SEA-SURFACE TEMPERATURE VARIABILITY IN THE SOUTHEAST PACIFIC DURING THE LAST GLACIAL-INTERGLACIAL CYCLE AND RELATIONSHIPS TO PALEOENVIRONMENTAL CHANGES IN CENTRAL AND SOUTHERN CHILE

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Vorgelegt von

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Bremen, den 1. November 2005

Jérôme Kaiser
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1. Introduction

1.1 Late Quaternary climate variability: Northern and Southern Hemispheres

The Late Quaternary time-period is characterized by several phases of long-term climate shifts between glacial and interglacial states, i.e. an oscillation between cold times with the development of large ice-sheets over the Northern Hemisphere (NH) and Southern Hemisphere (SH) high-latitudes with low sea-level, and relatively warm periods similar to the modern climate. The main origin of these cycles is linked to changes in the astronomical parameters of the Earth (Milankovitch, 1941), involving non-linear responses from continental ice-sheets and other climate components (Imbrie et al., 1992). The last glacial/interglacial cycle spanned the previous ~125,000 yr (125 kyr) and is probably the most thoroughly studied interval of the Earth’s history using a vast variety of proxy records from both marine and terrestrial archives, as well as modeling studies.

Superimposed on a long-term trend, high and abrupt climate variability on a multi-millennial to multi-centennial timescale characterize the last glacial period. Ice-cores and marine records have shown a number of climate oscillations called the Dansgaard-Oeschger cycles (DO; Dansgaard et al., 1984) and Heinrich events (HE; Heinrich, 1988), involving temperature changes at the ice surface of as much as 9°C in a few decades (e.g., Severinghaus and Brook, 1999). Presenting a recurrent pattern with a pacing of ~1-4.5 kyr and 5-10 kyr respectively, the ultimate origin of these events is still discussed controversially. A number of processes are being discussed including mechanisms linked to orbital forcing, solar variability, ice-sheet instabilities, or floods from glacier-dammed lakes (see for a review e.g., Alley et al., 2003; Labeyrie et al., 2003), that may involve stochastic resonance of the coupled ocean-atmosphere system (e.g., Alley et al., 2001; Ganopolski and Rahmstorf, 2002).

Independent of their ultimate origin, it is generally accepted that both DO and HE events are closely linked to modifications in the thermohaline circulation (THC; Broecker et al., 1985; see for a review Rahmstorf, 2002). The THC, or global conveyor circulation, corresponds to a hypothetic, large-scale oceanic surface and deep circulation mode. In the North Atlantic realm, and to a minor extent around Antarctica, respectively North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW) are formed by sinking of cold and salty waters. These water masses spread towards the south (NADW) and the north (AABW), filling the deepest part of the oceans. Most of these deep waters further outcrop around Antarctica and returns within the surface as warm water to the North Atlantic region through the Drake and Cape of Good Hope passages. The still predominant explanation for the aforementioned abrupt climate changes is on the one hand that changes in the hydrological cycle in the North Atlantic would affect the THC and thus the global heat distribution (e.g., Stocker and Wright, 1991; Knutti et al., 2004). On the other hand, it has been proposed that rapid climate oscillations may also originate from the tropical Pacific, potentially involving a long-term modulation of inter-annual to decadal climate changes of the eastern tropical Pacific El Nino–Southern Oscillation (ENSO) (Cane, 1998). Recently, a number of new data
sets and modeling studies suggest an important role of the SH high-latitudes within the millennial-scale climate and ocean variability as well.

An important step for a better understanding of the global pattern of rapid climate changes during the last glacial was the synchronization of ice-core records from Greenland and Antarctica using the methane concentrations measured in the ice (Blunier et al., 1998; Blunier and Brook, 2001). These data provided strong evidences for the so-called thermal seesaw mechanism (Crowley, 1992; Broecker, 1998; Stocker, 1998) that implies that major cold phases in the NH (such as HE events) correspond to warmings in the SH (the so-called A events) and vice versa, involving changes in the THC. Instead of an antiphase the ice-core data can also be interpreted in terms of a SH lead of ca. 1-3 kyr compared to the millennial-scale changes in the NH (e.g., Blunier and Brook, 2001; Brook et al., 2005), which does however not imply a SH trigger mechanism (Schmittner et al., 2003). Two modeling studies have shown that abrupt, millennial scale climatic changes over the last deglaciation as recorded in the Greenland ice-cores could have been triggered by the SH high-latitudes involving changes in sea-surface temperatures, sea-ice extent and freshwater input around Antarctica (Knorr and Lohmann, 2003; Weaver et al., 2003). Recently, Pahnke and Zahn (2005) presented a high resolution record of Antarctic Intermediate Water (AAIW) production which play an important role in redistributing heat and freshwater within the upper ocean. The results imply a direct control of climate warming on AAIW conversion in the SH high-latitudes and are consistent with the concept of the bipolar seesaw mechanism.

Antarctic sea-ice may have played an active role in climate changes by controlling atmospheric CO$_2$ concentration changes on glacial-interglacial changes (e.g., Crosta et al., 2004; Stephens and Keeling, 2000). Kanfoush et al. (2000; 2003) have shown that SH cooling episodes at a millennial timescale are marked by an increased flux of ice rafted detritus in the Southern Ocean high- to mid-latitudes. These events were apparently in phase with periods of warmth and active THC in the NH. Crosta et al. (2004), using fossil diatom assemblages, have pointed out that Antarctic sea ice appeared and disappeared in less than 1000 yrs, confirming its sensitivity to rapid climate changes as shown by modeling studies (Gildor and Tziperman, 2000, 2001), and that sea-ice fluctuations were mainly related to sea-surface temperature (SST) changes.

The Westerly winds (or Westerlies) in the SH mid-latitudes might have been an important factor in the past climatic changes too. Based on a coupled ocean-atmosphere model, Russell and Toggweiler (2004) have recently proposed a mechanism suggesting that the partition of CO$_2$ between the atmosphere and ocean in the transitions between atmospheric low-CO$_2$ content (during glacial periods) and high-CO$_2$ content (during interglacials) might be determined by the relative positions of the SH Westerlies and the Antarctic Circumpolar Current (ACC). Furthermore, changes in the strength and latitudinal position of the SH Westerly winds could also play an important role in controlling millennial-scale variations in the AAIW formation (Pahnke and Zahn, 2005). The changes in the latitudinal position of the Westerlies on different timescales are however still controversial considering both the available paleoenvironmental records as well as the modeling studies. A number of paleo-
records from the SH mid-latitudes suggests more equatorward located Westerlies during the Last Glacial Maximum (LGM; 23-19 kyr; Mix et al., 2001), but some others and in particular modeling studies reveal a more complex pattern (e.g. Markgraf et al., 1992; Lamy et al., 1998, 1999; Wyrwoll et al., 2000; Wardle et al., 2003; Stuut et al., 2004; see for a review Shulmeister et al., 2004).

1.2 Contributions of the Southeast Pacific

Southern South America is ideally situated in order to reconstruct the climate history in the SH mid- to high-latitudes as it is under the influence of the two main oceanographic and atmospheric circulation members, the ACC and the southern Westerly winds. Chile is a narrow (≈400 km) but long (≈4200 km) country situated between the Pacific Ocean and the western flanks of the Andes mountains, which acts as a barrier for the Westerlies, forcing orographic ascension of humid air masses that results in extremely high rainfall in the southern Andes. Latitudinally, precipitation patterns in Chile show one of the most pronounced gradients on Earth, ranging from hyper-arid conditions in the north (Atacama Desert) to extremely high rainfall in the mountains of southern Chile. Such a setting is ideal to reconstruct past changes in the extent of the SH Westerlies.

Caldenius, Mercer, Heusser, and colleagues were the pioneers in working on paleoenvironmental reconstructions in Chile (e.g., Caldenius, 1932; Mercer and Laugenie, 1973; Heusser and Streeter, 1980; Hollin and Schilling, 1981). Based mainly on pollen and geomorphological evidences, these authors have shown that Chile was sensitive to climate changes and occupied in its southern part by a large ice-field during the glacial times, the Patagonian Ice Sheet (PIS) (Figure 1). During the last glacial, the PIS extended up to 1800 km north-south and its ice volume was probably > 500,000 km³ in volume as recently reconstructed by modeling studies (Hulton et al., 2002; Sugden et al., 2002). Over the last 25 years a growing number of studies on land based on various proxies allow to draw a general pattern of the climatic changes in Chile since the LGM. The climate was colder and wetter over a broad range of latitude during the LGM, probably up to 30°S (Ammann et al., 2001), while at the same time the snowfall in the very south (50-55°S) was reduced (Hulton et al., 1994). This feature is best explained by an equatorward shift of the Westerlies, with their core possibly located 5° of latitude northwards than presently (e.g., Denton et al., 1999a). This pattern is however in disagreement with some other records (e.g., Markgraf et al., 1992) as well as with modeling results (Wyrwoll et al., 2000; Wardle et al., 2003). Although the last glacier advance around 17.5 kyr before present (BP) was previously identified as the most extensive one (Denton et al., 1999a; McCulloch et al., 2000), very recent studies based on new geomorphological and chronological data on glacier fluctuations in southernmost South America suggest an earlier maximum advance around 24 kyr BP (e.g. McCulloch et al., 2005). Over the last deglaciation, temperatures substantially increased and the Westerlies shifted southward to reach a position similar to the modern around 14.3 kyr BP (McCulloch et al., 2000). During the early Holocene, most of the records show a drier- and warmer-than-
today climate, obviously linked to a poleward displacement of the Westerlies (e.g., Moreno and León, 2003; Abarazúa et al., 2004). For the Late Holocene, most records suggest a trend towards cooler and wetter conditions (e.g., Moreno, 2004; Maldonado and Villagran, 2002).

Despite this general pattern, there are a lot of controversial evidences concerning the timing of millennial-scale climatic events and their significance for hemispheric or interhemispheric climate linkages, as for example the presence/absence of a cooling event during the Younger Dryas (YD; 13-11.5 kyr; e.g., Rutter et al., 2000). Working with reconstructions of glaciers fluctuations in southern Chile and New-Zealand that were correlated to HE events in the North Atlantic region, Denton and co-workers suggested interhemispheric synchrony of millennial-scale climate changes during the last glacial (Lowell et al., 1995; Denton et al., 1999a) in contrast to the results from Antarctic ice-cores (e.g., Blunier et al., 1998). Support for this view is based on evidences for glacier advances and pollen assemblages that imply a YD cooling in Chile (e.g., Denton et al., 1999a; Moreno et al., 2001). Changes in water vapor in the tropics might initiate such a synchrony (Denton et al. 1999a). Other records did however not find indications of a cooling during the YD interval (e.g., Ashworth and Hoganson, 1993; Bennett et al., 2000; Glasser et al., 2004). The aforementioned recent studies on glacier fluctuations in southernmost South America propose an intermediate pattern implicating the dominance of a NH signal at orbital timescale but during the deglaciation, at a millennial scale, the system was responding to conditions in the SH Antarctic domain (e.g. Sugden et al., 2005; McCulloch et al., 2005). This suggestion is mainly based on evidences of a glacier advance or stillstand during the Antarctic Cold Reversal (ACR; 14-12.5 kyr), a deglacial cold event recognized in Antarctic ice-cores (e.g., Jouzel et al., 1995).

A growing number of paleoceanographic publications reflect increasing interest in Late Quaternary ocean dynamics in the Southeast Pacific, along the Peru-Chile Current (PCC). In terms of paleoproductivity, the main emerging feature is that the position of the ACC, which is nowadays responsible for nutrient supply in the upwelling system off Chile, has also controlled past changes in marine productivity (e.g., Thomas, 1999; Marchant et al., 1998; Hebbeln et al., 2000; Romero and Hebbeln, 2003; Mohtadi et al., 2005). Generally, higher marine productivity off Chile occurred during the last glacial period compared to the Holocene. Such a consistent pattern over ~10° of latitude implies large-scale changes in the oceanic circulation, i.e. variations in the location and/or advection of the ACC/PCC. North of ~30°S however a slightly different pattern might be related to other factors linked with the low-latitudes (Mohtadi and Hebbeln, 2004).

Based on the terrigenous fraction of a core situated at ~27.5°S, Lamy et al. (1998; 2000) and Lamy and Stuut (2004) have shown that rainfall changes were precession-driven, i.e. relatively humid conditions during precession maxima and vice versa. A ~30 kyr-long, higher resolution record further south clearly suggests more humid conditions during the LGM, followed by a trend towards a more arid climate culminating in the mid-Holocene (Lamy et al., 1999). Finally, a work at high-resolution covering the middle to late Holocene highlights significant rainfall changes, and therefore variations in the latitudinal location of the
Westerlies, at a millennial to sub-millennial timescale off southern Chile (41°S; Lamy et al., 2001).

Available offshore sea-surface temperature (SST) reconstructions are restricted to central and southern Chile (between ~33°S and 41°S; Kim et al., 2002; Romero et al., in press; Lamy et al., 2004) and span at most the last ~30 kyr. The records at 33°S and 35°S have a similar pattern with SST around 12°C during the last glacial, a ~6°C warming over the deglaciation, starting around 18-19 kyr BP, followed by a SST decrease towards modern values. There is however no clear pattern during the YD and the ACR events. In agreement with the aforementioned mechanisms forcing climate changes in the Southeast Pacific, the authors
mention a decreasing influence of cold, subantarctic waters advected through the PCC since the LGM in order to explain the SST patterns (Kim \textit{et al.}, 2002; Romero \textit{et al.}, in press).

In conclusions, multi-proxy terrestrial and marine paleoenvironmental records in the southeast Pacific suggest that latitudinal shifts of the ACC/PCC and the Westerlies are the main driving-mechanism for regional climate changes in Chile since the last glacial period. However, as the position of this coupled system is controlled by the location of both the subpolar low-pressure belt around Antarctica and the southeast Pacific high-pressure system in the tropics (Cerveny, 1998; Strub \textit{et al.}, 1998), climate changes are under the influence of forcing mechanisms originating in both the high- and low-latitudes. Therefore, high resolution, long and continuous records might highlight some discrepancies as they would have the potential to study not only the long-term but also the short-term pattern on millennial and shorter timescales of the climate in the southeast Pacific region and ultimately within the still poorly documented SH.

\textit{1.3. Objectives}

The present thesis is primarily based on paleoenvironmental data obtained from Ocean Drilling Project (ODP) Site 1233 off southern Chile (Mix \textit{et al.}, 2003). The site was chosen in order to extend the promising Holocene records obtained from a gravity core at the same location (GeoB 3313-1) drilled during \textit{R/V Sonne} Cruise 102 in autumn 1995 (Hebbeln \textit{et al.}, 1995). This core, taken from a small forearc-basin on the upper continental slope spared from turbidity currents, was thoroughly studied by Lamy and co-workers (Lamy \textit{et al.}, 2001; 2002). Their studies revealed that at this location the mean sedimentation rates were extremely high (ca. 100 cm/kyr) during the Holocene and that the records show a pronounced variability on multi-centennial to millennial timescales. Furthermore, the core site is located in an area with several strong environmental boundaries, which is ideal to record even small past changes in the system, i.e. (1) the proximity to the core of the southern Westerlies, (2) a strong SST gradient linked to the northern flank of the ACC, (3) a sea-surface salinity (SSS) anomaly due to the input of freshwaters from the Chilean fjord region, and (4) the proximity to the land (~40 km offshore) which was occupied by the PIS during the last glacial period (see Section 2 for a detailed presentation of the settings). Thus, ODP Site 1233 provides the unique opportunity to study within the same archive the changes and interactions of ocean, land and ice in the Southeast Pacific during the last glacial/interglacial cycle with an extraordinary high resolution.

The main objectives based on ODP Site 1233 can be resumed as follows:

- To take advantage of the possibility to compare continental and marine paleoenvironmental records within the same archive, avoiding problems linked with dating errors between land and ocean records.
- To provide the first high resolution SST record spanning the last glacial/interglacial off southern Chile in order (1) to extend the available
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To reconstruct the fluctuations of the PIS during the last glacial and its collapse over the last deglaciation based on terrigenous sediment input changes and paleosalinity fluctuations.

To discuss the results regarding (1) the mechanisms involved in the Southeast Pacific climate changes, (2) the pattern of globally important events such as the HE events or the YD and (3) the ongoing discussion on interhemispheric versus hemispheric climate linkages.

In addition another core (GeoB 7139-2) situated more equatorward off Chile (30°S; Hebbeln et al., 2001), at the actual northern limit of the Westerlies influence and under more low-latitudes forcing was investigated for the last 40 kyr, the main aims being:

- To compare paleoceanographic changes in two different systems, one south of (Site 1233) and one within (GeoB 7139-2) the Peru-Chile upwelling area, and to try to constrain the relative influences of high-versus low-latitudes.
- To trace events highlighted at ODP Site 1233 in the south, in terms of possible impacts on the oceanic circulation off Chile.
- To provide a long-term record of vegetation changes on land by analyzing n-alkanes as a proxy for continental rainfall, and thus the fluctuations of the northernmost boundary of the Westerlies in comparison to previous results from the south.

In order to reach these aims, the sediment records were investigated in terms of alkenone-based SST and SSS reconstructions on both cores, Iron concentrations (Site 1233) and n-alkanes concentrations (GeoB 7139-2).
2. OCEANOGRAPHIC, ATMOSPHERIC AND PHYSIOGRAPHIC SETTINGS

2.1 Sea-surface and deep oceanic circulation in the Southeast Pacific

Southern Chile (40-45°S) is directly under the influence of the Antarctic Circumpolar Current (ACC) as a powerful oceanic surface current in the Southern Ocean (Figure 2). The ACC brings cold, relatively fresh, nutrient-rich (phosphate and nitrate), Subantarctic Surface Water (SASW) originating from the region north of the Subantarctic Front. The northern part of the ACC splits around ~43°S into the Peru-Chile Current (PCC) flowing northward and the Cape-Horn Current (CHC) turning towards the south (Strub et al., 1998). Northward, the PCC is divided in a coastal and an oceanic branch through the poleward-flowing Peru-Chile Countercurrent (PCCC) bringing warm and relatively salty Subtropical Surface Water (STSW).

**Figure 2.** Cartoon of the surface and deep oceanic circulation off central and southern Chile, and location of sediment cores discussed in this thesis. Surface currents: ACC, Antarctic Circumpolar Current; PCCc, Peru-Chile coastal current; PCCo, Peru-Chile oceanic current; PCCC, Peru-Chile Countercurrent; CHC, Cape Horn Current. SASW, subantarctic surface waters; STSW, subtropical surface waters; ESSW, equatorial subsurface waters; AAIW: Antarctic intermediate waters; PDW: Pacific deep waters; AABW: Antarctic bottom waters. SAF: subantarctic front; PF: polar front; AD: Antarctic divergence. SW: southern Westerly winds. Depth scale: km.
The PCC is the latitudinally most extensive Eastern Boundary Current system in the world, driven by south-easterly winds along the Pacific coast of South America (Strub et al., 1998). The resulting offshore Ekman flow drives perennial upwelling of cool, nutrient-rich waters that produces one of the biologically most productive regions in the oceans (Berger et al., 1987). At about 5°S, the PCC is deflected offshore, feeds the South Equatorial Current (SEC) and flows westward as the equatorial cold-tongue between 10°S and 4°N (Wyrtki, 1965). Thus, the PCC acts as a conduit for exchange of heat and nutrients between high- and low-latitudes in the eastern Pacific.

Subsurface currents in the study area include the southward-flowing Gunther Undercurrent (GUC) near the shelf edge, at depths of 100–300 m (Fonseca, 1989) which transports salty, equatorial subsurface waters (ESSW) (Figure 2). Between ~400 and ~1000 m, Antarctic Intermediate Water (AAIW) flows northward along the Chilean continental margin (Strub et al., 1998). Finally, the southward flowing Pacific Deep Water (PDW) and the Antarctic Bottom Waters (AABW) fill the deepest part of the Chilean trench (> 3400 m; Shaffer et al., 1995).

![Figure 3](http://www.cdc.noaa.gov/index.html) Austral summer, winter and annual long-term mean SST (°C) distribution in the Southeast Pacific between 10°S and 50°S. Data from NOAA-CIRES Climate Diagnostics Center (http://www.cdc.noaa.gov/index.html) (see Reynolds et al., 2002). Contour interval is 0.5°C.

Another feature of the subsurface circulation is the so-called Eastern South Pacific Intermediate Water (ESPIW) which today outcrops between 33 and 38°S and off the coast of
central Chile (not shown in Figure 2; Schneider et al., 2003). There, the ESPIW is subducted (Tsuchiya and Talley, 1998) and spreads northward between 150-250m, communicating surface properties of the waters off central Chile to tropical latitudes (Schneider et al., 2003). Furthermore, in this region the ESPIW is particularly important for the ventilation of the upper oxygen minimum zone (OMZ) which extends directly northward of 30°S in water depths between ~50 and 1000 m (in the deepest part around 5°S-10°S).

![Figure 4](image)

**Figure 4.** Sea-surface salinity distribution off southern and central Chile (austral summer) and locations of core GeoB 7139-2 and ODP Site 1233. Salinity in ‰ unit. Modified after Figure 10.6. in Strub et al. (1998).

The large-scale surface circulation off Chile is further revealed by the surface temperature and salinity distributions (Figure 3 and 4). The southern part is characterized by a steep latitudinal SST gradient linked to the northern boundary of the ACC. The mean annual SST at ~41°S (ODP Site 1233) is ~13.5-14°C and varies between 11-11.5°C in winter and 16-16.5°C in summer, i.e. a seasonal amplitude of ~5°C. Northward, the isotherms take a more meridional orientation, primarily as a result of the equatorward advection of cold water in the
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PCC and to a lesser extent as a direct consequence of coastal upwelling (Tomczak and Godfrey, 2003). In winter the PCC flow is enhanced (Strub et al., 1998). Furthermore, comparatively low-salinity water masses originating from the Chilean fjord region flow northward from ~43°S and return to the coast around 33-35°S (Figure 4). North of 33°S these low-salinity water continues to flow northward both inshore in a narrow band (within 40km of the coast) and offshore, probably within the oceanic branch of the PCC (Strub et al., 1998).

On the other hand, STSW formed south of 5°S and north of the Subtropical Front flows southward within the PCCC to reach about 35°S (Strub et al., 1998; Tsuchiya and Talley, 1998). Finally, salty and relatively cold waters from the GUC are upwelled next to the coast off Concepción (Figure 4).

2.2 The southern Westerly winds, or Westerlies

In the Southeast Pacific mid- to high-latitudes, the steepest SST gradient within the ACC is strongly related to the main atmospheric circulation member of the Southern Hemisphere, the westerly wind belt (Streten and Zillman, 1984). This intense and powerful circulation, annually centered around 50°S, results from the strong thermal gradient and atmospheric pressure difference between cold air masses over Antarctica and the warmer air and water masses in the subtropical regions (Cerveny, 1998). In southern South America, the Westerlies and associated storm tracks bring heavy rainfalls (Figure 5). The totals of precipitation are highest in the core of the Westerlies (> 7000 mm/yr at sea level), which moves seasonally from ~50°S in austral summer to ~45°S in winter, and decline northward towards central Chile where summer-dry Mediterranean rainfall regime is found. North of ca. 30°S winter rainfall diminishes further to almost zero in the Atacama Desert (Miller, 1976; New et al., 2001). The very high rainfall rates in southern South America result in large freshwater fluxes to the coastal ocean and are at the origin of the low-salinity tongue spreading northward along the southern and central Chilean margin (see previous section). South of ~39°S the yearly onshore blowing winds prevent coastal upwelling (Mohtadi et al., 2005).

Trenberth (1991) has described the modern seasonal fluctuation of the storm tracks associated to the Westerlies in the Southern Hemisphere. In summer, the storm track activity can be as strong as in winter, but is located slightly equatorward of its winter position, and is concentrated in a tight band centered around 49-50°S. In winter, storm track activity extends over a broader range of latitudes and is centered 2° poleward from its summer position. Therefore, the influence of the Westerlies/ACC coupled system (or at least its northern boundary) seasonally varies in latitude, i.e. equatorward during austral winter and poleward during summer.

A link exists between the seasonal formation of sea-ice and the atmospheric pattern in the SH high-latitudes. The minimum in sea-ice extent occurs during February with a surface approaching 4 millions km². Whereas March and May are the months of maximum production, the sea-ice extent reaches its maximum in September, i.e. ~19 millions km² (Comiso, 2003). It has been shown that a strong correlation exists between the regions of ice
growth and the location of cyclonic centres, i.e. the position of the Antarctic circumpolar trough (Cavalieri and Parkinson, 1981).

There are primarily two main modes of interannual variability known to influence the atmospheric and oceanic circulation in the Southeast Pacific. One is the ENSO phenomena that strongly influences rainfall variability, especially in central Chile (e.g., Ruttlant and Fuenzalida, 1991; Montecinos and Aceituno, 2003). During La Niña years, the subtropical high-pressure cell (STH) is consistently strong throughout the year. The storm track linked to the Westerlies remains south of 45°S reducing rainfall in the mid-latitudes. Conversely, the STH is weakened during El Niño years, allowing an equatorward shift of the Westerlies and a greater cyclonic activity in the Chilean mid-latitudes. Based on monthly data from weather stations in Chile (30°-41°S) for the 1958-1999 period, Montecinos and Aceituno (2003) have
studied the seasonality of ENSO-related rainfall variability. During El Niño events, precipitation is above the average between 30°-38°S in austral winter and spring. A rainfall deficit is observed from 38° to 41°S in summer, when El Niño development is maximum. Opposite precipitation anomalies characterize La Niña events. Blanco et al. (2002) found that positive SST anomalies propagated southward along the South American coast as far as 37°S during the 1997-1998 El Niño, confirming previous results related to the 1982-1983 El Niño event (Fonseca, 1985).

The second important extra-seasonal variability in the Southern Hemisphere mid- to high-latitudes is the so-called Antarctic Oscillation, or High Latitude Mode, or Southern Annular Mode (SAM) (Thompson and Wallace, 2000; Kidson, 1988). The SAM is a near-zonally symmetric see-saw in atmospheric pressures between high- and mid-latitudes, linked to variations in the strength and extent of the polar vortex. It is primarily active in austral spring and characterized by a surface cooling and lowering of geopotential heights over Antarctica and an increasing strength of the Westerlies over the subpolar Southern Ocean (Thompson and Wallace, 2000; Thompson et al., 2000). With a coarse resolution coupled ocean-atmosphere model, Hall and Visbeck (2002) have shown that much of the variability throughout the Southern Ocean poleward of 30°S can be linked to the SAM. During a positive SAM, a poleward shift and intensification of the jet stream results in enhanced winds around 55°S and weaker ones around 35°S. The Westerlies anomaly generates northward Ekman flow between 65°S and 45°S, while the easterlies anomaly excites southward Ekman flow between 30°S and 45°S. The circumpolar current (ACC) is more intense, and the divergent flow advects sea-ice farther north, resulting in an increase of the sea-ice coverage.

2.3 Geology and vegetation cover of the hinterland

The Chilean continental margin is characterized by the subduction of two oceanic plates (Nazca and Antarctic) beneath a continental plate (South American) at the Chile Trench. This underlying subduction geometry influences topography and volcanism in the Andes, the mountains of which define the present day volcanic arc (Scholl et al., 1970; Zeil, 1986; Thornburg and Kulm, 1987). Figure 6 presents the main geological formations between 38°S and 43°S, i.e. the source areas for sediments reaching ODP Site 1233 as the focus of this thesis.
South of 33°S, Plio-Quaternary volcanism and forearc alluvial basins form the Chilean Central Valley. The crestal elevation of the Coastal Range (average of 1500 m) and especially of the Andes decreases significantly. The latter reveals a gradual average crestal elevation decrease from about 5000 m at 33°S to only 2000 m at 42°S (Scholl et al., 1970). The geology of the Coastal Range south of 33°S is marked by abundant, primarily low-grade metamorphic rocks (Zeil, 1986). North of about 38°S Paleozoic plutonites are also common (Ruiz and Corvalan, 1968). The Chilean Central Valley is filled with up to 4000 m thick sequences of alluvial sediments (Zeil, 1986). The lower parts of the Andes mainly consist of iron-poor plutonic basement rocks, while the high Andes are dominated by iron-rich basaltic to andesitic volcanics resulting from Pliocene (to recent) volcanic activity (Thornburg and Kulm, 1987; Zeil, 1986). Considering the limits of the Pleistocene glaciations (dotted line on Figure 6), these basaltic to andesitic rocks were probably easily eroded through glacial and fluvio-glacial erosion and represented the dominant source of the terrigenous input at Site 1233 during these times.
Vegetation features in central and northern Chile is important for the biomarker study at site GeoB 7139-2. Within this range of latitudes, the vegetation types can be divided in major groups whose geographic distribution is closely linked to the climatic zonation of Chile (Figure 7). North of 27°S, the climate is hyper-arid with precipitation values < 50 mm/yr. In the Atacama Desert, vast areas receive virtually no rain and are largely free of vegetation. The strong influence of the subtropical high pressure (STH) is a major reason for this high aridity (Veit, 1996). Southward, annual precipitation increases slightly due to rare passages of frontal system of the Westerlies in winter. These latitudes are at the present northernmost limit of the influence of the Westerlies. Between 31°S and 37°S, the amount of winter rain increases and the climate is of a semiarid-Mediterranean type. The vegetation along the Chilean coast in this area is characterized by swamp forests, dominated by Myrtaceae trees and shrubs (Fuenzalida, 1965). Further south, the climate become more and more humid due to the increasing influence of the storm tracks evolving from humid temperate to cool humid
temperate type of climate. Semi-evergreen to evergreen broadleaf forests with *Nothofagus* are characteristic for southern Chile. Another vegetation type corresponds to the Andes mountain domain with crests ranging from 3500 to >5000 masl. Following growing altitudes, the vegetation is mainly composed by shrubs, succulents and grasses, respectively (Seibert, 1996; Latorre et al., 2002).
3. METHODOLOGY

3.1 Stratigraphy

The age model of the 135.7 mcd-long composite sequence at ODP Site 1233 has been constructed as follows. (1) The uppermost ~9 mcd have been correlated to the AMS $^{14}$C dated gravity core GeoB 3313-1 from the same location (Lamy et al., 2001) using magnetic susceptibility and Ca relative concentration records. This correlation allowed to transfer the age model of core GeoB 3313-1 (based on 7 AMS $^{14}$C-dating) to Site 1233. (2) Age control for the ~10 to ~70 mcd interval is provided by 17 AMS $^{14}$C-dates on mixed planktonic foraminifera samples (Lamy et al., 2004). (3) Paleomagnetic evidence indicate the presence of the “Laschamp Event” as the most prominent feature in late Pleistocene paleointensity fluctuations of the geomagnetic field with a mid-point core depth of 67.8 mcd (Lund et al., preprint; Mix et al., 2003), which an age of 41 kyr was assigned based on the GISP2-age scale (Voelker et al., 2000). (4) As $\delta^{18}$O data on planktic and benthic foraminifera are not yet available further downhole, the age model for the older part of the record, i.e. below the Laschamp excursion, is based on visual tuning. The millennial-scale SST variations in the AMS $^{14}$C-dated part of the record closely follow Antarctic temperature fluctuations as recorded in the Byrd ice core (Lamy et al., 2004) and the SST pattern further downcore shows a clear visible resemblance to the Antarctic record as well. Therefore, the alkenone SST record was tuned to the Antarctic record using a minimum number of correlation points between the SST data-set and the $\delta^{18}$O record of the Byrd ice core. The Byrd ice core has presently the most suitable age model for the last glaciation as it is linked to the Greenland GISP2 ice core record as well as our $^{14}$C age calendar year conversion. The age model was constructed assuming a linear interpolation between the age control points. The resulting mean sedimentation rates are extremely high, ranging between ~1.4 m/kyr in the Holocene to an average of ~2.2 m/kyr during MIS 2 to 4.

