Hydrology and Climatology at Laguna La Gaiba, lowland Bolivia: complex responses to climatic forcings over the last 25,000 years

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Pre review version. Published as Metcalfe et al. 2014 JQS 29, 289-300, doi:10.1002/jqs.2702

Abstract

Diatom, geochemical and isotopic data provide a record of environmental change in Laguna La Gaiba, lowland Bolivia, over the last ca. 25,000 years. High-resolution diatom analysis around the last glacial – interglacial transition provides new insights into this period of change. The full and late glacial lake was generally quite shallow, but with evidence of periodic flooding. At about 13,100 cal a BP, just prior to the start of the Younger Dryas chronozone, the diatoms indicate shallower water conditions, but there is a marked change at about 12,200 cal a BP indicating the onset of a period of high variability, with rising water levels punctuated by periodic drying. From ca. 11,800 to 10,000 cal a BP stable, deeper water conditions persisted. There is clear evidence for drying in the early to mid Holocene, but not as pronounced as that reported from elsewhere in the southern hemisphere tropics of South America. This was followed by the onset of wetter conditions in the late Holocene consistent with insolation forcing. Conditions very similar to present were established about 2,100 cal a BP. A complex response to both insolation forcing and millennial scale events originating in the North Atlantic is noted.

Key words: tropical South America; diatoms; Younger Dryas; geochemistry; last glacial-interglacial transition

Introduction

The environmental history of the southern hemisphere tropics of South America has become the focus of increasing interest, particularly the glacial precipitation regime of the tropical lowlands and its variability across the last glacial-interglacial transition. To date, the majority of lake studies from the region have focused on pollen and geochemical records, with limited use of diatoms as indicators of past change (Colinvaux *et al*., 2000; Mayle *et al*., 2000; Bush *et al*., 2004; Cordeiro *et al*., 2011; D'Apolito *et al*., 2013). In 2011 Whitney *et al*. published a 45,000 year palaeoclimatic record from Laguna La Gaiba in the Pantanal wetlands, based largely on the pollen record. Here we present an environmental reconstruction based on the diatom record (changes in water balance and water chemistry), complemented by geochemical and carbon isotopic data from the same core. Diatom analysis has been carried out at high resolution (every 50 – 100 years) through the Younger Dryas chronozone (ca. 12,900 to 11,700 cal a BP, Rasmussen *et al*., 2006) to provide new insights into the nature of the last glacial – interglacial transition (LGIT) and the associated high frequency climate fluctuations. Most existing lake records do not have the resolution necessary to explore this important interval, so our new data make an important contribution to understanding the expression of climate variability in the interior of tropical South America.

Study site

Laguna La Gaiba (17°45'S, 57°35'W) is a large lake in the Pantanal wetlands, in the upper basin of the Paraguay River (McGlue *et al*., 2011) (Fig. 1). The Pantanal is the world's largest freshwater wetland and at maximum inundation, covers more than 130,000 km^2. It contains thousands of lakes, the majority of which are ephemeral, but La Gaiba is one of a series of permanent lakes on the western margin of the Pantanal, along the Paraguay River lying within the Serra do Amolar (McGlue *et al*., 2011). La Gaiba itself can cover up to 100 km^2 during peak flood and maximum water depth varies between 4 and 6 m (Whitney *et al*., 2011). It receives surface inflow from the north west (from the Laguna Uberaba via the Corixo Grande) and west and drains to the north east over a sill into the Paraguay River, linking the lake with the Pantanal wetlands. The basin itself is divided into a shallow, northern sub-basin (< 3 m deep) and a deeper southern sub-basin (up to 6 m deep) (Whitney *et al*., 2011). The northern basin is bounded by extensive areas of aquatic vegetation (grasses and water hyacinths), while the southern part is more confined, less vegetated and bounded by hills. There is a narrow fringe of evergreen floodplain forest along the southern margin of the south basin, beyond which palm swamp occupies the low-lying terrain south of the lake. The lake water is dilute (EC 60 to 83 $\mu S\ cm^{-1}$), slightly alkaline (pH 7.7. to 8.6) and of Ca/Mg HCO_3 composition (Fitzpatrick unpublished data; McGlue *et al*., 2011).

