What Ends an Interglacial? Feedbacks Between Tropical Rainfall, Atlantic Climate and Ice Sheets During the Last Interglacial

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Abstract How long the present interglacial will last remains under debate. This project aims to determine the climatic mechanisms and sequence of events terminating an interglacial period. By comparing new paleoclimate reconstructions and climate model experiments, we investigate the impact of South American rainfall changes on tropical Atlantic sea-surface salinity and Atlantic thermohaline circulation at the end of the Last Interglacial (LIG). Model and proxy data show gradually intensifying South American monsoonal precipitation and enhanced Amazon discharge through the LIG, in response to increasing austral summer insolation. However, an increased meridional temperature gradient at the end of the LIG caused a strengthening of the North Brazil Current retroflection which deflected eastward the Amazon freshwater plume. Such changes in South American river discharge contributed to decrease tropical and North Atlantic surface salinities, resulting in a shift in regions of North Atlantic deep water convection and small reduction in deep water formation.

Keywords Last interglacial · Last glacial inception · Tropical precipitation · Atlantic ocean · Sea-surface salinity · Thermohaline circulation · Ice sheet · Model-data comparison

1 Introduction

When and how the present interglacial will end remains an open question (Tzedakis et al. 2012). With a relatively well-known climate, the Last Interglacial (LIG, 129 thousand years (ka) before present (BP)—116 ka BP) provides a unique framework to investigate the climatic mechanisms terminating an interglacial period.

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Although the decrease in boreal summer insolation is the primary driver ending the LIG, vegetation and ocean feedbacks are necessary to initiate ice sheet growth. However, the role of the prolonged North Atlantic warmth observed during the LIG is unclear: did it favor or delay the end of the LIG? Warm North Atlantic waters were likely sustained by an active thermohaline circulation (THC) across the LIG. Climate models, however, show no consistent temporal evolution of the THC throughout the LIG (Bakker et al. 2013), making involved climatic mechanisms uncertain. Past millennial-scale climate variability highlights strong interactions between tropical hydrology and the THC (Krebs and Timmermann 2007). However, the lack of detailed tropical proxy records and adequate simulations prevented investigating the role of feedbacks between tropical rainfall, Atlantic climate and ice sheets in the sequence of events ending the LIG.

By combining new high-resolution paleoclimate records and model experiments, we determine the influence of South American precipitation changes on tropical Atlantic salinity, North Atlantic mixed layer depth and the Atlantic THC. The effects of these changes on ice-sheet inception and growth at the end of the LIG presently remain under investigation.

2 Materials and Methods

We consider a transect of eight sediment cores from the South American margin (12°N–32°S). To reconstruct past changes in South American rainfall and freshwater delivery to the ocean, we applied well-established geochemical methods on the biogenic, terrigenous and organic fractions of the sediment. With the world's largest discharge, the Amazon River is the most likely river to impact tropical Atlantic salinity and the THC. We hence focus here on the northernmost sites (Fig. 1) located along the pathway of Amazon freshwater. We measured the sedimentary elemental composition which allows tracing the provenance of terrigenous material and reconstructing past climate variations over the source regions. We defined regional terrigenous endmembers based on six major elements and applied an endmember unmixing model to deduce the relative proportions of Amazonian Andean versus lowland material at 5°N and 9°N, and of Amazon versus Orinoco material at 12°N. See Govin et al. (2014) for detailed methods.

We use the Community Climate System Model version 3 (CCSM3) to co-verify the South American hydrologic reconstructions and investigate impacts on the climate system. The model was configured with T31 atmospheric resolution coupled to a nominally 3-degree ocean (Yeager et al. 2006). The fully coupled model further includes sea ice and a land surface model. We used CCSM3 for two equilibrated experiments, with orbital parameters and greenhouse gas concentrations at 125 and 115 ka BP as boundary conditions. The 125 ka BP experiment was initialized from a quasi-equilibrated 130 ka BP experiment. In turn, the 115 ka BP experiment was branched from the 125 ka BP experiment following an initial equilibration period. Both 115 and 125 ka BP simulations were allowed to

