental shelf. Mangrove pollen are absent, suggesting that mangrove, which has today its southernmost limits
Fig. 5. Dinocyst percentage diagram, showing the most frequent dinocyst taxa from core GeoB2107-3 grouped into phototrophic and heterotrophic taxa. The diagram also includes the age model and dinocyst zones (DZ) for the record.
Fig. 6. Dinocyst summary diagram showing the sedimentation rate (cm/kyr), groups of ecological preference distribution, living characteristics of dinoflagellate, dinocyst concentration and influx records, $k_t$ values, dinocyst sum values, dinocyst zones (DZ) and the CONISS dendrogram for core GeoB2107-3. The white shaded area of eutrophic environmental taxa shows the percentages of Spinifertites mirabilis.
at Florianópolis (ca. 27.5°S), did not play any important role during glacial times in southern Brazil on the exposed shelf, as mangrove occurrence may have been limited to lower latitudes. Evidence of *Ephedra tweediana*, which is typical for coastal areas in southern Brazil (up to 30°S) and Uruguay (Pinto da Luz, 2016), suggests an expansion of this shrub to the north. A typical highland tree such as *Araucaria* and lowland trees such as *Moraceae/Urticaceae, Alchornea, Arecaceae* and others formed a mosaic of grassland and forest in the highlands and in the lowlands, respectively. Our data suggest that the exposed continental shelf was covered by a mosaic of forest and grassland. Indeed, a mosaic of forest and grassland has been documented in the Volta Velha record for the pre-LGM and the LGM (Behling and Negrelle, 2001).

Interestingly, the relatively high frequency of *Araucaria* (6.5–7.5%, average 7%) in the lower part of the record (73–65 cal kyr BP), which is similar to its late Holocene abundance (2–11%, average 4.5%), except for the topmost sample (11%) which reflects the strong expansion during the last about 1000 years, is indicative of a frequent occurrence of *Araucaria* trees in the highlands (Fig. 3). As *Araucaria* is sensitive to rainfall and temperature, this early glacial period may reflect slightly wetter conditions with no marked dry periods and less cold climatic conditions than during the full glacial. In this and in the following periods *Sesbania commersoniana* was relatively frequent and might have been common in the gallery forests along rivers as it is nowadays (Smith et al., 1988). The tree fern *Cyatha* and other ferns occur in this period suggesting a relatively wet and cold climate, but the tree fern *Dicksonia sellowiana*, nowadays common in *Araucaria* forests was rare. The only continental vegetation record which spans back to this period, *Colonia* in southeastern Brazil, indicates a relatively low amount of arboreal and higher amount of non-arboreal pollen (Ledru et al., 2005, 2009). However, during this period a relatively high amount (about 1%) were also recorded at the *Colonia* site (PZ 7).

High pollen concentration and influx values suggest that during this period the coastline was placed closer to the coring site so that more continental material could be deposited at the core site. The pollen concentration and influx records correlate well with the sea level curve (Fig. 7) (Waelbroeck et al., 2002).

### 5.2.2. PZ II: 55.8–38.5 cal kyr BP – early to mid-MIS 3 (57–29 cal kyr BP)

Similar pollen assemblages, proportions and composition of herbs and tree taxa occurred in this period compared to the previous period (Figs. 3 and 4). Grassland became more frequent, while lowland forest became slightly decrease towards the end of the period. Also, tree ferns and ferns are slightly more frequent in this period. This may indicate that a similar climate occurred in the lowland with slightly wetter conditions. Indeed, higher proportions of arboreal than non-arboreal vegetation are also documented in the *Colonia* record in the highlands of southeastern Brazil (Ledru et al., 2005, 2009). Taken together, both records suggest wetter conditions. Lower pollen concentration and influx values suggest that during this period the coastline was at more distant to the coring site due to a slightly higher sea level (Fig. 7) (Waelbroeck et al., 2002). Still, a significant portion of the continental shelf was exposed and rivers delivered their sediments close to the shelf break (Lantzsch et al., 2014).