All AMS $^{14}$C-dates from Site 1233 were calibrated with the CALPAL software (www.calpal.de) using the CALPAL 2004 January calibration curve. It is the best presently available calibration curve because it considers the most important recent calibrations for different time-intervals. Beyond a tree-ring calibrated Holocene interval [identical to the INTCAL98; (Stuiver et al., 1998)], a cubic spline was built through U/Th-coral data (Burr et al., 1998; Bard et al., 1993, 1998), GISP2-synchronized planktonic foraminifera data of North Atlantic sediment core PS2644 (Voelker et al., 2000), and GISP2-synchronised varve greyscale data from the Cariaco Basin (Hughen et al., 2000, 2004). The $^{14}$C-AMS ages were corrected for a reservoir effect of ~400 years assuming no regional deviation from the global reservoir effect. This assumption is based on the fact that the core position lies significantly south of the Chilean upwelling zone (Mohtadi et al., 2005), where a regional deviation may apply (Reimer and Reimer, 2001). The next available data point in the Marine Reservoir Correction Database (Reimer and Reimer, 2001) is located ~10° in latitude southward of Site 1233 with a reservoir age of 595 years. Assuming that the oceanic fronts moved about 5°
northward during the last glacial maximum (Gersonde et al., 2003), this would potentially result in a greater reservoir age by up to ~100 years at 41°S. Therefore, the assumption of a 400-yr reservoir age which is also the mean reservoir age for the Pacific Ocean at ~40°S (Bard, 1998) appears to be reasonable. In addition, a volcanic ash layer at ~14.7 mcd at Site 1233 with an interpolated \(^{14}\text{C}\) age of ~9,600 years correlates to a regionally recorded tephra layer (Heusser et al., 1995; Moreno, 2004) with an independently dated age close to 9,500 \(^{14}\text{C}\) years B.P. (~11,000 calendar years B.P.). This strongly supports our ~400 yr reservoir age assumption.

The age model of core GeoB 7139-2 (30°S) is based on eight AMS \(^{14}\text{C}\) dates and has been corrected for distal turbiditic layers (Stuut and Hebbeln, subm.). The radiocarbon ages were converted in calendar age using the CALPAL January 2004 calibration curve and applying a 400 yr reservoir age correction. In upwelling areas, such as off central Chile, reservoir ages may be higher (Reimer and Reimer, 2001). In the south Peruvian upwelling area, it has been for example recently shown that during the early Holocene the reservoir age was apparently about two times higher than during the late Holocene (18°S; Fontugne et al., 2004). However, Fontugne et al. (2004) suggest that the doubling of the reservoir age appears much too high to result from an enhancement of upwelling alone and changes in ocean circulation at intermediate water depths could have been important as well. In particular, Antarctic Intermediate Water with higher reservoir ages might have been more important during the early Holocene and has then been replaced by South Antarctic Mode Water during the late Holocene (the water mass is presently important in the Peruvian upwelling). Off central and northern Chile the upwelling primarily involves Equatorial Subsurface Water (ESSW) flowing poleward within the Gunther Undercurrent at depths around 300-400 m (Navea and Miranda, 1980; Strub et al., 1998). ESSW is formed along the equator between 3°N and 4°S (Strub et al., 1998), and should thus not increase the reservoir age as equatorial water masses are characterised by reservoir ages close to the global mean of 400 years (Bard, 1988). Therefore, being aware that productivity might have been higher during the glacial (Hebbeln et al., 2002; Mohtadi and Hebbeln, 2004), we assume that the mean ocean reservoir age proposed by Bard (1988) can be used here, as no direct reservoir age estimates is available directly from the study area. The \(^{14}\text{C}\)-AMS dated part of core GeoB 7139-2 covers the last ~40 kyr. Assuming a linear interpolation between the age control points, the sedimentation rates increase from ~8 cm/kyr to 18-20 cm/kyr during late marine isotope stage (MIS) 3 (~40 to 25 kyr), are around 18-16 cm/kyr during MIS 2 (~25 to 12 kyr) and decrease to 8 cm/kyr during the middle and late Holocene.

3.2 Alkenone-based sea-surface temperature reconstruction

Alkenones are long-chain unsaturated methyl or ethyl ketones which are produced by a specific class of phytoplankton represented notably by the coccolithophorid *Emiliana huxleyi* (Volkman et al., 1980), the most abundant unicellular phytoplankton which plays a fundamental role in the total primary production in the oceans (Figure 8). Alkenones possess
several unusual characteristics, including their very long chain-length (C$_{35}$–C$_{40}$) and the spacing (C$_7$) and configuration (trans) of their positions of unsaturation (Marlowe et al., 1990) and they were shown to be membrane-unbound lipids (Sawada and Shiraiwa, 2004). The two most abundant alkenones (C$_{37}$:2 and C$_{37}$:3) have so far unknown physiological function but their characteristic is that they remain partially intact in oceanic sediments after the cellular death and thus may be used as biomarkers. The proportion of the more unsaturated alkenone is increased when the growth temperatures get colder and vice versa. Thus, a simple index [UK’37 = (C$_{37}$:2)/(C$_{37}$:2 + C$_{37}$:3)] was formulated to quantify the degree of unsaturation in a given alkenone series and was shown to be linear versus the growth temperature (Prahl and Wakeham, 1987).

![Emiliana huxleyi](image)

**Figure 8.** Photomicrograph of *Emiliana huxleyi* and the structure of the long-chain unsaturated C$_{37}$:3 and C$_{37}$:2 alkenones.

Alkenones were extracted on 1-3 g freeze-dried and homogenized sediment samples on both ODP Site 1233 (41°S) and core GeoB 7139-2 (30°S). After the addition of internal standards [squalane (C$_{30}$H$_{62}$) and 2-nonadecanone (C$_{19}$H$_{38}$O)], alkenones were extracted using mixtures of methanol and methylene chloride with decreasing polarity (MeOH, MeOH/CH$_2$Cl$_2$ 1:1, CH$_2$Cl$_2$) by ultrasonication (UP 200H sonic disruptor probe, Hielscher GmbH, 200W, 105µm amplitude, 0.5s pulse). After centrifuging, the extracts were combined, desalted with de-ionized water, dried with Na$_2$SO$_4$ and evaporated to dryness. The concentrated residue was dissolved in CH$_2$Cl$_2$. To avoid interferences with co-eluting C36-fatty acid methyl esters, saponification was performed using 0.1 N KOH in methanol (90/10 CH$_3$OH/H$_2$O) at 80°C for 2 hours followed by partitioning of the neutral fraction containing
the alkenones into hexane (C₆H₁₄). The extracts were finally concentrated under N₂ and taken up in 25µl MeOH/ CH₂Cl₂ (1:1).

The extracts were analyzed by capillary gas chromatography using a HP 5890 serie II Plus gas chromatograph equipped with a 60 m * 0.32 mm fused silica column (DB-5 MS, J&W) using split/splitless injection and flame ionization detection. Helium was used as carrier gas with a constant pressure of 150 kPa. After injection at 50°C, the oven temperature was programmed to 250°C at a rate of 25°C/min, then to 290°C at a rate of 1°C/min, held for 26 min, and finally to 310 at a rate of 30°C/min, where the final temperature was maintained for 10 min. Quantification of the alkenones was achieved using HPGC ChemStation as analytical software. UK’37 was calculated from UK’37 = (C₃₇:2)/(C₃₇:3 + C₃₇:2), where C₃₇:2 and C₃₇:3 are the di- and tri-unsaturated C₃₇ methyl alkenones. For conversion into temperature values, we used the culture calibration of Prahl et al. (1988) (UK’37 = 0.034T + 0.039), which has been validated by core-top compilations (Müller et al., 1998). The analytical precision was estimated to be around ±0.5°C to ±0.3°C (see Section 4).

In some samples of ODP Site 1233 (30 on a total of 223 samples) the presence of co-eluting organic compounds altered the peaks of the long-chain alkenones and thus the UK’37 values (Figure 9). To improve the measurements, liquid chromatography was applied to all the samples. The extracts were separated into three fractions by elution through a Bond silica column (Bond Elute column, Varian): (1) 4ml of hexane (apolar fraction), (2) 4ml of a mixture of hexane and methylene chloride (3:1) (ketone fraction, including the alkenones) and (3) 2ml of methylene chloride (alcohol fraction). Finally, all fractions were concentrated under N2 and taken up in 25µl MeOH/CH₂Cl₂ (1:1). The method was first tested on a reference sample and the UK’37 values obtained were within the estimated error bar (±0.056 UK’37, or 0.5°C). Figure 9A presents the gas chromatograms of the fractions containing the C₃₇:3 and C₃₇:2 alkenones and the organic compounds before (upper panel) and after (lower panel) liquid chromatography. [N.B.: If the organic compounds are still present in the ketone fraction, then conditioning the column with 6ml of C₆H₁₄/CH₂Cl₂ (6:1) may help without affecting the SST results (Kaiser, unpublished results)]. A precise identification of the co-eluting organic compounds using GC-MS is still unresolved (personal comm. M. Elvert) and is beyond the topic of the present study. The configuration is similar to cyclic hydrocarbons (molecule masses are 524, 526, 538, 540, 552) but the exact nature remains speculative. The SSTs determined with this additional analytical step result in very similar UK37’ values as those obtained without liquid column chromatography. The correlation between both data sets is r = 0.98 (Figure 9 B), and the highest SST differences occur at relatively low temperatures (8-10°C). Only 13% of the data have significantly different SSTs (i.e. >0.5°C relative to the estimated methodological error; Figure 9 C), and mainly result in a shrinking of the extreme SST values.
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Figure 9. Effects of applying liquid chromatography (LC) to the extracts and comparison with previous published results. (A) Gas chromatogram (GC) of the GC-window containing the C$_{37}$ and C$_{38}$ alkenones: whole fraction without LC (upper panel), after LC (middle panel, ketone fraction) and the fraction containing the altering organic compounds. (B) Correlation of SSTs based on measurements with and without LC and (C) SST difference between the individual measurements.

Up-to-now there are no surface water samples available in order to constrain the season of alkenone production off Chile. Kim et al. (2002) however have compared modern SST and alkenone-based SST reconstruction on surface samples off Chile (~33°S). The results show that alkenone-based SST estimates closely resemble annual mean temperatures of the surface-mixed layer. The alkenone-based SSTs based on the uppermost samples at the two sites studied in the present work correspond to the temperature annual average of the ocean sea water surface (Table 1). Therefore, the alkenone-derived paleo-SSTs are regarded to correspond to the annual average of the ocean sea water surface.
SECTION 3. METHODOLOGY

<table>
<thead>
<tr>
<th>Core (latitude; longitude)</th>
<th>Depth (cm)</th>
<th>Modern annual mean SST</th>
<th>Alkenone SST *</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>GeoB 3374-1 (27°28’S; 71°10’W)</td>
<td>0-1</td>
<td>17.1</td>
<td>18.5</td>
<td>Kim et al., 2002</td>
</tr>
<tr>
<td>GeoB 3368-4 (30°22’S; 71°58’S)</td>
<td>0-1</td>
<td>16.8</td>
<td>17.7</td>
<td>Kim et al., 2002</td>
</tr>
<tr>
<td>GeoB 7139-2 (30°15’S; 71°59’S)</td>
<td>3 b</td>
<td>16.5</td>
<td>17.4</td>
<td>This study</td>
</tr>
<tr>
<td>GIK17748-2 (32°45’S; 72°02’W)</td>
<td>3</td>
<td>15.9</td>
<td>16.1</td>
<td>Kim et al., 2002</td>
</tr>
<tr>
<td>GeoB 3301-1 (33°09’S; 71°59’W)</td>
<td>0-1</td>
<td>15.7</td>
<td>16.5</td>
<td>Kim et al., 2002</td>
</tr>
<tr>
<td>GeoB 3313-1 (33°13’S; 72°06’W)</td>
<td>0-1</td>
<td>14.0</td>
<td>14.0</td>
<td>Kim et al., 2002</td>
</tr>
<tr>
<td>ODP Site 1233 (41°00’S; 74°27’W)</td>
<td>0-1</td>
<td>14.0</td>
<td>14.0</td>
<td>This study</td>
</tr>
</tbody>
</table>

* calculated with UK’37 = 0.033T + 0.044 (Müller et al., 1998)
* The uppermost sample is dated to 1.16 kyr cal BP

Table 1. Modern annual mean SSTs at 0 m water depth (after Levitus and Boyer, 1994) and alkenone-based SST measurements on surface sediment off Chile (27°S to 41°S).

It has been recently observed that alkenones may be substantially older than co-occurring planktic foraminifera (Mollenhauer et al., 2005). Holocene age differences measured on the Site 1233 survey core GeoB 3313-1 showed rather constant age offsets of ~1000 years. Mollenhauer et al. (2005) explained this offset as most likely resulting from continuous re-suspension/re-deposition cycles induced by internal tides and sediment focusing in morphologic depressions such as the small basin at Site 1233. By comparing the age offsets in different continental margin settings, they further noted that age offsets were largest where Total Organic Carbon (TOC) contents and alkenone concentrations are highest. If the age offsets are indeed induced by re-suspension/re-deposition cycles, they should be much smaller for the glacial section where both TOC and alkenone concentrations are significantly lower [i.e. respectively ~2 % weight (wt) and >2000 ng/g in the Holocene and <1% wt and ~500 ng/g in the glacial section]. In addition, grain-size data suggest constant and rather undisturbed fine-grained hemipelagic sedimentation (at least during the Holocene; see Lamy et al., 2001). Available oceanographic data show that bottom water circulation at the depth of Site 1233 (within the Antarctic Intermediate Water; e.g., Shaffer et al., 2004) is rather too sluggish for the re-suspension of sediments and internal waves have not been described at the Chilean margin. Therefore, it is likewise conceivable that a constant admixture of older material would affect the $^{14}$C ages but not significantly the reconstructed alkenone temperatures, a possibility that Mollenhauer et al. (2005) did not exclude either.

3.3 Sea-surface salinity reconstruction

The $^{18}$O/$^{16}$O ratio of seawater ($\delta^{18}$O$_{sw}$) is linearly related to the salinity, being therefore a proxy for estimating modern salinity. The $\delta^{18}$O composition of foraminifera ($\delta^{18}$O$_{calcite}$) is controlled by temperature and $\delta^{18}$O$_{sw}$. Thus, $\delta^{18}$O$_{sw}$ can be reconstructed if the temperature is independently determined. The combination of alkenone-based SST results with $\delta^{18}$O$_{calcite}$ data on planktic foraminifera allows reconstructing the $\delta^{18}$O$_{sw}$ as follows:
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a) In order to transfer the $\delta^{18}\text{O}_{c}$ from the PDB to the SMOW unit, 0.27‰ was added to the $\delta^{18}\text{O}_{c}$ values (Coplen et al., 1983; Hut, 1987).

b) To reconstruct the $\delta^{18}\text{O}_{sw}$, the paleotemperature equation of Shackelton (1974) was used:

$$ T = 16.9 - 4.38(\delta^{18}\text{O}_{c} - \delta^{18}\text{O}_{sw}) + 0.1(\delta^{18}\text{O}_{c} - \delta^{18}\text{O}_{sw})_2 $$

\[ \Leftrightarrow \delta^{18}\text{O}_{sw} = \delta^{18}\text{O}_{c} - 21.9 + \sqrt{310.61 + 10T} \]

On glacial timescales, the $\delta^{18}\text{O}_{sw}$ is affected by variations in continental ice volume. Therefore the $\delta^{18}\text{O}_{sw}$ values have been corrected from this “ice effect” assuming an enrichment of 0.1‰ per 10 meters of sea-level lowering. For this correction, the sea-level curves from Fairbanks et al. (1992) between 0 and 22 kyr and Arz et al. (submitted, 2005) between 22 and ~70 kyr were used in order to obtain the local changes of $\delta^{18}\text{O}_{sw}$ ($\delta^{18}\text{O}_{swcorr}$):

c) Correction for the “ice effect”:

$$ \delta^{18}\text{O}_{swcorr} = \delta^{18}\text{O}_{sw} - \Delta \delta^{18}\text{O}_{sw} $$

To estimate the paleosalinity ($S$; psu) from the $\delta^{18}\text{O}_{swcorr}$ the regional $\delta^{18}\text{O}_{swcorr}$ – salinity relationship for the eastern equatorial Pacific by Fairbanks et al. (1992) was applied, which has a similar slope as modelled by Delaygue et al. (2000) for the Southeast Pacific. Finally, the salinity results were corrected for the sea-level (sl) dependent salinity changes of the global ocean after Rostek et al. (1993), using the sea-level reconstructions aforementioned:

d) Regional $\delta^{18}\text{O}_{swcorr}$ – salinity relationship:

$$ \delta^{18}\text{O}_{swcorr} = 0.26 \times S - 8.77 $$

\[ \Leftrightarrow S = \frac{\delta^{18}\text{O}_{swcorr} + 8.77}{0.26} \]

e) Correction for the “sea-level effect” (sl) on salinity:

$$ S_{corr} = S - (sl \times 35) / 3800 $$

For the sea-surface salinity reconstruction at ODP Site 1233 the absolute paleosalinity values have to be considered with caution as it is assumed that the slope of the regional $\delta^{18}\text{O}_{swcorr}$ – salinity relationship did not change through the deglaciation (see e.g., Wolff et al., 1998). However the focus lies on the large melt-water signal which is very robust. Concerning core GeoB 7139-2, only the $\delta^{18}\text{O}_{swcorr}$ are discussed because the $\delta^{18}\text{O}_{swcorr}$ – salinity
relationship has probably strongly changed over the last 40 kyr. Therefore, the $\delta^{18}$O$_{swcorr}$ calculated as the deviation from modern conditions is used as a proxy for past salinity changes relative to the present day. Additional effects such as changing isotopic signature of rainfall (Wolff et al., 1998) are unlikely in both study areas because they are under the influence of rainfalls derived entirely from the Westerly wind belt in the southeast Pacific (see Section 2).

3.4 X-ray fluorescence measurements

The X-ray fluorescence (XRF) Core Scanner at the Bremen Core Repository is equipped with a central sensor unit which consists of a molybdenum X-ray source (3-50 kV) and a Peltier-cooled PSI detector (KEVEX$^{\text{TM}}$) with a 125 µm beryllium window and a multichannel analyzer with a 20 eV spectral resolution (Röhl and Abrams, 2000). The system configuration allows the analysis of elements from potassium through strontium. The resulting data are element intensities in count per second (cps).

The measurements were performed on the spliced sequence at ODP Site 1233 with 1 cm resolution resulting in a total of ca. 16,000 measurements. Many sections showed numerous gas expansion cracks and fissures which significantly affected the XRF measurements. Such data-points were manually removed from the data-set. The mean temporal resolution of the elemental data presented in this thesis is 5 years. In order to reduce noise in the data-set, the record was smoothed by applying a 10-point moving average to the raw data. For this thesis, only the iron concentrations record was used as a proxy for the terrigenous sediment input.

3.5 Long chain n-alkanes

The sedimentary n-alkanes distributions consist of a series of predominant odd-numbered $\text{C}_{25}\text{--C}_{35}$ homologues superimposed on even-numbered $\text{C}_{24}\text{--C}_{34}$ n-alkanes. Odd-numbered n-alkanes are major lipid components of terrestrial plant epicuticular waxes (Eglinton and Hamilton, 1963) which can be removed from the leaf surfaces by rain or wind (e.g., Schefuss et al., 2003a). Therefore, these plant wax compounds are widely found in marine sediments and are frequently used as indicators of higher plant contributions to the marine environment (e.g., Prahl and Pinto, 1987; Madureira et al., 1995; Schefuss et al., 2003b, 2004). The carbon preference index (CPI) of n-alkanes, defined as the ratio of the amount of odd-carbon n-alkanes to the amount of even-carbon n-alkanes (Kolattukudy, 1976; see below), is known to be high (i.e. >5) for higher plant-derived compounds (Eglinton and Hamilton, 1963; Simoneit and Mazurek, 1982), whereas petroleum- or marine-derived n-alkanes show no carbon-number preferences (Simoneit, 1984).

\[
CPI = 0.5 \times \frac{\sum C27-C33(odd)}{\sum C26-C32(even)} + 0.5 \times \frac{\sum C27-C33(odd)}{\sum C28-C34(even)}
\]
For core GeoB 7139-2, the apolar fractions containing the \( n \)-alkanes were obtained by elution of the total extracts through a Bond silica column (Bond Elute column, Varian) with 4ml of Hexane, than concentrated under \( N_2 \) and taken up in 25\( \mu l \) MeOH/CH\(_2\)Cl\(_2\) (1:1). The fractions were analyzed by capillary gas chromatography using a HP 5890 serie II Plus gas chromatograph equipped with a 60 m * 0.32 mm fused silica column (DB-5 MS, J&W) using split/splitless injection and flame ionization detection. Helium was used as carrier gas with a constant pressure of 150 kPa. After injection at 70°C, the oven temperature was programmed to 130°C at a rate of 2°C/min, then to 320°C at a rate of 4°C/min, and the final temperature was maintained for 30 min. The concentrations of the \( n \)-alkanes were determined using squalane (\( C_{30}H_{62} \)) as internal standard and expressed as ng/g of dry weight sediment. The reproducibility of the \( n \)-alkane quantifications was better than 20%.
4. MANUSCRIPTS

4.1 Antarctic timing of surface water changes off Chile and Patagonian ice-sheet response

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Abstract:

Marine sediments from the Chilean continental margin are used to infer millennial-scale changes in southeast Pacific surface ocean water properties and Patagonian ice sheet extent since the last glacial. Our data show a clear “Antarctic” timing of sea surface temperature changes which appear systematically linked to meridional displacements in sea ice, westerly winds, and the circumpolar current system. Proxy data for ice-sheet changes show similar pattern as oceanographic variations offshore, but reveal a variable glacier response time of up to \textasciitilde1000 years which may explain some of the current discrepancies among terrestrial records in southern South America.
Resolving the origin and consequences of the millennial-scale climate changes evident during the last glacial period and particularly the last deglaciation, is a cardinal challenge of current paleoclimate research. A comprehensive understanding of such climate changes is invaluable for validating and improving prognostic climate models. In the North Atlantic region, large and abrupt temperature changes are clearly documented at intervals of about ~5-10 and ~1-4.5 thousand years (Heinrich and Dansgaard-Oeschger events). The origins of these events are commonly construed to be linked to reorganizations in Atlantic thermohaline circulation (THC) (e.g., Rahmstorf, 2002). More recently, abrupt millennial-scale climatic oscillations have been recognized in many places around the globe. Their source is also postulated to be variations in the North Atlantic ocean-climate system propagating via global oceanic and atmospheric feedbacks (e.g., Voelker, 2002).

Recent modeling studies on the other hand, indicate that the tropics and the southern high latitudes may also play an active role in initiating rapid climate change (Cane, 1998; Knorr and Lohmann, 2003). For example, it has been shown that rapid climate oscillations may originate from the tropical Pacific, potentially involving a long-term modulation of interannual-to-decadal climate changes of the eastern tropical Pacific El Niño-Southern Oscillation (ENSO) (Cane, 1998). This tropical driver hypothesis is strengthened (but not proved) by recent proxy evidence from the tropical Pacific suggesting significant millennial variability likely involving long-term ENSO changes (Koutavas et al., 2002; Stott et al., 2002). A high southern latitude control is indicated by new modeling results (Knorr and Lohmann, 2003; Weaver et al., 2003) implying that abrupt climate changes known from the North Atlantic region during Termination 1 might well be triggered by gradual changes in southern high latitudes.

Most studies of interhemispheric climate change focus on comparing Northern Hemisphere records to Antarctic ice-core data, particularly from the Byrd ice-core, which has the most reliable age model (Blunier and Brook, 2001). These comparisons suggest asynchronic changes between the Northern and Southern Hemisphere (Blunier and Brook, 2001) consistent with the “bipolar see-saw concept” of Southern Hemisphere warming in response to reduced North Atlantic THC (e.g., Stocker, 1998; Broecker, 1998). On the other hand, terrestrial data from mid-latitude South America are still discussed controversially as they indicate both interhemispheric synchrony (Denton et al., 1999a; Lowell et al., 1995; Moreno et al., 2001) and asynchrony (Bennett et al., 2000). Even more puzzling are new surface ocean proxy records from the southwest Pacific implying that the coupling of oceanographic changes in the mid-southern latitudes and Antarctica might have changed with time (Pahnke et al., 2003).
Here, we present new records of surface ocean conditions in the southernmost Peru-Chile Current and associated changes in the extent of the Patagonian ice-sheet (PIS) in adjacent southern Chile based on well-dated marine sediments recovered at Ocean Drilling Project Site 1233 from the southern Chilean continental margin (Mix et al., 2003) (Figure 1). Continental paleoenvironmental records show that this region reacted very sensitively to rapid fluctuations in climate (Denton et al., 1999a; Lowell et al., 1995; Moreno et al., 2001; Heusser et al., 1999). However, so far it has proven difficult to compare such records unambiguously to those from the Northern Hemisphere, due to discontinuities, inadequate temporal resolution, and limitations in dating.

Sediments at Site 1233 are characterized by lithologically homogeneous fine-grained terrigenous material with minor amounts of well preserved biogenic components suitable for paleoceanographic studies (Mix et al., 2003). We focus on the time interval from 8 to 50 thousand calendar years B.P. (kyr B.P.), which is dated by 20\(^{14}\)C AMS dates and further
paleomagnetic evidence (see Supporting Online Material). Resulting sedimentation rates are extraordinarily high (1-3 m/kyr), due to strong fluvial discharge in response to heavy continental rainfall in southern Chile (Lamy et al., 2001) and the proximity to the PIS, which advanced towards the Chilean Lake District (directly onshore Site 1233; Figure 1) during the last glacial (Denton et al., 1999b) and provided terrigenous material via glacial erosion.

**Figure 2.** Compilation of paleoclimatic data-sets from the Southern Hemisphere mid-latitudes (see Supporting Online Material) compared to Antarctic and Greenland ice-core records (8 to 50 kyr B.P.). (A) Diatom-based sea-ice reconstruction from South Atlantic core TN 057-13 (Stuut et al., 2004). (B) Mg/Ca SST record from the SW Pacific (Pahnke et al., 2003). (C) Oxygen isotope record of *Globigerina bulloides* based on core RC11-83 from the South Atlantic, primarily reflecting SST (Ninnemann et al., 1999). (D) Alkenone SST record from ODP Site 1233 (this study). (E) Oxygen isotope record of the Byrd ice-core, Antarctica (Blunier and Brook, 2001). (F) Oxygen isotope record of the GISP2 ice-core, Greenland (Grootes et al., 1993). Gray bars mark age and approximate duration of the Younger Dryas and Heinrich events (based on GISP2 ages).
Our primary proxy record is the alkenone-based sea surface temperature (SST) reconstruction at Site 1233 (see Supporting Online Material) indicating a ~6°C SST change over Termination 1 and millennial-scale variations in the order of ~2°C to ~3°C during the glacial (Fig. 2D). During Termination 1, two major warming steps are recorded (~3°C from 19.2 to 17.4 kyr B.P. and ~2°C from 12.7 to 12.1 kyr B.P.) of which the last one falls into the first half of the Younger Dryas (Fig. 3B). This pattern is strikingly similar to the deglacial warming record of the Byrd ice-core (Blunier and Brook, 2001) (Figure 3A). For the glacial interval (20-50 kyr B.P.), most millennial-scale SST fluctuations appear to correlate to Antarctic temperature changes as well (Figure 2D and 2E) suggesting a direct link of SST changes in the southeast Pacific to climate fluctuations in high southern latitudes.

**Figure 3.** Deglacial paleoceanographic records from Site 1233. (A) Oxygen isotope record of the Byrd ice-core, Antarctica (Blunier and Brook, 2001). (B) Alkenone SST record. (C) Oxygen isotope record of the planktic foraminifera *Globigerina bulloides* (5-point moving average). (D) Salinity reconstruction (3-point moving average). Age control points are shown below. Gray bar marks the Younger Dryas event and hatched bar the final PIS maxima before rapid deglaciation (after Denton *et al.*, 1999b; see Supporting Online Material).
The large amplitude of SST variations over Termination 1 as well as on millennial timescales during the last glacial suggests substantial oceanographic changes. The most plausible explanation is a northward translation of the Antarctic Circumpolar Current (ACC) during cold periods enhancing the influence of subantarctic water masses at Site 1233. Today, SST gradients within the northernmost ACC are very large (Figure 1) and intimately linked to the northern margin of the westerly wind belt making this region very sensitive to latitudinal shifts of atmospheric and oceanographic circulation resulting in the large signal in our proxy data. The position of the Westerlies is controlled by the location of the sub-polar low pressure belt and the strength and position of the southeast Pacific anticyclone (Cerveny, 1998) allowing the potential for both high (southern) latitude and tropical Pacific forcing mechanisms. A tropical forcing could involve a long-term modulation of ENSO (Cane, 1998) which may have a substantial influence on the position of the westerlies through a modulation of the strength of the southeast Pacific anticyclone. There is some evidence, that ENSO operated at least during the last 130 kyrs (Tudhope et al., 2001) and that millennial-scale oscillations would likely reveal a “Greenland pattern” of climate change (Koutavas et al., 2002; Stott et al., 2002) which can not be supported by our data. On the other hand, a new SST record from the Sulu Sea does not indicate significant change of zonal SST gradients in the tropical Pacific across the Bølling-Allerød/Younger Dryas climate reversals raising doubts whether interannual (ENSO) variability is a good analogue for longer-term climate change (Rosenthal et al., 2003).

Our data clearly suggest that millennial-scale climate changes documented in Antarctic ice cores extended into the Southern Hemisphere mid-latitudes and affected major oceanographic (i.e. the ACC) and atmospheric (the Westerlies) circulation patterns. Within the uncertainties of age models (see Supporting Online Material), these changes appear quasi hemisphere-wide as shown by a comparison to a Mg/Ca SST record from the SW Pacific (Pahnke et al., 2003) (Figure 2B) and a planktic foraminifera oxygen isotope record from the South Atlantic (Ninnemann et al., 1999) (Figure 2C). Although the sense and timing of our temperature changes are generally consistent with the bipolar see-saw mechanism (Blunier and Brook, 2001; Stocker, 1998; Broecker, 1998), i.e. cold North Atlantic temperatures during Heinrich events parallels increasing SST in the Southern Hemisphere mid-latitudes (Figure 2), model simulations of THC changes do not show a significant response in the southeast Pacific (e.g., Ganopolski and Rahmstorf, 2001). Thus it is equally plausible that the quasi Southern Hemisphere-wide millennial-scale pattern emerging in Pacific and Atlantic records is of Southern Hemisphere origin. Recent modeling studies suggest that comparatively slow climate changes around Antarctica might trigger abrupt events in the North Atlantic realm, most likely involving changes in sea-ice extent and salinities in the Southern Ocean (Knorr and Lohmann, 2003; Weaver et al., 2003). Diatom-based sea-ice reconstructions from the Atlantic sector of the Southern Ocean
(Figure 2A) (Stuut et al., 2004) do indeed parallel the SST changes in the Pacific and show reduced sea-ice extent during periods of warmer Southern Hemispheric mid-latitude SSTs.