The hydrology of the basin (and the wetlands in general) is controlled by the flood cycle of the Paraguay River, driven by convective precipitation during the austral summer (October to April) associated with the South American Summer Monsoon (SASM) (Zhou and Lau, 1998). Moisture is also brought into the Pantanal from the Amazon basin by the South American Low level jet (Fig. 1) which forms in response to development of the Chaco low (Garreaud *et al*., 2009). Precipitation varies from about 1700 mm per year in the north of the Pantanal to 1000 mm in the south, 70% of this falls in the summer (November to March). There is a delay between peak summer rainfall and peak water levels in the Pantanal (when the Paraguay River and its associated lakes overflow), which increases from north to south across the wetlands. In the central wetlands (including La Gaiba) this delay is several months (Alho, 2005; McGlue *et al*., 2012). Studies of precipitation, discharge in the Paraguay River and inundation area of the wetlands (Hamilton, 2002; Alho, 2005) have confirmed that there is a clear relationship between precipitation amount (monsoon strength) and water levels in the Pantanal wetlands and lakes, hence lake level variations in La Gaiba can be taken as being indicative of broad scale precipitation changes associated with changes in the SASM.

Methods

In 2001, coring was carried out in the deepest part (> 5 m water depth) of the south basin of Laguna La Gaiba using a 'Colinvaux-Vohnout' drop-hammer modified Livingstone piston corer and a Perspex tube and piston (for the soft surface sediments). Parallel, overlapping cores were collected using the Livingstone corer, which were cross correlated using magnetic susceptibility and pollen analysis. The surface core was correlated with the top of the Livingstone sequence based on loss-on-ignition (at 550^oC). The final composite sequence was 560 cm long. Dating control is based on a total of 19 ^{14}C AMS dates (mainly on terrestrial plant macrofossils, see Table 1), of which one Pleistocene date was rejected as being anomalously young (details in Whitney *et al.*, 2011). The dates were calibrated using the Fairbanks radiocarbon calibration program (Fairbanks *et al.*, 2005) and indicate that the core sequence provides a record of the last ~ 42,000 cal a BP.

The core has been analysed for a range of physical, chemical (including isotopic) and biological (pollen and spores, diatoms) parameters to help to provide a multi-dimensional picture of change in this part of the Pantanal over the late Pleistocene and Holocene. Magnetic susceptibility (χ) was measured at 2 cm intervals on the Livingstone cores using a Bartington Instruments loop system (in SI units). Unfortunately, the unconsolidated nature of the surface sediment core meant that it was unsuitable to run through the loop. Particle size analysis of 2 cm-thick slices at ca. 10 cm intervals was carried out on 33 samples using a Coulter LS230 particle size analyser, following air drying, sieving, crushing and treatment with dilute HCl and HNO_3 to remove carbonate and organic matter, respectively. Calgon was added to the samples as a dispersal agent prior to analysis. Both χ and particle size analyses can help to identify periods of catchment disturbance and inwash.

LOI at 550^o and 1000^oC of 1-cm thick slices was determined at 2 cm intervals on both the Livingstone and surface sediment cores. Results are expressed as % C and % carbonate respectively.

