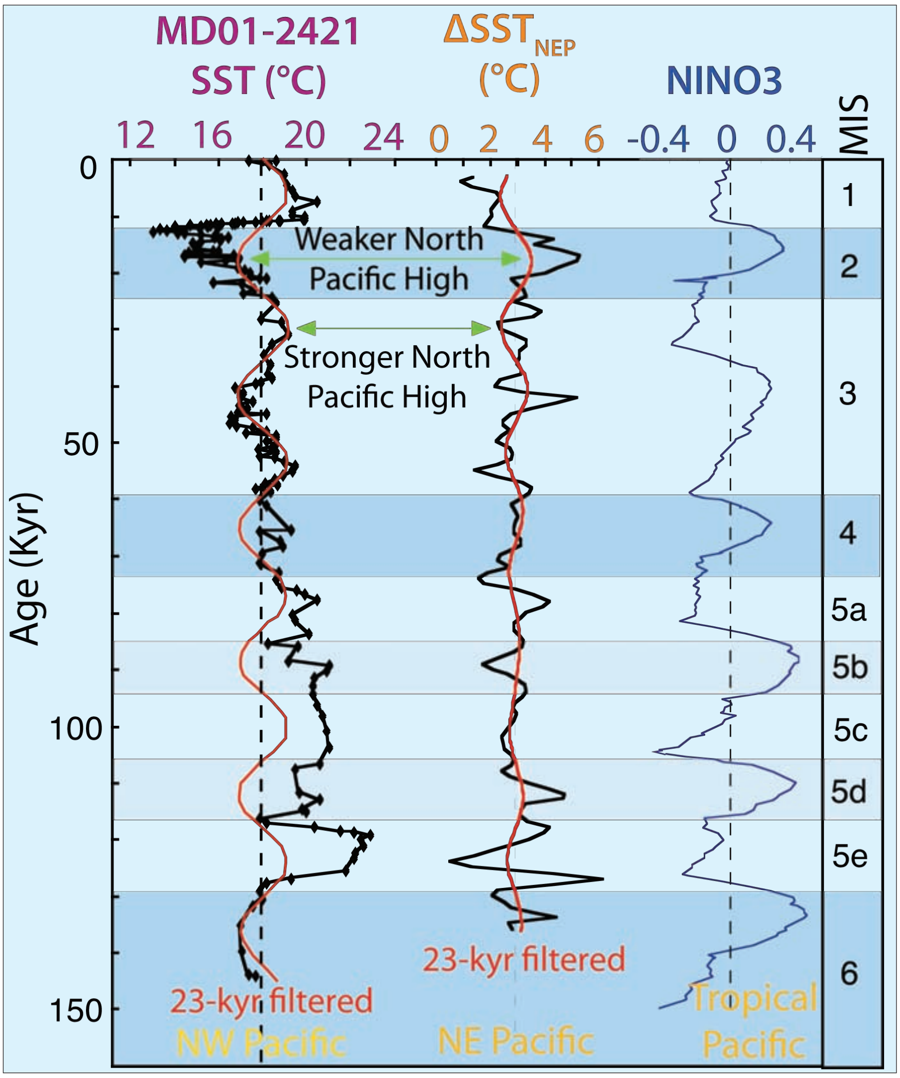

Figure 2: $U^{K'}_{37}$-derived SST at the Japan margin (core MD01-2421; Yamamoto et al., 2004, 2005), lateral temperature gradient ΔSST_{NEP} at the California margin, and the calculated NINO3 index (Clement et al., 1999) during the last 150 kyr. MIS = Marine Isotope Stage

timescales, although some shorter paleo-records in the eastern tropical Pacific and the tropical Andes regions are consistent with the model prediction (e.g., Koutavas et al., 2002; Moy et al., 2002). Long-term ENSO-like variability and wave propagation by teleconnection (Clement et al., 1999; Beaufort et al., 2001; Yamamoto et al., 2004) are potential driving forces of the North Pacific basin-scale climate response. The establishment of the linkage between this basin-scale response and tropical ocean-atmospheric dynamics will be a critical step toward better understanding the role of the Indo-Pacific in global climate change.

In summary, the east-west seesaw-like SST variation in the mid-latitude North Pacific during the last two glacial-interglacial cycles is part of a basin-scale oceanic and atmospheric response to precessional forcing. As this east-west seesaw is also typical of the modern North Pacific on interannual and decadal timescales, common climate-driving processes might exist in the response of the North Pacific to forcing on different timescales.

