the area around 30°S. (Grosjean et al., 1998). These morrains also exist in the surroundings of Cerro Tapado. Ongoing research aims to test whether the glacier model can produce the observed late Holocene glacier extent using the ice core derived climate conditions, and therefore link ice core and modeling results with geomorphological evidence of past glacier advances.

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The Southern Ocean as the Flywheel of the Oceanic Conveyor Belt Circulation

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The last ice age came to an end between 20 and 10 ka BP. This time span was punctuated by a series of abrupt climate sequences (Fig.1a). In particular, the rapid transition in the North Atlantic from the cold Heinrich 1 to the Bølling/Allerød (B/A) warm-phase and its cold reversal counterpart in Antarctica (ACR) have attracted much attention. During deglaciation, the North Atlantic was exposed to a large meltwater discharge from the melting Laurentide and Fennoscandian ice sheets. This continuous meltwater release on the order of about 0.1 Sv (Marshall and Clarke, 1999) posed a constant threat to the "Achilles Heel" of the oceanic conveyer belt circulation (Broecker, 1991), located in the North Atlantic (schematic picture in Fig. 2a, b). Paleodata (Duplessy et al., 1988; Sarnthein et al., 1994) and modeling work (e.g., Ganopolski and Rahmstorf, 2001; Prange et al., 2002) indicate a weaker glacial thermohaline circulation (THC) compared with the interglacial circulation. Based on evidence of a weak glacial conveyor belt, it is natural to ask about the "flywheel" of the ocean circulation, which might have initiated the transition to a strong interglacial ocean circulation. This "flywheel" is not necessarily confined to the North Atlantic realm, where the "Achilles Heel" is located. Our recent modeling results (Knorr and Lohmann, 2003) using an Oceanic General