The Antarctic timing apparent in our SST record is distinct from that observed in terrestrial glaciological and palynological data from the Chilean Lake District directly onshore Site 1233, which more closely follow the Northern Hemisphere pacing and have been used to argue for interhemispheric synchrony both during the glacial (Lowell et al., 1995) and deglaciation (Denton et al., 1999a; Moreno et al., 2001). Site 1233 offers the exceptional possibility to compare continental and marine paleoenvironmental changes within the same well-dated archive. The site is located in an ideal position to monitor PIS extent variations by recording compositional changes in the regional terrigenous sediment input to the continental margin. For this purpose, we use the Fe content of the bulk sediment measured at sub-decadal resolution (see Supporting Online Material). For the Holocene record of core GeoB 3313-1 from the same location, changing Fe contents have been related to a varying contribution of Andean (Fe-rich) versus Coastal Range (Fe-poor) source rocks ultimately controlled by continental rainfall changes (Lamy et al., 2001). Glacial erosion processes strongly enhanced the glaciofluvial sediment flux from Fe-rich basaltic volcanics in the Andes during the last glacial and ice-sheet advances provided more Fe-rich material, being subsequently transported to the continental margin by rivers. This scenario is supported by extensive geomorphological mapping and dating of moraines that documented pronounced PIS variability during the late glacial (Denton et al., 1999b). Three of four major ice-maxima correlate, within the limitations of dating (see Supporting Online Material), to maxima in our Fe record (Figure 4). Thus our proxy of glaciofluvial sediment input provides the first continuous record of PIS variability for a major part of the last glacial.
Figure 4. Iron contents (10-point moving average; plotted inverse) and alkenone SSTs from 8 to 50 kyr B.P. at Site 1233. Graphical correlation lines show lead of SST record (see also Figure S2 and S3 in Supporting Online Material). PIS maxima after (Denton et al., 1999b; see Supporting Online Material). Iron peak at ~11 kyr represents an ash layer (see “age model” in Supporting Online Material).

A modeling study of PIS changes during the late glacial points to a close dependence of ice extent on offshore SSTs and suggests a 6°C SST lowering in the southeast Pacific off southern Chile during the regional ice maximum (Hulton et al., 2002) exactly matching our alkenone SST reconstructions at Site 1233. In addition, SST fluctuations of ~2°C to ~3°C during the glacial follow a pattern strikingly similar to the variations in Fe (Figure 4). This comparison demonstrates that the repeated perturbations in offshore SST between ~20 and 50 kyr B.P. are regularly accompanied by substantial changes in onshore ice-extent - seemingly confirming the sensitivity of the northern PIS limb to oceanographic variations offshore observed in models (Hulton et al., 2002).

Though the patterns of the Fe and paleo-SST records are very similar, SST changes lead the Fe variations by up to ~700 years (Figure 4; Figure S2, and Figure S3, see Supporting Online Material). The offset is largest between ~20 and 40 kyr B.P. and disappears in the earliest part of our record. On one hand, this offset may indicate that the relation of Fe changes to glacial dynamics is not as straightforward as we assume. For example, it is conceivable that a glacier retreat in response to rising SSTs would initially result in enhanced sediment and thus Fe output as material in storage is released as the ice margin retreats. On the other hand, the independently dated glacier maxima (Denton et al., 1999b) correlate in most cases to periods of rising SST
(Figure 4) - particularly the well-dated glacier maxima between ~18.0 to 17.7 kyr B.P. (Denton et al., 1999b; see Supporting Online Material) that occurred while SSTs were already increasing rapidly for ~1000 years (Figure 4). Additional support for a delayed ice sheet response comes from our reconstruction of paleosalinity over Termination 1 (see Supporting Online Material). The substantial decrease in salinities from ~17.8 to 15.8 kyr B.P. (Figure 3D) suggests that the PIS was wasting rapidly after the last glacier maxima inferred from terrestrial studies (Denton et al., 1999b). During this period, Fe contents remain high and most likely reflect strong fluvial erosion of the rapidly exposing glacial deposits and thereafter decrease towards the Holocene when they become rainfall-controlled (Lamy et al., 2001). Taken together, these observations suggest a substantial time-lag between climate forcing and PIS response - assuming that the atmospheric system responds roughly synchronously to changes in SSTs which is reasonable for the extremely maritime climate conditions in southern Chile. The changing time-lag along the record suggests a possible relationship to ice sheet size. Though not precisely dated, terrestrial studies show that the PIS was substantially reduced in size during early marine isotope stage 3 (Denton et al., 1999b) consistent with the disappearance of the delay before 40 kyr B.P. The largest lag is observed for the decay of ice after its maximum extent before the deglaciation.

Our records provide an important advance toward a better understanding of interhemispheric climate change during the last glacial and deglaciation which has been hampered by the lack of high resolution paleoceanographic records from the South Pacific region (e.g., Stocker, 2002). Together with proxy evidence from the southwestern Pacific and Atlantic, our data suggest a quasi Southern Hemisphere-wide millennial-scale pattern of atmosphere-ocean changes in phase with Antarctic ice-core records providing important constraints for the optimization of climate models. The apparent climate inertia in the PIS, and its variable influence on terrestrial sites whose climate may be strongly influenced by changes in the size and proximity of the ice-sheet, could on the other hand explain some of the current discrepancies among terrestrial records in southern South America e.g. during Termination 1 (Moreno et al., 2001; Bennett et al., 2000).

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Supporting Online Material

Sampling

Our study is based on marine sediments recovered at Ocean Drilling Project (ODP) Site 1233 drilled during Leg 202 in April 2002 (Mix et al., 2003). Site 1233 (41°00´S; 74°27´W) is located 38 km offshore (20 km off the continental shelf) at 838 m water depth in a small forearc basin on the upper continental slope off Southern Chile. Five Advanced Piston Corer holes were drilled at Site 1233 to ensure a complete stratigraphic overlap between cores from different holes. Detailed comparisons between high-resolution core logging data performed shipboard demonstrated that the entire recovered sedimentary sequence to 116.4 m below surface (mbsf). Based on these data, a composite sequence (the so-called splice) was constructed representing 135.65 m composite depth (mcd). The working halves of all sections from Site 1233 were shipped after the end of the cruise to the Bremen ODP Core Repository (BCR) where we performed X-ray fluorescence (XRF) scanning on the splice. Discrete samples for alkenone and oxygen isotope analyses were taken after XRF scanning from the splice and samples for $^{14}$C accelerator mass spectrometry (AMS) dating were taken from outside the splice.

Age model

In this study we present data from the composite sequence between 8 and 50 thousand calendar years (kyr) B.P. representing ~9.5 to ~89 mcd. The age model of this interval is primarily based on twenty $^{14}$C-AMS datings (Table S1) and linear interpolation between the dates. Ages were calibrated with the Calpal software (http://www.calpal.de) using the new Calpal 2004 January calibration curve. In our opinion it is the best presently available calibration curve because it considers the most important recent calibrations for different time-intervals. Beyond a tree-ring calibrated Holocene interval (identical to the INTCAL98; (Stuiver et al., 1998)), a cubic spline was built through U/Th-coral data (Burr et al., 1998; Bard et al., 1993, 1998), GISP2-synchronized planktonic foraminifera data of North Atlantic sediment core PS2644 (Voelker et al., 2000), and GISP2-synchronised varve greyscale data from the Cariaco Basin (Hughen et al., 2000, 2004). We assume no regional deviation from the global reservoir effect of ~400 years because the core position lies significantly south of the Chilean upwelling zone (Strub et al., 1998) and north of the southern polar front. According to the Marine Reservoir Correction Database compiled by P. Reimer (http://depts.washington.edu/qil/marine/; (Reimer and Reimer, 2001)), a regional deviation may apply for upwelling influenced regions of the Peru-Chile Current (PCC) further north (e.g., off Valparaiso) but prevailing winds, the Southern Westerlies, prevent coastal upwelling off southern Chile (Strub et al., 1998). Therefore, the assumption of a 400-yr reservoir age which is also the mean reservoir age for the Pacific Ocean at ~40°S (Bard,
1998) appears to be the most reasonable assumption. In addition, a volcanic ash layer at ~14.7 mcd at Site 1233 with an interpolated $^{14}$C age of ~9,600 years correlates to a regionally recorded tephra layer on nearby Chiloé Island (Heusser et al., 1995) and in the Chilean Lake District (Moreno, 2004) with an independently dated age close to 9,500 $^{14}$C years B.P. (~11,000 calendar years B.P.). This strongly supports our ~400 yr reservoir age assumption. During the glacial, slightly higher reservoir ages may apply because of the northward movements of fronts in the Southern Ocean. To the south, the next available data point in the Marine Reservoir Correction Database is located in the southern Chilean fjords at ~51°S with a reservoir age of 595 years. There is no evidence that the oceanographic fronts in the Southern Ocean moved 10° latitude northward during the glacial, which using the modern as a guide, would result in up to 200 year older reservoir ages at our core site. Evidence from northern Chile rather suggests that the Southern Westerlies moved about 5° northward during the last glacial maximum (Lamy et al., 1998) consistent with estimates for the displacements of fronts in the Atlantic-Indian sector of the Southern Ocean (Gersonde et al., 2003). Potentially this would result in a greater reservoir age at our site by up to ~100 years which does not change any of our interpretations and lies well within the dating uncertainty in this time-interval.

The $^{14}$C-AMS based age model is used between ~8 and 40 kyr (Figure S1). Three additional datings beyond 40 kyr are disregarded as both the dating and the calendar year conversion have a substantial error (Table S1). Therefore, we use here paleomagnetic evidence indicating the presence of the “Laschamp Event” as the most prominent feature in late Pleistocene paleointensity fluctuations of the geomagnetic field with a mid-point core depth of 67.8 mcd (Mix et al., 2003), which we assigned an age of 41 kyr based on the GISP2-age scale (Voelker et al., 2000). Beyond Laschamp age control is only limited. We extrapolate down to 50 kyr by assuming constant sedimentation-rates between 41 kyr and marine isotope stage (MIS) 4.2. (65 kyr after (Martinson et al., 1987)) (Figure S1), which can be defined from the alkenone SST record (J. Kaiser, unpublished data). Low resolution records from the subpolar South Pacific have shown that SSTs show a pronounced minimum during MIS 4.2. (Mashiotta et al., 1999). The resulting age-depth relationship is shown in Figure S1.

**XRF core scanning**

The XRF Core Scanner is a non-destructive analysis system for relatively fast and closely spaced analyses of major and minor elements by scanning split sediment cores. XRF measurements of the entire suite of elements between potassium and strontium can be recorded. XRF data show a significantly higher signal-to-noise ratio and a more consistent hole-to-hole agreement than standard core logs. XRF measurements were performed at the BCR on the working halves of the primary Site 1233 splice which provides a continuous sediment record from 0 to 135.65 mcd. At correlation points of the splice between sections from different holes
overlapping measurements (20-70 cm) were done. All measurements were performed with 1 cm resolution (representing sub-decadal time-resolution in most intervals) resulting in a total of ca. 16,000 measurements. Many sections showed numerous gas expansion cracks and fissures which affected the XRF measurements. Such measurements had to be disregarded and were manually extracted from the data-set.

**Oxygen isotopes**

Stable isotope analyses for the 8 to 25 kyr B.P. interval were performed at the University of Bergen on specimens of the planktonic foraminifer *Globigerina bulloides* selected from the >250 to 355 µm size fraction with an average time resolution of ~130 years. Prior to analysis, all shells were cracked open and sonicated for 1 minute in methanol to remove any fine-grained particles. Samples were analyzed using a Finnigan MAT 251 mass spectrometer coupled to an automated Kiel device. The data are reported on the VPDB scale calibrated with NBS-19. The long term analytical precision of the system as defined by the reproducibility of carbonate standards exceeds ±0.05 ‰ and ±0.07 ‰ for δ¹³C and δ¹⁸O respectively.

**Alkenone measurements**

To determine past SST variations off Chile, we measured the alkenone unsaturation index $U'_{37}$ (Prahl *et al.*, 1988) with an average time resolution of ~300 years. Alkenones were extracted from 1-3 g portions of the freeze-dried and homogenized sediment following a procedure described in detail in (Müller *et al.*, 1998). The extracts were analysed by capillary gas chromatography using an HP 5890 serie II Plus gas chromatograph equipped with a 60 m column (J&W DB5MS, 0.32 mm • 0.1 µm), split/splitless and flame ionization detection. Helium is used as carrier gas with a constant pressure of 150 psd. The oven temperature is programmed to reach 50-250°C at 25°C/min, 250-290 at 1°C/min, followed by a plateau of 26 min, and 290-310 at 30°C/min, with the final temperature being maintained for 10 min.

Quantification of the alkenones was achieved using squalane as internal standard and HPGC ChemStation as analytical software. The alkenone unsaturation index $U'_{37}$ was calculated from $U'_{37} = (C_{37:2})/(C_{37:3} + C_{37:2})$, where $C_{37:2}$ and $C_{37:3}$ are the di- and tri-unsaturated C₃₇ methyl alkenones. The analytical precision is better than +/- 0.01 $U'_{37}$ (or 0.3°C). For conversion into temperature values, we used the culture calibration of Prahl *et al.* (1988) ($U'_{37} = 0.034T + 0.039$), which has been validated by core-top compilations (e.g., Müller *et al.*, 1998). We assume that alkenone-derived SST estimates at Site 1233 reflect annual mean sea surface temperatures. This is confirmed by measurements on surface sediments at Site 1233 (J. Kaiser, unpublished data) and further north along the Chilean continental margin (Kim *et al.*, 2002).
Paleosalinity

The $\delta^{18}O$ of planktic foraminifera mainly depends on the temperature and $\delta^{18}O$ of ambient sea water ($\delta^{18}O_w$). Since $\delta^{18}O_w$ is linearly related to salinity it is possible to reconstruct paleosalinity if an independent estimate of temperature is available (e.g., Rostek et al., 1993). Here we used the $\delta^{18}O$ of the planktic foraminifera *Globigerina bulloides* ($\delta^{18}O_{\text{carb}}$) and the alkenone temperature record (T) for estimating paleosalinity variations during the deglaciation (8 to 22 kyr). To match the average resolution of the alkenone SST record in this interval, we interpolated the $\delta^{18}O_{\text{carb}}$ record to a resolution of 350 years. In order to eliminate the global ice volume signal from the $\delta^{18}O_{\text{carb}}$ record, we corrected the data with the mean-ocean $\delta^{18}O_w$ record of (Fairbanks et al., 1992). Then, we used the paleotemperature equation of (Shackleton, 1974) to reconstruct the local $\delta^{18}O_w$:

$$T = 16.9 - 4.38(\delta^{18}O_{\text{carb}} - \delta^{18}O_w) + 0.1(\delta^{18}O_{\text{carb}} - \delta^{18}O_w)^2$$

(1)

$T = \text{paleotemperature} \ [^\circ\text{C}]$

$\delta^{18}O_w = \delta^{18}O$ of ambient sea water [‰ vs. SMOW]

$\delta^{18}O_{\text{carb}} = \delta^{18}O$ of carbonate (*G. bulloides*) [‰ vs. PDB]

To estimate the local changes in paleosalinity from the $\delta^{18}O_w$ record we applied the regional $\delta^{18}O$-salinity relationship for the Eastern Equatorial Pacific by Fairbanks et al. (1992) (which has a similar slope as the regional $\delta^{18}O$-salinity relationship for the SE Pacific as modelled by (Delaygues et al., 2000)) (equation (2)):

$$\delta^{18}O_w = 0.26S - 8.77$$

(2)

$\delta^{18}O_w = \delta^{18}O$ of ambient sea water [‰ vs. SMOW]

$S = \text{paleosalinity} \ [\text{psu}]$

Finally we corrected also for the sea level dependent salinity changes of the global ocean ($\Delta S = \text{sea level} \cdot 35/3800$) (Rostek et al., 1993). We assume that the slope of the regional $\delta^{18}O$-salinity relationship (2) did not change significantly through the deglaciation which is probably not correct (see e.g., Wolff et al., 1998)). Therefore, the absolute paleosalinity changes reported in this study should be regarded with caution. However, we focus in our interpretation on the large melt-water signal during the deglaciation which is a very robust signal. Additional effects such as changing isotopic signatures of precipitation (Wolff et al., 1998) are unlikely because our study area is situated within or near the source region of rainfall derived from the westerly wind belt in the Southeast Pacific.
Supporting Online Figures and Tables

**Figure S1.** Age control points used to construct the age model for Site 1233, which is based on calibrated $^{14}$C-AMS datings and linear interpolation between the dates from 8 to ~40 kyr. Ages were extrapolated down to 50 kyr based on the well defined paleomagnetic Laschamp event (41 kyr) (Mix *et al.*, 2003) and the definition of MIS 4.2. based on the Alkenone SST record (Jérôme Kaiser, unpublished data). Dashed line defines age-depth window discussed in this paper.

**Figure S2.** Upper panel shows alkenone SST record shifted in order to match the iron content changes (using Analysis Software (Paillard *et al.*, 1996)) applying the tie points shown in Figure 2 (linear interpolation between the tie points). The correlation coefficient is 0.47. Lower panel shows resulting offset; SST lead iron content changes by ~400 to 700 years in the interval 20 to 40 kyr. Nearly no offset between the records can be observed from 40 to 50 kyr.
**Figure S3.** Cross correlation of alkenone SST and iron content records with different time lead/lags (200 yr steps). Iron data were interpolated in order to achieve the mean resolution of the SST data-set. Bold lines show results for the 20-40 kyr interval, indicating a maximum correlation with a SST lead of ~600 years. Dashed line shows results for the 40-50 kyr interval indicating no significant lead/lag between the two data-sets. Both results are in agreement with the results shown in Figure S2.
**Table S1.** $^{14}$C Ages obtained by Accelerator Mass Spectrometry dating of mixed planktonic foraminifera samples (primarily *Globigerinoides bulloides* and *Neogloboquadrina pachyderma*), performed at the Leibniz-Labor AMS facility in Kiel, Germany (Nadeau *et al.*, 1997) and calibrated using the *Calpal 2004 January* calibration curve ([http://www.calpal.de](http://www.calpal.de)). Additional age control points shown are derived from paleomagnetic measurements (Mix *et al.*, 2003) and a correlation of the Alkenone SST record to marine isotope stage 4.2 (Martinson *et al.*, 1987).
4.2 A 70-kyr sea surface temperature record off southern Chile (ODP Site 1233)

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_Paleoceanography, in press_

Abstract

We present the first high resolution alkenone-derived sea surface temperature (SST) reconstruction in the Southeast Pacific (ODP Site 1233) covering the major part of the last glacial period and the Holocene. The record shows a clear millennial-scale pattern that is very similar to climate fluctuations observed in Antarctic ice cores suggesting that the Southern Hemisphere high-latitude climate changes extended into the mid-latitudes, involving simultaneous changes in air temperatures over Antarctica, sea-ice extent, extension of the Antarctic Circumpolar Current, and westerly atmospheric circulation. A comparison to other mid-latitude surface ocean records suggests that this “Antarctic” millennial-scale pattern was probably a hemisphere-wide phenomenon. In addition, we performed SST gradient reconstructions over the complete latitudinal range of the Pacific Eastern Boundary Current System (PEBCS) for different time-intervals during the last 70 kyr. The main results suggest an equatorward displaced subtropical gyre circulation during MIS 2 and 4.
1. Introduction

While climate changes at millennial timescales during the last glacial period (Marine Isotope Stages (MIS) 4 to 2) are relatively well-known in the Northern Hemisphere (NH), there is a clear lack of records in the Southern Hemisphere (SH). Nevertheless, a number of new proxy records have been published over the last years and begin to provide a clearer picture of paleoceanographic pattern in the SH mid- to high-latitudes (e.g., Charles et al., 1996; Ninnemann et al., 1999; Kanfoush et al., 2000; Pahnke et al., 2003; Lamy et al., 2004). In the most widely accepted view, the primary trigger of millennial-scale changes on a global scale is located in the NH and involves abrupt changes in the global thermohaline circulation (THC), in particular in the formation of North Atlantic Deep Water (NADW) (e.g., Rahmstorf, 2002). These changes result in large and abrupt climate shifts most clearly observed in the North Atlantic realm but also in other parts of the NH (e.g., Voelker, 2002). The synchronization of ice cores from Antarctica and Greenland using methane concentrations provides strong evidence for a climatic seesaw pattern of the temperature changes in the NH and SH polar regions and the reconstruction suggests that the onset of seven major millennial-scale warmings in Antarctica preceded the onset of Greenland warmings (Blunier and Brook, 2001). Many modeling studies provide evidence that this interhemispheric seesaw pattern could be largely induced by changes in NADW formation (e.g., Rahmstorf, 2002). Other models suggest on the other hand that changes in temperature, sea-ice extent and/or salinity around Antarctica could influence the strength of the North Atlantic THC (Shin et al., 2003b) and possibly trigger abrupt events in the North Atlantic region as well (Knorr and Lohmann, 2003; Weaver et al., 2003), which would support a more prominent role of the SH in abrupt climate changes. These different modeling results show that the ultimate mechanism behind short-term climate variability during the last glacial and the seesaw pattern still remains uncertain and high resolution paleoceanographic records from the SH can greatly contribute to solving some of the open questions.

Wherever the ultimate origin of millennial-scale climate and ocean variability is located, the surface eastern boundary currents along the western margins of the major continental land masses act as conduits for the exchange of heat from the cold, high- to the warm, low-latitudes. The Peru-Chile Current (PCC), or Humboldt Current, is one of the largest and most productive Eastern Boundary Current systems in the world. Up-to-date, its spreading and functioning during the last glacial period is not well known because of the lack of records with sufficient resolution, especially in its southernmost part. Near the equator, recent studies suggest that during glacial maxima, the Pacific Eastern Boundary Current System (PEBCS) flow was stronger-than-today and thus substantially contributed to the cooling in the equatorial region (Feldberg and Mix, 2003; Martinez et al., 2003).
Southernmost South America is ideally located to reconstruct climate variability in the SH as it is situated under the influence of the dominant oceanographic (Antarctic Circumpolar Current, ACC) and atmospheric (Westerly winds) circulation members. On land, extensive climate reconstructions mainly based on glaciological and palynological studies have shown the sensitivity of southernmost South America to climate changes since the Last Glacial Maximum (LGM) and during the Holocene (e.g., Lowell et al., 1995; Denton et al., 1999a, 1999b; Moreno et al., 2001). Some terrestrial records suggest a link to NH millennial-scale climate changes, such as a cooling during the NH Younger Dryas (YD) cold event (e.g., Moreno et al., 2001), whereas others show no response to the YD (e.g., Bennett et al., 2000).

Recently, Lamy et al. (2004) have presented high resolution marine records in the southeast Pacific spanning the interval from 8 to 50 kyr. Contrary to reconstructions on the adjacent land, the record of past sea surface temperatures (SST) shows a clear millennial-scale “Antarctic timing” suggesting a close connection to SH high-latitude climate changes. Based on the record of iron concentrations on the same core, the authors proposed that the inertia of the Patagonian ice sheet to respond to rapid climate changes could partly explain the disagreements between land and ocean records.

Here we present a high resolution alkenone-based SST record from the SE Pacific mid-latitudes off southern Chile (Ocean Drilling Project (ODP) Leg 202 Site 1233) covering the last ~70 kyr. The study contains five main points: (1) the prolongation and improvement of the alkenone-based SST reconstruction published in the work of Lamy et al. (2004), which confirms our previous interpretations; (2) the improvement of the age-model by tuning the SST to the oxygen isotope record of the Antarctic Byrd ice core between ~40 and 70 kyr; (3) the regional implications of the SST reconstruction for the southern PCC and adjacent southern South America; (4) a zonal comparison to other paleoceanographic records in the SH mid-latitudes and a discussion of the possible forcing mechanisms at millennial to sub-millennial timescales during MIS 4 to 2; (5) a latitudinal SST gradient reconstruction covering the complete PEBCS in order to better understand the different SST patterns and their implications for the atmospheric and oceanic circulations at different time-intervals during the last glacial period and the Holocene.

2. Oceanographic and Atmospheric Settings

The study area (Figure 1) is located at the northern margin of the ACC under the influence of cold, subantarctic surface waters and steep latitudinal SST gradients (~5°C between 43°S and 39°S) (from Levitus and Boyer, 1994). Mean annual SSTs are around 14°C and the seasonal amplitude is ~5°C. The northern part of the ACC splits around ~43°S into the PCC flowing northward and the Cape-Horn Current (CHC) turning towards the south (Strub et al., 1998). Subsurface currents at the core site include the southward-flowing Gunther Undercurrent near the shelf edge, at depths of 100–300 m (Fonseca, 1989). Between ~400 and
~1000 m, Antarctic Intermediate Water flows northward along the Chilean continental margin (Strub et al., 1998).

**Figure 1.** Modern annual mean sea surface temperature distribution (°C; after Levitus World Atlas 1994) (Levitus and Boyer, 1994) in the Southeast Pacific, and the location of ODP Site 1233 (41°00’S, 74°27’W), as well as sediment cores discussed in the text: GeoB3302-1 (72°02’W, 33°13’S) (Kim et al., 2002), GIK17748-2 (72°02’W, 32°45’S) (Kim et al., 2002), TG-7 (78°60’W, 17°14’S) (Calvo et al., 2001), ODP846B (90°49’W, 3°05’S) (Martinez et al., 2003), RC13-110 (95°65’W, 0°09’N) (Feldberg and Mix, 2003), TR163-19 (86°26’W, 2°12’N) (Lea et al., 2000). ACC: Antarctic Circumpolar Current; CHC: Cape-Horn Current; PCC: Peru-Chile Current; SEC: South Equatorial Current; STH: Subtropical High Pressure; L: Low Pressure Belt associated with the Westerlies. Inset: location of the cores in the Southern Hemisphere mid- to high-latitudes used in the study (see Table 2); PF: Polar Front; SAF: Subantarctic Front.

In the SE Pacific mid- to high-latitudes, the steepest SST gradient within the ACC is strongly related to the main atmospheric circulation member of the Southern Hemisphere, the
westerly wind belt (Streten and Zillman, 1984). This intense and powerful circulation, annually centered around 50°S, results from the strong thermal gradient and atmospheric pressure difference between cold air masses over Antarctica and the warmer air and water masses in the subtropical regions (Cerveny, 1998). In southernmost South America, the Westerlies and associated storm tracks bring heavy rainfalls, e.g. an annual mean greater than 2000 mm in Puerto Montt (41°S), and prevent upwelling south of 42°S (Strub et al., 1998).

Trenberth (1991) has described the modern seasonal fluctuation of the storm tracks associated to the Westerlies in the Southern Hemisphere. In summer, the storm track activity can be as strong as in winter, but is located slightly equatorward of its winter position, and is concentrated in a tight band centered around 49-50°S. In winter, storm track activity extends over a broader range of latitudes and is centered only 2° poleward from its summer position. The strong SST gradients associated with the ACC are marked by a northward latitudinal shift of ~5° in winter. The seasonal shifts of this coupled system are apparently controlled by seasonal changes in sea-ice extent around Antarctica (Markgraf et al., 1992), which has been estimated to range between 4 millions km$^2$ in summer and 19 millions km$^2$ in winter (Comiso, 2003).

Site 1233 (41°S) is located at a key position to investigate the meridional oceanic heat exchanges in the Southeast Pacific, i.e. at the origin of the PCC, the latitudinally most extensive Eastern Boundary Current system in the world, driven by south-easterly winds along the Pacific coast of South America (Strub et al., 1998). The resulting offshore Ekman flow drives perennial upwelling of cool, nutrient-rich waters that produces one of the biologically most productive regions in the oceans (Berger et al., 1987). At about 5°S, the PCC is deflected offshore, feeds the South Equatorial Current (SEC) and flows westward as the equatorial cold-tongue between 10°S and 4°N (Wyrtki, 1965). North of the SEC, the Equatorial Front separates the cold, salty waters of the Peru-Chile Current from warmer and fresher tropical waters from the Northern Hemisphere. Thus, the PCC acts as a conduit for exchange of heat and nutrients between high- and low-latitudes in the eastern Pacific.

3. Material and Methods

Site 1233 was drilled during ODP Leg 202 off southern Chile (41°0.01’S, 74°26.99’W; 40 km offshore; 838 m water depth) in a small basin on the upper continental slope away from the pathway of major turbidity currents (Mix et al., 2003). Five Advanced Piston Corer holes were drilled at Site 1233 to ensure a complete stratigraphic overlap between cores from different holes. Detailed comparisons between high-resolution core logging data performed shipboard demonstrated that the entire sedimentary sequence to 116.4 m below surface (mbsf) was recovered. Based on these data, a composite sequence (the so-called splice) was constructed representing 135.65 m composite depth (mcd).
Sediments at Site 1233 are dominated by terrigenous components (clay and silty clay) with varying but generally small amounts of calcareous components (primarily nannofossils and foraminifera). Calcium carbonate concentrations and TOC contents range from 1 to 11 wt% (average = 5.4 wt%) and from 0.4 to 2.5 wt% (average = 0.9 wt%) (Mix et al., 2003). The TOC contents are substantially lower between 30 and 136 mcd (0.4 to 1 wt%) in comparison to the top of the core (up to 2.5 wt%). Samples for alkenone measurements were taken with intervals ranging from 12 to 149 cm (average = 61 cm) from the splice. Samples for ¹⁴C accelerator mass spectrometry (AMS) dating were taken from outside the splice (Lamy et al., 2004).

To determine past SST variations off Chile, we have measured the alkenone unsaturation index UK’₃₇ as defined by Prahl and Wakeham (1987) on 1-3 g freeze-dried and homogenized sediment samples. After the addition of internal standards (squalane (C₃₀H₆₂) and 2-nonadecanone (C₁₉H₃₈O)), alkenones were extracted using mixtures of methanol and methylene chloride with decreasing polarity (MeOH, MeOH/CH₂Cl₂ 1:1, CH₂Cl₂) by ultrasonication (UP 200H sonic disruptor probe, Hielscher GmbH, 200W, 105µm amplitude, 0.5s pulse). After centrifuging, the extracts were combined, desalted with de-ionized water, dried with Na₂SO₄ and evaporated to dryness. The concentrated residue was dissolved in CH₂Cl₂. To avoid interferences with co-eluting C₃₆-fatty acid methyl esters, saponification was performed using 0.1 N KOH in methanol (90/10 CH₃OH/H₂O) at 80°C for 2 hours followed by partitioning of the neutral fraction containing the alkenones into hexane. The extracts were finally concentrated under N₂ and taken up in 25µl MeOH/CH₂Cl₂ (1:1).

The extracts were analyzed by capillary gas chromatography using a HP 5890 serie II Plus gas chromatograph equipped with a 60 m × 0.32 mm fused silica column (DB-5 MS, J&W) using split/splitless injection and a flame ionization detection. Helium was used as carrier gas with a constant pressure of 150 psd. After injection at 50°C, the oven temperature was programmed to 250°C at a rate of 25°C/min, then to 290°C at a rate of 1°C/min, held for 26 min, and finally to 310 at a rate of 30°C/min, where the final temperature was maintained for 10 min.

Quantification of the alkenones was achieved using HPGC ChemStation as analytical software. UK₃₇ was calculated from UK’₃₇ = (C₃₇:2)/(C₃₇:3 + C₃₇:2), where C₃₇:2 and C₃₇:3 are the di- and tri-unsaturated C₃₇ methyl alkenones. For conversion into temperature values, we used the culture calibration of Prahl et al. (1988) (UK’₃₇ = 0.034T + 0.039), which has been validated by core-top compilations (Müller et al., 1998). The analytical precision was estimated to be around ±0.5°C. The SST estimate for the uppermost sample (14°C) matches the modern annual mean SST value for the core site (Levitus and Boyer, 1994). This is in agreement with other alkenone temperature analyses of surface sediments recovered north of our study site (Kim et al., 2002). We thus consider that alkenone-derived SSTs correspond to the annual average of the ocean sea water surface. The alkenone content (defined as the sum
of the C\textsubscript{37:3} and C\textsubscript{37:2} alkenones) ranges from \textasciitilde2600 ng/g (between \textasciitilde0-10 mcd) to \textasciitilde700-1000 ng/g (for the rest of the core).