Note

Data are available from NOAA Paleoclimatology website www.ncdc.noaa.gov/paleo/paleo.html

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Last glacial SST changes in the SE Pacific—a bipolar seesaw perspective

Jérôme Kaiser[1] and Frank Lamy[2]

[1]Royal Netherlands Institute for Sea Research, Texel; jkaiser@nioz.nl; kaiserj@gfz-potsdam.de
[2]Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany; frank.lamy@awi.de

The SE Pacific is a key region for studying natural variability of globally important atmospheric and oceanic circulation components of the southern hemisphere, from the last glacial and beyond. High resolution paleoceanographic studies have particularly focused on continental margin records off Chile, which were recovered by several international research cruises during the last decade, including Ocean Drilling Program (ODP) Leg 202. The current network of sediment cores along the northern and central Chilean margin have greatly improved our understanding of late Quaternary terrestrial climate change in Chile (e.g., Hebbeln et al., 2007; Lamy et al., 1998, 1999, 2001; Stuut and Lamy, 2004) and the paleoceanography of the adjacent Peru-Chile Current (PCC) system (e.g., Hebbeln et al., 2002; Kim et al., 2002; Mohtadi and Hebbeln, 2004). These findings are summarized in two recent review articles (Marchant et al., 2007; Stuut et al., 2006).

Here, we focus on results based on ODP Site 1233, located at the upper continental slope off southern Chile (41°S) at the northern margin of the Antarctic Circumpolar Current (ACC) and the southern end of the PCC (Fig. 1). This site has received particular attention because the ~70-kyr-old sequence extends over ~135 m composite core depth, resulting in high sedimentation rates, unprecedented in the South Pacific. Site 1233 is ideally located to compare past variations of both surface and deep-ocean water masses with climate records from high southern latitudes (e.g., Antarctic ice-cores). Modern sea sur-

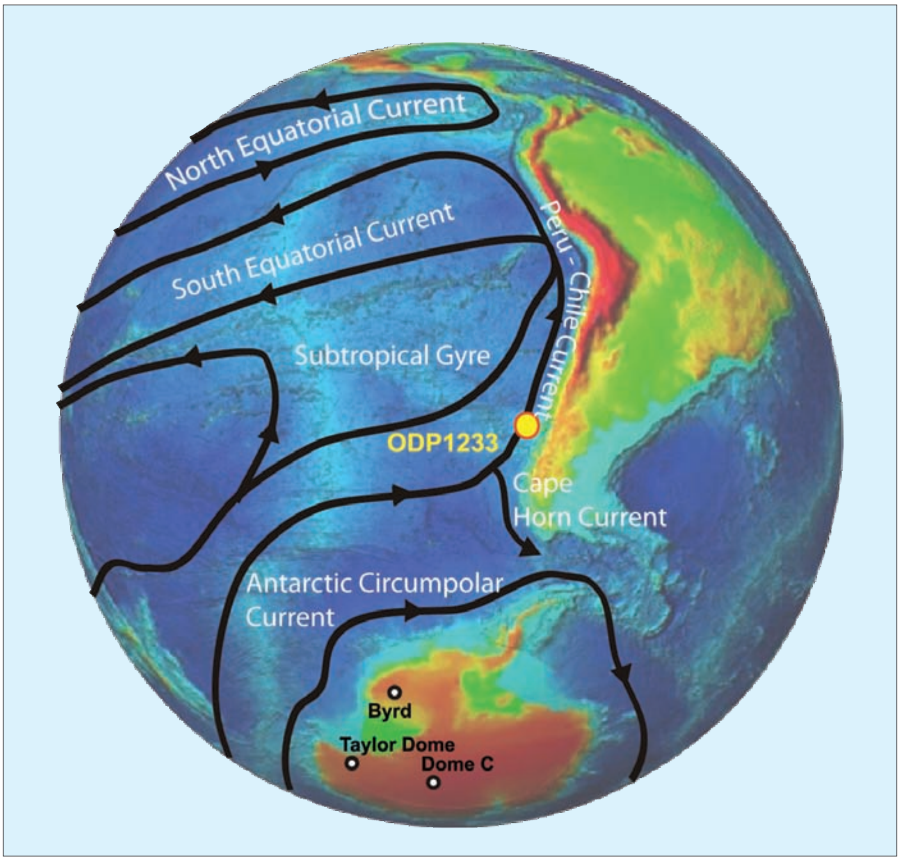

Figure 1: Major surface currents of the South Pacific Ocean and the locations of ODP Site 1233 and Antarctic ice cores discussed in the text.

face temperature (SST) gradients within the northernmost ACC are very large and intimately linked to the northern margin of the southern westerly wind belt (SWW), making this region very sensitive to latitudinal shifts in atmospheric and oceanographic circulation associated with the SWW. Furthermore, Site 1233 is located close to the southern Chilean coast (~40 km) and close to the northwestern margin of the glacial Patagonian Ice Sheet (PIS), which occupied a large area of southernmost South America during the last glacial. This unique location allows a detailed comparison of various continental climate and paleoceanographic proxy records within the same archive and, therefore, avoids problems linked to age model uncertainties. A number of different proxy records from Site 1233 have been published, including alkenone and radiolarian-based SST reconstructions (Kaiser et al., 2005; Lamy et al., 2007, 2004; Pisias et al., 2006), terrestrial sediment input and pollen-based continental climate studies (Heusser et al., 2006; Kaiser et al., 2007; Lamy et al., 2004; Pisias et al., 2006), and nitrogen isotope analyses (Martinez et al., 2006).