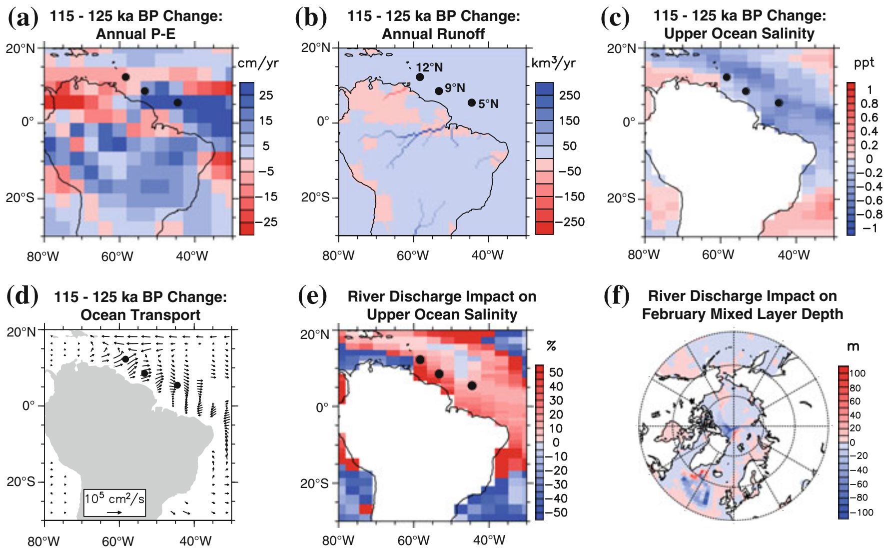

Fig. 1 Changes in South American climate from 125 to 115 ka BP (**a**–**d**). **a** Changes in total annual net precipitation (precipitation–evaporation), **b** changes in runoff, **c** change in upper ocean (0–150 m) salinity, **d** changes in water column integrated oceanic transport. Impact of 115–125 ka BP changes in South American river discharge (**e**–**f**). **e** Fraction of 115–125 ka BP upper ocean salinity change due to river runoff, **f** changes in February mixed layer depth in high northern latitudes linked to river discharge increase from 125 to 115 ka BP. *Black dots* show the locations of marine sediment cores (see caption of Fig. 2 for details)

equilibrate for 700 years. Two additional simulations were performed with 115 ka BP boundary conditions to isolate the impact of changes in river discharge, i.e. with South American river flow fixed to 115 or 125 ka BP conditions.

3 Key Findings

The sedimentary geochemical composition confirms that sites at 5°N and 9°N exclusively receive sediments from the Amazon River, while the Orinoco and Amazon Rivers both contribute to terrigenous input at 12°N (Govin et al. 2014). Cores at 5°N and 9°N exhibit a progressive increase in the relative proportion of Andean material between 126 and 111 ka BP (Fig. 2). It reflects the increasing input of detrital particles from Andean regions, where most of Amazon terrigenous material originates (Guyot et al. 2007), and agrees with the higher precipitation and runoff simulated over most of the Amazon basin at 115 ka BP compared to 125 ka BP (Fig. 1a, b). This result also agrees with western Amazonian speleothem records that suggest strong coupling between the intensity of the South American monsoon and