It has been recently observed that alkenones may be substantially older than co-occurring planktic foraminifera (Mollenhauer et al., 2005). Holocene age differences measured on the Site 1233 survey core GeoB 3313-1 showed rather constant age offsets of \textasciitilde1000 years. Mollenhauer et al. (2005) explained this offset as most likely resulting from continuous re-suspension/re-deposition cycles induced by internal tides and sediment focusing in morphologic depressions such as the small basin at Site 1233. By comparing the age offsets in different continental margin settings, they further noted that age offsets were largest where TOC contents and alkenone concentrations are highest. Therefore, we expect that the age offsets if they are indeed induced by re-suspension/re-deposition cycles should be much smaller for the glacial section where both TOC and alkenone concentrations are significantly lower. We also note that grain-size data suggest constant and rather undisturbed fine-grained hemipelagic sedimentation (at least during the Holocene; see Lamy et al. (2001)). Available oceanographic data show that bottom water circulation at the depth of Site 1233 (within the Antarctic Intermediate Water; e.g., Shaffer et al. (2004)) is rather too sluggish for the re-suspension of sediments and internal waves have not been described at the Chilean margin. Therefore, it is likewise conceivable that a constant admixture of older material would affect the \textsuperscript{14}C ages but not significantly the reconstructed alkenone temperatures, a possibility that Mollenhauer et al. (2005) did not exclude either.

In some samples of the core (30 on a total of 223 samples), mainly located between \textasciitilde30 and 80 mcd, the presence of co-eluting organic compounds altered the peaks of the long-chain alkenones and thus the UK’37 values (Figure 2 A upper panel). To improve the measurements, liquid chromatography was applied to all the samples. The extracts were separated into three fractions by elution through a Bond silica column (Bond Elute column, Varian): (1) 4ml of Hexane (apolar fraction), (2) 4ml of a mixture of hexane and methylene chloride (3:1) (ketone fraction, including the alkenones) and (3) 2ml of methylene chloride (alcohol fraction). Finally, all fractions were concentrated under N\textsubscript{2} and taken up in 25\textmu l MeOH/CH\textsubscript{2}Cl\textsubscript{2} (1:1). The method was first tested on a reference sample and the UK’37 values obtained were within the estimated error bar (\textpm0.056 UK’37, or 0.5°C). Figure 2 A shows the gas chromatograms of the fractions containing the C\textsubscript{37:3} and C\textsubscript{37:2} alkenones and the organic compounds before (upper panel) and after (lower panel) liquid chromatography. A precise identification of the co-eluting organic compounds using GC-MS is still unresolved (personal comm. M. Elvert) and is beyond the topic of the present study.
Figure 2. Effects of applying liquid chromatography (LC) to the extracts and comparison with previous published results. (A) Gas chromatogram (GC) of the GC-window containing the C\textsubscript{37} and C\textsubscript{38} alkenones: whole fraction without LC (upper panel) and after LC (lower panel, ketone fraction). (B) Correlation of SSTs based on measurements with (this study) and without LC (as published by Lamy et al. (2004)) and (C) SST difference between the individual measurements. Only 13% of the data have significantly different SSTs (i.e. >0.5°C relative to the estimated methodological error).

The SSTs determined with this additional analytical step result in very similar UK37’ values as those obtained by Lamy et al. (2004) on the 10-90 mcd interval of the core. The correlation between both data sets is $r = 0.98$ (Figure 2 B), and the highest SST differences occur at relatively low temperatures (8-10°C). Only 13% of the data have significantly different SSTs (i.e. >0.5°C relative to the estimated methodological error; Figure 2 C), and mainly result in a shrinking of the extreme SST values. Therefore, the interpretation of the previous published SST record is not significantly affected by our new data.
4. Stratigraphy

The age model of the 135.7 mcd-long composite sequence at Site 1233 (Figure 3 and Table 1) has been constructed as follows. (1) The uppermost ~9 mcd have been correlated to the AMS $^{14}$C dated gravity core GeoB 3313-1 from the same location (Lamy et al., 2001) using magnetic susceptibility and Ca relative concentration records (Figure 3 A). This correlation allowed us to transfer the age model of core GeoB 3313-1 (based on 7 AMS $^{14}$C dating) to Site 1233. (2) Age control for the ~10 to ~70 mcd interval is provided by 17 AMS $^{14}$C-dates on mixed planktonic foraminifera samples (Lamy et al., 2004) and the record of the Laschamp magnetic field excursion (S. Lund, preprint, 2005). All AMS $^{14}$C-dates were calibrated with the CALPAL software (www.calpal.de) using the CALPAL 2004 January calibration curve. We assume no regional deviation from the global reservoir effect of ~400 years because the core position lies significantly south of the Chilean upwelling zone and north of the southern polar front. Therefore, the assumption of a 400 years reservoir age which is also the mean reservoir age for the Pacific Ocean at ~40°S appears to be the most reasonable assumption. For more details the reader would refer to the Supporting Online Material of Lamy et al. (2004). (3) As $\delta^{18}$O data on planktic and benthic foraminifera are not yet available further downhole, we propose here an updated and better constrained age model than that published by Lamy et al. (2004) for the older part of the record, i.e. below the Laschamp excursion, based on visual tuning. The millennial-scale SST variations in the AMS $^{14}$C-dated part of the record closely follow Antarctic temperature fluctuations as recorded in the Byrd ice core (Lamy et al., 2004) and the SST pattern further downcore shows a clear visible resemblance to the Antarctic record as well. Therefore, we decided to tune our alkenone SST records to the Antarctic record using a minimum number of correlation points between our SST data-set and the $\delta^{18}$O record of the Byrd ice core (Figure 3 B). For our purposes, the Byrd ice core has presently the most suitable age model for the last glaciation as it is linked to the Greenland GISP2 ice core record as well as our $^{14}$C age calendar year conversion.
Figure 3. Age-model of ODP Site 1233. (A) Correlation of Site 1233 to the $^{14}$C-AMS dated core GeoB3313-3 (Lamy et al., 2001) based on the magnetic susceptibility and Ca relative concentration records in the middle and late Holocene. (B) Alkenone-based SST reconstruction at Site 1233 compared to the Byrd $\delta^{18}$O record over the last 70 kyr. The empty arrows represent the correlation points to the core GeoB3313-1, the black arrows the $^{14}$C-AMS datings and the Lashamp event at 41 kyr (S. Lund, preprint, 2005), and the gray arrows the tuning points to the oxygen isotope record of the Byrd ice-core. A1 to A5: warm events after Blunier and Brook (2001). ACR: Antarctic Cold Reversal. MIS: Marine Isotope Stage 1 to 4.

The 135.7 mcd-long core covers the last ~70 kyr. The resulting mean sedimentation rates range between ~1.4 m/kyr in the Holocene to an average of ~2.2 m/kyr during MIS 4 to 2. These high sedimentation rates are consistent with strong fluvial discharge in response to heavy continental rainfall in southern Chile during the Holocene (Lamy et al., 2001). During the last glacial (MIS 2 to 4), the continental hinterland of Site 1233 was extensively glaciated.
as the Patagonian ice-shield advanced towards the north (Denton \textit{et al.}, 1999b) explaining even higher terrestrial input through glacial erosion processes (Lamy \textit{et al.}, 2004).

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* Correlation to the $^{14}$C AMS dated core GeoB 3313-1 from the same location (Lamy \textit{et al.}, 2001) using the magnetic susceptibility and Ca relative concentration records.

**Table 1.** Age-depth relation for ODP Site 1233. All radiocarbon ages are calibrated using the \textit{CALPAL} 2004 \textit{January} calibration curve (www.calpal.de) and a constant reservoir age correction of 400 years (see Section 4 for details).
5. Results and Discussion

5.1 SST changes off Chile during the last 70 kyr: Results and regional aspects.

The alkenone-based sea surface temperature reconstruction at Site 1233 covers the last 70 kyr with a mean resolution of 320 years (Figure 3 B) and thus provides the longest high resolution SST record in the SE Pacific presently available. After a maximum of 14.7°C, probably corresponding to MIS 5.1, SSTs decrease to 8°C in MIS 4, the coldest temperatures of the record. Temperatures rise again up to ~12°C in early MIS 3 and display a general long-term cooling trend until ~45 kyr B.P. Superimposed on this trend, the major Antarctic warm events A2 to A4 (Blunier and Brook, 2001) are characterized by SST increases of up to 3°C. From 45 to 19 kyr B.P., the SSTs show millennial-scale variability of 2-3°C around a mean temperature of 9.5°C. The LGM is not clearly defined in the record. Denton et al. (1999a) have reconstructed the summer mean air temperature in the adjacent Lake District region based on a combination of glacier fluctuations and pollen records spanning the last 60 kyr (not shown). Despite an apparent disagreement in the details of the timing of the terrestrial compared to the marine record in the SE Pacific (see Lamy et al., 2004), their results are similar to our SST reconstruction in terms of main tendencies and amplitudes: ~8°C around 60 kyr BP, an abrupt increase to 12°C at ~57 kyr BP, decreasing values towards the LGM with temperatures around 8°C.

A 6°C SST warming over Termination I is similar to results obtained from land, other marine records and modeling studies in the region. First, the previously cited summer air temperature reconstruction in the Lake District shows a 6°C warming over the last deglaciation. Second, two alkenone-based SST reconstruction further to the north at 35°S and 33°S have a 6°C-7°C SST-increase between 19 and 12.5 kyr BP (Kim et al., 2002; O. Romero, preprint, 2005). Third, in a recent modeling study of the changes in the Patagonian ice-sheet extent during the LGM and the deglaciation, Hulton et al. (2002) have shown a good agreement between modeled ice extent and empirical evidence at the LGM by applying a temperature decrease of 6°C relative to present day. In our record Termination I is interrupted by one major cooling event (~0.8°C) between 14.8 and 13.3 kyr BP, followed by a plateau until 12.7 kyr BP (Figure 3 B). This cooling matches the Antarctic Cold Reversal (ACR; 14 to 12.5 kyr BP) (e.g., Jouzel et al., 1995) and clearly precedes the NH Younger Dryas (YD; 13-11.5 kyr BP) (e.g., Rutter et al., 2000). Instead, we observe a SST increase of 2.1°C during the early part of the YD (12.7 and 12.1 kyr BP.) and early Holocene values thereafter. This pattern seems to be confirmed by two other alkenone-based SST records situated at 35°S and 30°S along the Chilean coast (O. Romero, preprint, 2005; J. Kaiser, unpublished data, 2005). Based on terrestrial records, the presence or absence of the NH YD in southern South America is discussed controversially. A cooling during the YD has been for example proposed from pollen records in NW Patagonia close to Site 1233 (Chilean Lake District region and Isla Grande de Chiloé) (e.g., Denton et al., 1999a; Moreno et al., 2001) and seems
to be present in subantarctic Patagonia as well (Heusser et al., 2000; Massaferro and Brooks, 2002). However, it has been recently suggested that the deglacial cold reversal in NW Patagonia started earlier (at ~14.7 to 13.4 kyr BP.), and that the YD interval is rather characterized by fire disturbances (Hajdas et al., 2003; Moreno, 2004) that may not necessarily imply cooling. In addition, other paleoenvironmental reconstructions in southern Chile (~40°S to 48°S) based on pollen, glacial morphology, and beetle assemblages did not find evidence of a cooling during the YD epoch either (e.g., Ashworth and Hoganson, 1993; Bennett et al., 2000; Glasser et al., 2004).

The SSTs reach a maximum of 15.6°C in the early Holocene (~11 to 9 kyr BP) and generally decrease thereafter, reaching the modern SST (~14°C) in the Late Holocene (Figure 3 B). A warmer and drier-than-today climate over south-western South America in the early Holocene was also recorded on the adjacent land (e.g., Massaferro and Brooks, 2002; Moreno and León, 2003; Abarzúa et al., 2004), and even in the low-latitudes, e.g. in the Huascaràn ice core (Thompson et al., 1995). Furthermore, most Antarctic ice core records show a widespread early Holocene optimum between 11.5 and 9 kyr BP (Masson et al., 2000). This early Holocene optimum was not documented in the earlier SST record based on the short core (GeoB 3313-1; Lamy et al., (2001)) drilled at the same location as Site 1233 that only covers the last ~8 kyr. Details on millennial to multi-centennial scale variations during the middle and late Holocene can be found in the work of Lamy et al. (2002).

Holocene and glacial climate fluctuations in the SE Pacific region and adjacent South America have often been related to changes in the latitudinal position of the SH Westerlies and a northward shift of this wind belt has been proposed for this region based on a number of terrestrial and marine archives (e.g., Heusser, 1989; Lamy et al., 1998; Benn and Clapperton, 2000; Moreno and León, 2003). Together with the Westerlies, the ACC was apparently displaced northward at the LGM as well. High paleoproductivity at ~33°S off Chile during the LGM suggests that an equatorward shift of the ACC would have brought the main nutrient source closer to the core sites resulting in increased productivity (Hebbeln et al., 2002; Mohtadi and Hebbeln, 2004). We note that a northward displacement of the Westerlies during the LGM is in disagreement with some other paleoenvironmental records (e.g., Markgraf et al., 1992) as well as with modeling results (Wyrwoll et al., 2000; Wardle, 2003) that suggest little latitudinal change or even a slight poleward shift. Nevertheless, Wyrwoll et al. (2000) point out that associated with the southward shift and increase westerly flow around 60°S, there was a distinct widening of the zone of strong Westerlies, similar to the modern winter conditions (see Section 2). Taken together, the overall regional proxy evidences strongly suggest that the SST variability at Site 1233 was predominantly caused by latitudinal shifts of the ACC and the southern Westerlies (or their northern boundary), i.e. cold temperatures associated with a northward shift of the coupled system and vice versa.
5.2 Surface water changes in the SH mid-latitudes: towards a common millennial-scale pattern and associated forcing mechanisms

**Figure 4.** Comparison of the Site 1233 SST record in the SE Pacific with other SST proxy records from the Southern Hemisphere, and the Antarctic air temperature records of Byrd and EPICA Dome C ice cores, during the past 70 kyr. (A) Oxygen isotope record on planktic foraminifera in the South Atlantic (Ninnemann et al., 1999). (B) Mg/Ca SST reconstruction in the Southwest Pacific (Pahnke et al., 2003). (C) Mg/Ca SST reconstruction in the South Pacific (Mashiotta et al., 1999). (D) Alkenone SST reconstruction at ODP Site 1233 (this study). (E) Oxygen isotope record of the Byrd ice core (Blunier and Brook, 2001). (F) Deuterium profile from the EPICA Dome C ice core (EPICA Community Members, 2004). ACR: Antarctic cold reversal; A1 to A5: Antarctic warm events after Blunier and Brook (2001). See Figure 1 for the location of the cores.
The close resemblance of SST changes at Site 1233 to Antarctic temperature changes within the $^{14}$C-AMS dated section and the very similar temperature pattern in the earlier part of the records, allowed us to transfer the Byrd age model to Site 1233 for the older interval (see Section 3). Our new results are thus prolonging the previously discussed pattern of close climate linkages between the SH mid- and high-latitudes (Lamy et al., 2004) into late MIS 5. In Figure 4, our 70 kyr SST record off southern Chile is compared with other records of changes in surface water properties in the SH mid-latitudes (see Figure 1 for site locations): an oxygen isotope record of *Globigerina bulloides* in the South Atlantic (Ninnemann et al., 1999), and two Mg/Ca SST records, one from the southwest Pacific (Pahnke et al., 2003) and a second from the central south Pacific (Mashiotta et al., 1999). The $^{14}$C-based parts of the age-models were recalculated with the CALPAL January 2004 calibration curve. A recalibration was not possible for the record in the central South Pacific (Mashiotta et al., 1999), that is based on tuning (see Table 2). Considering the errors of dating and the differences in the mean resolutions (between 350 and 920 years), the records present a common pattern which is very similar to the Antarctic Byrd $\delta^{18}$O and the recent EPICA $\delta$ deuterium records (Figure 4 E-F): warmer SSTs during the Antarctic warm events A1 to A4 (as defined by Blunier and Brook, (2001), a 4°C to 6°C warming over Termination I, beginning simultaneously around 19 kyr BP, the record of the Antarctic Cold Reversal (except in the south Pacific, most likely due to the low resolution of the record), and finally a Holocene climatic optimum between ~9 and ~11 kyr BP. This common pattern suggests that Antarctic climate changes extended into the SH mid-latitudes involving changes in the ACC and the Westerlies. The most likely mechanism is a common latitudinal shift of the coupled system, i.e. equatorward during cold phases and poleward during warm intervals. Assuming a global mean LGM cooling of ~2°C as predicted by a coupled ocean-atmosphere GCM model for the intertropical oceans (Ganopolski et al., 1998) and that the remaining SST changes in the SE Pacific were mainly driven by coeval shifts of the Westerlies (or their northern boundary) and the ACC during the last 70 kyr, it is possible to give a rough estimation of the latitudinal shifts when extrapolating from the modern SST pattern (after Levitus and Boyer, 1994). Our results suggest that the whole coupled system might have shifted northward by 4-5° of latitude during the LGM. Applying the same assumptions to MIS 4 would result in a 5-6° northward shift of the system. The estimated displacement for the LGM is consistent with the 5-10° northward latitudinal expansion of Antarctic cold waters as recently suggested by Gersonde et al. (2005) and the 5° latitudinal shift of the Westerlies as proposed by works in South America (Heusser, 1989; Lamy et al., 1998; Mohtadi and Hebbeln, 2004). On the other hand, a warmer-than-today climate during the early Holocene as suggested by the records of surface water changes would imply a southward shift of the coupled system. This is in agreement with most of the climate reconstructions on terrestrial and marine archives of the SH mid-latitudes (e.g., Brathauer and Abelmann, 1999; Moreno and León, 2003; Haberle and Bennett, 2004; Shulmeister et al., 2004).
**Table 2.** Modifications made to the published age models from some records used in Figure 4 and 5. All other records coming from the literature presented in this study are plotted on their original age models.

A dust content record from Antarctica provides additional evidence for a close coupling of atmospheric circulation around Antarctica and temperature changes in the SH mid-latitudes at millennial timescales. In Figure 5 C-D the SST record at Site 1233 is plotted against the dust content as measured on EPICA Dome C ice core (Delmonte *et al.*, 2002; EPICA Community Members, 2004). The main origin of Antarctic dust is the Patagonian region in southernmost South America (Grousset *et al.*, 1992; Basile *et al.*, 1997). The general increase in the dust contents during the coldest periods, i.e. MIS 4 and 2 in our case, has been explained by expanded source regions linked to the global sea-level drop, a decrease of the vegetation and a general dryer climate in Patagonia (Petit *et al.*, 1981; Delmonte *et al.*, 2002). Despite these pronounced long-term signal in the dust record, short-term variations on millennial and sub-millennial timescales appear to parallel the short-term variations in our SST record. Considering the offsets between 70 and 41 kyr BP induced by age model discrepancies between the EPICA Dome C and Byrd ice cores (Figure 5 A-B) and the limitations in dating accuracy of our record (Figure 5 D) as well as in the age models of the ice cores, we observe a reasonable correlation of high dust contents to millennial-scale SST cold peaks and conversely. Environmental changes in the source areas of the dust might have played a role in dust variability on millennial timescales (Rothlisberger *et al.*, 2002). High resolution palynological studies from Patagonia are unfortunately not yet available in order to proof this hypothesis. On the other hand, dust input maxima on millennial timescales could have been induced by intensified circumpolar winds probably linked to a strengthening of the polar vortex by a steeper latitudinal thermal gradient, generated by the northward extension of sea-ice (COHMAP, 1988; Delmonte *et al.*, 2002). A faster dust transport from Patagonia to Dome.
C during the LGM has also been proposed based on GCM simulations (Krinner and Genthon, 2003). In addition, intensified SH Westerlies during the LGM are suspected (but not proofed) in records of dust/loess and glacier advances in New Zealand (for a review see Shulmeister et al., 2004) and are often proposed in simulations of a global LGM climate (e.g., Wyrmoll et al., 2000; Shin et al., 2003a). It is thus conceivable that the millennial scale SST variability in the SE Pacific was likewise linked to changes in the intensity of the Westerlies in addition to the latitudinal shifts as discussed above.

Recent modeling studies on the last deglaciation suggest that changes in sea-ice extent and/or salinity in the Southern Ocean may have had large consequences for millennial-scale changes on a global scale (Knorr and Lohmann, 2003; Weaver et al., 2003). The involvement of sea-ice extent changes in SH millennial-scale climate variability is consistent with the comparison of our SST record to an index of the sea-ice presence during the last ~45 kyr in the South Atlantic (Shemesh et al., 2002) (core TN057-13, location in Figure 1). The sea-ice record suggests millennial-scale variations that imply, within the errors of dating, extended sea-ice duration during the cold intervals in the Southeast Pacific as shown by our data (Figure 5 D-E). Therefore, we suggest that the extended sea-ice in the Southern Ocean displaced the ACC equatorwards and triggered enhanced advection of cold, subantarctic surface waters into our study area. Furthermore, Kanfoush et al. (2003) improved the chronology of the ice-rafted detritus (IRD) record in the SE Atlantic (Kanfoush et al., 2000) and concluded that major IRD events occurred during the cooling phases following the A1 to A4 warm events (not shown). It has been argued that the IRD events were associated with increased NADW production during major NH interstadials (Kanfoush et al., 2000) what would be consistent with the bipolar seesaw mechanism (Broecker, 1998; Stocker, 1998; Blunier and Brook, 2001). On the other hand, the mid- to high-southern latitude-wide millennial-scale pattern of surface ocean changes with Antarctic timing during the last ~70 kyr in all ocean basins (see Figure 4) is inconsistent with most modeling studies on the SH response to THC throttling or shutdown (Ganopolski and Rahmstorf, 2001; Schmittner et al., 2003). Therefore, as already discussed in relation to the 14C-dated part of our record (Lamy et al., 2004), it is equally conceivable that the millennial-scale changes are of SH origin.
Figure 5. Relationship of the SE Pacific SST reconstruction and Southern Hemisphere high latitudes. (A) Oxygen isotope record of the Byrd ice-core (Blunier and Brook, 2001). (B) Deuterium record from the EPICA Dome C ice-core (EPICA Community Members, 2004). (C) EPICA Dome C dust content (plotted inverse) (EPICA Community Members, 2004; Delmonte et al., 2002). Original data (gray line) and 3 points moving average data between 15 and 35 kyr (dark line). (D) Alkenone SST at Site 1233 (this study), plotted with the age control points of the core (see Table 1). (E) Sea-ice presence reconstruction based on diatoms in the South Atlantic (Shemesh et al., 2002) (core TN057-13; see Figure 1 for location). A1 to A5: Antarctic warm events after Blunier and Brook (2001). Note that the offsets between SST and EPICA Dome C dust records from 70 to 41 kyr are primarily due to the offset between Byrd $\delta^{18}$O and EPICA $\delta$D records.
The emerging pattern of common millennial-scale climate and ocean changes in the SH mid- and high-latitudes suggests similar SST changes in the mid-latitudes, most likely controlled by changes in the strength and latitudinal position (or extension) of the Westerlies and the ACC. These variations appear to be closely linked to changes in Antarctic temperatures and the extent of sea-ice as well. The paleo-records suggest a scenario that largely resembles the coupled atmosphere-ocean mechanisms linked to the Southern Annular Mode (SAM), an important modern mode of interannual to decadal-scale climate variability in the SH (Thompson and Wallace, 2000; Thompson et al., 2000). During a positive SAM, the surface temperature over Antarctica cools and the strength of the Westerlies over the subpolar Southern Ocean increases (Thompson and Wallace, 2000). Enhanced westerly winds could generate a northward Ekman flow advecting sea-ice farther north, as proposed by a coarse resolution model (Hall and Visbeck, 2002), that would act as a positive feedback mechanism. Therefore, we speculate that long-term changes in the interannual SH climate modes, such as the SAM, may ultimately be involved in millennial-scale ocean and atmosphere changes in the SH mid- and high-latitudes during the last glaciation.

5.3 SST gradient changes along the Pacific Eastern Boundary Current System (PEBCS) during the last glacial period (MIS 4 to 2) and the early Holocene

Based on coupled ocean-atmosphere models, Liu et al. (2002) and Shin et al. (2003a) have proposed that the upper ocean circulation in the southern mid- and high-latitudes plays a key role in explaining tropical cooling at the LGM. A similar line of evidence comes from a number of paleoenvironmental reconstructions in the tropical eastern Pacific low-latitudes. Based on a Mg/Ca SST reconstruction near the equator, Lea et al. (2000) have hypothesized a link between polar and tropical temperature changes because of some similarities with isotopic changes in Antarctic ice cores. High southern latitude foraminifera species were present even north of the equator suggesting an intensification of the Peru-Chile Current during the LGM (e.g., Feldberg and Mix, 2003; Martinez et al., 2003). Sea surface temperature reconstructions based on foraminiferal faunal assemblages have shown that the meridional SST gradient in the Eastern Equatorial Pacific (EEP) was stronger during the LGM, suggesting “La Niña-like” conditions (Martinez et al., 2003). Likewise, a reconstruction of zonal gradients in the tropical Pacific Ocean suggests a shallower thermocline with a steeper east-west slope resulting in an intensified Walker circulation during the LGM (Andreasen and Ravelo, 1997), as presently occurring during La Niña events. However a reversed pattern for the LGM, i.e. “El Niño-like” conditions, has been proposed by other authors (Koutavas et al., 2002).

Our new SST record off southern Chile provides the opportunity to reconstruct paleoceanographic changes in the PEBCS in its mid- to low-latitude section during the last 70 kyr, based on a SST gradient reconstruction. For this purpose, we used our alkenone record at
41°S, two alkenone-based SST reconstructions at 33°S (Kim et al., 2002) and 17°14’S (Calvo et al., 2001), two SST reconstructions based on foraminiferal fauna assemblages at 3°05’S (Martinez et al., 2003) and 0°09’N (Feldberg and Mix, 2003), and a Mg/Ca SST reconstruction at 2°15’N (Lea et al., 2000) (see Figure 1 for the location of the cores).

![Figure 6](image_url)

**Figure 6.** Latitudinal distribution of SST within the Pacific Eastern Boundary Current, between 2°N and 41°S. (A) Mg/Ca SST (core TR163-19) (Lea et al., 2000). (B) SST reconstruction based on planktonic foraminifera fauna distribution (core RC13-110) (Feldberg and Mix, 2003). (C) SST estimation from the planktonic foraminifera assemblage data using the modern analog technique MAT (core ODP846B) (Martinez et al., 2003). (D) Alkenone-based SST reconstruction (core TG7) (Calvo et al., 2001). (E) Alkenone-based SST (cores GIK17748-2 and GeoB3302-1) (Kim et al., 2002). (F) Alkenone-based SST (core ODP1233; this study). The gray bars mark the time-intervals as defined for Figure 7 and Table 3: the modern (SST values from Levitus and Boyer (1994)), 8-12 kyr (Holocene Climatic Optimum), 19-22 kyr (Last Glacial Maximum), 51-60 kyr (early MIS 3) and 63-68 kyr (MIS 4).

As the records have very different time resolutions, age-models (the original age-models were used here) and SST proxies, we have focused on the meridional SST gradients in five
time intervals defined as follows (Figure 6): the present day (from Levitus and Boyer, 1994), the Holocene Climatic optimum (HCO; 8-12 kyr), the Last Glacial Maximum (LGM; 19-23 kyr), early MIS 3 (51-60 kyr) and MIS 4 (63-68 kyr). In Table 3, we report the values of the present and reconstructed SST gradients, calculated from the mean SSTs for each record and each time interval, and Figure 7 shows the reconstructed SST gradients in the PEBCS for the different time-intervals. As the records used here have different SST proxies (alkenone, Mg/Ca and foraminiferal fauna assemblages) with various analytical errors (±0.3 to ±0.5°C, ±0.6°C and ±1 to ±1.8°C respectively; details in publications aforementioned), small SST gradient changes should be considered with caution.

During the coldest intervals, the overall mid-latitude-to-equator gradient (2°N-41°S) was around 2.8°C (MIS 2) and 3.7°C (MIS 4) higher than today. Conversely, we observe similar to slightly reduced gradients during the HCO and slightly increased gradients during early MIS 3. The increase in meridional SST gradients during the LGM and MIS 4 is mainly derived from a relatively strong cooling in the southern and central part of the PEBCS (41-17°S), with particularly enhanced gradients in the southernmost part between ~33°S and 41°S. This is in agreement with modeling results suggesting stronger SST gradients in the mid-latitudes at the LGM (Shin et al., 2003a). In terms of oceanic surface circulation (and linked atmospheric circulation) during the last glacial cold periods (MIS 4 and 2), our SST gradient reconstruction suggests a northward shift of the strong SST gradient area (linked to the ACC) of which the northern limit is nowadays located around 40°S. Based on Figure 7, this limit could have been situated around or south of 33°S at the LGM. This would be in the same order of magnitude as the aforementioned ACC northward shift of ~5° in latitude at the LGM in comparison to the present day (see Section 5.2). An enhanced northward influence of the ACC up to ~33°S during MIS 2 has also been suggested in paleoproductivity reconstructions along the Chilean coast (Hebbeln et al., 2002; Mohtadi and Hebbeln, 2004). In terms of atmospheric circulation, reconstructions of glaciers movements (Ammann et al., 2001) and humidity changes (Stuut and Lamy, 2004) have shown that ~27°S should have been the northernmost limit of the Westerlies influence during winter at the LGM. Ultimately, a northward displacement of the Westerlies (or their northern boundary), as implied by our results, would be in agreement with the proposed northward shift of the STH at the LGM (e.g., Andreasen and Ravelo, 1997; Mohtadi and Hebbeln, 2004).
In the low latitudes, previous studies have mentioned an influence of the PCC in the EEP during MIS 2 as MIS 4 (e.g., Mix et al., 1999; Feldberg and Mix, 2003; Martinez et al., 2003). Furthermore, following Hostetler and Mix (1999), who have modeled the LGM tropical climate based on a SST field in which lower tropical SSTs than those of CLIMAP are prescribed in the eastern tropical Pacific and equatorial Atlantic Oceans (see Mix et al., 1999), the westward wind flow over northern South America into the Pacific and the tropical Walker circulation were enhanced at the LGM. During cold intervals, we observe similar-than-today SST gradients between 17°S and the equator as well as around the equator (2°N-3°S), within the Equatorial Front, (Figure 7, Table 3). With this kind of SST gradient configuration, it is not possible to conclude on a stronger (or weaker) circulation in the PEBCS. In comparison to the present day however, the whole SST distribution was similar to the modern winter pattern (a northward shift of the strong SST gradient area in the south and the presence of the Equatorial Front near the Equator), while the PCC flow is enhanced (Strub et al., 1998). Therefore our reconstruction would be consistent with a stronger Peru-Chile Current and a cold water tongue extended westward in the low latitudes during MIS 4 and 2, typically a “La Niña-like” pattern as proposed by Martinez et al. (2003).
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</table>

Table 3. Latitudinal SST gradients reconstruction in the Pacific Eastern Boundary Current System for the 5 time-intervals as defined in Figure 6. The values represent the SST differences (in °C) between the different latitudes (left column). Abbreviations are HCO, Holocene Climatic Optimum; LGM, Last Glacial Maximum; MIS, marine isotope stage.