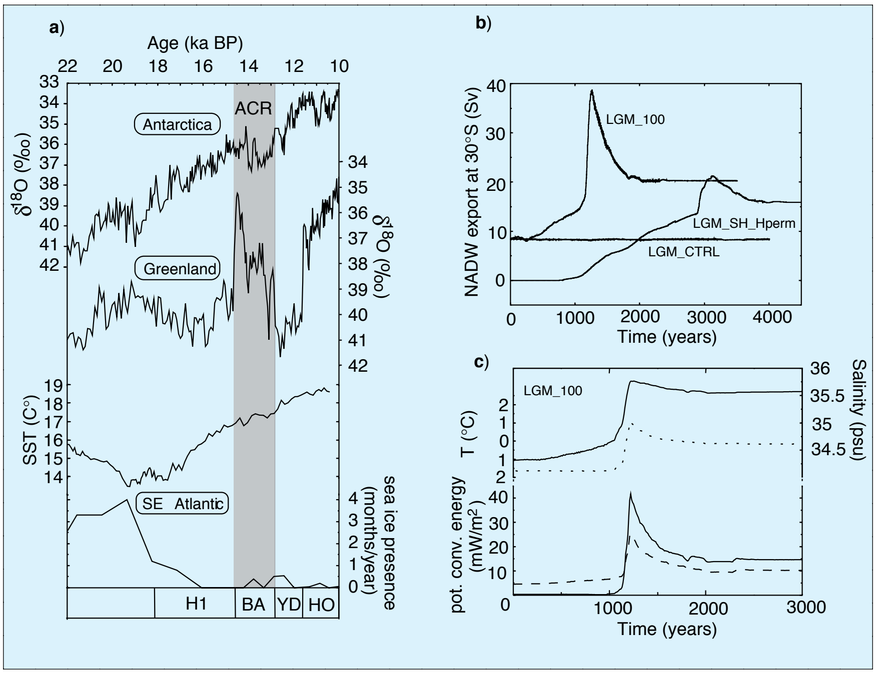

*Fig. 1: Deglacial climate records and modeling results for the Bølling/Allerød transition induced by Southern Hemisphere warming. (**a**) High-resolution climate records from 22 to 10 ka BP based on polar ice cores from Antarctica (BYRD) and Greenland (GISP2) during the last deglaciation (Blunier and Brook, 2001), including a sequence of abrupt climate changes (boundaries of climate intervals, defined as per the GISP2 record: H1, Heinrich 1; BA, Bølling-Allerød; YD, Younger Dryas; HO, Holocene). The temperature evolution of alkenone-based sea-surface temperatures (SST) in the south east Atlantic (Sachs et al., 2001), showing that deglacial warming at 41°S, 7.5°E commenced between 17.5 to 19 ka BP, similar to the Antarctic warming trend. At the same time, sea ice in the Southern Ocean retreated to present day limits (Shemesh et al., 2002). (**b**)Temporal changes in NADW export at 30°S. In LGM_100 and LGM_SH_Hperm, glacial conditions in the Southern Ocean (south of 30°S) are gradually replaced by interglacial conditions over 1500 years. LGM_SH_Hperm is started from the THC "off-mode" and superposed by a permanent freshwater flux of 0.15 Sv (1 Sv = 10^6 m^3 s^{-1}) to the North Atlantic. LGM_CTRL represents the glacial control run. (**c**) LGM_100 time series of sea surface temperature (°C, dotted curve), salinity (psu, solid curve) and potential energy loss by convection (mW/m^2) in the North Atlantic averaged between 55°N and 65°N (solid curve) and between 40°N and 55°N (dashed curve).*

Circulation Model (OGCM) (Maier-Reimer et al., 1993; Lohmann et al., 2003) suggest that Southern Ocean warming and the accompanying sea ice retreat induced a non-linear transition to a strong Atlantic overturning circulation (Fig. 1b). This is consistent with ice core and ocean-sediment records, showing that a progressive warming in the Southern Hemisphere preceded Greenland warming by more than 1000 years (Sowers and Bender, 1995), a time lag that was even lon-