### 5.2.3. PZ III: 38.5–13.0 cal kyr BP – late MIS 3 and MIS 2 (29–13 cal kyr BP)

This period experiences the largest expansion of grassland, probably not only in the lowlands but also in the highlands (Figs. 3 and 4). However, all tree taxa including *Araucaria angustifolia*, *Moraceae/Urticaceae, Alchornea* and *Arecaceae* are still present but in decreased proportions. The occurrence of ferns did not change much, but tree ferns are slightly less frequent. Taken together, this indicates a colder and/or drier climate. These results are in accordance with continental records from southern Brazil, indicating treeless grassland on the highlands (e.g. Behling, 2002; Behling et al., 2004) and a mosaic of subtropical forest and grassland in the lowlands (Behling and Negrelle, 2001). A previously published review of terrestrial pollen records indicate that grassland extended at least over 750 km from the southern to southeastern Brazilian highlands from latitudes of about 28°/27°S to at least 20°S (Behling, 2002). Two marine sediment cores collected off southeastern Brazil at 19–21°S indicate that the tropical lowland rainfall was also reduced in that region during full glacial times, in particular during the LGM (Behling et al., 2002). However, the decrease in tropical lowland rainfall was not that strong during the pre-LGM in the marine cores off southeastern Brazil as it is recorded in core GeoB2107-3, indicating that the lowland rainfall area was more stable in southeastern than in southern Brazil during full glacial times. This confirms genetic diversity studies which suggested that larger areas in the Atlantic lowlands of southeastern Brazil acted as climatic refugia for the rainforest (Carnaval et al., 2009; Butchart et al., 2010). The high proportions of arboreal vegetation during the pre-LGM (28.5–23.5 cal kyr BP) documented in the colonization of northeastern Brazil (Ledru et al., 2005) are reflected in the records from GeoB2107-3 and GeoB3229-2 (Fig. 1a). Thus the *Colonia* site may have recorded a more local pollen signal compared to the more regional signal archived in the marine cores. Several single *Nothofagus* pollen grains have been found only during this period (up to 1.5%). *Nothofagus* occurs only in the Andes of southern South America, where forests were reduced during full glacial times (Fontana et al., 2012). Therefore, the deposition of *Nothofagus* pollen suggests an efficient transport by Argentinean rivers and/or winds (i.e., the southern westerlies) into the continental margin off Argentina, a northward transport along the Argentinean continental margin via the MC, and, finally, a continued northward transport along the Uruguyan and Brazilian continental margins via the BCC. The strong increase of the pollen concentration and influx values with a maximum during the LGM and the general decrease, suggest an increase of the exposed continental shelf area due to minimum sea level during the LGM and subsequent sea level rise during the Lateglacial (Waelbroeck et al., 2002; Lantzsch et al., 2014). Due to the topography of the continental shelf, changes in sea level during glacial times (between around ~60 m and ~90 m, and about ~120 m during the LGM) in comparison to the Lateglacial and early Holocene (from about ~120 m to modern sea level) may have a not so strong influence on the pollen influx. Also, *Ephedra tweediana* was slightly more frequent in this period, suggesting the largest expansion in the coastal area to the north.

### 5.2.4. PZ IV: 13.0–0 cal kyr BP – MIS 1 (14–0 cal kyr BP)

A marked expansion of forests and a decrease of grasslands started in the Lateglacial. This Lateglacial expansion of tropical forest in the lowland of southern Brazil is also well documented in the coastal record from Volta Velha (Behling and Negrelle, 2001), while on the highlands in southeastern Brazil the expansion started later at 9 cal kyr BP (e.g. Ledru et al., 2009). A continuous expansion of forest with frequent ferns and in particular tree ferns occurred in the lowlands reflecting a change to warmer and/or wetter climatic conditions. Interestingly, lowland forest expansion to the south started already about 15 cal kyr BP. Thus, lowland forests had the chance to expand on the exposed shelf during part of the last deglaciation and early Holocene, as the sea level was still low. *Araucaria angustifolia* increased, but a widespread occurrence is found only during the late Holocene due to wetter climatic conditions, in particular in the uppermost sample of GeoB2107-3. This reflects the general first stronger expansion of *Araucaria* at 9 cal kyr BP.
angustifolia was at 4-3 cal kyr BP and the strongest expansion during the last ca. 1 cal kyr BP, due to a change from drier to wetter conditions on the highlands, which has been also documented in several pollen records from the highlands (e.g. Behling et al., 2004). The lowest pollen concentration and influx values characteristic for this period is compatible with the change from a nearshore to an offshore position of the coring site due to postglacial sea level rise (Waebroek et al., 2002; see Fig. 7), and the consequent strong inland displacement of the coastline (Lantzsch et al., 2014).

5.3. Preconditions for the interpretation of dinocyst data

The dinocyst assemblages are controlled by their initial production in the upper water column which, in turn, is strongly influenced by environmental conditions like SST, SSS and nutrient availability that are influenced by climatic conditions (Gonçalves-Araujo et al., 2016). Additionally, dinocyst assemblages can also be influenced by secondary processes such as lateral transport and preservation (see references in Zonneveld et al., 2013).

