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Holocene sea-surface temperature variability in the Chilean fjord region

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ABSTRACT

Here we provide three new Holocene (11–0 cal ka BP) alkenone-derived sea surface temperature (SST) records from the southernmost Chilean fjord region (50–53°S). SST estimates may be biased towards summer temperature in this region, as revealed by a large set of surface sediments. The Holocene records show consistently warmer than present-day SSTs except for the past ~0.6 cal ka BP. However, they do not exhibit an early Holocene temperature optimum as registered further north off Chile and in Antarctica. This may have resulted from a combination of factors including decreased inflow of warmer open marine waters due to lower sea-level stands, enhanced advection of colder and fresher inner fjord waters, and stronger westerly winds. During the mid-Holocene, pronounced short-term variations of up to 2.5°C and a cooling centered at ~5 cal ka BP, which coincides with the first Neoglacial glacier advance in the Southern Andes, are recorded. The latest Holocene is characterized by two pronounced cold events centered at ~0.6 and 0.25 cal ka BP, i.e., during the Little Ice Age. These cold events have lower amplitudes in the offshore records, suggesting an amplification of the SST signal in the inner fjords.

Introduction

The Holocene (since ~11.7 cal ka BP) has been traditionally considered as a period characterized by relatively stable climate conditions when compared to the last glacial period. However, substantial Holocene climate variability on millennial to centennial timescales has been reported mainly from the Northern Hemisphere (e.g., Mayewski et al., 2004; Wanner et al., 2008) while high-resolution Holocene temperature records from the Southern Hemisphere are still sparse (e.g., Kilian and Lamy, 2012). A recent effort to reconstruct a stacked temperature record from the latitudinal range 30°–90°S includes, for example, only about ten marine and ice-core records (Marcott et al., 2013). Thus, more well-dated marine records from the Southern Hemisphere are needed.

Paleoclimate archives from Antarctica and the Southern Ocean reveal contrasting results pointing to a complex temperature evolution throughout the Holocene (e.g., Masson et al., 2000; Masson-Delmotte et al., 2004; Bentley et al., 2009; Divine et al., 2010; Shevenell et al., 2011). An early Holocene Climatic Optimum (11.5–9 cal ka BP) has been widely documented in Antarctic ice-core records, with temperatures up to ~2°C warmer than present (e.g., Masson et al., 2000; WAIS Divide Project Members, 2013). Thereafter, results from ice cores suggest a long-term Antarctic cooling during the Holocene (Masson-Delmotte et al., 2004). However, a secondary mid-Holocene temperature maximum between ~8 and 6 cal ka BP appears to be important in the Ross Sea area whereas in eastern Antarctica some records show a weak secondary warming between ~6 and 3 cal ka BP (Masson et al., 2000). A recent TEX$_{86}$-based SST record from the Palmer Deep at the continental margin of the western Antarctic Peninsula shows a cooling by 3–4°C over the past 12,000 yr following the decline in local spring insolation (Shevenell et al., 2011). However, absolute SST values of this record appear to be low and doubts have been raised about the reliability of TEX$_{86}$-based SST reconstructions in the Southern Ocean (Ho et al., 2014). Marine and lacustrine records around the Antarctic Peninsula confirm the complexity of the Holocene temperature evolution as maximum warming was registered during different time intervals in the early to middle Holocene (e.g., Bentley et al., 2009).

Marine records from the South Atlantic sector of the Southern Ocean (50°–53°S) reveal an early Holocene temperature optimum and the onset of cooling together with sea-ice expansion between ~9 and 7 cal ka BP (Bianchi and Gersonde, 2004; Nielsen et al., 2004). Earlier work in this region suggested an increase in the deposition of ice-

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rafted debris in the subantarctic South Atlantic starting abruptly at ~5.5 cal ka BP, which coincides with the onset of the Neoglacial phase and with an advance of sea-ice cover around Antarctica (Hodell et al., 2001; Iizuka et al., 2008).