Percent total organic carbon (%TOC), C:N and $\delta^{13}C$ analyses were performed at Swansea University to help identify potential sources of organic matter. An aliquot of the dried core material (*ca.*1 cm^3) was gently crushed and washed with an excess of

5% HCl to remove carbonates, rinsed with deionised water to remove any residual HCl and dried at 60°C for 48 hours. Stable carbon isotope analyses and C:N ratios were measured using a PDZ Europa ANCA GSL Elemental Analyser coupled with a 20/20 isotope ratio mass spectrometer. Samples of the dried sediment were weighed into tin foil capsules and combusted over chrome oxide in helium with excess oxygen at 1000°C. The resulting gases were reacted over hot copper (600°C) to reduce oxides of nitrogen and the resulting CO_2 and N_2 resolved gas chromatographically. Elemental composition and C:N ratios were calculated based upon peak areas relative to standard reference materials acetanilide and atropine. For stable carbon isotope analysis, samples yielding peak values equivalent to between 100-150 µg of carbon were weighed into tin capsules and combusted on-line as described above. The isotopic ratio of the resulting carbon dioxide gas was reported as per mille (‰) deviations from the VPDB standard. Replicate analyses of laboratory reference and standard materials yielded the following precision data ($n=12\sigma_{n-1}$): 0.10%, 0.65%, and 0.09‰ for %N, %C, and stable carbon isotopes, respectively.

XRF analysis of the Livingstone core was carried out using the ITRAX core scanner (Croudace *et al.*, 2006) at Aberystwyth University at a step size of 2000µm or 500µm. Again, the surface sediment core was unsuitable for this analysis. The data have been normalised against incoherence and smoothed to a plotting resolution of approximately 50 years based on the age-model detailed above.

Diatom samples were prepared following standard procedures (Battarbee, 1986) to remove carbonate and organic matter. The Pleistocene and Holocene sequences were sampled at ca. 400 and 150-200-yr resolution, respectively, although sediments spanning the Younger Dryas were sampled at especially high resolution (50 – 100 yr, every 2 – 3 cm) to enable potentially abrupt changes in diatom assemblages to be captured across this interval. Samples were mounted using Naphrax and counted at x1000 magnification. A minimum of 400 diatoms were counted per sample and results expressed as relative percent abundance. Identification and ecological interpretation was based on both standard texts (e.g. Krammer and Lange-Bertalot, 1986, 1988; 1991 a and b; Patrick and Reimer, 1966; Schmidt *et al.*, 1874-1959) and regional floras (e.g. Metzeltin and Lange-Bertalot, 1998, 2007; Rumrich *et al.*, 2000). To help with the interpretation of the core record, in 2006 modern surface samples were collected from 19 locations across the basin and analysed in the same way as the core material. These samples have been particularly valuable in exploring the relationship between diatom assemblages and water depth (see Whitney *et al.*, 2011).

The stratigraphic plots of the diatom data were made using C2 (Juggins, 2003); only diatom taxa present at >1% in three or more of the samples, were included. Zonation was carried out using Psimpoll and 'optimal splitting by information content' (Bennett, 2007). Based on this, 6 diatom zones (DZ) were identified in the part of the core dating between ca. 25,000 cal a BP and present. Prior to this, no countable diatoms were preserved. Diatoms were also grouped by ecological preference (e.g. planktonic, facultatively planktonic/littoral, aerophilous) based mainly on information in regional floras (see above) and the modern diatom samples from the lake (see Table 2).

DCA (detrended correspondence analysis) was performed on the diatom assemblage data (all taxa present in at least three samples) from the core using the VEGAN package in the program R (R Development Core Team, 2007). This was applied to help identify patterns of community variation through time.

Results and Interpretation: stratigraphy, diatoms and sediment chemistry

The core stratigraphy shows a predominance of clays, mixed with charcoal and wood fragments toward the base of the sequence, between about 30,000 and 24,000 cal a BP, and between about 21,000 and 16,000 cal a BP. The latter period also has sand in the matrix. The last glacial – interglacial transition (LGIT, ca. 16,000 – 11,000 cal a BP) shows a mixture of clays and organic matter, while the Holocene part of the core is notable for its higher organic content (Fig. 2). The trend of increasing organic matter is clearly reflected by LOI at 550°C and by TOC, which reaches nearly 10% in the mid Holocene. Over the full core, the average value of $\delta^{13}C$ is -24‰, with a range from -21‰ (in the mid Holocene) to -29.5‰ (in the late glacial). C/N values average 13.5, with a range from 8 (in the most recent sediments) to 16 (ca. 39,000 cal a BP). Used together, the combination of C/N and