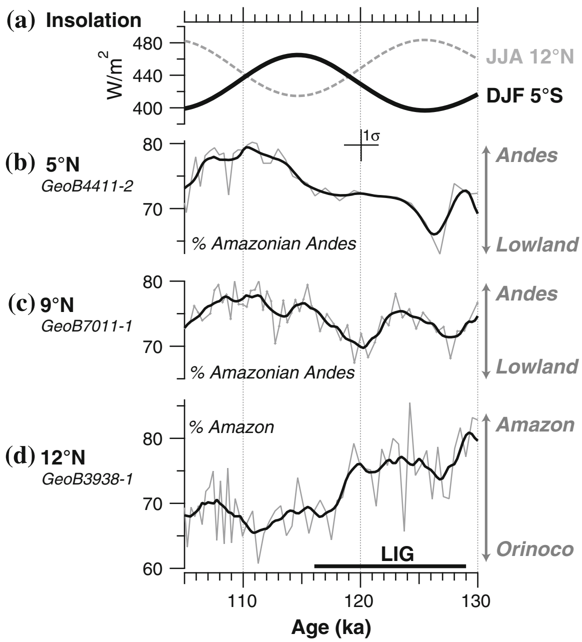

Fig. 2 Paleoclimatic records across the last interglacial (*LIG*). **a** Austral summer (DJF at 5°S, *black line*) and boreal summer (JJA at 12°N, *grey dotted line*) insolation, **b** proportion of Amazonian Andean (vs. lowland) material within the terrigenous fraction of core GeoB4411-2 (5.4°N, 44.5°W, 3,295 m), **c** same as **b** for core GeoB7011-1 (8.5°N, 53.3°W, 1,910 m), **d** proportion of Amazonian (vs. Orinoco) material within the terrigenous fraction of core GeoB3938-1 (12.3°N, 58.3°W, 1,972 m). The *black line* above the X-axis highlights the LIG period, as defined by benthic foraminiferal δ^{18}O values

austral summer insolation variations over the last 250 ka (Cheng et al. 2013). Therefore, the increase in austral summer insolation throughout the LIG (Fig. 2a) enhanced the ocean-land temperature gradient and moisture transport, thereby intensifying precipitation over the Amazon basin. Enhanced rainfall over South America and the adjacent ocean led to the reduced sea-surface salinities (SSS) that are observed close to the Amazon mouth and advected further northward at 115 ka BP compared to 125 ka BP (Fig. 1c). Strong stratification of surface waters indicated by planktic foraminiferal δ^{18}O records at 5°N and 9°N (not shown) supports this result.

While model and proxy data suggest increasing Amazon precipitation and runoff across the LIG, the core at 12°N exhibits a decrease in the relative proportion of Amazon (vs. Orinoco) material that is centered around ~119 ka BP (Fig. 2d). The model also simulates reduced precipitation and runoff in the Orinoco basin at 115 ka BP compared to 125 ka BP (Fig. 1a, b), which agrees with the decrease in boreal summer insolation (Fig. 2a) but seems to disagree with the relative increase in Orinoco input at 12°N (Fig. 2d). In order to reconcile these findings, we suggest that surface ocean currents, which redistribute freshwater input from the Amazon

River, exert a strong influence on the signal at 12°N. Today, the North Brazil Current (NBC) carries Amazon freshwater towards the Caribbean Sea. However, the NBC retroflection deflects up to 70 % of the Amazon plume eastward between July and December (Lentz 1995). In a way similar to cold episodes of the last 30 ka (Wilson et al. 2011), we propose that the NBC retroflection was seasonally intensified or prolonged in duration at the end of the LIG, deflecting oceanward the plume of Amazon freshwater. Such changes would explain the relative decrease in Amazon material recorded around 119 ka BP at 12°N (Fig. 2d), despite increasing Amazon River discharge. The enhanced NBC retroflection simulated by the climate model (Fig. 1d) at 115 ka BP compared to 125 ka BP supports this hypothesis (Wilson et al. 2011). Our experiments isolating the impact of river runoff show that the 16 % increase in Amazon river discharge contributed to the plume of decreased SSS in the tropical Atlantic (Fig. 1e). As a result of the fresher North Atlantic, the position of the North Atlantic Deep Water formation region is shifted southward (Fig. 1f), inducing a significant ($p < 0.05$) 4 % decrease in deep water formation. This change in North Atlantic salinity and circulation led to changes in sea-surface temperatures (not shown), which may impact Northern hemisphere atmospheric circulation and ice sheet inception at the end of the LIG.

In summary, our model-data comparison indicates substantial shifts in South American hydrologic cycle and upper tropical Atlantic salinities that may impact the THC and North Atlantic climate at the end of the LIG.

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