Our SST gradients reconstruction suggests also some interesting pattern for the relatively warm periods (HCO and early MIS 3). During a warmer-than-today climate as the HCO the SST gradients along the whole coast of South America were slightly weaker, especially in the mid-latitudes. Consequently the ACC influence through the PCC was weaker, and the associated Westerly winds probably situated more poleward. A stronger gradient between 17°S and 3°S could eventually reflect a more southward influence of the equatorial warm waters. Nevertheless, a weaker SST gradient in the south agrees with the previous suggestion of a southward shift of the ACC and the Westerlies during the early Holocene (see Section 5.2). Finally the SST gradient distribution during early MIS 3 shows an intermediate pattern. Whereas the whole gradient was stronger-than-present, the latitudinal distribution was different than during MIS 4 and 2, and closer to the HCO distribution.

6. Summary and Conclusions

(1) At a regional scale, the general trends of our SST record are in agreement with paleoenvironmental records from the adjacent continent and previous SST reconstructions that cover the last ~30 kyr, in particular the SST increase of ~6°C over Termination I. Other features like a cooling that matches the ACR as defined in Antarctic ice cores are partly inconsistent with land records. Some of these latter results provided evidences for a cooling synchronous with the NH YD cold event whereas our new SST record suggests a pronounced warming of ~2°C during this time interval similar to the Antarctic ice core records.

(2) Our SST record reveals a clear “Antarctic timing” of millennial-scale temperature changes during the last 70 kyr. A comparison to other paleoceanographic records from the SH mid-latitudes suggests that these changes occurred quasi hemisphere-wide. In addition, coeval changes can be observed in Antarctic dust and sea-ice extent records that would be consistent with the following scenario. For SH cold periods, the westerly wind circulation around

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Antarctica was enhanced and the northern boundary of the Westerlies moved equatorwards resulting in sea-ice export away from Antarctica through an enhanced Ekman drift. Linked to a northward widening of the Westerlies, the ACC was displaced northwards and advected cold, subantarctic water into the SH mid-latitudes. Conversely, during SH warm phases wind intensities decreased, the Westerlies and the ACC were more poleward confined and eventually decreased the advection of cold water masses into the mid-latitudes. Our scenario for SH millennial-scale changes resembles the observed pattern related to interannual to decadal-scale SH climate modes such as the SAM, suggesting that long-term changes in these modes may ultimately be involved as well. Finally, the clear “Antarctic timing” pattern is consistent with the seesaw mechanism often discussed in relation to NH versus SH millennial-scale climate pattern. However, the consistent temperature pattern around Antarctica in different ocean basins could also imply a larger involvement or even a source of millennial-scale climate variability in the Southern Hemisphere.

(3) A paleo-SST gradient reconstruction covering the complete latitudinal range of the PEBCS suggests an equatorward displaced subtropical gyre circulation during MIS 2 and 4, similar to the modern winter pattern. This configuration would be mainly linked to an equatorward shift of the northernmost boundary of the ACC resulting in enhanced SST gradients in the southern part of the PEBCS, and to the presence of the Equatorial Front near the equator. Therefore, we might suggest that the PCC flow was stronger, that more cold waters of a southern high-latitude origin entered the southeast equatorial Pacific and that the cold-tongue was extended westward. Conversely, the oceanic circulation in the PEBCS was probably weakened and the ACC, and associated westerly wind belt, moved southward during relatively warm periods (early MIS 3 and HCO).

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4.3 Variability of sea-surface temperatures off Chile and the dynamics of the Patagonian Ice Sheet during the last glacial period based on ODP Site 1233

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Abstract

The ultra-high sedimentation rates at ODP Site 1233, situated at 41°S off Chile, enabled the investigation of the millennial to multi-centennial scale relationship and variability of the Patagonian Ice Sheet (PIS) extent, as indicated by the Fe relative concentration record, and offshore sea surface temperatures (SST) during the last glacial period. The close relationship of the Fe record and the SST pattern as described previously for the 50-19 kyr time-interval (Lamy et al., 2004) extends in the older part of the records (70 to 50 kyr). During marine isotope stage (MIS) 4, a delay of ~500 yr of PIS retreats relative to SST increases has been found, similar to that described for the coldest part of MIS 3 and 2. During early MIS 3 (~60 to 56 kyr), synchronous variability in both records resembles the deglacial-to-Holocene time-interval, reflecting either a meltwater pulse or a dominant control of the Fe input by rainfall changes related to a rather small PIS. Results of spectral analysis on the detrended records show three main periodicity-bands at ~4.5-3.1 kyr, 2.4-2.2 kyr and 1.2-1 kyr. The possible origins of these bands are discussed in terms of stochastic resonance, solar forcing and Northern Hemisphere high and/or low-latitudes influence on the SE Pacific, respectively.
1. Introduction

Detailed analyses of millennial-scale climate and ocean variability during the last glacial have so far primarily focused on Northern Hemisphere (NH) records as the origin of the large and abrupt climate changes (the Dansgaard-Oeschger and Heinrich events) is suspected to be mainly linked to reorganizations in the North Atlantic thermohaline circulation (THC) and associated feedbacks in the global ocean-atmosphere system (Rahmstorf, 2002; Voelker, 2002). On the other hand, recent modeling studies suggest an active role of the Southern Hemisphere (SH) high-latitudes in the initiation of rapid climate variability (Knorr and Lohmann, 2003; Weaver et al., 2003). In order to verify this however, there is a strong demand on continuous, high resolution records from regions in the Southern Hemisphere (SH) where climate changes in both atmospheric and oceanic systems can be traced over the last glacial period.

The mid-latitudes of southern Chile (Southeast Pacific) have such a potential because the modern climate is characterized by an extreme N-S precipitation gradient controlled by the latitudinal position of the Southern Westerly Winds (SWW) which are geographically and dynamically linked to the Antarctic Circumpolar Current (ACC). Previous continental and marine climate reconstructions propose the SWW as the main driver for climate changes (e.g., Denton et al., 1999a; Moreno et al., 2001; Lamy et al., 2004). During the last glacial period, southernmost Chile was covered by the Patagonian Ice Sheet (PIS). While nowadays two main icecaps are centered on the higher parts of the Andes (the North and South Patagonian Icefields), the PIS extended up to ~1800 km along the axis of the Andes between ~38°S and 56°S during the last glacial maximum (Figure 1). Modeling studies of the PIS suggest a close dependence of the ice-sheet to the offshore sea surface temperatures (SST). Particularly the northwestern limb of the ice-sheet (north of 43°S; Hulton et al., 2002) appears to be very sensitive to small climate fluctuations. A recent paleo-environmental reconstruction covering the period from ~50 to 19 kyr BP has confirmed the modeling results by showing a close relationship at millennial timescales between the expansion of the PIS and the offshore SST (Lamy et al., 2004).

Based on an ultra-high resolution sediment sequence drilled off Chile (ODP Site 1233; 41°S), we discuss the millennial scale variability and relationship of offshore SST to the PIS in its northeastern part over the last 70 kyr. We further perform a detailed analysis of the short-term cyclicities (<5 kyr) of our records to assess the millennial-scale variability of this coupled system during the last glacial period (MIS 4 to 2). The potential origins of these short-term variations are discussed in terms of hemispheric to inter-hemispheric linkages.
2. Regional Setting

Off southern Chile, the large-scale oceanic surface circulation is controlled by the ACC which transports cold, subantarctic water towards the Chilean coast (Figure 1). Around 43°S the ACC splits into the poleward-flowing Cape Horn Current and the equatorward-flowing Peru-Chile Current (PCC) (Strub et al., 1998). ODP Site 1233 is thus located right at the origin of the PCC, within a strong SST gradient linked to the northern boundary of the ACC. The mean annual SST is ~14°C and varies between 11.5°C in winter and 16.5°C in summer. An important hydrographic feature off southern Chile is the low-salinity surface water tongue originating from the high fresh water supply to the Chilean fjord region (Strub et al., 1998). The low-salinity Chilean Fjord Water (CFW) flows northward within 150 to 200 km off the coast (Figure 1).

Figure 1. Location of ODP Site 1233 (41°00’S, 74°27’W) off Southern Chile. Full lines indicate the modern annual mean sea surface temperature distribution (data from the NOAA-CIRES Climate Diagnostics Center; http://www.cdc.noaa.gov/index.html). Also shown are the location of presently existing Andean icefields (black areas) and limits of the Patagonian Ice Sheet (PIS) during the Last Glacial Maximum as derived from field evidences (dotted line). ACC: Antarctic Circumpolar Current; PCC: Peru-Chile Current; CHC: Cape Horn Current; CFW: Chilean Fjord Water.
In the SE Pacific mid- to high-latitudes, the steepest SST gradient within the ACC is strongly related to the SWW (Streten and Zillman, 1984). The storm tracks associated to the SWW are centered around 50°S and controlled by the strength and latitudinal position of both the subtropical high pressure (SHP) and the circum-Antarctic low pressure belt (Cerveny, 1998). Concentrated in a tight band in austral summer, the storm track activity extends over a broader range of latitudes in winter. The totals of precipitation are highest in the core of the Westerlies (> 7000 mm/yr at sea level) and decline northward and southward to around 2500 mm/yr at 40°S and 1000 mm/yr at 55°S, respectively. The center of precipitation moves seasonally from ~50°S in summer to ~45°S in winter. South of ~39°S the yearly onshore blowing winds prevent coastal upwelling (Mohtadi et al., 2005).

Interannual rainfall variability is strongly related to the El Niño-Southern Oscillation (ENSO) phenomena, especially in central Chile (Ruttl and Fuenzalida, 1991; Cerveny, 1998; Montecinos and Aceituno, 2003). Changes in the STH provide most of the explanation for the climate variability in Chile. During La Niña events, the STH is consistently strong throughout the year. The storm track linked to the SWW remains south of 45°S reducing rainfall in the mid-latitudes. Conversely, the STH is weakened during an El Niño event, allowing an equatorward shift of the SWW and a greater cyclonic activity in the Chilean mid-latitudes. Based on monthly data from weather stations in Chile (30°-41°S) for the 1958-1999 period, Montecinos and Aceituno (2003) have studied the seasonality of ENSO-related rainfall variability. During El Niño events, the precipitations are above the average between 30°-38°S in austral winter and spring. A rainfall deficit is observed from 38° to 41°S in summer, when El Niño development is maximum. Opposite precipitation anomalies characterize La Niña events. Blanco et al. (2002) found that positive SST anomalies propagated southward along the South American coast as far as 37°S during the 1997-1998 El Niño, confirming previous results related to the 1982-1983 El Niño event (Fonseca, 1985).

ODP Site 1233, situated offshore Chile at 41°S (Figure 1), is ideally positioned to track past latitudinal shifts of the coupled ACC-SWW system in the SE Pacific mid-latitudes (Lamy et al., 2004; Kaiser et al., in press). On the one hand, shifts of the ACC should be registered as the site lies within the strong SST gradient linked to the northern boundary of the ACC. On the other hand, the proximity of the site to the Chilean coast permits to follow changes in continental erosion that is mainly driven by rainfall during warm intervals (Lamy et al., 2001) and by glacial erosion through the PIS during the last glacial period (Lamy et al., 2004).

3. Material and Methods

Site 1233 was drilled during ODP Leg 202 off southern Chile (41°0.01’S; 74°26.99’W; 838 m water depth). The core site is situated 40 km offshore, within a small forearc basin on the upper continental slope (Mix et al., 2003). A complete sedimentary sequence down to
116.4 m below sea floor was recovered. A composite sequence was constructed representing 135.65 m composite depth (mcd). The sediment is mainly terrigenous (clay and silty clay) with small amounts of biogenic compounds. Calcium carbonate, total organic carbon (TOC) and opal concentrations range from 1 to 12%, 0.2 to 3.2 wt%, and 3 to 10 wt% respectively (Mix et al., 2003; Hebbeln, unpubl. data, 2005).

3.1 Stratigraphy

The age model of the recovered sequence at Site 1233 has recently been updated and improved (Kaiser et al., in press) and is based on: (1) a correlation of the uppermost ~9 mcd to the AMS \(^{14}\)C dated gravity core GeoB 3313-1 from the same location (Lamy et al., 2001) using magnetic susceptibility and Ca relative concentration records; (2) 17 AMS \(^{14}\)C-dates on mixed planktonic foraminifera samples (Lamy et al., 2004) covering the interval from ~9--41 kyr [all ages were calibrated with the CALPAL software (www.calpal.de) using the CALPAL 2004 January calibration curve] and the record of the Laschamp magnetic field excursion consistent with the \(^{14}\)C datings (Lund et al., subm.); (3) a tuning of the alkenone SST record to the \(^{18}\)O record of the Byrd ice core in the interval from 41 to 70 kyr (for our purposes, the Byrd ice core has presently the most suitable age model for the last glaciation as it is linked, like our \(^{14}\)C age calendar year conversion, to the Greenland GISP2 ice core record).

Site 1233 covers the last ~70 kyr. The sedimentation rates are exceptionally high, ranging from 1.4 m/kyr in the Holocene to >2 m/kyr during the last glacial period (MIS 4 to 2) (Figure 2 C). The Holocene sedimentation rates are consistent with strong fluvial discharge in response to heavy continental rainfall in southern Chile (Lamy et al., 2001). During the last glacial, the continental hinterland of Site 1233 was extensively glaciated as the PIS advanced towards the north (Denton et al., 1999b) explaining even higher terrigenous sediment input through glacial erosion.

3.2 Iron measurements

Iron relative concentration was measured with a X-ray fluorescence (XRF) Core Scanner at the University of Bremen. The XRF Core Scanner is a non-destructive analysis system for relatively fast and closely spaced analyses of major and minor elements by scanning split sediment cores. The measurements were performed with 1 cm resolution resulting in a total of ca. 16,000 measurements. Many sections showed numerous gas expansion cracks and fissures which significantly affected the XRF measurements. Such data-points were manually removed from the data-set. The mean temporal resolution of the iron record is 5 years. In order to reduce noise in the data-set, we smoothed the record by applying a 10-point moving average to the raw data.
3.3 Alkenone measurements

Alkenones were extracted from 1-3g of dried and homogenized sediment samples using successively less polar solvent mixtures of methanol and methylene chloride. Squalane (C$_{30}$H$_{62}$) and 2-nonadecanone (C$_{19}$H$_{38}$O) were added to the samples as internal standards prior to extraction. To avoid interferences with co-eluting components, the extracts were first saponified. Thereafter, we applied a liquid column chromatography to the extracts. The fraction containing the alkenones was analyzed by capillary gas chromatography using a Hewlett-Packard (HP) 5890 Series II plus gas chromatograph equipped with a DB-5MS fused silica capillary column (60 m, 0.32mm). We calculated the alkenone unsaturation index from $\text{UK}'_{37} = (C_{37:2})/(C_{37:3} + C_{37:2})$, where C$_{37:2}$ and C$_{37:3}$ represent the di- and tri-unsaturated C$_{37}$ alkenones, respectively (Brassell et al., 1986). The UK’$_{37}$ values were converted into temperature values applying the culture calibration of Prahl et al. (1988) ($\text{UK}'_{37} = 0.034T + 0.039$), which has been validated by core-top compilations (Müller et al., 1998). After Kim et al. (2002), alkenone-based SST estimates closely resemble annual mean temperatures of the surface-mixed layer off Chile. The precision of the measurements was estimated to be ±0.5°C. The SST estimate for the uppermost sample (14°C) matches the modern annual mean temperature at the core site. The mean resolution of the SST reconstruction is around 380 yrs between 0 and 40 kyr, and ~260 yrs in the older part of the record. Further details on the analytical procedure used for the determination of alkenone SSTs at Site 1233 can be found in Kaiser et al. (in press).

3.4 Spectral analysis

Blackman-Tuckey (B-T) and wavelet spectral analyses were performed on Site 1233 records (Fe and SST data) and three other data sets: Byrd and GISP2 ice-core temperature records (Grootes et al., 1993; Blunier and Brook, 2001) and a tropical precipitation record based on color reflectance from the Cariaco basin (Peterson et al., 2000). Prior to the spectral analyses, the time-series first were detrended by removing the linear trend, and then normalized to unit variance and evenly re-sampled. In a second step, the records were further detrended in order to pronounce the short-term variability domain (cycles <5 kyr) by applying a high pass filter at a cutoff frequency of 0.2 on the evenly re-sampled, padded records. The chronologies and the time resolutions of the five investigated records are summarized in Table 1 in order to give an estimation of the uncertainties of the results from the spectral analyses.

Wavelet analysis was performed using the online available Interactive Wavelet Plot (Torrence and Compo, 1998; http://paos.colorado.edu/research/wavelets/). The wavelet transform decomposes a one-dimensional time series into two-dimensional time-frequency space simultaneously (Torrence and Compo, 1998). To perform B-T spectral analyses, we used the AnalySerie 1.1 software (Paillard et al., 1996). This algorithm first computes the
autocovariance of the data, then applies a Tuckey window, and finally Fourier transformation to compute the spectrum.

4. Results and Discussion

4.1 SST variations and changes in the terrigenous input over the last 70 kyr

Figure 2. Data from ODP Site 1233 in the SE Pacific. (A) Fe record (cps, count per second; 10 point moving average; reversed plotted), (B) alkenone-based SST reconstruction (°C) and (C) sedimentation rates (m/kyr) from 70 kyr to present. The age control points are shown with the error bars on the radiocarbon datings (see text for details). Gray bars highlight time-intervals discussed in the text (see also Figure 3 for details).
For the Holocene (as recorded in core GeoB 3313-1 from the same location as Site 1233), the observed variability in the Fe record has been largely attributed to continental rainfall changes involving varying contributions of Andean (Fe-rich) versus Coastal Range (Fe-poor) source rocks (Lamy et al., 2001). Relatively humid intervals are characterized by a higher relative contribution of Fe-poor Coastal Range source rock that dilutes the Fe-rich Andean source rock signal. Conversely, when the climate is dryer, more iron reaches the core site as the Andean Fe-rich input is not diluted.

In their previous work on ODP Site 1233, Lamy et al. (2004) have shown that during the last glacial period (50 to 19 kyr) the Fe relative concentration of the bulk sediment can be used to trace variations in the extent of the PIS. During this interval the northeastern limit of the PIS was very close to Site 1233 (Figure 1) and erosion processes linked to ice-sheet advances enhanced the sediment input from Fe-rich volcanic Andean source rocks. This scenario is supported by the correlation (within the limitation of dating) of three major ice maxima as recorded on land (Denton et al., 1999b) to iron maxima at Site 1233 (Lamy et al., 2004). Thus, the Fe record at Site 1233 provides a continuous record of PIS advances (Fe-rich) and retreats (Fe-poor) between 50 and 19 kyr BP.

Another important point emphasized in the work of Lamy et al. (2004) is the strong similarity of the Fe and the alkenone-based SST record from 50 to 19 kyr at Site 1233, i.e. cold SST related to Fe maxima and vice versa. This pattern is in agreement with modeling results of PIS changes during the LGM and the deglaciation which suggest a close dependence of PIS variability on offshore SSTs (Hulton et al., 2002). However, between ~40 and 20 kyr the records of Lamy et al. (2004) displays a lag of ~700 yrs in the PIS response (Fe record) to climate changes as recorded by the alkenone-based SST. In the ~50 to 40 kyr interval the variability of both the PIS and the SST are synchronous. This pattern has been attributed to a delay of the PIS response to SST changes between ~40 and 20 kyr, with the response time probably related to the large size of the PIS. Before 40 kyr, when the PIS was smaller, it reacted synchronously with SSTs to climate changes.

In the present study, we have extended the Fe record to the base of Site 1233 sequence covering the last ~70 kyr (Figure 2). The extended SST record has already been published and thoroughly discussed elsewhere (Kaiser et al., in press). After a maximum of ~14.5°C during late MIS 5.1, the SSTs decreased to reach the coldest temperatures of the record (~8°C) during MIS 4 (Figure 2 B). The temperatures increased within ~2-3 kyr to reach ~12.5°C in early MIS 3 and displayed a general long-term cooling trend towards the LGM (around 19 kyr BP). Superimposed on this trend is a strong millennial scale variability of 2-3°C around a mean temperature of 9.5-10°C. Over the last deglaciation, the SSTs increased by ~6°C to reach 15.5°C during the Holocene climatic optimum. This warming was interrupted by one major cooling event (or plateau) corresponding to the Antarctic Cold Reversal (ACR; 14 to
12.5 kyr BP), whereas the Younger Dryas period (YD; 13-11.5 kyr BP) was mainly characterized by a warming of ~2.1°C. Finally, the SSTs decreased over the Holocene to present-day values (14°C). The long- and short-term variability of the SST records was attributed to common shifts of the coupled ACC-SWW system (i.e. a northward displacement bringing cold, subantarctic water in the core area and conversely for warm SST peaks), ultimately involving Antarctic sea-ice extent variability and subpolar wind intensity (Kaiser et al., in press).

Figure 3. Detailed data from ODP Site 1233 and core GeoB 3313-1 in the SE Pacific. (A) Deglacial Fe record (upper panel; cps, count per second; 10-pt moving average; reversed plotted), alkenone-based SST reconstruction (°C) and sea surface salinity (SSS) reconstruction (lower panel; psu, practical salinity unit; after Lamy et al. (2004). The dashed line represents the last maximum extent of the Patagonian Ice Sheet (PIS) extent as reconstructed on land (after Denton et al., 1999). (B) Early MIS 3 Fe and SST records (66 to 52 kyr BP). (C) Middle to late Holocene Fe and SST relationship (data from survey core GeoB 3313-1; Lamy et al., 2002). (1) Deglacial meltwater pulse due to the PIS collapse and (2) possible meltwater pulse during early MIS 3.

The comparison of the prolonged iron and SST records suggests that the general glacial pattern, i.e. Fe maxima during SST minima and vice versa, was likewise valid for the major part of the earlier MIS 3 and MIS 4 (Figure 2). Similar to the 19 to 40 kyr interval discussed
in Lamy et al. (2004), the increased SSTs led PIS retreats (Fe decreases) by up to ~500 yrs during the relatively cold MIS 4 (here ~68 to 62 kyr). This offset disappeared during early to middle MIS 3 (55 to 43 kyr) when the size of the PIS was probably reduced. Between ~60 and 56 kyr however, the trends in Fe and SST records are even anti-correlated (i.e. high iron values paralleling warm SST, and vice versa; Figures 2 and 3).

One possible explanation for this anomalous pattern could be in analogy to the Termination I scenario. Lamy et al. (2004) have shown that a strong decrease in sea-surface salinity (SSS) occurred from ~17.8 to 15.8 kyr BP, just after the last glacier maximum as recorded on land (Figure 3 A). This SSS anomaly is related to the rapid melting of the PIS within ~2 kyr resulting in a strong meltwater pulse entering the ocean. This is in agreement with modeling results suggesting a huge and rapid collapse of the PIS at the beginning of the deglaciation, especially in its northern part (Hulton et al., 2002). Synchronously to the SSS decrease, the Fe relative concentration stays high until ~15 kyr BP while the SST has already reached ~12.5°C (Figure 3 A). Therefore, high Fe input during this time-interval could be due to an anomalously high terrigenous input of Andean sources linked to the PIS melting. Such a scenario is plausible for early MIS 3. Similar to Termination I, a pronounced SST warming of ~4°C (from 8°C to ~12°C) within 2.2 kyr is observed during the MIS 4/3 transition, that likewise could have led to an anomalously strong terrigenous input resulting in high Fe values while the SSTs were relatively warm. At this point there are no planktonic $\delta^{18}O$ data available to reconstruct the $\delta^{18}O$ of the seawater during early MIS 3 in order to obtained further evidence for this hypothesis. Moreover, while this scenario is supported by a synchronous increase in the sedimentation rates during early MIS 3, no significant increase in the terrigenous input is recorded during the deglaciation (Figure 2 C).

Another possibility would imply a SST/Fe relation similar to that suggested for the Holocene (Lamy et al., 2002). During early MIS 3 (i.e. ~60 to 56 kyr), the mean SST was around 12°C off southern Chile (Figure 3 B), following a ~4°C warming at the MIS 4/3 transition as mentioned above. When applying a raise in temperatures by 6°C at the beginning of Termination I, Hulton et al. (2002) obtained a drastic reduction in the PIS ice volume from ~500,000 km$^3$ at the LGM to <200,000 km$^3$ within less than 1000 yr. It is plausible that, considering a 4°C warming at the MIS 4/3 boundary (as shown by our SST reconstruction), the PIS ice volume was likewise substantially reduced, especially in its northern part which is very sensitive to climate changes (Hulton et al., 2002). Therefore, during early MIS 3 the Fe signal could document a similar process as during the Holocene, i.e. being controlled by the continental rainfall changes that are related to the position of the SWW. Accordingly, high Fe values would be linked to reduced rainfall during periods of warmer SST and vice versa (Figure 3 B). While the main trend during this time-interval supports this interpretation, it is difficult to compare short-term variations in both records due to the lower resolution of the SST reconstruction. Nevertheless, it appears that between ~60 and 56 kyr the variability in the SST and Fe records on short, millennial to multi-centennial time-scales does not exactly
follow the general antiphasing of the trend. Interestingly, similar results have been obtained for the late Holocene (Lamy et al., 2002) when many of the multicentennial- to millennial-scale variations in paleo-temperatures do not exactly match the reconstructed shifts of the SWW (as inferred by the Fe variability) (Figure 3 C). These mismatches might be related to a different impact of low-latitude (including ENSO) and high-latitude factors controlling continental rainfall and paleoceanographic changes. Considering that positive SST anomalies during modern ENSO events reach as far south as 37°S (e.g., Blanco et al., 2002), paleo-SSTs in the southern PCC during the late Holocene are most likely not affected by changes in ENSO. In contrast, rainfall in central and southern Chile was probably strongly influenced by ENSO events as indicated by studies on the modern situation (e.g., Rutland and Fuenzalida, 1991; Montecinos and Aceituno, 2003). The mismatch of millennial scale variability in atmospheric (i.e., SWW) and oceanographic (i.e., ACC and southern PCC) circulation patterns, might thus partly be related to long-term changes in ENSO during the late Holocene as proposed by Lamy et al. (2002), and perhaps also during early MIS 3.

4.2 Climate variability at millennial to sub-millennial timescales: hemispheric to interhemispheric linkages

The SST and the Fe records at Site 1233 reveal a pronounced short-term variability at millennial to sub-millennial timescales during the last glacial period that can be primarily attributed to latitudinal shifts of the ACC/SWW coupled system (Kaiser et al., in press; Lamy et al., 2004; and discussion above). In order to analyse this variability in more detail and to compare periodicities and their changes over the last 70 kyr, we performed wavelet and Blackman-Tuckey spectral analyses of the detrended records (using a 5 kyr high pass filter). The results are presented in Figure 4 and 5.

The Fe and SST records show comparable spectra (Figure 5 C-D). Based on the wavelet results, we can isolate main periodicity-bands: around 3.5, 2 and 1.2 kyr, and some others in the multicentennial domain (< 1 kyr). The B-T spectra permit a more detailed identification of the involved periodicities. First, the ~3.5 kyr cycle is in fact composed of two periodicities at ~4.5-4.4 and 3.1-3.2 kyr. The 4.5-4.4 kyr period is above the 80% confidence level for both Fe and SST records, while the 3.1 kyr period is slightly under the significance level for the SST spectrum (Figure 5 D). In both the Fe and SST records, the ~3.5 kyr periodicity-band tends to shift from its relatively longer component (~4.5 kyr) between ~60 and 70 kyr to its shorter component (~3.1 kyr) during MIS 3, and again to a longer period in the middle to late Holocene (Figure 5 C-D left column). The ~2 kyr period seen in the wavelet analysis appears in the B-T results to be centred around 2.3-2.4 kyr. This period is again not firmly significant for the SST record. However, the 2.2 kyr cycle in the Fe record is clearly above the significance level. Based on the wavelet results of both records, the period appears to be particularly marked around 10 kyr BP, 20-25 kyr BP, and 40 to 50 kyr BP. Finally, the periodicity band around 1.2-1.3 kyr shown in the wavelet analyses is significant in both
records (B-T results). This ~1.2 kyr cyclicity is mainly concentrated in the 42 to 60 kyr time-interval. One can argue that this short-term variability may result from an artefact linked to the age model, as two time-intervals with a stronger 1.2 kyr period correspond to increased sedimentation rates (around 42 and 58 kyr BP; see Figure 2), and therefore an increased resolution. This could be true for the alkenone SST record. However, the 50 year resolution iron record shows this periodicity in other time-intervals where the sedimentation rates are not increased (e.g., ~38 or 50 kyr BP). Furthermore, the Fe record displays significant multicentennial variability around 0.8 to 0.9 kyr and an additional millennial-scale cycle at ~1.6 kyr (Figure 5 C).

In order to discuss possible origins and hemispheric to inter-hemispheric linkages related to millennial to sub-millennial variability in the SE Pacific, we have compared our spectral results to three other high resolution records situated in the northern and southern high latitudes, and the tropics (Figure 4 and 5): the oxygen isotope records from the GISP2 (Grootes et al., 1993) and the Byrd (Blunier and Brook, 2001) ice cores, and a reflectance record from the Caricaco basin (Peterson et al., 2000). We assume that these records are representative for the different latitudes. The ice core records primarily reflect changes in the air temperature in high-latitudes. For the Caricaco basin record, changes in terrigenous input, ultimately related to rainfall and runoff, are at the origin of the reflectance variability (Peterson et al., 2000). We have detrended the data-sets with a 5 kyr high pass filter (Figure 4) and performed the spectral analyses with both the wavelet and B-T methods (Figure 5 A-B-E).
Figure 4. Records used for wavelet and Blakman-Tuckey analysis. Left column: raw data. Right column: the same records after resampling, normalizing (norm.) and high pass filtering (cutoff frequency at 0.2 Hz). From top to bottom: oxygen isotope record of the GISP2 ice core (Grootes et al., 1993), reflectance record from Cariaco basin (Peterson et al., 2000), Fe and SST records from Site 1233 (this study; Kaiser et al., in press), oxygene isotope record of Byrd ice core (Blunier and Brook, 2001).
The wavelet analyses reveal that all five records show a pronounced periodicity band centred at ~3.5 kyr. The B-T spectra indicate that this band is composed of two dominant periods close to ~4.5 kyr and ~3 kyr. As aforementioned for the Fe and SST records from the SE Pacific, this periodicity seems to shift to its shorter component during relatively cold periods, i.e. around 35 to 45 kyr BP, in most of the records. These results suggest that both ~4.5 and 3 kyr cycles are globally important and occur in very different climate subsystems. Alley et al. (2001) have shown that the GRIP and GISP2 ice core isotope data produce a recurrence histogram for waiting times between warmings (interstadials) with main bands near 1.5, 3 and 4.5 kyr, and shorter waiting times in colder parts of ice ages. These waiting times are consistent with the so-called stochastic resonance model, involving a system in which a weak periodic signal combines with other signals to cause mode switches. Their results suggest that there is a ~1.5 kyr climate cycle and “noise”. Both are individually too weak to cause climate mode switches, but a combination of both is required to explain climate switches such as Dansgaard-Oeschger (DO) cycles (Alley et al., 2001). From a modelling experiment based on the interaction of a “white noise” and a 1.5 kyr period (both defined as freshwater fluxes in the North Atlantic realm), Ganopolski and Rahmstorf (2002) obtained a pattern similar to the DO cycles, with preferred inter-spike intervals of 1.5, 3 and occasionally 4.5 kyr, supporting the conclusion of Alley et al. (2001) that stochastic resonance is at work in these events. We thus suggest that the ~4.5 to 3 kyr periodicity in the records from the SE Pacific, as well as in the SH and NH high-latitudes and the low-latitudes, could be part of a mechanism involving stochastic resonance. A ~1.5 kyr cycle is obviously present but not statistically significant in the SST reconstruction from the SE Pacific. However, we found a significant ~1.6 kyr cycle in the Fe record (Figure 5 C). In addition, the Fe record of the middle to late Holocene of the survey core at Site 1233 (GeoB 3313-1) also revealed a period of ~1.5 kyr (Lamy et al., 2001). The potential origin of a 1.5 kyr cycle remains up to now controversial, ranging from internal oscillations of the ocean-atmosphere system (e.g., Schulz, 2002; Timmermann et al., 2003), calving of the Greenland ice-sheet (van Kreveld et al., 2000), to external forcing through solar variability (e.g., van Geel et al., 1999). Clemens (2005) has recently proposed that this 1.5 kyr cycle is an artefact resulting from the GISP2 age model. In turn, two strong peaks centred on 1.667 and 1.19 kyr have been attributed to solar forcing (Clemens, 2005). Interestingly such periodicities are close to our results, i.e. 1.6 and 1.2 kyr in the Fe record and 1.3-1.1 kyr in the SST reconstruction.