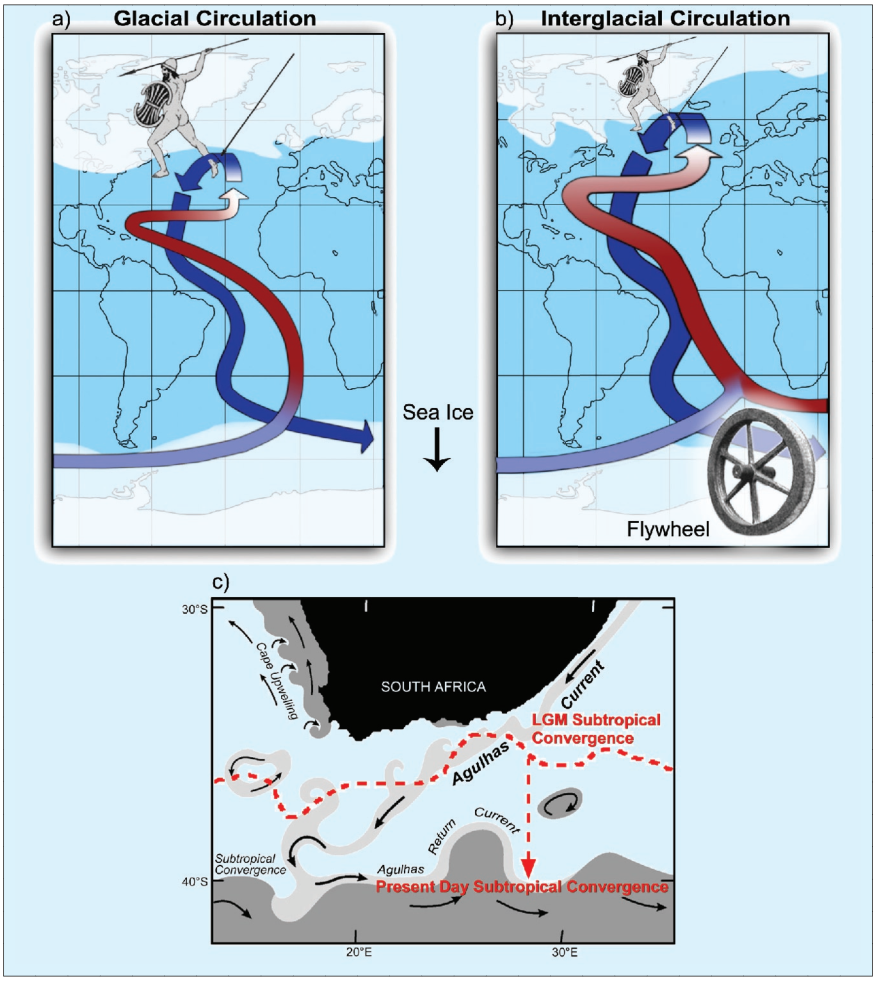

*Fig. 2: Schematic representation of the differences between the glacial and the restarted interglacial ocean circulation, and a conceptual diagram of the Agulhas Current system. (**a**) Glacial circulation is characterized by a weaker mode without a warm water route that is activated by Southern Hemisphere warming, operating as a pathway for relatively warm and saline water from the Indian Ocean in the interglacial mode (**b**). Moreover, the Antarctic circumpolar current accelerates and increases volume transport from the Pacific Ocean via the cold-water route into the South Atlantic. (**c**) Conceptual diagram of the southern Agulhas Current system (adapted from Lutjeharms, 1981) summarizing the main circulation features and a potential northward displacement (red line) of about 2 - 4° of latitude of the glacial subtropical convergence zone (Brathauer and Abelmann, 1999; Gersonde et al., 2003) that might cause a reduction or "switch-off" of the warm water route.*

ger for the penultimate deglaciation (Petit et al., 1999).

The flywheel of the ocean conveyor belt, located in the Southern Ocean, worked as follows: the warming and sea ice retreat in the Southern Ocean induced a southward migration of the Antarctic Circumpolar Current (ACC) and associated ocean-fronts, which increased mass transport into the Atlantic Ocean via the warm and cold water routes of the oceanic conveyor belt circulation (Broecker, 1991; Gordon et al., 1992). The thermal anomaly was attenuated along the northward conveyor route but the salinity characteristics of the warm water route persisted (Weijer et al., 2002). The salinity increase in the upper layer of the North Atlantic preconditioned North Atlantic deep water (NADW) formation comparable to a mechanism proposed by Gordon et al. (1992) that gradually intensified convection during the first 1000 years (Fig. 1c). Along with increased Atlantic overturning, the meridional heat transport warmed the surface water of the North Atlantic, triggering a sea ice retreat after 1000 years. In addition to the advective feedback, a convective feedback contributed to the resumption of the THC. Once convection was initiated in parts of the formerly ice-covered North Atlantic, the relatively warm and saline water masses from deeper layers coming up to the surface lost their heat readily, but kept their salt, and thus reinforced the starting process of convection (Fig. 1b, c). This catalyst of NADW formation lead to an abrupt decrease of sub-surface temperatures. Experiment LGM_SH_Hperm has shown that this mechanism prevailed over the destabilizing effect of meltwater on THC, characterizing the deglacial Heinrich sequence (Fig 1b).

As a result of the restarted conveyor circulation (Fig. 1b), the maximum heat transport and temperature in the North Atlantic increased dramatically, consistent with the temperature rise of the B/A onset (Bard et al., 2000). This demonstrates that slow changes in the South can have abrupt and far-reaching consequences on the THC or ice-sheet discharges (Stocker, 2003). The ACR represents the Southern Hemisphere counterpart (Fig. 1a), in accordance with the oceanic interhemispheric teleconnection that increased THC cools the Southern Hemisphere (Crowley, 1992; Stocker, 1998).

We speculate that, in conjunction with other effects, (Toggweiler, 1999; Stephens and Keeling, 2000, Weaver et al., 2003), the increase in maximum northward oceanic heat transport from 0.8 PW to 1.6 PW contributed to the reduction of the great Northern Hemisphere ice sheets. If this additional heat was exclusively dissipated as latent heat, the modelled onset of the THC would account for a melting of 12 x 10^{15} m^3 ice within two centuries, which is an upper estimate for the oceanic contribution for deglaciation. This reduction of global ice volume captures the order of magnitude representative for the B/A warm period. Such a meltwater input would weaken but not stop NADW formation, due to the stabilising effect of the different sources of deep water formation (Lohmann and Schulz, 2000). Southern Ocean warming and the associated sea ice retreat during deglaciation as observed in paleoclimatic data (Shemesh et al., 2002) might be the result of tropical sea surface temperature anomalies that were transmitted from the tropical Pacific to the Antarctic region (Lea et al., 2000; Koutavas et al., 2002), or a response to local Milankovitch forcing on the precessional period (Kim et al., 1998). Another possibility is that a 19-kyr meltwater pulse originating in the Northern Hemisphere contributed to early deglacial warming in the Southern Hemisphere, while maintaining a cold Northern Hemisphere through its effect on the Atlantic THC and ocean heat transport (Clark et al., 2004).