Holocene climate fluctuations in the Chilean fjord region (~42°–55°S), the closest land mass to Antarctica, are still not well documented due to the lack of records covering the complete Holocene with a high temporal resolution (Kilian and Lamy, 2012). In contrast, more detailed paleoceanographic reconstructions have been obtained from the Southeast Pacific off mid-latitude Chile (~30°–41°S). At ODP Site 1233 (41°S) located offshore the Northern Patagonia fjord region, warmest conditions occurred in the early Holocene (~12–9 cal ka BP) (Kaiser et al., 2005); SSTs during this interval were generally ~1–2°C above modern values. Thereafter, temperatures gradually declined reaching modern values (~14°C) in the late Holocene. The GeoB 3313-1 record (same location as ODP Site 1233; Lamy et al., 2002) covers the past ~8 cal ka BP and shows a secondary mid-Holocene warming at 6–5 cal ka BP and declining SSTs towards the late Holocene in a similar mode as the comparatively lower-resolution SST record from Site 1233. The recently published record from the Pacific entrance of the Strait of Magellan (Harada et al., 2013) shows warming in the early Holocene reaching a climate optimum from ~11 to ~6 cal ka BP but interrupted by a cool event at ca. 10.5 cal ka BP.

The early to mid-Holocene temperature maximum appears to coincide with widespread arid conditions onshore, as recorded in various terrestrial and marine records from central Chile (32°–35°S) (Villagrán, 1990; Lamy et al., 1999; Jenny et al., 2002; Maldonado and Villagrán, 2002; Villa-Martínez et al., 2003) and Northern Patagonia in Isla Grande de Chiloé (Abarzúa et al., 2004). It has been proposed that the more arid conditions on land resulted from a southward displacement of the southern westerly wind belt (SWW), which is the main source of precipitation (e.g., Kaiser et al., 2005). Offshore, changes within the Antarctic Circumpolar Current (ACC) might have diminished the intrusion of cold subantarctic waters into the Peru–Chile Current leading to a warming in the SSTs at least at the central Chilean margin. For the southernmost Chilean fjord region on the other hand, new precipitation reconstructions point to humid/windier conditions in the early Holocene, decreasing during the middle and late Holocene and suggesting an antiphase behavior between the core and the northern margin of the SWW (Lamy et al., 2010).

With the goal of filling the gap of paleoclimate information between high and mid-latitudes of southwestern South America, we provide new high-resolution records of SST variability throughout the complete Holocene in the Chilean fjord region (Churruca fjord at ~53°S, Canal Concepción at ~51°S, and Canal Wide at ~50°S). With the aim of describing regional patterns of paleoclimate changes and identify common forcing mechanisms, we compare our alkenone-derived SST data with previously published paleotemperature records from the Chilean margin and Northern Patagonian fjords between ~41° and ~53°S. Furthermore, in order to detect potential seasonality in the alkenone-derived SST signal, we analyzed a set of surface sediments distributed within the Chilean fjord region (~42°–55°S).