**Figure 5.** Spectral analysis of the detrended records from (A) the GISP2 ice core, (B) the Cariaco Basin, (C-D) the SE Pacific, and (E) the Byrd ice core (see Figure 4 and text for details). Left column: wavelet power spectra. The contour levels are chosen so that 75%, 50%, 25%, and 5% of the wavelet power is above each level, respectively. Black contour is the 80% confidence level, using a red-noise background spectrum. Right column: results of Blackman-Tuckey (BT) spectral analysis. The analyses were performed with a Barlett-type window. Those peaks of the spectrum (filled with gray) that rise above the low resolution spectrum (thin solid line) by a distance greater than the one-sided confidence interval at the 80% level (lower spectra filled with white) are declared to be significant (e.g., Felis et al., 2000). Gray bars highlight the main periodicity bands discussed in the text.
SECTION 4.3 MANUSCRIPT: VARIABILITY OF SST OFF CHILE AND THE DYNAMICS OF THE PIS...

A) GISP2 ice core, Greenland

B) Reflectance at Site 1002, Cariaco basin

C) Fe-content at Site 1233, SE Pacific

D) SST at Site 1233, SE Pacific

E) Byrd ice core, Antarctica
The importance of multiples of the 1.5 kyr cycle in all records does however not imply synchronous interhemispheric climate fluctuations on these time-scales. SST changes at Site 1233 and temperature changes in Antarctica appear to change in phase (Kaiser et al., in press; Lamy et al., 2004) at least for the large fluctuations (e.g., Antarctic warming events A1-A4 that occurred during the most pronounced D-O stadials in Greenland) consistent with the bipolar sea-saw mechanism (Broecker, 1998; Stocker, 1998; Blunier and Brook, 2001). Moreover, a recent modelling study emphasized a possible triggering role of the Southern Ocean within abrupt climate changes during the last deglaciation and suggests that a similar mechanism could have triggered the D-O oscillations as well (Knorr and Lohmann, 2003).

A clear documentation of the presence of Southern Hemisphere equivalents also to the smaller D-O oscillations however is still missing.

<table>
<thead>
<tr>
<th>Record</th>
<th>Time resolution</th>
<th>Age error</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe-content (ODP Site 1233)</td>
<td>ca. 5 yr</td>
<td>ca. 30 to 800 yr</td>
<td>Lamy et al., 2004</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Kaiser et al., in press</td>
</tr>
<tr>
<td>SST (ODP Site 1233)</td>
<td>ca. 360 (0-40 kyr) to 260 (40-70 kyr)</td>
<td>ca. 30 to 800 yr</td>
<td>Lamy et al., 2004</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Kaiser et al., in press</td>
</tr>
<tr>
<td>Byrd δ¹⁸O</td>
<td>ca. 70 yr (10-40 kyr) to 100-350 yr (40-70 kyr)</td>
<td>ca. 500 yr</td>
<td>in Hinnov et al., 2001</td>
</tr>
<tr>
<td>GISP2 δ¹⁸O</td>
<td>ca. 40-100 yr (0-50 kyr) to 300 yr (50-70 kyr)</td>
<td>ca. 200 to 1000 yr</td>
<td>in Hinnov et al., 2001</td>
</tr>
<tr>
<td>Cariaco Basin reflectance (ODP Site 1002)</td>
<td>ca. 50 yr</td>
<td>ca. 30 to 900 yr</td>
<td>Peterson et al., 2000</td>
</tr>
</tbody>
</table>

**Table 1.** Mean resolutions and age uncertainties of the records investigated in this study. See text and figures for details.

In addition, a 2.2 to 2.4 kyr periodicity seems to be present in the SE Pacific, especially in the Fe record, whereas this periodicity is slightly under the significance level of the B-T spectral results for the SST reconstruction (right column of Figure 5). Such a pacing was also recognized in the Δ¹⁴C residual series (Stuiver and Braziunas, 1993; Mayewski et al., 1997) and in worldwide Holocene glacier advances (e.g., Denton and Karlen, 1973; Zhang et al., 2000) suggesting in these cases a solar modulation of climate (see also Chambers et al., 1999; Charvatova, 2000; Damon and Peristykh, 2000). A possible mechanism linking variations in solar activity and significant climate changes could involve changes in the atmospheric circulation (e.g., Haigh, 1996; Christoforou and Hameed, 1997). Based on the 11 yr solar cycle, Haigh (1996) has shown that increased UV radiation could ultimately lead to a poleward shift of the mid-latitude storm tracks, involving shifts of the tropospheric subtropical jet streams and the Hadley cells. A reversed mechanism could be true for decreased UV radiations (van Geel and Renssen, 1998). As mentioned above the SST and Fe records from the SE Pacific are closely linked to the ACC/SWW coupled system, controlled by the SE Pacific subtropical high pressure (STH). Thus, there might be a link between climate changes in the SE Pacific and atmospheric reorganization under solar variations.
Based on a comparison of the GISP2 $K^+$ record and a SST reconstruction from the Aegean Sea during the Holocene, Rohling et al. (2002) have also found a $\sim$2.3 kyr cycle. It is important to note, that the Aegean Sea likewise is an area that largely records atmospheric variability, in this case linked to the intensity of the Siberian high pressure system (Rohling et al., 2002).

Concerning the relative high periodicities, we already mentioned a possible solar origin of the 1.1-1.3 kyr cycle as recorded in the SE Pacific (see above). An interesting feature is the absence of a similar cycle in the oxygen isotope record of the Antarctic Byrd ice-core (Figure 5 E) while it is present and above the significance level in all other records. In the SE Pacific this period is strongest within the first half of MIS 3, a relatively warm period of the last glacial time. Whatever the origin of this short-term variability, the results suggest that the SE Pacific mid-latitudes were obviously not influenced by the Southern Ocean high-latitudes, and therefore possibly by the Northern Hemisphere high-latitudes and/or the low-latitudes. As proposed in Section 4, Fe and SST mismatches at millennial to multi-centennial time-scales during early MIS 3 could result from a similar-to-ENSO mechanism.

Finally, a $\sim$0.8 kyr period appears in all the records (Figure 5). Lamy et al. (2001) found a similar cycle ($\sim$0.9 kyr) based on the Holocene part of the record (see above). The authors proposed a relation to Hadley cell intensity as for the $\sim$1.5 kyr cycle. Changes in the orbital parameters (Loutre et al., 1992) and/or in solar activity (a 805 yr period appears in the spectrum of the tree-ring calibrated $\Delta^{14}C$ record; Damon and Sonnett, 1991) could be related to this multi-centennial cycle, thus obviously involving changes in the atmospheric circulation (i.e. Hadley cell intensity).

5. Conclusions

Continuous ultra-high resolution records of the variability in the PIS extent (Fe input) and SSTs (alkenone-based) off Chile during the last 70 kyr based on ODP Site 1233 indicate that the close relationship of the Fe and the SSTs pattern in the SE Pacific as described by Lamy et al. (2004) for the 50-19 kyr time-interval extents in the older part of the records (70 to 50 kyr). The results suggest a similar delay of $\sim$500 yr of the PIS retreats on the offshore SST warmings during MIS 4 and almost synchronous variability in both records during early MIS 3 at a time when the size of the PIS was probably much smaller. We suspect furthermore a meltwater pulse in early MIS 3 (around 58 kyr BP), similar to the deglacial section. Alternatively, the pattern of the Fe and SSTs relationship during the $\sim$60 to 56 kyr time-interval suggests strong resemblances to the Holocene records (Lamy et al., 2002) and may also imply a dominant control by rainfall changes. It is thus conceivable that the PIS was substantially smaller or even absent (at least in its northern part) during early MIS 3 when the mean SSTs were only 2°C colder than today.
The results of spectral analysis (using the wavelet and B-T methods) on our detrended records show three main periodicity-bands at ~4.5-3.1 kyr, 2.4-2.2 kyr and 1.2-1 kyr. Comparing these results to high-latitudes ice-core records (Byrd and GISP2) and a low-latitude marine record (Cariaco Basin) indicates that the 4.5-3.1 kyr band could be an expression of the so-called stochastic resonance mechanism involving a combination of a weak periodic signal with other signals to cause climate mode switches, e.g. the D-O events. During both the Holocene (Lamy et al., 2001) and the last glacial period (this study), a ~1.5 to 1.6 kyr periodicity is recorded in the SE Pacific (especially in the Fe record). The origin of this world-wide recognized cycle is as yet unexplained. For the 2.2-2.4 kyr periodicity-band a solar origin can be assumed. As proposed in several studies, changes in UV radiations could have ultimately an impact on the location of the mid-latitude storm tracks, which are prominent actors for climate variability in southernmost Chile. The absence of a ~1.3-1 kyr period in the oxygen isotope record of the Antarctic Byrd ice-core suggests a NH high- and/or low-latitudes influence on the SE Pacific at millennial time-scale, especially during early MIS 3.

Acknowledgements:

The data that we report here are accessible at the World Data Center for Marine Environmental Sciences (http://www.wdc-mare.org/PangaVista?query=@Ref26570). The study was funded by the German Science Foundation through the grant DFG-He-3412-1-3 and technically supported by the Research Center Ocean Margins (RCOM) in Bremen. This research used samples provided by the Ocean Drilling Program (ODP). The ODP is sponsored by the U.S. National Science Foundation (NSF) and participating countries under management of Joint Oceanographic Institutions (JOI), Inc. This is RCOM contribution XXX.
4.4 The last deglaciation off southern Chile at a sub-centennial resolution: interactions of the Patagonian Ice Sheet, sea-surface temperatures and alkenone productivity

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\textbf{Manuscript in preparation}

\textbf{Abstract}

Previous studies based on ODP Site 1233 situated off southern Chile have shown that the millennial scale SST pattern over the last glacial time was very similar to Antarctic air temperature changes and that a close relation existed between the SST and the Patagonian Ice Sheet (PIS) fluctuations as reconstructed from the record of the iron concentrations (Lamy \textit{et al.}, 2004; Kaiser \textit{et al.}, in press; Kaiser \textit{et al.}, in review). Here, new, high-resolution (sub-centennial timescale) SST and SSS records over the last deglaciation robustly confirm the previous records and provide important new details on the centennial-scale evolution. The SST record is clearly in phase with Antarctic air temperature records and no influence from the Northern Hemisphere is visible, especially regarding the Younger Dryas event. New and better time-constrained records of the PIS fluctuations on adjacent land that became recently available are in phase with the iron concentrations, reinforcing the utilization of this proxy for PIS movements during older times. The SSS reconstruction suggests three main freshwater inputs linked to the melting of the PIS, one being in close agreement with results on the adjacent land. Furthermore, the freshwater inputs strongly influenced the offshore productivity, as inferred by the alkenones concentration, probably linked to the supply of micronutrients and the presence of a well-stratified upper water column favoring light penetration.
Introduction

In their recent studies, Lamy et al. (2004) and Kaiser et al. (in press) have shown that the sea-surface temperature (SST) changes over the last 70 kyr off southern Chile (ODP Site 1233; 41°S) and air temperature changes over Antarctica (based on the oxygen isotope record of the Byrd ice core; Blunier and Brook, 2001) present very similar millennial-scale variability. Furthermore, the record of iron concentrations from the same archive, interpreted as a proxy for terrigenous input through the fluctuations of the Patagonian Ice Sheet (PIS) during the last glacial, shows a pattern very close to that of the SST record (i.e. PIS growth during SSTs cooling and vice versa). However, the authors showed that SST warmings preceded PIS retreats by ~700 years during the last glacial and up to 1000 yr at the beginning of the last deglaciation. The rapid melting of the PIS during the deglaciation is documented as a pronounced sea surface salinity (SSS) anomaly suggesting large inputs of meltwater (Lamy et al., 2004). On the one hand, these results confirm a strong influence of the SSTs on the PIS as suggested by a modelling study of the PIS over the last deglaciation (Hulton et al., 2002). On the other hand the delayed response of the PIS could partly explain the disagreement between the marine and terrestrial records in southern Chile as a number of paleoenvironmental studies on land suggest a climate linkage with the Northern Hemisphere in particular regarding the presence of a Younger Dryas cooling in Chile (e.g. Heusser et al., 1999; Denton et al., 1999a; Moreno et al., 2001).

The main forcing for climate changes over the last 70 kyr in the southeast Pacific are latitudinal shifts of the Westerly wind belt and the Antarctic Circumpolar Current / Peru-Chile Current (ACC/PCC) system, as suggested by most of the paleoclimatic reconstructions on land and in the ocean (e.g., Abarazua et al., 2004; Kaiser et al., in press). Furthermore, it has been recently shown that the pronounced millennial-scale SST variations in the southeast Pacific are closely related to sea-ice extent and the strength (and/or the position) of the winds around Antarctica (Lamy et al., 2004; Kaiser et al., in press).

In this paper, we present new, high resolution data over the last deglaciation (25 to 5 kyr) at ODP Site 1233 (Figure 1). The new records provide a similar time resolution as the Byrd ice core and allow a detailed comparison to the Antarctic temperature fluctuations even on sub-centennial time-scales. In addition, the new SSS reconstruction gives further insights into the deglacial melting history of the PIS that are discussed under consideration with new terrestrial data that have been published recently (Sugden et al., 2005).
Oceanographic and atmospheric settings

![Map of the Southern Ocean](image)

**Figure 1.** Location of ODP Site 1233 (41°0.01'S, 74°26.99'W; 40 km offshore; 838 m water depth), modern annual mean sea-surface temperature distribution (Levitus and Boyer, 1994) and austral summer sea-surface salinity distribution off southern Chile (right panel; psu unit; after Brandhorst, 1971). Dotted lines: limits of the last glacial maximum extent of the Patagonian Ice Sheet as reconstructed on land. Surface currents: Antarctic Circumpolar Current (ACC), Peru-Chile Current (PCC) and Cape Horn Current (CHC). CFW: Chilean Fjord Waters.

The study area (Figure 1) is located at the northern margin of the ACC under the influence of cold, subantarctic surface waters and within a steep latitudinal SST gradient (~5°C between 43°S and 39°S; Levitus and Boyer, 1994). Mean annual SSTs are around 14°C and the seasonal amplitude is ~5°C. The ACC splits around ~43°S into the PCC flowing northward and the Cape-Horn Current (CHC) turning towards the south (Strub *et al.*, 1998). In the Southeast Pacific mid- to high-latitudes, the steepest SST gradient within the ACC is strongly
related to the main atmospheric circulation member of the Southern Hemisphere, the Westerly
wind belt (Streten and Zillman, 1984). This intense and powerful circulation, annually
centered around 50°S, results from the strong thermal gradient and atmospheric pressure
difference between cold air masses over Antarctica and the warmer air and water masses in
the subtropical regions (Cerveny, 1998). In southernmost South America, the Westerlies and
associated storm tracks bring heavy rainfalls, e.g. an annual mean greater than 2000 mm in
Puerto Montt (41°S), and prevent upwelling south of 39°S (Mohtadi et al., 2005). Finally, at
41°S off Chile the SSS distribution (Figure 1) is characterized by a strong anomaly resulting
from freshwater inputs in the Chilean fjord region. These low salinity waters (33-34 psu)
spread northward within the PCC (Strub et al., 1998). The position of Site 1233 offers thus an
excellent opportunity to monitor sea-surface salinity anomalies caused by variations in river
runoff or by melting pulses associated with episodes of net glacier retreat.

Material and Methods

The age model of the 135.7 mcd-long (mcd, meter composite depth) composite sequence
at Site 1233 has been discussed and published in Lamy et al. (2004) and Kaiser et al. (in
press). Here we focus on the ~6 to 42 mcd interval (i.e. ~5 to 25 kyr). For this time interval
the age model is based on (1) correlation with the AMS 14C dated gravity core GeoB 3313-1
from the same location (Lamy et al., 2001) for the uppermost ~9 mcd and (2) 9 AMS 14C-
dates on mixed planktonic foraminifera samples (see Figure 2). The radiocarbon dates were
corrected for a reservoir effect of ~400 years and calibrated with the CALPAL software
(www.calpal.de) using the CALPAL 2004 January calibration curve (see for discussion Lamy
et al., 2004). The mean sedimentation rates range between ~2 m/kyr (late glacial and
deglaciation) and 1.5 m/kyr (middle Holocene).

We measured alkenone-based sea-surface temperature (SST) with a resolution ranging
from 360 yr (between ~5-11 and 19-25 kyr) to 70 yr (11-19 kyr). The method used is
described elsewhere (e.g. Müller et al., 1998; Kaiser et al., in press). We applied the Prahl et
al. (1988) calibration curve for conversion of the UK’37 (Prahl and Wakeham, 1987) into
temperature values [T (°C) = (UK’37-0.039)/0.034]. The method uncertainty was estimated to
be ±0.3°C. Based on cores situated further south at ~33°S, Kim et al. (2002) have shown that
the SSTs derived from alkenone measurements on surface sediments agree well with the
modern annual mean SST at 0 m water depth (from Levitus and Boyer, 1994). Furthermore,
we used the sum of the C37:3 and C37:2 alkenone concentrations (ng/g) as a proxy for the past
production of coccolithophorids (Villanueva et al., 1997).

Stable isotope (δ18O) analyses for the 5 to 22 kyr BP interval were performed at the
University of Bergen on specimens of the planktonic foraminifer Globigerina bulloides
selected from the >250 to 355 µm size fraction with an average time resolution of ~150 years.
Samples were analysed using a Finnigan MAT 251 mass spectrometer coupled to an
automated Kiel device. The data are reported on the VPDB scale calibrated with NBS-19. The long term analytical precision of the system as defined by the reproducibility of carbonate standards exceeds ±0.07‰. To reconstruct the SSS, we have interpolated (100 yr) and combined the stable oxygen isotope on *G. bulloides* and the alkenone-based SST results following Lamy *et al.* (2004).

The total organic carbon (TOC) was measured on freeze-dried and homogenized sediment samples. After decalcification of the samples by 6 N HCl, TOC was obtained by combustion at 1050°C using a Heraeus CHN-O-rapid elemental analyzer as described by Müller *et al.* (1994). The resolution is the same than for the alkenone measurements.

Iron relative concentration was measured with a X-ray fluorescence (XRF) core scanner at the University of Bremen. The XRF core scanner is a non-destructive analysis system for relatively fast and closely spaced analyses of major and minor elements by scanning split sediment cores. The mean temporal resolution of the iron record is 5 years. In order to reduce noise in the data-set, we smoothed the record by applying a 10-point moving average to the raw data.

**Results and discussion**

Within the limitation of dating of both the ice core and our marine records, we observe a very similar pattern between our SST record in the high resolution interval (between 19 and 11 kyr) and the oxygen isotope composition of the Byrd ice-core even at a centennial to sub-centennial time scale (Figure 2 A-B). However the main trend is slightly different. After a final cold event at 18.8 kyr (8.3°C), the SSTs increase by ~5°C within ~2 kyr. During the next 4 kyr the temperatures stabilize around a mean of ~13°C with minor short-term variability of up to ~1°C. The last 1.5 kyr of this plateau correspond to the Antarctic Cold Reversal (ACR; 14-12.5 kyr; e.g., Jouzel *et al.*, 1995). During most of the Northern Hemisphere Younger Dryas time-interval (YD; 13-11.5 kyr; e.g. Rutter *et al.*, 2000), the SSTs increase by ~2°C to reach finally a temperature maximum of 15.5°C (about 1.5°C warmer-than-today) during the early Holocene Climatic Optimum (HCO; 12-9 kyr; Kaiser *et al.*, in press). The warming during most of the YD confirms the previous results from Kaiser *et al.* (in press). Over the middle Holocene, there is a cooling trend of ~1°C interrupted by a slight warm event (called here Holocene Warm Event, HWE) of ~0.5°C centred around 6 kyr cal BP. In conclusions, the last deglaciation off southern Chile lasted ~7.5 kyr with a SST warming of ~6-7°C. The two steps feature of the SST warming might suggest that the Westerlies/ACC coupled system has shifted poleward in two phases over the last deglaciation, i.e. between ~18.8-19.7 and ~12.6-11.2 kyr.
The records of the SSS and the iron concentrations (Figure 2 D-E) highlight the different stages of the PIS advances during the last glacial and the following retreats over the deglaciation. A recent study in southernmost South America (central strait of Magellan and
Bahia Inutil; 53-55°S) presents a revised chronology of moraines deposits during the late glacial (McCulloch et al., 2005). The advance representing the glacial maximum in Patagonia (between ~31.2 and 23.1 kyr) was earlier than the global Last Glacial Maximum (LGM) and was followed by a less extensive advance sometime before 22.4-20.3 kyr BP. These results support another similar study in Patagonia (46.5°S) suggesting that ice was at its maximum extent prior to 22 ka and that at least five successive moraines were deposited before 16 kyr (Kaplan et al., 2004). The Fe record at Site 1233 (interpreted here as a proxy for terrigenous input through glacial erosion; see Lamy et al., 2004) shows high values between 25 and ~21.7 kyr, in agreement with the results on land within the limitation of dating. Before the general decreasing trend towards the Holocene, the iron reaches its highest values between ~19.4 and 17 kyr with at least four short-term maxima. Within this time-interval another glacier maximum (dated at ~17.5-17.7 kyr BP) has been recognized in southern Patagonia (53-55°S; McCulloch et al., 2005) and on Chiloe Island (41°S; Denton et al., 1999a). Finally, the iron concentrations begin to decrease from ~16 kyr BP what corresponds to PIS retreats in southern South America as reconstructed on land (Denton et al., 1999a; Turner et al., 2005). During the ACR (mentioned as being a phase of glacier advance or stillstand; Fogwill and Kubik, 2005; McCulloch et al., 2005; Turner et al., 2005) and the YD there is no clear pattern in the iron concentrations. It is conceivable that since this period (or even before), the terrigenous input at 41°S was under the influence of both rainfall variability and glacier movements and it is thus difficult to distinguish between both forcings (Kaiser et al., in review). Following the modelling study of Hulton et al. (2002), a 6°C warming would produce a drastic reduction in the PIS ice volume from ~500,000 km³ at the LGM to <200,000 km³ within less than 1000 yr. It is plausible that, considering a 4.5 to 5°C warming within ~2 kyr at the beginning of the last deglaciation (as shown by our SST reconstruction), the PIS ice volume was likewise substantially reduced already since ~16.7 kyr BP, especially in its northern part which is very sensitive to climate changes (Hulton et al., 2002). Therefore, it is likely that iron concentrations are primarily controlled by rainfall changes after ~16.7 kyr BP.

Independent of the terrigenous input changes, the SSS record provides information on the history of the PIS retreat because this record is largely influenced by meltwater input from the decaying ice sheet during the deglaciation as shown by Lamy et al. (2004). Our new, more detailed record suggests that SSS oscillated around a mean value slightly lower than the modern values between ~22 to 19 kyr (Figure 2 D). Thereafter, salinities were relatively high (higher-than-today) until ~17.3 kyr BP, a period corresponding to glacier advances on land (see above) suggesting that the PIS was in a growth phase and less freshwater was released to the ocean. At ~17.3 kyr BP, the SSS strongly decreases from ~34 psu at 17.3 kyr BP to ~30 psu at 15.5 kyr BP within two steps: strongly and abruptly between 17.3 and 17 kyr B.P. and then more gently between 17 and 15.5 kyr BP. As already mentioned in Lamy et al. (2004), this SSS anomaly is obviously related to an important melting phase of the PIS related to the SST warming of ~4.5-5°C at the beginning of the last deglaciation. The melting phase is
consistent with terrestrial data suggesting a rapid retreat after the last advance into the Chilean Lake District around 17.5 kyr BP (Denton et al., 1999a) and a second phase between ~16 and 15 kyr observed around 46-48°S (Turner et al., 2005). During the following 2.6 kyr, the SSS increase again to reach values close to the modern (or slightly higher) around 12.9 kyr BP. At the beginning of the Northern Hemisphere YD time-period, the SSSs decrease strongly and abruptly (~2.4 psu within 0.3 kyr) suggesting a second freshwater pulse. This is very interesting because Turner et al. (2005) have shown that at ~12.8 kyr BP there was a strong input of freshwater in the Pacific Ocean around 48°S. At this time a large lake occupying at least present-day Lago Buenos Aires suddenly drained ~2000 km³ of freshwater into the Pacific through the gap between the North and South Patagonian ice-fields. Not mentioned on land is a possible third large freshwater pulse at ~12 kyr BP (a decrease of ~1.6 psu within 0.5 kyr) that may result from the warming during the YD. Though the extent of the PIS was already quite small during this time-interval, this fresh-water pulse might represent the final melting of the PIS after a glacier stillstand or minor advance during the ACR. All these three “meltwater pulses” of the PIS are characterized by salinities significantly fresher-than-today (~0.5 to 0.7‰). During the early to middle Holocene, the SSS were higher-than-today possibly due to smaller-than-today ice-fields on the one hand, assuming a warmer-than-today climate (e.g., Massaferro and Brooks, 2002; Abarazúa et al., 2004; Kaiser et al., in press), releasing less freshwater, and on the other hand a stronger influence of the relatively saltier waters coming from the low-latitudes within the Peru-Chile Countercurrent (Strub et al., 1998). In addition, rainfall controlled fluvial freshwater input was likely reduced as the Westerlies were located southwards during the early and middle Holocene (Kaiser et al., in press; Lamy et al., 2002).

Based on core GeoB 3313-1 drilled at the same location than ODP Site 1233, Lamy et al. (2002) have shown that changes in the iron concentrations were linked to changes in the rainfall during the middle to late Holocene. Relatively dry intervals are characterized by a higher Fe input at the core site as the Andean Fe-rich input is not diluted by Fe-poor Coastal Range source rock (what happens during relatively humid periods). Ultimately, continental rainfall changes are related to the position of the Westerlies, i.e. lower rainfall during relatively warm periods linked to a poleward shift of the Westerlies and vice versa. The mechanisms proposed by Lamy et al. (2002) are supported by the Holocene long-term trend of the records (Figure 2) as after the HCO the iron concentrations, the SSS and the SST decrease suggesting a northward shift of the Westerlies – ACC/PCC coupled system. As well, just after the warm (15°C) and dry (high iron concentrations) HWE, the SSS decrease slightly (~0.7 ‰) in agreement with increased rainfall and runoff on land linked to a slight northward shift of the Westerlies.
Figure 3. Relationship between the PIS melting and the paleoproductivity over the last deglaciation (20 to 10 kyr) at 41°S off Chile (ODP Site 1233). (A) Iron concentration (reversed plotted; cps), (B) Total Organic Carbon (TOC, dry weight %), (C) Sum of the C_{37:3} and C_{37:2} alkenones concentrations (ng/g), (D) Sum of the C_{37:3} and C_{37:2} alkenones concentrations normalized to TOC (µg/gTOC), (E) SSS reconstruction.

Freshwater inputs from land at millennial to sub-millennial timescales, as deduced from the SSS reconstruction, might have played an important role on the productivity offshore. On Figure 3 B-C the TOC record, a proxy for paleoproductivity (e.g., Wefer et al., 1999), is compared to the total concentration of C_{37:3} and C_{37:2} alkenones, which provides information on the past production of coccolithophorids (Villanueva et al., 1997). At Site 1233 however, the sediment is for >80 % of terrigenous origin (clay and silty clay; Mix et al., 2003),
corroborated by the overall high sedimentation rates. Therefore, the variations of the content of the productivity proxies such as the TOC might well be affected by the terrigenous input. This is highlighted in Figure 3 A-B where the iron concentrations and the TOC content are compared over the last deglaciation. The main trend shows a gentle decrease in iron concentrations while the TOC content increases. Moreover the short-term variations seem to be also influenced by the terrigenous input, i.e. higher iron content corresponds to less TOC and *vice versa*. If normalized to TOC (Figure 3 D), the raw alkenone concentration (Figure 3 C) should be compensated for the dilution effect associated with changes in terrigenous input and sedimentation rates. Furthermore, the main trend of the normalized alkenone concentrations presents a typical pattern of paleoproductivity off southern Chile, i.e. higher productivity during the last glacial decreasing over the last deglaciation and the Holocene (e.g. Hebbeln *et al.*, 2002; Mohtadi and Hebbeln, 2004), whereas the record of the TOC content differs completely. Therefore, we propose that in this particular case the normalized alkenone concentration is a worthy proxy for paleoproductivity, while the TOC record is strongly influenced by the terrigenous input. The short-term trend of the alkenone productivity was apparently strongly influenced by the supply of micronutrients by fluvial input, rather than by changes in the SST (Figure 3 F). When comparing the alkenone productivity to the SSS record, most of the productivity increases correspond to SSS decreases, i.e. freshwater inputs from land (highlighted by the green bars on Figure 3). The best illustration is the pronounced increase in alkenone productivity between ~17.2 and 16.5 kyr, i.e. during a major freshwater input (see above). On the other hand, the alkenone productivity is apparently not directly influenced neither by the iron concentrations (Figure 3 A and D), nor the SSTs (Figure 3 A-D-F). Furthermore, freshwater inputs might bring a well-stratified upper water column favoring light penetration and thus enhanced productivity. These results support a recent study based on surface sediment samples (Mohtadi *et al.*, 2005).