$\delta^{13}C_{organic}$ (Fig. 2) can provide a powerful tool to identify sources of organic matter (Meyers and Teranes, 2001). However, the C/N values here are all within the range for algal or mixed algal/terrestrial plant sources, with no values (> 20) clearly indicative of higher land plant inputs only. They are significantly lower than those reported from a number of other studies in lowland South America (e.g. Sifeddine *et al*., 2003; Cordeiro *et al.*, 2011). The relationship between C/N ratio and $\delta^{13}C_{organic}$ indicates no clear trend over time in the core, with only the most recent core samples being distinct (see below). Changes in $\delta^{13}C_{organic}$ alone can provide an indication of organic matter source, with low values for C3 plants and higher values for C4 (means of -27‰ and -13‰, respectively, reported by Ruiz Pessenda *et al.*, 2009). Where algae use dissolved CO_2 in equilibrium with the atmosphere, their $\delta^{13}C_{organic}$ values are approximately the same as those of C3 land plants (Meyers and Teranes, 2001), however high productivity may lead algae to use dissolved bicarbonate from the water column, resulting in higher $\delta^{13}C_{organic}$ values. Jacob *et al.* (2004) report algal values of around -20‰ from a site in northern Brazil.

Initial diatom sampling showed that prior to ca. 25,000 cal a BP, diatoms were either absent or too poorly preserved to be counted. As a result, the study was focused on the more recent part of the core (top 2.5 m). In the rest of this section, the part of the La Gaiba sequence with diatom preservation (i.e. younger than ca. 25,000 cal a BP) is discussed. The following section then puts these results into the context of the full core record (extending to ca. 45,000 cal a BP), including the previously published pollen data.

Horizons > 25,000 cal a BP, no preserved diatoms: The full diatom record from the La Gaiba core is shown in Figure 3a and the results of a DCA of these data in Figure 4. As mentioned above, diatoms were only preserved in sediments younger than 25,000 cal a BP; a few valves are present in older sediments, but are too sparse and poorly preserved to be identified securely and interpreted. Just prior to the start of the diatom record, higher magnetic susceptibility (χ) and Fe/K indicates increased catchment inputs between about 30,000 and 24,000, although C/N values and $\delta^{13}C$ remain fairly stable.

Diatom Zone 1: Between 24,500 and about 13,100 cal a BP (DZ1), the assemblages are dominated by *Staurosira* species (*S. construens* and *S. construens* var. *venter*) and *Aulacoseira* species (primarily *A. granulata* var. *valida* and *A. ambigua* var. *robusta* with lower percentages of *A. distans*). It should be noted that *Staurosira* and *Staurosirella* were all formerly part of the genus *Fragilaria*, and were referred to as such in Whitney *et al.* (2011). The most abundant taxa in these assemblages have been classified as facultatively planktonic/littoral, based on both published ecological records (e.g. Kilham and Kilham, 1975; Gasse, 1986) and their presence in the modern surface sediments (although *A. granulata* var. *valida* was only recorded in small amounts in these, see Whitney *et al.*, 2011). The *A. granulata* complex has been described as a cosmopolitan freshwater group, which is common in shallow lakes, the margins of large lakes and in rivers (Stone *et al.*, 2011). Based on samples from East Africa, Gasse (1986) reports *A granulata* var. *valida* as occurring in alkaline lakes of relatively high pH (> 8.5), although it was only found in low percentages (< 5%) in the modern sediment samples at Laguna la Gaiba. The highest percentages of *A. ambigua* var. *robusta* in the modern samples (up to 60%) were collected from water depths of between 2 and 5.5 m, in both the north and south basins. *Staurosira* species were not common in the modern sediments, occurring mainly in the shallower water of the north basin. As *S. construens* is a major component of the diatom assemblages in this zone, especially between about 18,000 and 14,000 cal a BP, its ecological interpretation is important. It was not abundant in the modern surface sediment samples at LAGUNA LA GAIBA and does not appear to be that common in South American records, although Haberzettl *et al.* (2005) interpret it as littoral in their Patagonian record. Gasse (1986) based on modern samples from East Africa describes it as being common in the shallow areas of lakes and swamps of medium pH (> 7) and alkalinity. The limited numbers of *A. granulata* var. *valida* were also present in the north basin, indicating that it may be facultatively planktonic here. The overall dominance of *Staurosira* spp. (often more than 60%) probably indicates relatively shallow water, with the more heavily silicified *Aulacoseira* valves being kept in the water column by mixing. It is interesting to note that today, during the austral winter, high winds that accompany cold polar fronts from the southern high latitudes (locally known as 'surazos'), mix the shallow Laguna La Gaiba. We can speculate that these may have been more common during the last glacial, a suggestion also made by Bush and Silman (2004) and Cruz *et al*. (2006).