A similar temporal shape to the B/A onset (Fig. 1a) is detected at other abrupt stadial (cold) to interstadial (warm) transitions, named Dansgaard-Oeschger (DO) events, during the last glacial period (Dansgaard et al., 1984). These millennial-time scale variations have been linked to various mechanisms such as a salt oscillator (Broecker et al., 1990), deep-decoupling oscillations (Winton, 1993; Schulz et al., 2002), latitudinal shifts in convection sites associated with THC changes induced by freshwater flux perturbations in the North Atlantic (Ganopolski and Rahmstorf, 2001), and a stochastic resonance phenomenon (Ganopolski and Rahmstorf, 2002; Rahmstorf and Alley, 2002). The trigger of these millennial-time scale variations is unknown and there is debate as to whether these fluctuations are regular or stochastic (Wunsch, 2000; Schulz, 2002; Rahmstorf, 2003). Here we argue that our mechanism for the B/A transition might be similar to other DO events during the glacial phase. However, the warm and cold water routes of the oceanic conveyor belt only temporarily gained in strength, and returned to the glacial mode with reduced strength of the ACC and a relatively northward circum-Antarctic frontal system compared to its present day position. In contrast, the southward migration of these fronts prior to the B/A transition is accompanied by deglacial warming, which activates the "flywheel" of the oceanic conveyor belt (Fig. 1, 2). Like the "conveyor belt" metaphor (Broecker, 1991; Brüning and Lohmann, 1999) the flywheel metaphor illuminates a basic idea. In our case the Southern Ocean can be understood as the engine for the oceanic transport system on glacial-interglacial time scales.

Our study suggests that the Achilles Heel (Broecker, 1991) and the flywheel of the Atlantic overturning circulation on paleoclimate timescales are located in the North Atlantic and the Southern Ocean, respectively (Fig. 2). A zone of special interest is the area around the Cape of Good Hope because it represents an import route of relatively warm and saline water from the Indian Ocean (Fig. 2c) that is thought to precondition NADW formation (Gordon et al., 1992). Berger and Wefer (1996) surmise that this narrow portal is directly related to the position of the sup-tropical convergence zone. Therefore, a northward displacement of this front could reduce (Gersonde et al., 2003; Paul and Schäfer-Neth, 2003) or even pinch off access, leading to speculation that the reopening of the Agulhas gap at the end of the last ice age may have played a role in restarting the Atlantic THC (Berger and Wefer, 1996). Since the South Atlantic is characterized by a number of unique dynamical features, such as the large Agulhas Rings (Schouten et al., 2002) that form a key link in the THC, it is of interest to investigate the flywheel and its respective energy source, using high-resolution models of the South Atlantic, to obtain a more detailed view of this region.

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Sharp Cooling of the Northern Hemisphere in the Early Subatlantic Age (650 - 280 BC)

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About 2,500 years ago, a strong cooling happened on the Earth. The evidence for this is found not only in numerous climatic indicators (glacier and tree-line position in the mountains, tree ring thickness, fossil pollen spectra, isotopic composition of ice, lacustrine and marine deposits) but in social history as well. Papers by many ancient authors (Herodotus, Livy Andronicus, Eratosthenes), as well as Chinese and Babylonian chronicles, describe a climatic pattern that differs greatly from the present, not only in temperature but also in humidity. They come from that period when the Scandinavian legend of Ragnarök originated (the doom of the gods and the entire world). Presumably, it implies that there was a critical change in the common natural environment. It is not surprising that it was this cooling that was chosen in paleoclimatology as a universal chronological boundary separating the penultimate (Subboreal) from the present (Subatlantic) epoch. However, there are still no satisfactory answers to the following fundamental questions:

- Was the Subatlantic cooling-global?
- When and at what level was the maximum cooling attained?
- What was the distribution pattern of temperature and precipitation during this period?

A few highlights of my study, which addresses these questions, are presented here. Detailed information is given elsewhere (Klimenko, 2004).