In conclusions, these high-resolution records robustly confirm the assumptions made in the previous publication by Lamy *et al.* (2004). The SST record is clearly in phase with Antarctic air temperature records and no influence from the Northern Hemisphere is visible, especially regarding the YD event. New and better time-constrained records of the PIS extent and retreats on adjacent land are in phase with iron concentrations at Site 1233 reinforcing the utilization of this proxy for PIS movements during older times (see also Kaiser *et al.*, in review). The SSS reconstruction shows a strong decrease at ~12.8 kyr BP exactly when a large lake suddenly drained ~2000 km³ of freshwater into the Pacific. The first and huge SSS decrease at ~17.5 kyr BP was thus obviously linked to the main melting phase of the PIS. Furthermore, the record shows a third freshwater input around 12 kyr BP following the YD warming, what could reflect the final melting of the PIS. The offshore productivity finally, as inferred by the alkenone concentrations, was strongly influenced by the freshwater inputs, probably linked to the supply of micronutrients and the presence of a well-stratified upper water column favoring light penetration.
Acknowledgements:

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4.5 Southeast Pacific sea-surface circulation and vegetation changes in central Chile during the last 40 kyr

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Abstract:

The relative influence of the high- versus the low-latitudes for the initiation of the last deglaciation, as well as for millennial-scale climate oscillations during the last glacial, remains a challenging question for understanding past climate changes. Off central Chile, warm, more salty waters from the low-latitudes converge with cold, comparatively low-salinity waters originating from the high-latitudes. Here, we used alkenone-derived sea-surface temperature and sea-surface salinity reconstructions to estimate changes in this zone of convergence over the last 40 kyr. Furthermore, we used long-chain n-alkanes to reconstruct the main vegetation changes which are ultimately linked to the latitudinal shifts of the northernmost boundary of the southern Westerly winds. The main results propose a strong high-latitude influence along the Eastern Pacific Boundary Current during the last glacial period, whereas sea-surface temperature and salinity changes around 22 kyr BP might be a signal of an early deglacial warming coming from the low-latitudes. The record of vegetation changes presents on the one hand a close relation to the sea-surface temperature variations at multi-millennial to sub-millennial timescales, suggesting a common forcing, and on the other hand shows evidences that the last full-glacial conditions might have been around 25 kyr BP, accentuating the fact that the last glacial maximum is still not clearly defined in southern South America.
1. Introduction

The timing and causes of the large climate transition from the last glacial maximum (LGM) at ~23-19 kyr before present (Mix et al., 2001) to the present warm stage (the Holocene) remains a challenging question for understanding past climate changes. Ice-core records suggest that deglacial warming started a few thousand years earlier in the Southern Hemisphere (SH), whereas in the Northern Hemisphere (NH), a slight early warming trend was interrupted by a strong cooling related to Heinrich event 1 (e.g., Hemming, 2004). Later on during the deglaciation, a pronounced return to nearly glacial conditions occurred in the NH (the Younger Dryas event) but only a slight cooling that happened ~1000 years earlier is characteristic for large parts of the SH (the Antarctic Cold Reversal). A high–southern latitude control of this deglacial pattern is indicated by new modeling results (Knorr and Lohmann, 2003; Weaver et al., 2003), which imply that abrupt climate changes known from the North Atlantic region during the last deglaciation might well be triggered by gradual changes in SH high-latitudes. On the other hand, it has been shown that climate oscillations may originate from the tropical Pacific, potentially involving a long-term modulation of interannual-to-decadal climate changes of the eastern tropical Pacific El Nino–Southern Oscillation (ENSO) (Cane, 1998). This tropical driver hypothesis is strengthened by recent proxy evidences from the tropical Pacific, suggesting substantial millennial variability that likely involves long-term ENSO changes (Koutavas et al., 2002; Stott et al., 2002).

The surface Eastern Boundary Currents (EBC) along the western margins of the major continental land masses act as conduits for the exchange of heat from the cold, high- to the warm, low-latitudes. The Peru-Chile Current (PCC), or Humboldt Current, is one of the largest EBC systems in the world. Up-to-date, its spreading and functioning during the last glacial period is not well known because of the lack of records with sufficient resolution. Near the equator, recent studies suggest that during glacial maxima, the flow of the Pacific EBC system was stronger-than-today and thus substantially contributed to the cooling in the equatorial region (e.g., Lea et al., 2000; Feldberg and Mix, 2003). In the eastern Pacific mid- to low-latitudes both surface currents from the low- and high-latitudes converge. Therefore, studying changes in sea-surface properties off central Chile could highlight the respective influences of both high- and low-latitudes on driving climate changes.

Furthermore, the Chilean mid- to low-latitudes are situated at a key place to trace changes in the main atmospheric feature of the Southern Hemisphere: the Westerly wind belt. Recently, it has been proposed that the Westerlies played an important role in the glacial/interglacial transitions by determining the partition of CO₂ between the atmosphere and the ocean in the SH (Russell and Toggweiler, 2004). The latitudinal position of the Westerlies in relation to the Antarctic Circumpolar Current (ACC) would determine the strength of the divergence around Antarctica. During interglacial periods poleward-shifted Westerlies aligned with the ACC should enhance the divergence and flush the deep oceanic...
CO₂ in the atmosphere. On contrary, CO₂ would accumulate in the deep ocean during glacial periods when the Westerlies are shifted equatorward and the divergence weakened. Central Chile is located at the modern northernmost limit of the Westerlies, at the southern limit of one of the driest deserts on earth: the Atacama Desert. Within such a strong climatic boundary, changes in the vegetation, which is sensible to variations in humidity, should provide evidences of variations in the influence and latitudinal position of the Westerly winds as proposed by paleoenvironmental records in Chile (e.g., Heusser et al., 1999; Maldonado and Villagran, 2002).

Here we provide a 40 kyr-long record of the evolution of the sea-surface temperature (SST), the oxygen isotopic composition of the seawater (which is directly linked to sea-surface salinity) and the vegetation on land (using odd-numbered n-alkanes) based on a marine sediment core situated at 30°S off central Chile. The results suggest strong influences of cold, subantarctic waters during the end of the last glacial period, followed by a possible early warming of the SST (in comparison to the Southeast Pacific mid-latitudes and SH high-latitudes), which was accompanied by an important decrease of the vegetation on adjacent land.

2. Settings

2.1 Oceanography

Core GeoB 7139-2 has been taken off central Chile (30°12’S, 71°58’W; Hebbeln et al., 2001) at ~3270 m water depth (Figure 1 A). The study area is under the influence of both the southward flowing Peru-Chile Countercurrent (PCCC), bringing warm water from the low latitudes, and the northward flowing Peru-Chile Current (PCC) which can be divided into a coastal (PCCcoastal) and an oceanic (PCCoceanic) branch (Strub et al., 1998). The PCC supplies cold, subantarctic surface waters (SASW) originating from the region north of the Subantarctic Front. In austral summer the influence of the PCCC is strong in the study area, whereas the PCC influence is greater during austral winter. Beneath the surface, major currents include the poleward Gunther Undercurrent (GUC) between ~100 and 400 m, the Antarctic Intermediate Water (AAIW) flowing equatorward at depths of ~400 to 1200 m, the southward flowing Pacific Deep Water (PDW) and finally the Antarctic Bottom Waters (AABW) that fills the deepest part of the Chilean trench (> 3400 m; Shaffer et al., 1995). Off central and northern Chile the upwelling primarily involves Equatorial Subsurface Water (ESSW) flowing poleward within the GUC at depths around 300-400 m (Navea and Miranda, 1980; Strub et al., 1998). At 30°S, the upwelling is a quasi-perennial feature.
Another view of the surface circulation off Chile is provided by the sea surface salinity (SSS) distribution (Figure 1B). Salty, nutrient-poor Subtropical Surface Waters (STSW), formed south of 5°S and north of the Subtropical Front, flows southward within the PCCC to reach about 35°S (Strub et al., 1998; Tsuchiya and Talley, 1998). On the other hand, low-salinity waters originating from the Chilean fjord region flow northward from ~43°S and return to the coast around 33-35°S. North of 33°S low salinity waters continue to flow northward both inshore in a narrow band (within 40 km of the coast) and offshore, probably within the oceanic branch of the PCC (Strub et al., 1998). Finally, more salty waters from the GUC are upwelled next to the coast off Concepción.

2.2 Continental climate and vegetation

In central and northern Chile, the coastal vegetation can be divided in major types which are closely linked to the climatic zonation of Chile. North of 27°S, the climate is hyper-arid with precipitation values < 50 mm/yr. In the Atacama Desert, vast areas receive virtually no rain and are largely free of vegetation. The strong influence of the subtropical high pressure (STH) is a major reason for this high aridity (Veit, 1996). Southward, annual precipitation...
increases slightly due to rare passages of frontal system of the Westerlies in winter. These latitudes are at the present northernmost limit of the influence of the Westerlies. Between 31°S and 37°S, the amount of winter rain increases and the climate is of a semiarid-Mediterranean type. The vegetation along the Chilean coast in this area is characterized by swamp forests, dominated by *Myrtaceae* trees and shrubs (Fuenzalida, 1965). Further south, the climate become more and more humid due to the increasing influence of the storm tracks, evolving from humid temperate to cool humid temperate type of climate. Semi-evergreen to evergreen broadleaf forests with *Nothofagus* are characteristic for southern Chile. Another vegetation type corresponds to the Andes mountain domain with crests ranging from 3500 to >5000 masl (meters above sea-level). Following growing altitudes, the vegetation is mainly composed by shrubs, succulents and grasses, respectively (Seibert, 1996; Latorre *et al*., 2002).

3. Material and Methods

3.1 Stratigraphy

GeoB core 7139-2 is 841 cm-long and is dominated by olive-brown to light-olive silty-clays characteristic for hemipelagic sediment of terrigenous origin. Between ~10 and 600 cm, the age model is based on eight AMS ¹⁴C dates and has been corrected for distal turbiditic layers (Stuut and Hebbeln, *subm*.). The radiocarbon ages were converted in calendar age using the *CALPAL January 2004* calibration curve and applying a 400 yr reservoir age correction. In upwelling areas, such as off central Chile, reservoir ages may be higher (Reimer and Reimer, 2001). In the south Peruvian upwelling area, it has been for example recently shown that during the early Holocene the reservoir age was about two times higher than during the late Holocene (18°S; Fontugne *et al*., 2004). However, Fontugne *et al*., (2004) suggest that the doubling of the reservoir age appears much too high to result from an enhancement of upwelling alone and changes in ocean circulation at intermediate water depths could have been important as well. In particular, AAIW with higher reservoir ages might have been more important during the early Holocene and has then been replaced by South Antarctic Mode Water during the late Holocene (the water mass is presently important in the Peruvian upwelling). Off central and northern Chile, ESSW, formed along the equator between 3°N and 4°S (Strub *et al*., 1998), is upwelled and should thus not increase the reservoir age as equatorial water masses are characterised by reservoir ages close to the global mean of 400 years (Bard, 1988). Therefore, being aware that productivity might have been higher during the glacial (Hebbeln *et al*., 2002; Mohtadi and Hebbeln, 2004), we assume that the mean ocean reservoir age proposed by Bard (1988) can be used here, as no direct reservoir age estimates is available directly from the study area. The ¹⁴C-AMS dated part of core GeoB 7139-2 covers the last ~40 kyr. Assuming a linear interpolation between the age control points, the sedimentation rates increase from ~8 cm/kyr to 18-20 cm/kyr during late marine isotope stage (MIS) 3 (~40 to 25 kyr), are around 18-16 cm/kyr during MIS 2 (~25 to 12 kyr) and decrease to 8 cm/kyr during the middle and late Holocene.
3.2 Alkenone-based SST

We have reconstructed alkenone-based sea-surface temperatures (SST) with a 5 cm resolution (~400 yr). The method used is described elsewhere (e.g. Müller *et al.*, 1998; Kaiser *et al.*, in press). We applied the Prahl *et al.* (1988) calibration curve for conversion of the UK’37 (Prahl and Wakeham, 1987) into temperature values. Based on cores situated further south at ~33°S, Kim *et al.* (2002) have shown that the SSTs derived from alkenone measurements on surface sediments agree well with the modern annual mean SST at 0 m water depth (from Levitus and Boyer, 1994). The uppermost sediment sample of core GeoB 7139-2 is dated at 1.16 kyr BP. However, considering no significant change, or a slight decrease, of the annual mean SST over the last ~1.2 kyr, the alkenone-based SST result (17.4°C) is relatively close to the modern annual mean (16.5°C), considering a method error of ±0.3°C.

3.3 Corrected δ¹⁸O of seawater as proxy for sea-surface salinity

The δ¹⁸O/¹⁶O ratio of seawater (δ¹⁸O sw) is linearly related to the salinity, being therefore a proxy for estimating modern salinity. The δ¹⁸O composition of foraminifera (δ¹⁸O calcite) is mainly controlled by temperature and δ¹⁸O sw. Thus, δ¹⁸O sw can be reconstructed if the temperature is independently determined. In our case, we combined our alkenone-based SST results with δ¹⁸O c data on planktic foraminifera (*N. pachyderma* dextra and sinistra; Mohtadi and Hebbeln, 2004) in order to reconstruct the δ¹⁸O sw following equation A (from Shackleton, 1974).

\[
(A) \quad T = 16.9 - 4.38 \left( \delta^{18}O_c - \delta^{18}O_w \right) + 0.1 \left( \delta^{18}O_c - \delta^{18}O_w \right)^2 \\
\Leftrightarrow \delta^{18}O_w = \delta^{18}O_c - 21.9 + \sqrt{310.61 + 10T}
\]

On glacial timescales however, the δ¹⁸O sw is affected by variations in continental ice volume. Therefore, we have corrected the δ¹⁸O sw using the sea-level curve from Arz *et al.* (subm.) and assumed an enrichment of 0.1‰ per 10 meters of sea-level lowering in order to obtain the local changes of δ¹⁸O sw (δ¹⁸O sw cor), i.e. the related SSS changes. The record is presented as the deviation from modern conditions (Figure 3 D).

3.4 Long chain n-alkanes

The sedimentary n-alkanes distributions consist of a series of predominant odd-numbered C₂₅-C₃₅ homologues superimposed on even-numbered C₂₄-C₃₄ n-alkanes. Odd-numbered n-alkanes are major lipid components of terrestrial plant epicuticular waxes (Eglinton and Hamilton, 1963) which can be removed from the leaf surfaces by rain or wind (e.g., Schefuss *et al.*, 2003a). Therefore, these plant wax compounds are widely found in marine sediments
and are frequently used as indicators of higher plant contributions to the marine environment (e.g., Madureira et al., 1995; Prahl and Pinto, 1987; Schefuss et al., 2003b, 2004). The carbon preference index (CPI) of \( n \)-alkanes, defined as the ratio of the amount of odd-carbon \( n \)-alkanes to the amount of even-carbon \( n \)-alkanes (Kolattukudy, 1976), is known to be high (i.e. >5) for higher plant-derived compounds (Eglinton and Hamilton, 1963; Simoneit and Mazurek, 1982), whereas petroleum- or marine-derived \( n \)-alkanes show no carbon-number preferences (Simoneit, 1984).

The apolar fractions containing the \( n \)-alkanes were obtained by elution of the total extracts through a Bond silica column (Bond Elute column, Varian) with 4ml of Hexane, than concentrated under \( N_2 \) and taken up in 25µl MeOH/CH\(_2\)Cl\(_2\) (1:1). The fractions were analyzed by capillary gas chromatography using a HP 5890 serie II Plus gas chromatograph equipped with a 60 m * 0.32 mm fused silica column (DB-5 MS, J&W) using split/splitless injection and flame ionization detection. Helium was used as carrier gas with a constant pressure of 150 kPa. After injection at 70°C, the oven temperature was programmed to 130°C at a rate of 2°C/min, then to 320°C at a rate of 4°C/min, and the final temperature was maintained for 30 min. The concentrations of the \( n \)-alkanes were determined using squalane (C\(_{30}\)H\(_{62}\)) as internal standard and expressed as ng/g of dry weight sediment. The reproducibility of the \( n \)-alkane quantifications was better than 20%.

4. Results

4.1 Long chain \( n \)-alkanes

Figure 2 presents the total odd-numbered \( n \)-alkanes distribution of a typical glacial and a typical Holocene sample from core GeoB 7139-2. The results illustrate that the amount of \( n \)-alkanes is about two times higher during the glacial interval compared to the Holocene and that the C\(_{29}\) and C\(_{31}\) \( n \)-alkanes are the dominant odd-numbered \( n \)-alkanes. Therefore, we consider hereafter the amount of the C\(_{29+31}\) \( n \)-alkanes as representative for the total amount of odd-numbered \( n \)-alkanes. The record of C\(_{29+31}\) \( n \)-alkanes shows significantly higher contents of ~450-500 ng/g around ~32 to 25 kyr that decrease to ~300-325 ng/g in the Holocene (Figure 4 A).
Furthermore, we have calculated the accumulation rates (AR) of the C_{29+31} n-alkanes as indicator for onshore vegetation changes (Figure 4 B). Whereas the short-term trends of both the n-alkanes content and AR records are similar (Figure 4 A and B), the long-term trend of the AR C_{29+31} n-alkanes shows a first decrease around 25-23 kyr BP, followed by a plateau between 24 and 16 kyr and a second decrease between 16 and 10 kyr. The lowest AR C_{29+31} n-alkanes characterize the Holocene period with perhaps a very slight increase in the late Holocene. The CPI values finally range between 2.2 and 5.4, indicating that the majority of the long chain n-alkanes is derived from terrestrial plant sources (see section 3.4). However, we found relatively high CPI values during the glacial section and the late Holocene (means of 3.7 and 3.5, respectively) and low values during the deglaciation and early Holocene (mean of 2.8).
4.2 Alkenone-based SST, $\delta^{18}O$ calcite and $\delta^{18}O$ seawater corrected

During the glacial interval (40-22 kyr), SSTs generally fluctuate between ~14 and 16°C with a minor cooling at ~31 kyr BP and two colder intervals centred around 27 and 22 kyr BP that are separated by a slightly warmer phase (Figure 3 B). From ~22 to 16 kyr, the SST record shows a moderate increase (14 to 15.5°C), most likely representing the initial deglacial warming, followed by a strong warming of ~3°C between 16 kyr and the early Holocene interrupted by a little plateau between ~14.5 and 12.5 kyr. After an early to middle Holocene maximum of ~19°C, SSTs begin to decrease gently from ~6 kyr and reach about 17.5°C at the top of the record. The pattern of the $\delta^{18}O_{\text{calcite}}$ record on planktonic foraminifers is significantly different from the SST record, and is even opposite between 40 and 17-16 kyr (Figure 3 C). The oxygen isotopic composition of foraminifers is influenced by both changes in sea-water chemistry and temperature. However, as the $\delta^{18}O_{\text{calcite}}$ is enriched in $^{18}O$ when the SSTs are decreasing between ~40 and 16 kyr (as well as during the late Holocene), variations in sea-water composition are obviously at the origin of the signal rather than temperature changes. Assuming that $N. pachyderma$ habitat was restricted in the upper most water column during glacial times and the Holocene, changes in the sea-surface salinity most likely explain the pattern of the $\delta^{18}O_{\text{calcite}}$ record (linked to changes either in the advection of fresher water from the south or in the river discharges from the adjacent land). However, the depth habitat of $N. pachyderma$ may vary substantially. Two studies from the California Current have suggested that $N. pachyderma$ calcifies in near surface waters (i.e., the upper ~100 mwd; Sautter and Thunell, 1991), or in the upper thermocline (Ortiz et al., 1996). Hydrographic measurements offshore Chile at the onset of winter suggest that the thermocline comes to the surface near the coast at 28°S and 35°S and is situated below 50 mwd westward (Leth et al., 2004). Furthermore, Hebbeln et al. (2000) have shown that surface water characteristics are preserved in the stable isotopic composition of $N. pachyderma$ off Chile. It is thus reasonable to assume that the $\delta^{18}O_{\text{calcite}}$ of $N. pachyderma$ largely recorded changes in the surface mixed layer off central Chile.

Assuming that the $\delta^{18}O_{\text{calcite}}$ represents changes in surface water properties, it is possible to reconstruct the $\delta^{18}O_{\text{swcorr}}$ which is directly related to the SSS (see section 3.3). The $\delta^{18}O_{\text{swcorr}}$ record at the core site suggests relatively saltier waters, even saltier-than-today, during relatively warm SSTs (Figure 3 B and D). Conversely, the coldest phase of the last 40 kyr (i.e. between ~30 and 20 kyr) corresponds to an input of waters fresher-than-today, with two main pulses around 27.5 and 23.5 kyr BP. To give an order of magnitude, we could roughly estimate that changes of ±0.4 ‰ in $\delta^{18}O_{\text{swcorr}}$ would correspond to variations of ±1 ‰ in SSS, if we consider that today the mean SSS at 30°S (~ 34.2 ‰; after Levitus and Boyer, 1994) corresponds to a $\delta^{18}O_{\text{calcite}}$ value of ~1.23 ‰ (data from Mohtadi et al., 2005).
5. Discussion

5.1 Sea-surface circulation changes: low- versus high-latitudes

We first compared our new SST record based on core GeoB 7139-2 at 30°S to the recently published high resolution record from ODP Site 1233 at 41°S off Chile (Lamy et al., 2004; Kaiser et al., in press). The two records reveal some similarities in the millennial-scale pattern but major differences in the main trends and amplitudes (Figure 3 A and B). Whereas the warming over the last deglaciation starts around 19 kyr BP in the south, synchronously with ice-core records from Antarctica (see Kaiser et al., in press), it seems to begin earlier at 30°S, around 22 kyr BP, though this initial deglacial warming is comparatively small. This is in agreement with recent reconstructions of glacier fluctuations in the Peruvian and Bolivian Andes where glaciers began to retreat at 21 kyr BP (Smith et al., 2005). The amplitude of deglacial warming at 30°S is smaller than at 41°S (~5°C versus 6.5°C, respectively). In addition, the major warming steps are different between the two sites with a three step warming off southern Chile and only two main steps at 30°S (22-17.5 kyr and 16-11 kyr). The Holocene pattern of both records shows a Holocene Climatic Optimum (~11-9 kyr; Kaiser et al., in press) followed by a cooling towards the modern. The amplitude of the cooling is however ~1°C stronger at 30°S (~2.5°C) than in the south. As shown by Kaiser et al. (in press), the changes of the SSTs at 41°S were strongly related to the northward extent of the sea-ice around Antarctica and the latitudinal shifts of the Westerlies during the last 70 kyr. Therefore, the different pattern at 30°S, in particular during the deglaciation, suggests an influence of the low-latitudes, most likely involving changes in the PCCC.

At a millennial timescale, two major cold events around ~27 and 22 kyr BP (and a minor event at ~31 kyr BP) during the last glacial period coincide in both SST records (within dating uncertainties) (Figure 3 A and B). These two cold maxima are also recorded in a Mg/Ca SST reconstruction from the east equatorial Pacific (2°15’N; Lea et al., 2000) (not shown here). Such a pattern seems to confirm the suggestion of Lea et al. (2000) of an influence of the Southern Hemisphere high-latitudes up to the equator through the South Pacific Eastern Boundary Current system during the last glacial period. Our $\delta^{18}$Osw corr reconstruction at 30°S (Figure 3 D) furthermore suggests that salinities were generally reduced during the glacial cold events and higher during warm time-intervals, e.g. during late MIS 3, around 25 kyr or for the early to middle Holocene. Therefore, our $\delta^{18}$Osw corr reconstruction at 30°S might represent the relative influences of warm, comparatively salty waters from the low-latitudes (an equivalent to the modern STSW) versus colder and fresher waters from the high-latitudes (similar to the actual SASW off southern Chile) at the core site. Beginning at ~22 kyr BP, paleosalinities increase rather continuously until the middle Holocene, suggesting an increasing influence of low-latitudes water masses. It might thus be that the early onset of the deglaciation at 30°S, compared to the high-latitudes, originates from the low-latitudes.
Finally, the influence of colder and fresher waters appears to be higher again during the late Holocene.

![Figure 3](image)

**Figure 3.** Sea surface temperature and sea surface salinity reconstructions at 30°S off central Chile compared to records from ODP Site 1233. (A) Alkenone-based SST reconstruction at 41°S (Kaiser et al., in press). (B) Alkenone-based SST reconstruction at 30°S (this study). (C) Oxygen isotope on planktic foraminifera (Mohtadi and Hebbeln, 2004). (D) and (E), respectively, oxygen isotopic composition of seawater corrected from continental ice volume (swcorr) at 30°S (this study) and 41°S (modified after Lamy et al., 2004), presented as the deviation from modern conditions. The grey bars highlight periods with low-salinity waters at 30°S, and vertical dotted lines the beginning of two freshwater inputs linked to the collapse of the PIS at 41°S (see text for details).

The presence/absence of equivalents to the Antarctic Cold Event (ACR; 14 to 12.5 kyr; e.g. Jouzel et al., 1995) and the Younger Dryas (YD; 13-11.5 kyr; e.g. Rutter et al., 2000)
cold events are controversially discussed in Chile, especially in southern Chile (see for a short review Kaiser et al., in press). Recent studies from southernmost South America based on well-dated geomorphological evidences have shown that glaciers on land advanced during the ACR (e.g. McCulloch et al., 2005; Fogwill and Kubik, 2005). The SST reconstruction at 41°S off Chile (Figure 3 A) by Kaiser et al. (in press) suggests a SST cooling followed by a plateau during this time interval. Our record presents a similar pattern which might imply an influence of cold, high-latitudes waters northward to at least 30°S during the ACR. This trend is confirmed by another alkenone-based SST reconstruction situated further south at 33°S (Kim et al., 2002) where the SSTs decreased by ~1°C at this time. For the YD period, our SST results are again in agreement with previous alkenone-based SST records off the Chilean coast at 41°S (Kaiser et al., in press) and 35°S (Romero et al, in press), i.e. all three records present a temperature warming between 1°C (this study) and 2°C (at 41°S and 35°S), reinforcing the absence of a YD-like cooling event in opposition to earlier terrestrial data-sets from southern Chile (e.g., Denton et al., 1999a; Moreno et al., 2001).

Lamy et al. (2004) have shown that after a δ18Oswcorr maximum corresponding to a glacier advance on the adjacent land, there was a strong δ18Oswcorr decrease (reduced salinity) at 41°S between ~18 and ~16 kyr. This event can be explained by a strong freshwater input linked to the collapse of the Patagonian Ice Sheet (PIS) after a ~3.5°C SST warming within ~2 kyr (Figure 3 A and E). Recent works on PIS fluctuations over the deglaciation seem to confirm this pattern (McCulloch et al., 2005; Turner et al., 2005). Furthermore, a second δ18Oswcorr decrease occurred around 13 kyr BP at 41°S, synchronously to a second SST warming of ~2°C. This event could be related to the drainage of a large lake into the Pacific Ocean through the gap between the North and South Patagonian ice-fields at ~12.8 kyr BP as suggested by a recent study on land (Turner et al., 2005). These two major freshwater events appear to be traceable northwards to 30°S though with much smaller amplitudes (Figure 3D, vertical dotted lines). The first event slightly precedes the beginning of an interval of lower-than-modern salinities from ~17 to 14 kyr that falls in an interval of SST warming (in contrast to the general trend in the salinity reconstruction and the glacial low-salinity phases). The second event is marked by a slight δ18Oswcorr decrease as well. Based on the modern salinity distribution off southern and central Chile (Figure 1 B), it is conceivable that the fresh waters have flown northward within the PCC. Interestingly, in a recent study based on the δ15N record of core GeoB 7139-2, De Pol-Holz et al. (in review) propose that the ventilation of the Oxygen Minimum Zone off Chile was affected by the input of relatively fresher waters. Thus, our results suggest that the collapse of the PIS was a major event of the deglaciation influencing the hydrology of the Eastern Pacific at least northwards to 30°S.

5.2 Vegetation changes coupled to SST variations offshore

Off central Chile the vegetation and temperature changes were closely related as inferred by the comparison of the SST and AR n-alkanes reconstructions (Figure 4). On both
millennial and longer timescales, cold SSTs are correlated to high n-alkanes AR suggesting abundant vegetation on the adjacent land, and vice versa. During the last glacial period, the vegetation was significantly more abundant than today (high n-alkanes concentrations), especially prior to 25 kyr BP. This pattern is consistent with the high CPI values (see section 4.1), considering that higher CPI values represent fresher plant material (Schefuss et al., 2003a). The most obvious explanation for a more abundant vegetation together with colder SST at 30°S would be an increase in mean rainfall rates in relation to an equatorward shift of the Westerlies (or their northernmost boundary) and the ACC/PCC surface current system during the last glacial period. Such a pattern was also proposed by a large amount of marine as well as continental paleoenvironmental studies in Chile (e.g., Lamy et al., 1998, 1999; Denton et al., 1999a; Heusser et al., 1999; Hebbeln et al., 2002; Mohtadi and Hebbeln, 2004; Kaiser et al., in press). Over the deglaciation the AR of n-alkanes decreases and the SSTs warm up gently between 22 and 16 kyr and than stronger until ~11.5 kyr BP. During the early to middle Holocene, the SSTs reach a maximum whereas the vegetation abundance was very low on the adjacent land. Most of the aforementioned studies also proposed a poleward shift of the Westerlies and the ACC/PCC system during the early to middle Holocene. Over the late Holocene, there is a trend towards cooler SSTs accompanied by a possible slight increase of the vegetation on land (Figure 4 A).

Terrestrial paleoenvironmental reconstructions in central Chile slightly south of our core location are generally consistent with our vegetation abundance reconstruction based on n-alkanes. Changes in pollen assemblages from the Laguna Tagua-Tagua (34°30’S), suggest for example a wet climate from ~33 to 14 kyr, shifting to a warm and dry climate between ~14 and 5 kyr, and finally again wet conditions over the last ~5 kyr (Heusser, 1984). These results were partly confirmed by more recent pollen studies based on swamp forest sediments in the Norte Chico semi-arid region (around 32°S) (Nunez et al., 1994; Villagran and Varela, 1990; Maldonado and Villagran, 2002). These records suggest that the main shift from wetter late glacial conditions to more arid early Holocene climates occurred at ~10.6 kyr. Drier-than-today conditions lasted until ~4.2 kyr followed by an increase in rainfall towards the modern. More humid conditions during the late Holocene are further supported by glacier advances in the Andes (Grosjean et al., 1998) and paleosols in northern Chile (Veit, 1996). Our vegetation record would give a support to three main features: (1) decreasing wet conditions over the late glacial and the deglaciation, (2) a transition from wet to arid conditions around 10 kyr BP and (3) a possible slight increase of rainfall starting around 6.5-5 kyr into the late Holocene. Our data do not support any abrupt changes in the vegetation during the YD which is a subject of controversy in southern Chile (see above).
Figure 4. Vegetation changes on adjacent land based on core GeoB 7139-2 over the last 32 kyr. (A) Sum of the \( \text{C}_{29} \) and \( \text{C}_{39} \) \( n \)-alkanes (ng/g) here considered as representative for the content of all the odd-numbered \( n \)-alkanes (\( \text{C}_{25} \) to \( \text{C}_{35} \)). (B) Accumulation rates (AR) of the \( \text{C}_{29} \) and \( \text{C}_{39} \) \( n \)-alkanes (mg*cm\(^{-2}\)*kyr\(^{-1}\)). (C) Alkenone-based SST record at 30°S. (D) Alkenone-based SST record at 41°S (Kaiser et al., in press). Green bars mark the close relation between increased vegetation and SST cooling.