"Antarctic timing" of SST changes

The alkenone SST record from Site 1233 shows a clear "Antarctic timing" of millennial-scale temperature changes over the past 70 kyr (Kaiser et al., 2005; Lamy et al., 2004) (Fig. 2). The major Antarctic warm events A1 to A4 (Blunier and Brook, 2001) are characterized by SST increases of up to 3°C. The global Last Glacial Maximum (LGM) is not well defined in the record. Deglacial warming starts at ~18.8 kyr BP, with a ~2-kyr-long increase of nearly 5°C until ~16.7 kyr BP. Thereafter, temperatures remain comparatively stable until the beginning of a second warming step of ~2°C between ~12.7 and ~12.1 kyr BP (Lamy et al., 2007). This pattern is consistent with independent SST estimates based on radiolarian assemblages (Pisias et al., 2006). The first warming step coincides with a major shift in the $\delta^{15}N$ record from Site 1233 that has been explained by a southward shift of fronts in the Southern Ocean (Martinez et al., 2006), and coincides with a major change in pollen assemblages (Heusser et al., 2006).

Millennial-scale temperature changes in Antarctica over the last glacial may be consistently explained by the bipolar seesaw concept, which suggests an out-of-phase millennial-scale climate pattern between the northern and southern hemispheres during the last glacial (Stocker and Johnsen, 2003). Over Termination 1 (T1), detailed radiocarbon dating reveals that the SST in the mid-latitude SE Pacific rose at the same time that the Atlantic meridional overturning circulation (AMOC) decreased (Lamy et al., 2007). Though this timing is largely consistent with Antarctic ice core records, the initial warming in the SE Pacific is more abrupt, suggesting a direct and immediate response to the slowdown of the Atlantic thermohaline circulation through the bipolar seesaw mechanism. This response requires a rapid transfer of the Atlantic signal to the SE Pacific, without involving the thermal inertia of the Southern Ocean that may contribute to the substantially more gradual deglacial temperature rise seen in Antarctic ice cores. The most plausible mechanism is a seesaw-induced change of the coupled ocean-atmosphere system of the ACC and the southern westerly wind belt, as supported by North Atlantic water hosing model experiments (Timmermann et al., 2005). The SST response to a weakening of the AMOC in these and other model simulations (e.g., Knutti et al., 2004; Schmittner et al., 2002) is, however, much smaller than the initial warming observed at Site 1233 (Fig. 2). Apart from the pronounced regional sensitivity of Site 1233 due to strong regional SST gradients, global forcings (such as changes in insolation, CO_2 and atmospheric dust) explain an important fraction of the deglacial SST rise in the SE Pacific (Lamy et al., 2007).

Link to CO_2 changes?

The connection of atmospheric CO_2 content to SST changes in the SE Pacific and the position of the westerlies may be very relevant to our future climate, as some models display significant shifts of the westerlies under future greenhouse scenarios (see e.g., Yin, 2005). Based on a general circulation model, Toggweiler et al. (2006) showed that the equatorward shifted southern hemisphere westerlies during the glacial allowed more respired CO_2 to accumulate in the deep ocean. During glacial terminations, the southward moving westerlies reduced polar stratification and enhanced upwelling of deepwater masses around Antarctica, which would then have released large amounts of the stored CO_2 to the atmosphere. We observe a similar link between SE Pacific SSTs and CO_2 for older intervals. For example, the transition from marine isotope stage (MIS) 4 to MIS 3 (Fig. 2) that did not initiate interglacial conditions, even though insolation changes were similar to those of T1. We suggest that the particular combination of orbital-scale insolation changes and millennial-scale climate variability over T1 (i.e., two major slowdowns of the AMOC (Heinrich Event (HE)1 and Younger Dryas (YD)) over an interval of rising northern hemisphere summer insolation) has been a crucial factor for the shift of the climate system into the present interglacial conditions (for details see Lamy et al., 2007).