In the study area, the major source of nutrient input is by small rivers, mainly by Rio Itajaí as it is the largest one close to the study area. Furthermore, nutrients can be brought towards the coring site by the BC transporting river discharge waters from the Paraná, Do Sul and Rio Doce, which are about 1000 km to the north, as well as productivity signals of the upwelling area of Cabo Frio. The input of fresh water from the south, more specifically from the Rio de la Plata, can occur via the BCC (Fig. 1a) (Souza and Robinson, 2004; Piola et al., 2005). The influence is expected to be small because of the long distance of more than 1000 km. However, we have to consider that at least under high sea levels with the BCC confined to the continental shelf and during the austral summer, there is a decrease in strength of the BCC (Piola et al., 2005).

In core GeoB2107-3 the kt values (an indicator of dinocysts preservation) range from 3 to 7 (Fig. 6). According to Zonneveld et al. (2007), lower kt values indicate better preservation, then higher values due to the individual degradation degrees of different dinocyst types. Although no information is so far available from our study region, relatively high kt values suggest that post-depositional species selective degradation might have altered the sedimentary signal. Consequently, we base our environmental reconstruction on signals provided by the species resistant to aerobic degradation.

5.4. Marine palaeoenvironmental reconstruction

5.4.1. DZ I: 73.5–53.9 cal kyr BP – MIS 4 (71–57 cal kyr BP)

The cyst association of DZ I is characterized by high relative abundances of Lingulodinium machaerophorum, Tuberculodinium vancampae, Spinifertites mirabilis and Spinifertites ramosus. These species nowadays have high relative abundances in regions with moderate to high nutrient availability in surface waters. Lingulodium machaerophorum is a temperate to tropical euryhaline species and occurs frequently in the vicinity of active upwelling cells and in river plumes (Dale et al., 1999; Mertens et al., 2009). In regions influenced by riverine input it appears to be a very sensitive indicator for changes in fluvial discharge (Zaragosi et al., 2001; González et al., 2008; Mertens et al., 2009; Holzarth et al., 2010; Penaud et al., 2011; Zonneveld et al., 2012; Zonneveld and Siccha, 2016). Tuberculodinium vancampae is a typical species for subtropical and tropical coastal areas, and can be very abundant in eutrophic coastal embayments as well as in upwelling regions (Zonneveld et al., 2013). Although not restricted to eutrophic regions Spinifertites ramosus is very abundant in areas influenced by upwelling or river discharge waters. Enhanced presence of fluvial waters (shorter distance to the coastline) and/or western boundary upwelling off southeastern Brazil (southward transport via the BC) may have delivered the slightly higher nutrients required to produce DZ I. A recent record of the activity of the western boundary upwelling off southeastern Brazil covering the last 110 kyr in high temporal resolution does not support enhanced upwelling activity during DZ I (Portilho-Ramos et al., 2015). Thus, the most probable origin of the nutrients for the period is the enhanced presence of fluvial waters associated with a shorter distance of the coring site to the coastline due to low sea level (Fig. 7). Here, primarily the input of the Rio de La Plata, and secondarily of the Rio Itajaí were probably responsible for the enhanced abundance of Lingulodinium machaerophorum, Tuberculodinium vancampae and Spinifertites ramosus.

During DZ I, we observed low abundances of Operculodinium centrocarpum. In general, Operculodinium centrocarpum is recorded in a wide range of temperature and salinity conditions, being often regarded as a cosmopolitan taxon (Zonneveld et al., 2013). The distribution of Operculodinium centrocarpum in the study area shows that high abundances of this taxon are restricted to the tropical and subtropical western South Atlantic and this species is less abundant to the south of the Brazil-Malvinas Confluence. Nowadays, it is characteristically present in high abundances in the warm waters of the BC (Zonneveld et al., 2013). The relatively low abundances of this species during DZ I might indicate a reduced influence of the BC at the coring site. Indeed, DZ I may be related to a stronger presence of Rio de La Plata waters transported by the BCC to the coring site. In modern days, Brigantedinium spp. can be a good indicator for increased upper water nutrient availability in tropics. Enhanced cysts production can be observed when nutrient concentrations increase, for instance in upwelling regions, river plumes and polluted coasts (e.g. Zonneveld et al., 2009). However, Brigantedinium spp. is very sensitive to aerobic degradation. The somewhat higher relative abundances of Brigantedinium spp. observed in this zone, might, therefore, be the result of the higher nutrient availability, as indicated by Lingulodinium machaerophorum, Tuberculodinium vancampae and Spinifertites ramosus, but could also indicate a somewhat better preservation.