Study area

Between ~42° and 55°S, the Chilean continental margin is characterized by up to 200 km wide fjord belt, formed mainly by Pleistocene glacial erosion, that extends partially across the Andes Cordillera (Breuer et al., 2013). Over the last glacial termination, during the early stage of the Patagonian Ice Field retreat, up to 1100 m deep proglacial lakes were formed. The subsequent marine transgression across the shallow coastal shelf (today 50–80 m water depth) started after 14.3 cal ka BP at the western entrance of the Strait of Magellan (Kilian et al., 2007). The Chilean fjord region intersect the core of the SWW with maximum precipitation of westerly origin that is recorded between ~50° and 55°S and diminishing northward and southward of these latitudes (e.g., Schneider et al., 2003; Garreaud et al., 2013). Modern oceanic surface circulation is dominated by the northern boundary of the ACC that bifurcates at ~45°S into the Peru–Chile Current (PCC) flowing equatorward and the Cape Horn Current (CHC) flowing southward, both transporting Pacific subantarctic waters (SAAW) (e.g., Strub et al., 1998; Chaigneau and Pizarro, 2005; Sievers and Silva, 2008) (Fig. 1). The CHC transports anomalously warmer waters (~1.5°C) compared to subantarctic water masses in the open Pacific. At the same latitude, SSTs are similar to air temperatures during winter, whereas in spring and summer they are comparatively lower due to the input of fresh and cold water from snow and glacier melting (Kilian et al., 2013). The inner fjord system is characterized by a 30- to 70-m thick freshwater layer (salinity of 10–27 psu) derived from the very high regional precipitation (4000 to >10,000 mm/yr, Schneider et al., 2003). Since the low-density of the surface cold freshwater layer strongly hampers mixing with warmer fjord subsurface water (Kilian et al., 2007), the summer fjord SST's are often 2–4°C lower than local air temperatures (Kilian et al., 2013). The westward expansion of this freshwater layer towards the Pacific is additionally controlled by the SWW strength. Relatively warmer SAAW, with salinities of >32 psu, enters the fjord system below the freshwater layer and forms a dense and thus stable bottom water body (e.g., Sievers and Silva, 2008). Thus, fjord freshwaters and Pacific SAAW constitute a two-layer estuarine circulation, with fresh waters flowing towards the ocean at the surface and saltier Pacific SAAW into the fjords at depth (e.g., Sievers and Silva, 2008). The three coring sites studied here are in different oceanographic and continental settings. Canal Concepción is characterized by a strong marine influence, while Canal Wide is under the strong influence of glacier meltwater as it is located close to the Southern Patagonian Ice Field. The Churruca fjord, which is located within the Magellan fjord system, receives a high amount of freshwater from annual precipitation and glacier melting in austral spring.

Annual mean SST (World Ocean Atlas 2009 (WOA09); Locarnini et al., 2010) increases from 8°C at ~52°S to 13°C at ~42°S in the oceanic area adjacent to the Chilean fjords (Fig. 1). For the Northern Patagonian fjords, in-situ SST measurements have been performed during several Chilean cruises in austral spring, summer and/or winter since 1995 within the CIMAR Program (Cruceros de Investigación Marina en Áreas Remotas) (e.g., Silva et al., 1997; Silva and Calvete, 2002) whereas further south only austral spring data are available within this program (http://www.shoa.cl/n_cendhoc/index.html). Data from individual cruises as well as from an environmental monitoring network at 52°–53°S have been added to the dataset from the southernmost fjords (Kilian et al., 2013). Compared to SST data in the adjacent open ocean, temperatures in the fjords are generally colder due to the high contribution of estuarine waters, the influence of colder air temperatures inland and high meteoric precipitation reaching up to 10 m/yr in western Patagonia (e.g., Schneider et al., 2003).

Materials and methods

The alkenone-derived SST records from the Chilean fjord region include core MD07-3124 (22.25 m) from Canal Concepción (50°30.96′S; 74°58.33′W; 564 m water depth) collected during the XV-MD-159-PACHIDERME Expedition on board R/V Marion Dufresne; core JPC-42 (12.5 m) recovered between the Europa and Penguin fjords in the Canal Wide (49°55′S; 74°23′W; 904 m water depth) during the NBP05-05 Palmer Expedition with RV/IB N.B. Palmer; and core CHURR which was retrieved from the Churruca fjord (53°02′S; 73°54′W; 80 m water depth; 11.2 m core length) in the western basin of the Strait of Magellan, on board R/V Gran Campo II. Core MD07-3124 was sampled at 8-cm intervals (corresponding to a mean temporal resolution of ~100 yr); core JPC-42 was sampled at 10-cm intervals (mean resolution of ~110 yr); and core CHURR was sampled at 20-cm intervals (mean resolution of ~200 yr).