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Dynamics of Pleistocene climate change in the South Atlantic Ocean

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English abstract

This Ph.D. thesis deals with the reconstruction of climatic features from the Earth's past. Namely, it aims at understanding aspects of climate in the South Atlantic region during periods of prominent, global climate change of the Pleistocene epoch. Understanding past climate changes, and the dynamics behind them, is the key to understand the present change, and its consequences.

Climatic reconstructions for the Pleistocene have revealed that the mean temperature and composition of the atmosphere and of the oceans varied over time-scales from millennia to millions of years. They responded to two dominant forcings: continental drift and changes in solar radiation. Solar radiation changes together with the three parameters that characterize the Earth's orbit around the sun: 1) eccentricity, or the degree of deviation from a circular orbit; 2) obliquity, or the tilt of the Earth's rotational axis with respect to the orbital plane; and 3) precession of the equinoxes, or the orientation of the rotational axis with respect to the firmament. The combination of the frequencies of change in those three parameters resulted, for the Pleistocene epoch, in the periodical change of state of the climate system, swaying between glacials and interglacials: the glacial cycles.

Paleoclimate research investigates the physical mechanisms behind these cycles. Developments in the use of so-called climate proxies enable us to infer past regional and global climatic states, and the age thereof, with higher precision and accuracy. By these means, paleoclimate reconstructions, like those contained in this thesis, aim to improve our knowledge of the sensitivity of the climate system.

As an important component of the climate system, the oceans act in a variety of ways to influence it. A much important way is the distribution of heat operated by the ocean's circulation. In particular, the circulation of the Atlantic Ocean, the so-called

Atlantic meridional overturning circulation (AMOC), is a sensitive component of the climate system. A prominent result of the Atlantic circulation, is that a net surface transfer of heat from the tropics to higher latitudes in the North Atlantic occurs. Recently, the relevance of processes of South Atlantic origin to the equilibrium and variability of the AMOC has emerged more clearly, motivating research efforts aimed at a better understanding of the South Atlantic history. This is the topic of my thesis.

Surface and intermediate waters circulating within the South Atlantic mostly come from the Indian Ocean, through the Agulhas leakage (AL). This is constituted of relatively warm and saline waters from the Indian Ocean, transported by the southeast flowing Agulhas Current. Water from the AL are the main component of the upper branch of the AMOC. Because it occupies such a crucial position in the scheme of oceanic currents, the Agulhas system is simultaneously a sensible and an influential bottleneck of ocean circulation. It entertains important cause-effect relationships with the other parts of the Earth's oceans and climate. In particular, during Pleistocene glacial periods, the subtropical and subpolar fronts at the south of South Atlantic basin, are believed to have seized more northerly locations. This might have meant restrained Indian to Atlantic passage of the AL. On the other hand, during glacial terminations a southward shift of fronts and attendant wind belts seems to have opened a wider-than-present passage for the AL to enter the South Atlantic.

The paleo-Agulhas system has recently been investigated in its different sections, i.e, the northern and southern Agulhas Current, the AL, the retroflexion and Agulhas return current. No proxy study to date has aimed to capture the effect of the AL in the Atlantic. The work presented here focuses on the paleoceanographic phenomena that took place downstream the AL in the AMOC, specifically in the southeast Atlantic and in the western tropical Atlantic. The objective is to test the hypothesis that the AL might have had a considerable effect upon the AMOC during times of climate change. For this, two marine sediment cores were selected, one at a proximal and one at a more distal location with respect to the AL area.

Making use of proxies mostly from the geochemistry of planktic foraminifera (microplankton which produces of a calcite shell that, once settled to the sea-floor, is

preserved in the sediments), I inferred upper water properties from these two locations, reconstructing the ocean depths from the surface to the thermocline.

The proximal core, 64PE-174P13, was extracted from the central Walvis Ridge, on the east flank of the subtropical gyre, at a location presently underneath the trajectory of most Agulhas rings. This makes the setting ideal for our scope of assessing the result of the AL in this region at the origin of the upper branch of the AMOC.