5.4.2. DZ II: 53.9–35.0 cal kyr BP – early to mid MIS 3 (57–29 cal kyr BP)

The high occurrence of Operculodinium centrocarpum suggests that the presence of waters transported by the BCC decreased and the BC largely dominated the upper water column at the coring site during this period. The decrease of dinocyst taxa with eutrophic environmental preferences indicate less nutrient availability and suggests that nutrient loaded fluvial waters did not reach to the coring site. This was probably related to the slightly higher sea level (Veitbrock et al., 2002) relative to the previous DZ that increased the distance of the coring site to the coast. The lower relative abundance of Brigantedinium spp. suggests that bottom waters might have been more oxygenated.

5.4.3. DZ III: 35.0–14.0 cal kyr BP – late MIS 3 and MIS 2 (29–13 cal kyr BP)

The decrease of Operculodinium centrocarpum at the beginning of DZ III and its increase at the end of the period indicate changes in the fraction of waters transported by the BC versus waters transported by the BCC (i.e., higher percentages of Operculodinium centrocarpum is associated to the massive dominance of waters transported by the BC) (Zonneveld et al., 2013).

Indeed, a larger fraction of waters transported by the BCC during this DZ is corroborated by the increase in abundance of eutrophic environmental dinocyst taxa, which reached a maximum during the LGM (lowest sea level during the last glacial; Waelbroeck et al., 2002). Thus, the most probable origin of the nutrients for the period is the enhanced presence of fluvial waters associated with a shorter distance of the coring site to the coastline due to low sea level (Fig. 7). Here, primarily the input of the Rio de La Plata, and secondarily of the Rio Itajaí were probably responsible for the enhanced abundance of Lingulodinium machaerophorum, Tuberculodinium vancampae and Spinifertites ramosus.
suggest dry environmental conditions. The relatively high frequency of *Brigantedinium* spp. from the LGM onward suggests somewhat lower bottom water oxygen concentrations.

5.4.4. DZ IV: 14.0–0 cal kyr BP – MIS 1 (14–0 cal kyr BP)

The relatively high abundance of *Operculodinium centrocarpum* suggests a massive influence of the BC at the upper water column at our coring site. The relatively low abundance of eutrophic environmental dinocyst taxa indicates a smaller fraction of waters transported by the BCC to the coring site. The increasing distance to the coastline due to the post-glacial sea level rise probably played an important role (Waelbroeck et al., 2002; Lantzsch et al., 2014). The results suggest as well that even under a stronger influence of the BC, lower salinity waters from the Rio Paraíba do Sul, Rio Doce, and nutrient rich waters from the upwelling off southeastern Brazil are still could not reach to the study area, as also suggested by Razik et al. (2015). The lower frequency of *Brigantedinium* spp. suggests that the bottom waters had higher oxygen content during this period.

5.5. Comparison of pollen, spore and dinocyst records

The dendrogram performed with CONISS for each record (Figs. 4

![Diagram](image-url)
and 6) shows that the major changes coincided. Thus, the PZ and the DZ are almost synchronous with 1–3.5 kyr offsets (see also the PZ and DZ in Fig. 7), hinting for a similar timing of major environmental changes over southern Brazil and the adjacent western South Atlantic. Major vegetational changes occurred earlier than the changes in the adjacent marine environment during MIS 3, but the phase between both records is the opposite during the transition from MIS 2 to MIS 1 (Fig. 7). The reason we do not know yet. The rather small difference in timing between the PZ and the DZ could be the subject of a further high-resolution study on core GeoB2107-3 to understand in detail leads and lags in land—ocean interactions.

For MIS 4 (early last glacial period), our vegetation reconstruction suggests cold and relatively wet climate over southern Brazil, in particular for the early MIS 4 that showed higher occurrence of *Araucaria angustifolia*. Higher rainfall with a short or without a marked annual dry season, as this is the requirement of *Araucaria*, might be related to an enhanced activity of the South American Monsoon System and the South Atlantic Convergence Zone, as suggested by Cruz et al. (2005, 2006). During MIS 4 the dinocyst records suggest a stronger influence of the BCC in the study area. Besides the influence of the BCC (the Rio de La Plata), Rio Itajai may also have contributed with more freshwater to the coring site. The low sea level facilitated the participation of a larger fraction of fluvial waters in the upper water column of our core site.