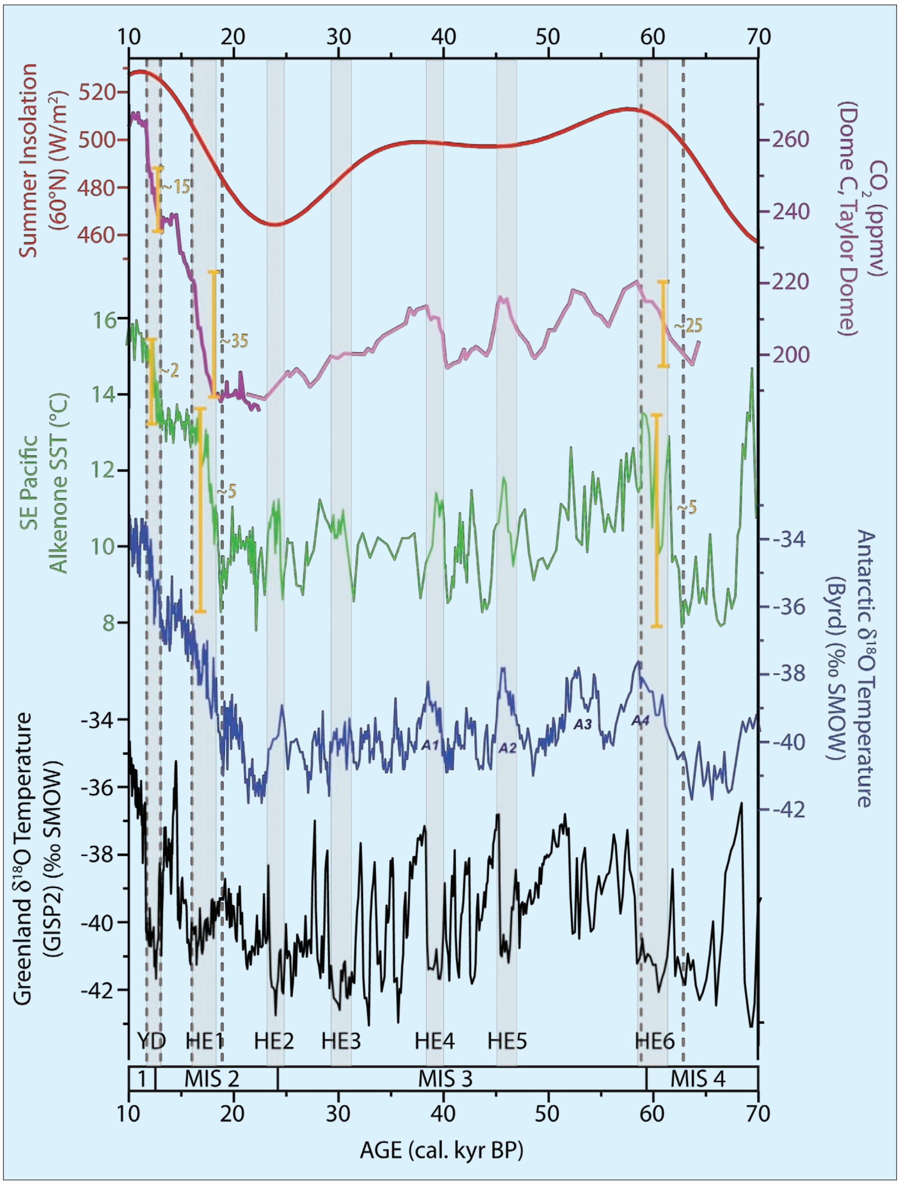

*Figure 2: Comparison of Southeast Pacific SST to Antarctic and Greenland ice core records (atmospheric CO_2 and $\delta^{18}O$ as a temperature proxy) over the past 70 kyr. Summer insolation at 60°N (Berger and Loutre, 1991; **red**). CO_2 record from Dome C (Monnin et al., 2001; **purple**) and Taylor Dome (Indermühle et al., 2000; **pink**) ice cores. (Timescale of the Taylor Dome record has been adapted to the GISP2-synchronized age model of the Byrd ice-core (Blunier and Brook, 2001)). Alkenone SST record from Site 1233 (Kaiser et al., 2005; Lamy et al., 2007; **green**). Oxygen isotope record of the Antarctic Byrd (Blunier and Brook, 2001; **blue**) and Greenland GISP2 (Grootes et al., 1993; **black**) ice cores. HE1-6: Heinrich Events (**gray bars**). YD: Younger Dryas. Dotted lines indicate intervals with substantial increase in SST and CO_2. Yellow numbers show approximate amplitude in ppmv and °C.*

Outlook

A major issue for future research will be to follow the millennial-scale pattern recorded off southern Chile along the Pacific Eastern Boundary Current System (PEBCS) into the tropics. 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, with enhanced cold-water advection along the PCC. Conversely, the oceanic circulation in the PEBCS was weakened, and the ACC and associated southern westerly wind belt moved southward during relatively warm periods (early MIS 3 and the Holocene climate optimum) (Kaiser et al., 2005). Furthermore, ultra high-resolution sediment records from the Chilean Fjords and the adjacent continental margin were recovered in February 2007 during the "Marion Dufresne" cruise PACHIDERME. These will provide new Holocene and late glacial records with the potential to look into centennial- or even decadal-scale climate variability.

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