In **Chapter 2**, I address the following research questions: How did the South Atlantic upper ocean stratification change during Pleistocene climate change? How does that relate to shifts in the amount of Indian Ocean input? For this scope, I studied the whole extent of the core, using the oxygen-isotope composition ($\delta^{18}\text{O}$) of two planktic foraminifera taxa with distinct depth habitat. The results show that **the upper ocean $\Delta^{18}\text{O}$ gradient between shallow and deep dwelling planktic foraminifera, used as a proxy for upper ocean density stratification, reveals a sawtooth pattern strictly connected to G-IG cycles** from MIS 12 to 5. Stratification was minimal during interglacials, increased until the following termination and then dropped relatively fast. **Previously observed variations of AL are a likely cause of the pattern observed in the southeast Atlantic.**

In **Chapter 3**, the focus is on an interval of prominent climate change, the penultimate termination (T-II, around 130,000 years before present), and address the question as to whether the previously observed AL peak actually penetrated the subtropical gyre circulation. **The outcome gives a positive answer to the research question.** Making use of the oceanographic time series generated with a high-resolution ocean circulation model, it is revealed that high density variability at thermocline depth over the Walvis Ridge is related to the passage of Agulhas rings. Based on this observation, a new proxy is devised that, using the geochemical variability associated with populations of thermocline-dwelling planktic foraminifera, infers **higher presence of paleo Agulhas rings over the core site during T-II**, closely coupled to the published AL reconstructions. This provides necessary

grounding to the hypothesis of an effective role in the AMOC played by the AL during deglaciations.

In **Chapter 4**, still on T-II, I am interested in connecting changes in the temperature and salinity of this delicate area to prominent variability at the AL area, revealed by published records. I am interested also in understanding the role of South Atlantic temperature and salinity in the frame of the T-II rearrangements of the AMOC. To address these questions, temperature and salinity proxies were reconstructed for different depths in the upper water column. Results show high correlation of salinity with the Agulhas rings proxy unravelled from the same core in Chapter 3, and a high degree of connectivity between salinity and temperature at the Walvis Ridge and at the AL area surface. These correlations strongly suggest that **the southeast Atlantic lay directly under the influence of the AL**. Additionally, the results point at a **negative buoyancy of the AL downstream**, potentially due to dissipation of its heat anomaly across the Cape Basin. Another important outcome of this study is that the reconstructed surface temperature and salinity show reversal of their high T-II values at ~133-134 thousand years before present, coinciding with their high counterparts from the AL area. These South Atlantic reversals appear synchronous with climatic events from Northern Hemisphere records. The hypothesis is therefore put forward that **the South Atlantic reacted to the inter-hemispheric seesaw effect of a mid-termination resumption of the AMOC during T-II**, echoing the events of T-I.

Further, this thesis presents work from a core from the western tropical Atlantic Ocean, geographically located close to the continental shelf of NE of Brazil (core MD09-3246, water depth 900 m). The objective here is the reconstruction of the precipitation regime of the adjacent continent over several glacial cycles, and the connection of these changes in sedimentology to changes in atmospheric circulation. It was already shown that precipitation over the NE Brazilian continent, and therefore the intensity of the South American monsoon, increased during the abrupt North Atlantic cooling events of the last glacial period. Moreover, a connection was recently hypothesized between the paleo monsoons of the two hemispheres. A recent

research question is whether displacements of the intertropical convergence zone were synchronous during climate changes of the Pleistocene; in other words: can we talk of a Global-Paleo-Monsoon? I address this question in **Chapter 5** of this thesis, where I present a high-resolution record of continental runoff, and therefore of the intensity of the South American monsoon, which extends previous reconstructions to about 420 thousand years before present. I compared this record to hydroclimate reconstructions from other parts of the continent, from Greenland, and from the Northern Hemisphere tropics (speleothem records of East Asian monsoon). It is concluded that **during the last 420 thousand years the South American monsoon reflected both the effect of regional insolation and, more prominently, that of forcing by high-latitude Northern Hemisphere cold phases.** An important implication of the results, which responds to the main research question, is that **the South America monsoon seems to be coupled, and anti-phased, with the East Asia monsoon during the Pleistocene.** Stepping into the recent debate regarding the existence of a "global-paleo-monsoon", the contribution of Chapter 5 is that both the Austral (South American) and the Boreal (East Asian) monsoon systems responded to climate forcing by high-latitude NH cold phases during the last four glacial cycles. **This points to the Pleistocene persistence of a “global-paleo-monsoon response” to Northern Hemisphere forcing.**