During the early to mid-MIS 3 (mid last glacial period), southern Brazil was cold and a slightly wetter than MIS 4, probably only in the lowlands (as *Araucaria* shows low occurrence), while our core site experienced a dominant influence of the tropical BC. A recent study based on marine sediment core GL-1090 collected off southeastern Brazil (24.92°S, 42.51°W, ca. 470 km further northeast to the study site) indicates a trend of increasing SST during the late MIS 3 (Santos et al., 2017). During the late MIS 3 and MIS 2 (pre-LGM, LGM and early Lateglacial periods), the climate over southern Brazil was colder and/or drier compared to the previous last glacial period, and the study area had a stronger influence of the BCC due to lower sea level. The presence of a few *Nothofagus* pollen (up to 1.5%) in our marine record, which were most likely transported first by the MC, and then by the BCC, suggests either the enhanced discharge of southern South American rivers draining the Andes or strengthened southern westerlies. We favour the second hypothesis, since a strengthening of the southern westerlies may have happened during the LGM (e.g. Kohfeld et al., 2013).

During MIS 1 (late Lateglacial and Holocene period) southern Brazil was dominated by warm and humid climate as supported by different reconstructions (e.g. Cruz et al., 2005, 2006; Chiessi et al., 2010, 2015), but on the highlands the climate changed to more permanent wet conditions only during the late Holocene. The BC dominated the upper water column at the core site most probably due to the longer distance of the coring site to the coast and together with the higher sea level (Lantzsch et al., 2014).

The comparison between the between pollen/spore and dinocyst records shows that changes on the continent and in the ocean during the last 73.5 kyr are in general well related to each other and occur at similar pacing.

5.6. Land — ocean comparison including other proxies and records

Data sets of previous studies from the same marine sediment core GeoB2107-3 obtained by X-ray fluorescence scanning (Heil, 2006), and records from other archives (e.g. Cruz et al., 2005, 2006; Chiessi et al., 2010, 2015), as well as the global sea level curve (Waelbroeck et al., 2002) and 30°S February insolation and obliquity (Berger, 1978a, 1978b; Berger and Loutre, 1991) are used in order to understand past continental and marine environmental changes (Fig. 7).

The relative amount of tree pollen in GeoB2107-3 reflects the extension of forest cover and can be used as an indicator for temperature and precipitation changes over southern Brazil during the past 73.5 cal kyr BP. The comparison of the records available in Fig. 7 suggests that the tree pollen record is related to the orbital obliquity rather than to the local summer insolation.

The ln(Fe/Ca) record from the same marine sediment core (Heil, 2006) reflects changes in continental terrigenous input to the core site (Govin et al., 2012). The curve follows changes in sea level and obliquity during the last glacial, but decouples from those parameters during the last deglaciation and the Holocene. According to Cruz et al. (2005) the stalagmite δ18O record from the Botuverá Cave mainly indicates changes in the source of moisture reaching the cave and follows February insolation at 30°S. During periods of high summer insolation an intensification of the South American Monsoon System with high summer rainfall over subtropical Brazil was described (Cruz et al., 2005).

The tree pollen record is not correlated to the stalagmite δ18O record from Botuverá Cave (Cruz et al., 2005). In particular, during the LGM the Botuverá record shows values as negative as those of the late Holocene, implying high southern hemisphere summer precipitation. However, the GeoB2107-3 tree pollen record shows low values, suggesting relatively cold and/or dry conditions. In this context, it is important to point out that the stalagmite δ18O and the trace elements (i.e., Mg/Ca and Sr/Ca) records from Botuverá Cave are markedly different (Cruz et al., 2007), particularly for the LGM. While Botuverá Cave δ18O reflects the source of moisture (Cruz et al., 2005), its trace elements records reflect precipitation amount (Cruz et al., 2007). Taken together, these records (i.e., GeoB2107-3 tree pollen and Botuverá Cave δ18O) suggest that summer precipitation may not be representing mean annual precipitation. Here, climate seasonality may play an important role. Indeed, the Cambará do Sul record from southern Brazil suggests that markedly seasonal climatic conditions with a long annual dry period occurred during the LGM and prevailed until the mid-Holocene (Behling et al., 2004).