As mentioned before, our SST record suggests that the last deglacial warming begun around 22 kyr BP at 30°S, in agreement with a study on glacier fluctuations in the Peruvian and Bolivian Andes (Smith et al., 2005). However, our \( n \)-alkanes record suggest that the vegetation abundance on land (i.e. high rainfall rates) over the last ~30 kyr was at its maximum around ~28-26 kyr BP, while both SST reconstructions at 30°S and 41°S show a pronounced cold phase. This pattern suggests that the last full-glacial conditions might have been somewhere between ~28-26 kyr BP rather than around 22-19 kyr BP as seen on a global scale. This would be in agreement with a grass pollen record in southern Chile (Heusser et al., 1999), as well as recent pollen data from New Zealand (Vandergoes et al., 2005), and further reinforces the fact that the LGM is still not clearly defined in the Southeast Pacific.
5. Conclusions

The main conclusions obtained in this study on the oceanic and atmospheric changes off central Chile over the last 40 kyr can be resumed as follows:

- Our SST reconstruction at 30°S off Chile shows a similar millennial-scale pattern as both a SST record from the Chilean high-latitudes (41°S; ODP Site 1233) and SST changes close to the equator, suggesting a strong high-latitude influence along the Eastern Pacific Boundary Current during the last glacial period.
- During glacial time, colder intervals are generally characterised by reduced salinities reflecting the influence of lower-salinity southern water masses.
- Starting at ~22 kyr warmer and saltier water masses most likely advected by the PCCC become more important and may be a signal of an early deglacial warming of the low-latitudes.
- During the deglaciation, the major freshwater pulses from the PIS as reconstructed from ODP Site 1233 are traceable northward to 30°S. This suggests that the collapse of the PIS was a major event of the deglaciation influencing the hydrology of the Eastern Pacific at least northwards to 30°S.
- The late Holocene is characterised by generally colder conditions and reduced salinities suggesting an equatorward shift of the ACC/PCC – Westerlies coupled system.
- Based on the n-alkanes content of core GeoB 7139-2, we can provide a record of vegetation changes on land over the last 32 kyr. These changes were closely linked to the SST changes offshore in terms of both long-term trends and millennial-scale changes, suggesting a common forcing, i.e. the latitudinal shifts of the ACC/PCC – Westerlies coupled system. An equatorward shift during cold periods would bring cold waters and increase precipitation on land resulting in more abundant vegetation, and vice versa for relatively warm periods.
- The vegetation abundance on land was maximum around ~28-26 kyr BP at 30°S, in agreement with previous pollen records from southern Chile (Heusser et al., 1999). This pattern suggests that the last full-glacial conditions in central and southern Chile might have been around 28-26 kyr BP rather than around 22-19 kyr BP.
Acknowledgements:

The data that we report here are accessible at the World Data Center for Marine Environmental Sciences (http://www.wde-mare.org/PangaVistaXXXX) and at the NOAA Paleoclimatology Program (http://www.ncdc.noaa.gov/paleo/). The study was funded by the German Science Foundation through the grant DFG-He-3412-1-3 and technically supported by the Research Centre Ocean Margins (RCOM) in Bremen. This is RCOM contribution XXX.
4.6 Melting of the Patagonian Ice Sheet and deglacial perturbations of the nitrogen cycle in the Eastern South Pacific

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Abstract

We report the last glacial-interglacial transition of marine denitrification off northern Chile based on sedimentary nitrogen isotopes. Our results show a relatively early, large and abrupt transition from low to high denitrification regimes consistent with recently-reported data from off Peru. The deglaciation is characterized by millennial-scale adjustments of the oxygen minimum zone that mimic the atmospheric temperature record from Antarctica. We also show that the sharp denitrification onset was not caused by an increase in local primary productivity, nor by ventilation changes occurring in the Southern Ocean, as previously proposed. We found that the magnitude and timing of the deglacial denitrification changes are in close agreement with the fresh-water pulses that resulted from the melting of the Patagonian Ice Sheet. We consequently attribute the deglacial onset of marine denitrification in the area to a collapse of the thermocline ventilation occurred at the mid-latitude subduction region of the Eastern South Pacific.
Introduction

Water-column denitrification (WCD) occurring in the Oxygen Minimum Zones (OMZs) of the Eastern North Pacific (ENP), Eastern South Pacific (ESP) and the Arabian Sea (AS) has undergone broad changes at glacial-interglacial time-scales. Despite the apparent synchronicity of the different WCD records at the last glacial termination (Ganeshram et al., 2000), there are marked differences regarding the timing and magnitude of the changes (Galbraith et al., 2004). For the particular case of the ESP, Higginson and Altabet (2004) found that the last glacial-interglacial transition was noticeable large and abrupt. They attributed this to a change in the intensity of the OMZ, related to the ventilation of the Subantarctic Mode Water (SAMW) that forms in the Southern Ocean. This explanation differs from that of Ganeshram et al. (2000), which attributed the glacial-interglacial difference to changes in local primary productivity.

Here we present a new high-resolution sedimentary nitrogen isotope record, alkenone-paleotemperature, and local $^{230}$Th-normalized biogenic vertical fluxes from the Chilean continental margin. They document in detail the sharp transition from relatively low WCD rates during the Last Glacial Maximum (LGM) to high ones during the deglaciation and Holocene but give no evidence that the glacial-interglacial difference of WCD could have been caused by changes in local primary productivity. Furthermore, we found no evidence that changes in ventilation due to SAMW formation could explain the nitrogen isotope record. We present evidence for an alternative mechanism related to the melting of the Patagonian Ice Sheet (PIS), which agrees better with recent published proxy data and the regional physical oceanography.

Material and Methods

We have analyzed the nitrogen isotope composition of bulk organic matter in the deep-sea sediment core GeoB 7139-2 (30°12’ S, 71°59’ W, 3269 m), collected from the Chilean margin at the southern edge of the present-day OMZ. Since in this upwelling center nitrate is consumed completely by phytoplankton on an annual basis and the relatively high mean sedimentation rate of ~13 cm/kyr would prevent significant diagenetic effects, we interpret the changes in nitrogen isotopic composition as changes in WCD intensity (Altabet et al., 1999). Sediment samples were taken at 1 cm, freeze-dried, grounded in an agate mortar and measured in a Flash EA coupled to a Finnigan Delta Plus mass spectrometer. Normalization to the $\delta^{15}$N$_{air}$ scale was done by running internal lab-standards every five samples. Isotopic reproducibility was better than ±0.2‰.

We used an updated version of the published radiocarbon-based age model (Mohtadi and Hebbeln, 2004) converted to calendar years using the CALPAL 2004 January calibration...
curve (http://www.calpal.de). The age model has been corrected for few distal turbidites along the core that have been revealed by grain size distribution analysis (J.-B. Stuut, unpublished results). Here, we present data that cover the last 30 kyr before present (BP).

We measured the $^{230}$Th$_{ex}$-corrected vertical biogenic fluxes to infer past changes in local primary productivity as well as the Alkenone insaturation ratio $U_{37}^{K}$, a proxy for past changes in sea surface temperature (SST) (detailed methodology in Dezileau et al. (2004) and Lamy et al. (2004), respectively).

Results

![Figure 1](http://www.calpal.de)

**Figure 1.** (a) $^{230}$Th$_{ex}$ normalized vertical organic carbon and biogenic opal rain rates of GeoB 7139-2. Error bars denote a 10% error envelope. (b) Alkenone sea-surface temperature reconstruction in core GeoB 7139-2 obtained by the $U_{37}^{K}$ method. (c) The $\delta ^{15}$N record of GeoB 7139-2. The blue shading represents the time frame of the sharp increase in $\delta ^{15}$N.
The nitrogen isotope data, expressed as $\delta^{15}N$, display two distinct regimes separated by an abrupt transition at about 17.5 kyr BP (Figure 1c). The first regime, between 30 and 17.5 kyr BP, which includes the LGM, is characterized by relatively low mean $\delta^{15}N$ values, an indication of decreased WCD rates in the glacial ESP, although ~3.5‰ greater than glacial values off Peru (Ganeshram et al., 2000; Higginson and Altabet, 2004) (see Discussion). The second regime, covering the glacial termination and the Holocene, starts abruptly with a dramatic increase in $\delta^{15}N$ at ~17.5 kyr BP in ~1000 yr. During this time, SST off northern Chile was relatively stable, with glacial values until 16 kyr BP (Figure 1b). On the other hand, the $^{230}$Th$_{ex}$-normalized biogenic vertical fluxes show a decreasing trend between 23 and 16 kyr BP (Figure 1a). After the rapid reorganization of the OMZ at 17.5 kyr BP, the deglaciation was characterized by millennial-scale variations in the WCD intensity, as evidenced by a decrease in $\delta^{15}N$ between 13-15 kyr BP followed by an increment to a second peak at 11-13 kyr BP. During the early Holocene, the $\delta^{15}N$ record follows a decreasing trend that reached a mid-Holocene minimum at 7 kyr BP, finishing with a moderate increasing trend towards the present.

Discussion and Conclusions

Our $\delta^{15}N$ results are in close agreement with those obtained by Higginson and Altabet (2004) off Peru, regarding the timing and magnitude of the glacial-interglacial changes. The reorganization of the OMZ ecosystem was thus a phenomenon affecting a large region of the ESP. We found however higher $\delta^{15}N$ glacial values in our core. The straight forward explanation would be that WCD was still taking place off Chile but not off Peru (and the other OMZs). However, considering that our data do not show an increased productivity, it is difficult to foresee lower ventilation off Chile than off Peru at glacial times (see below). Alternative explanations include the progressive enrichment in $^{15}N$ of the upwelling nitrate as the nutrient source-water moved into the region, either from the north (with the Peru-Chile undercurrent) or from the south (cf. Hebbeln et al., 2000). Our site should have been located “downstream” of the nutrient source for upwelling. At the moment we cannot distinguished among the different alternatives and thus further work is needed to explain our high $\delta^{15}N$ glacial values.

When compared to the WCD records of the Northern Hemisphere (NH), the Southern Hemisphere (SH) shows marked differences at millennial time-scales (Figure 2). Indeed, after the deglacial increase at 17.5 kyr BP, the ESP $\delta^{15}N$ record shows an “Antarctic” timing with a decrease in $\delta^{15}N$ between 13-15 kyr BP, coincident with the Antarctic cold reversal (ACR), followed by a second peak at 11-13 kyr BP that is also seen in the Antarctic temperature record (Figure 2b). In contrast, the NH records exhibit a pronounced “Greenland” pattern, with an increase during the Bølling/Allerød (BA) warming between 13-15 kyr BP, and a decrease during the Younger Dryas (YD) between 11.8-13 kyr BP (Figure 2c, 2d and 2e). The
fact that the ESP-WCD record is responding to southern high-latitude timing implies that it
matches more closely the evolution of atmospheric CO$_2$ as recorded in Antarctica (Figure 2a).
This finding provides further support to the hypothesis of a tight coupling between the
nitrogen and carbon cycles at glacial-interglacial transitions (Falkowski, 1997) and highlights
the importance of the WCD activity in the SH as a probable pacer of both records at the early
stages of the deglaciation. Comparing all the OMZs at the time of the initial rise in
atmospheric CO$_2$ (~17 kyr BP), the ESP-WCD onset stands certainly out as the most
prominent $\delta^{15}$N signal (~5‰ change) with respect to the rather moderate NH increase (1‰
change). If we consider that for open ocean sites, the nitrogen isotopic change will be
proportional to the amount of nitrate which is ‘denitrified’, this would imply that the largest
and earliest glacial-interglacial reorganization of the global nitrogen cycle was occurring in
the SH.

Glacial-interglacial WCD changes in the ESP have been previously related to local
productivity (Ganeshram et al., 2000), and remote ventilation changes (Higginson and
Altabet, 2004). In line with the latter, we find no direct relationship between the $\delta^{15}$N and the
local vertical biogenic flux component derived from correcting the total export flux with the
$^{230}$Th$_{ex}$ method (Dezileau et al., 2004) (Figure 1a). Moreover, we find that the time window of
the sharp increase in WCD (16.5 17.5 kyr B.P.) is characterized by relatively constant SST,
indicating probably that there was no alteration in the upwelling intensity during this period
(Figure 1b).

The sudden intensification of the OMZ in the ESP by a reduction in the SAMW
ventilation has been recently proposed by Higginson and Altabet, (2004) to interpret their
$\delta^{15}$N record off Peru. We find this hypothesis difficult to conciliate with regional physical
oceanographic aspects. First, the SAMW is associated with the Subantarctic Front. The
majority of the coldest, densest SAMW, the Antarctic Intermediate Water (AAIW), forms in
the ESP to the west of Chile (McCartney, 1977). Yet, proxy evidence from intermediate
depths of the South West Pacific (Bostock et al., 2004; Pahnke and Zahn, 2005) show a
reinforcement of the AAIW ventilation at the time of the sharp increase in WCD in the ESP
(Figure 3). We believe that this is the result of the reduction of the permanent sea-ice cover
and the return of wind mixing in the surface waters of the Southern Ocean (Bostock et al.,
2004; Shemesh et al., 2002). Furthermore, the $\delta^{13}$C curve of Pahnke and Zahn (2005) shows
that at millennial time-scales, AAIW renewal rates varied in total opposition to what would be
required to explain the ESP $\delta^{15}$N records (Figure 3).

Second, it is unlikely that the renewal rates of the SAMW/AAIW, which presently
occupies the deepest part of the ESP thermocline (~500-1000 m) (Schneider et al., 2003), and
probable reached deeper depths during the LGM (Bostock et al., 2004), could have alleviated
the O$_2$ deficit that occurs upper in the water column. According to modern-day nutrient
analysis, the core of the WCD center in the ESP lies between 200 and 400 m depth (Gruber and Sarmiento, 1997), implying that for AAIW to be the responsible of the OMZ changes, it should have ventilated a much shallower oceanic layer during the LGM, which again, is not supported by proxy evidence (Bostock et al., 2004).

Figure 2. (a) CO$_2$ record from the EPICA Dome-C ice core (Monnin et al., 2004). (b) Deuterium record from Dome-C (EPICA Community Members, 2004). (c) $\delta^{15}$N record of core GeoB 7139-2. Black triangles are the age control points. (d), (e) $\delta^{15}$N records from the Arabian Sea (RC27-23) (Altabet et al., 2002) and eastern North Pacific (ODP 1017E) (Ganeshram et al., 2000) respectively. (f), $\delta^{18}$O record of the Greenland GISP 2 ice core (Grootes et al., 1993). The Antarctic Cold Reversal (ACR), the Heinrich event 1 (H1), the Bolling/Allerød (BA) and the Younger Dryas (YD) are displayed by shaded vertical lines.
We propose that changes that occurred in the region where the present day Eastern South Pacific Intermediate Water (ESPIW) is subducted (Schneider et al., 2003), may have caused the variations of the OMZ intensity observed in our data. The modern ESPIW occupies the upper meters of the ESP thermocline. The low WCD values at the LGM could be explained by greater ESPIW formation rates and direct ventilation of the water masses forming the current-day OMZ. This in turn could have been the natural consequence of increased subduction due to more intense mid-latitude eddy activity in the atmosphere (Wardle, 2003) and closer distance of the formation region to the present day OMZ area, in response to a northward displacement of the oceanographic fronts in the ESP (Kaiser et al., 2005). At the same time, the larger LGM meridional temperature gradient and enhanced buoyancy lost during the cooler winter would have resulted in a thicker ESPIW ventilated layer. On the other hand, hydrographic changes associated with the sea-surface salinity (SSS) evolution off southern Chile during the last glacial termination (Lamy et al., 2004) could have altered the subduction rates at mid-latitudes. Indeed, the melting of the Patagonian Ice Sheet (PIS) caused a decrease in the SSS off Southern Chile from 34 to 30 during the deglaciation. The early rise of temperatures in the SH caused a rapid melting of the most northerly extension of the PIS releasing \( \sim 222 \times 10^{12} \text{ m}^3 \) of freshwater to the ESP during the first 300 yr (Hulton et al., 2002). This translates in a freshwater flux of \( \sim 0.024 \text{ SV} \). Similarly, we would expect that a time-evolving enhancement of the stratification off southern Chile will result from the combination of the warming and freshening trends of the surface ocean (Lamy et al., 2004) and may result in a collapse of the ESPIW formation.

The most compelling support for our hypothesis however comes from the close agreement between the deglacial SSS incursions off Southern Chile and the $\delta^{15}$N record (Figure 3b and 3c). Indeed, the decrease in $\delta^{15}$N during the ACR and the smaller sharp increase soon after are well correlated with salinity incursions in the area. Furthermore, the large decrease in WCD from the end of the deglaciation to the mid-Holocene is also consistent with the salinity (ventilation) changes. Alternative explanations for this large decrease would be reduction of the local primary production (not seen in our data) and the global effect of sea-level rise on the partition between denitrification occurring in the water-column and that in the sediments (Deutsch et al., 2004). During the Holocene, the reduced ventilation could be attributed to the decreased wind forcing and latitudinal SST gradient affecting the ESPIW subduction area (Kaiser et al., 2005) which would translate in a thinner ventilated layer in the vertical. Therefore, we propose that the melting of the PIS acted as a trigger for the abrupt collapse of the ventilation and subsequent deglacial millennial-scale readjustments of the ventilation process in the ESP.
Our proposed mechanism has several implications for our understanding of the nitrogen cycle and its connections to the climate system during abrupt climate change. Besides supporting the idea of a close link between WCD and CO$_2$ through the modulation of the global oceanic fixed N inventory, our results do not support the “productivity-driven” glacial-
interglacial WCD variability explanation, which was based on lower δ¹⁵N resolution records and the total organic carbon composition of the sediments (e.g., Ganeshram et al., 2000). The interhemispheric difference in WCD seems to be the direct result of the individual OMZs response to regional feedbacks. Our results and interpretations highlight the role of the glacier dynamics in Patagonia for the ventilation rates of the thermocline in the ESP. Thus, the PIS and the ESPIW should be considered key elements in our understanding of the OMZ and WCD dynamics in the ESP, as well as of the global nitrogen cycle during abrupt climate change.

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ODP Site 1233, located in the Southeast (SE) Pacific mid-latitudes (41°S), has a well-constrained age model (Manuscripts 1 and 2) and presents unprecedented high sedimentation rates (ranging between ~1.5 and >3 m/kyr) over the last 70 kyr, having therefore a huge potential to reconstruct past climate changes at multi-millennial to sub-centennial timescales in the still poorly studied Southern Hemisphere (SH). Site 1233 is furthermore located in a region under the influence of the major oceanographic and atmospheric circulation members of the SH mid-latitudes, respectively the Antarctic Circumpolar Current (ACC) and the Westerly winds, as well as close to the Patagonian Ice Sheet (PIS) which occupied a large area of southernmost South America during the last glacial time. In addition, the proximity of the site to the southern Chilean coast (~40 km) allows studying land and marine proxies within the same archive avoiding problems linked to age uncertainties. The same applies for the second site investigated within the present thesis, GeoB 7139-2 situated off central Chile (30°S). Though sedimentation rates are much lower in this region, the likewise well-dated records of SST and vegetation changes at the southern margin of the Atacama Desert allow following some of the signals documented at Site 1233 towards the north where they interact with tropical climate influences. The main results and conclusions based on the sedimentological and geochemical analyses from the two sites are summarized as follows:

The alkenone-based sea-surface temperature (SST) record at Site 1233 presents very similar millennial-scale fluctuations as the air temperature record from the well-dated Byrd ice-core over the last 70 kyr suggesting an “Antarctic timing” in the SE Pacific on these timescales (Manuscripts 1 and 2). During the last glacial time, at the same timescale, the SST record is closely correlated to sea-ice fluctuations in the SE Atlantic high-latitudes as well as to the dust content record of the EPICA Dome C ice-core situated in eastern Antarctica. This patterns suggest a mechanism similar to the modern Southern Annular Mode, a major interannual mode of variability in the SH mid- to high-latitudes. During cold periods, the winds around Antarctica are strengthened and/or occupy a broader range of latitudes, resulting in and/or favoring an extension of the sea-ice. As a result, the ACC is shifted equatorward and supplies larger amounts of subantarctic cold waters into the SE Pacific. Other records of changes in the sea-surface water properties in the South Pacific and in the SE Atlantic show a similar pattern to the SST reconstruction at Site 1233. The proposed mechanism might thus be valid at a hemisphere-wide scale, and the SH high-latitudes might have been less isolated as previously thought during the glacial time (Manuscript 2).

The apparent “Antarctic timing” of the SH mid-latitudes SST records suggests that the so-called thermal see-saw mechanism was operating during the last glacial in the SH mid-latitudes (Manuscripts 1 and 2). The origin of the see-saw effect is generally considered to lie in a slowdown of the thermohaline circulation (THC) during the Northern Hemisphere (NH) Heinrich events, due to changes in the surface density in the North Atlantic realm, resulting in
warm events in the Southern Ocean. However, as the SE Pacific region is not directly under the influence of the THC, changes in the SSTs and sea-ice extent around Antarctica might have played a significant role in either amplifying or even initiating these abrupt climate shifts as proposed by recent modeling studies (Manuscripts 1 and 2).

The South Pacific Eastern Boundary Current system (PEBCS), as one of the most productive areas in the world ocean characterized by strong coastal upwelling off Chile and Peru, acts like a conduit for heat exchange between the SH high-latitudes and the eastern tropical Pacific. Its functioning during the last glacial time, as well as over the last deglaciation, remains a challenging question for understanding SH and even global paleoclimates. By merging the SST results at Site 1233 with previously published SST records all along the PEBCS, it has been possible to draw major features of this system at different time-intervals over the last 70 kyr based on a SST gradient reconstruction (Manuscript 2). During cold periods as marine isotope stage (MIS) 4 and 2 on the one hand, the temperature gradients were substantially stronger-than-today reflecting an equatorward shift of the subtropical gyre circulation by ~5° in latitude resulting in a stronger supply of cold waters into the eastern tropical Pacific. On the other hand, the system was shifted poleward during the Holocene Climatic Optimum, when the climate was warmer-than-today. A reconstruction of the sea-surface circulation off central Chile spanning the last 40 kyr seems to confirm this pattern at a millennial timescale (Manuscript 5). At this site, located at the convergence of low- and high-latitudes waters, periods under cold, relatively fresh, subtropical waters influence contrast to periods with larger influence of warm, saltier, equatorial waters. Furthermore, the millennial-scale SST variations were closely linked to changes in the vegetation abundance on the adjacent land, based on the \( n \)-alkanes fraction of the same archive (Manuscript 5). Common latitudinal shifts of the ACC and the Westerlies (and related storm tracks) would better explain this close relationship.

In southern and central Chile, terrestrial peleoenvironmental records are mainly based on pollen assemblages and geomorphological evidences of glaciers fluctuations, and suggest latitudinal shifts of the Westerlies as being the main forcing mechanism. Part of these results suggests a climate linkage with the Northern Hemisphere in disagreement with the aforementioned SST reconstructions at Site 1233 and GeoB 7139-2. At Site 1233, iron concentrations were used as a proxy for PIS fluctuations during the last glacial time (Manuscripts 1 and 3), an assumption which is strongly confirmed by salinity reconstructions over the last deglaciation (Manuscripts 1 and 4). The glacier advances as reconstructed on land correlate with iron maxima and cold offshore SST which would be in agreement with common latitudinal shift of the ACC/Westerlies system at a millennial timescale, bringing simultaneously subtropical waters and higher rainfall feeding the ice-sheet. There is however a delay of the PIS retreats over the SST warmings of about 700-1000 years during MIS 4, late MIS 3 and MIS 2 suggesting a delayed response of the ice sheet to large-scale temperature changes as shown by the SST record. The strong dependence of PIS fluctuations on offshore
SST changes in the SE Pacific has been independently derived from regional modeling studies. The offset disappeared during the early and middle parts of MIS 3, a relatively warm time-interval of the last glacial, suggesting that the PIS was significantly reduced in its northern part, or even absent (Manuscript 3), and could thus react more rapidly to temperature and snow accumulation changes.

Spectral analysis on the short-term variability (<5 kyr) of both the iron and the SST records reveals three main, significant cyclicity-bands around 4.5-3 kyr, 2.3-2 kyr and 1.3-1 kyr (Manuscript 3). The supposed origins comprise the so-called stochastic resonance mechanism for the 4.5-3 kyr band, which implies that the combination of a weak periodic signal with other signals might cause climate mode switches, e.g. the DO cycles in the NH and equivalents in the SH. A 2.3 kyr-periodicity has been recognized in residual $\Delta^{14}C$ record from tree-rings and might thus have a solar origin. Furthermore, spectral analysis of records from the Cariaco Basin, Greenland (GISP2 ice-core) and Antarctica (Byrd ice-core) show similar results suggesting global climate forcing. Another dominant periodicity (1.3-1 kyr), which is especially present during early MIS 3 and the early Holocene in the SE Pacific, does not appear in the Antarctic record. This cycle might thus have a low-latitudes origin, possibly involving mechanisms such as a long-term modulation of the El Nino Southern Oscillation (ENSO). Modifications in the location and/or strength of the subtropical high-pressure system might provide the link between the forcing and the variability of the Westerlies/ACC system for the very short-term periodicities (<3 kyr).

A comparison of results based on Site 1233 and core GeoB 7139-2 over the last deglaciation provides additional insight in sea-surface circulation changes in the SE Pacific during the last major climate transition (Manuscript 5). Manuscript 1 shows that following a first, abrupt SST increase starting around 19 kyr BP a huge freshwater input occurred at ~17.5 kyr BP due to the melting of the PIS. The updated results at a higher resolution further show two successive freshwater pulses at ~13 and 12 kyr BP (Manuscript 4). The large PIS melting event at ~17.5 kyr BP is traceable northward to 30°S, suggesting that the collapse of the PIS was a major event of the deglaciation influencing the hydrology of the Eastern Pacific at least northwards to 30°S (Manuscript 5). In addition, a $\delta^{15}N$ record from these latitudes (core GeoB 7139-2) shows a huge and abrupt denitrification increase (~6 ‰) at that time, whereas there are no significant changes, neither in the SST, nor in the paleoproductivity records of the same archive. A ventilation collapse of the intermediate waters due to surface density changes in relation to the PIS melting might well explain this abrupt denitrification increase during the last deglaciation off central Chile (Manuscript 6).

The presence or absence of the NH climate event of the Younger Dryas has been controversially discussed based on terrestrial records in Chile. Both the SST reconstructions at 41°S and 30°S show a temperature plateau during the ACR and there is clearly no YD
cooling (Manuscript 1, 2, 4 and 5). On the contrary, SSTs increase by ~1.5-2°C during the later part of the Younger Dryas consistent with Antarctic ice-core records.

Finally, the two SST reconstructions (41°S and 30°S) and a vegetation abundance record (30°S) studied here reinforces the fact that the last glacial maximum and the deglacial onset are still not clearly defined in southern South America. On the one hand, the vegetation abundance on land was maximum around ~28-26 kyr BP at 30°S, in agreement with previous pollen records from southern Chile, while both SST reconstructions at 30°S and 41°S show a pronounced cold phase. This pattern suggests that the last full-glacial conditions might have been earlier than previously suggested. On the other hand, whereas the SST record in the south rather abruptly starts to increase at ~19 kyr BP, the SST reconstruction at 30°S presents indices of an earlier warming, from ~22 kyr BP, which might have a low-latitudes origin (Manuscript 5).
6. PERSPECTIVES

The results presented in this work as well as other recent studies based on ODP Site 1233 (Heusser et al., 2005; Pisias et al., 2005) have shown the extraordinary potential of this site for high resolution paleoenvironmental reconstructions. In the following are summarized some ideas and already ongoing projects that are interesting to proceed in order to test and further develop the proposed mechanisms linked to climate changes during the last glacial/interglacial cycle in the Southeast Pacific realm.

(1) As described in Section 3.2, “altering” organic compounds are present in the alkenone fraction of some samples from Site 1233. Using additional liquid chromatographic steps during sample clean-up, these compounds could be analyzed in more details. Within this study it was not possible to proceed such a detailed work on the compounds including its exact identification. Nevertheless, preliminary results show that the configuration is similar to cyclic hydrocarbons (molecule masses are 524, 526, 538, 540, 552), but the exact nature remains speculative. As the compounds are mainly present in the glacial section of Site 1233, they might be related to specific paleoenvironmental conditions at this time. Further analyses using coupled gas chromatography and mass spectrometry (GC-MS) could provide a new tool for paleoenvironmental reconstructions off southern Chile [ongoing work in collaboration with Marcus Elvert, RCOM, Bremen, Germany].

(2) Grain-size distribution analyzes on Site 1233 might provide interesting additional results on the variability of the PIS during the last deglaciation and/or during warm event in the last glacial period. By sieving samples for analyses on foraminifera quartz grains were found in some samples, giving a first indication of possible ice-rafted detritus (IRD) events (pers. comm. Ulysses Ninnemann). These grain-size distribution results might support the previous assumptions based on the SSS and iron concentrations records.

(3) The time resolution at Site 1233 provide a unique opportunity to reconstruct alkenone-based SST and productivity changes over the millennial-scale cycles (equivalents of Heinrich and DO events) in the Southern Hemisphere mid-latitudes at unprecedented time-resolution (<100 yrs). Recent results from the Southwestern Pacific mid-latitudes suggest for example strong increases of productivity (mainly based on the alkenone content) during the Heinrich events and Antarctica warm events, but no significant signal during the DO events (Sachs and Anderson, 2005). These new records provide the first evidence for prominent alterations of the productivity in the Southern Ocean during Heinrich events. Existing data however do not permit an unequivocal distinction between upwelling and stratification as the principal factor responsible for increased subantarctic productivity associated with Heinrich events. Based on Site 1233 it would be possible not only to provide a second record based on similar productivity proxies and situated in the southern mid-latitudes too, but also to combine the SSTs results and $\delta^{18}$O measurements on planktic foraminifera in order to reconstruct the SSS.
Furthermore, the alkenone-based productivity record during the de-glaciation off Chile suggests a strong link with freshwater input (this study) [ongoing work and collaboration with Ulysses Ninnemann and Helga Kleiven, University of Bergen, Bergen, Norway].

(4) As first shown by Lamy et al. (2004), there are discrepancies between oceanic and land climate changes in terms of hemispheric versus interhemispheric coupling during the last glacial time off Chile. Whereas climate records on land suggest a climate linkage with Northern Hemisphere, the alkenone-based sea-surface temperature reconstruction at Site 1233 is clearly in phase with Southern Hemisphere records. In particular, the comparison of SST changes to the Antarctic Byrd $\delta^{18}$O record suggests a southern high-latitude control of the climate on the Southeast Pacific at millennial to sub-millennial timescales during the last 70 kyr (Kaiser et al., in press). In this context, it will be very interesting to reconstruct the main vegetation changes on adjacent land based on Site 1233 to avoid problems linked with dating errors between land and ocean records. Therefore, the use of lipid biomarkers (fatty acids) and their $\delta^{13}$C isotopic composition as a tool to reconstruct major vegetation changes (e.g., Hughen et al., 2004) on the adjacent land might provide a tool to solve the aforementioned discrepancies [ongoing work in collaboration with Konrad Hughen, Woods Hole Oceanographic Institute, MA, USA].

(5) By merging the results from ODP Site 1233 with previous multi-proxy studies based on marine records all along the Chilean coast, a rather consistent general pattern of past climate changes and mechanisms in the Southeast Pacific is emerging, involving mainly variations in the latitudinal position of the dominating atmospheric, the southern Westerlies, and oceanographic, the ACC, circulation members. A modeling study of the past oceanic circulation and linked productivity would be a major element to test the assumptions based on proxy records. Working on a regional scale should allow a high enough resolution (0.5°), either choosing a relatively large area (20°S-55°S x 70°W-80°W) or two smaller realms, e.g. off northern and southern Chile. The model would include an oceanic circulation part, such as the ROMS model (Regional Oceanic Modeling Systems; Shchepetkin and McWilliams, 2003, 2005) coupled with a biological model, beginning with a simple NPZD-type model (Nutrient, Phytoplankton, Zooplankton, Detritus; Oschlies and Garçon, 1999; Oschlies et al., 2000). This should bring a first, robust idea of the possible mechanisms involved in primary production variability linked with oceanographic and climatic conditions. Therefore, within 3-4 snapshots (i.e. modern, HCO, LGM and a PIS melting event) and modifying parameters like the nutrient and oxygen content, temperature and salinity of the water masses, as well as the wind stress, it should be possible to test different scenarios, and to compare them to available paleoenvironmental reconstructions [collaboration with Xavier Giraud, RCOM, Bremen, Germany].
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