The differences between the tree pollen, the ln(Fe/Ca) and the speleothem records are probably related to the combined effect of the seasonality in precipitation as well as changes in air temperature and sea level. During the glacial period (i.e., MIS 4 to MIS 2), the ln(Fe/Ca) record correlates well with sea level curve (i.e., periods of particularly low sea level are associated to high ln(Fe/Ca) and high terrigenous input) (Fig. 7), but this correlation get lost after about 10 cal kyr BP. The reason might be due to the marked increase in precipitation, in particular during the late Holocene (e.g. Behling, 1993; Chiessi et al., 2010), dominate the ln(Fe/Ca) record, despite of the high sea level stand and the longer distance of the coring site to the coast. The speleothem record probably reflects changes in the source of moisture and is not much influenced by temperature and sea level. The marked increase in tree pollen around 15 cal kyr BP and the high values throughout the Holocene, may be also related to a strong increase in southeastern South American mean annual temperatures (Chiessi et al., 2015), on top of changes in precipitation, as both parameters are known to influence tropical arboreal vegetation (Beelring and Mayle, 2006). Thus, our results may suggest that (besides precipitation) the interplay of obliquity, and continental temperatures were potentially driving factors controlling changes in southern Brazil arboreal vegetation.

In the comparison diagram (Fig. 7), the proportion of eutrophic environmental dinocysts is well correlated with the sea level curve throughout the whole record, indicating that the distribution of eutrophic environmental dinocysts is highly influenced by the discharge of nutrient rich waters delivered by rivers and transported by oceanic currents. Here, the Rio de La Plata and the BCC
were most probably very important. Sea level changes during the last 73.5 kyr, partly controlled the delivery of freshwater and terrestrial sediments to the coring site, as indicated by the higher pollen influx and ln(Fe/Ca) values during relatively low sea level stands. The relationship between the delivery of terrestrial material and sea level does not hold for the late Holocene (i.e., high ln(Fe/Ca) and high sea level), most probably due to the marked increase in precipitation over southeastern South America (Chissi et al., 2010; Prado et al., 2013a, 2013b), which is also reflected by the tree pollen record. Opeucleodium centrocarmacum suggests changes in the proportion of BC waters at the core site, which is well correlated with obliquity (Fig. 7).

6. Summary and conclusions

Pollen, spores and dinocyst data of marine sediment core GeoB2107-3 offered the first 73.5 cal kyr BP long records for the reconstruction of vegetation, climate and ocean dynamics in southern Brazil and the adjacent ocean. Available continental vegetation records from southern Brazil, which dates back to 42 cal kyr BP, support that the new marine pollen and spore records appropriately reflect the vegetation changes on the adjacent continent.

In southern Brazil, grasslands were much more frequent in the highlands and lowlands, including the exposed continental shelf, during glacial times compared to the late Holocene. The area of the Atlantic rainforest was reduced during the recorded last glacial period, in particular during the pre-LGM and the LGM (38.5–13.0 cal kyr BP). While the area of rainforest in southern Brazil was unstable, the rainforest in southeastern Brazil was more stable according to marine pollen records off southeastern Brazil confirming results on genetic diversity dynamics. Patches of subtropical forests covered the lowland and exposed continental shelf in southern Brazil during glacial times and were markedly reduced during the pre-LGM and LGM period. From 73.5 cal kyr BP to 65 cal kyr BP, the population of Araucaria angustifolia trees in southern Brazilian highlands were similar to the late Holocene, but were rare during the remaining last glacial to mid-Holocene periods. Araucaria angustifolia became frequent again only during the late Holocene. The Atlantic rainforest expanded since the Lateglacial in the lowlands of southern Brazil, including the still exposed continental shelf during the Lateglacial, before postglacial sea level rise flooded the continental shelf.

The proportion of eutrophic dinocysts reflects well nutrient input, mainly delivered by the BCC (Rio de La Plata) and partly by Rio Itajaí. The presence of the BCC over the coring site, as well as pollen influx and terrestrial-derived material (ln(Fe/Ca)), is linked to glacial and postglacial changes in sea level. During MIS 4 and late MIS 3 to MIS 2, the coring site was influenced by the BCC. Enhanced discharge of southern South American rivers draining the Andes or strengthened southern westerlies during MIS 2 were responsible for the arrival of exotic Nothofagus pollen grains, which were transported by the MC and then by BCC to the study site. The cluster analysis indicates that major changes in the pollen/spore and dinocyst assemblages occurred at similar pacing, pointing to a strong relationship between continental and marine environmental changes. The comparison of the pollen and dinocyst records with other proxies suggest that orbital obliquity is one of the most important driving factors controlling marine and continental environmental changes during the last 73.5 cal kyr BP.

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