The pH and conductivity of the lake may have been higher from 24,500 to 13,100 cal a BP compared with the modern Laguna La Gaiba. Abundant *A. granulata* and *A. distans* have been reported from the south Pantanal floodplain and the Parana River during post-flood periods when water levels were falling (Train and Rodriques, 1998; de Oliveira and Colheiros, 2000), so periodic flooding may be indicated here. Although the interval between 21,000 and 16,000 cal a BP has a higher visible sand content than the earlier parts of the core, there is a more muted response in χ. Between 16,000 and 13,000 cal a BP, there is one marked peak in LOI (550^{o}C), which probably reflects a terrestrial macrofossil or piece of charcoal captured by the core. C/N shows a small increase, while the falling trend in $\delta^{13}C_{organic}$ is more pronounced, reaching its lowest recorded level of the whole core (- 29‰) at the end of this interval. The slightly elevated C/N values (> 14) probably means that the low ^{13}C values are due to input from terrestrial plants. There is a slow rise in %TOC and an increase in Rb/K possibly reflecting greater weathering.

Diatom Zone 2; Between about 13,100 BP and 12,200 cal a BP (DZ2) there is a minor change in the flora, with species of *Staurosirella* (*S. pinnata*, *S. pinnata* var. *lancettula*) becoming more abundant and a peak in *A. distans* (>20%). *A. distans* was reasonably common in modern surface sediment samples (see Whitney *et al.*, 2011), being most abundant in samples near the junction of the northern and southern sub-basins and at more marginal sites in the southern sub-basin. *A. distans* was reported from Lake Fuquene (Colombia) in water 2 – 5 m deep (Velez *et al.*, 2003) and from rivers in the state of Parana in Brazil (Dunck *et al.* 2012). It is described by Gasse (1986) as being littoral, sometimes aerophilous. The presence of this taxon therefore probably indicates shallower water than the other species of *Aulacoseira*. The DCA of the core samples clearly places all the assemblages from DZ1 and DZ2 towards one end of axis 1, with no overlap with the assemblages recorded over the last 10,000 years. It is notable that although DZ2 corresponds in time to the early part of the YD chronozone, there is only a muted response recorded by the diatoms. At ca. 13,100 cal a BP there is a further peak in χ and wood fragments are present. These may reflect events associated with the onset of climate change associated with the YD, only some of which persisted through time.

Overall, the period from about 24,500 to 12,200 cal a BP appears to reflect a generally shallow lake with periodic flooding. This flooding and the associated catchment disturbance may have been most intense prior to about 24,000 and just after the last global glacial maximum (20,000 to 16,000). The relative decline in *A. ambigua* and increase in *Staurosira* spp. probably indicate that during the period after the LGM the water level was lower than before. This shallowing trend seems to continue into DZ2, with subtle changes in species composition, such as greater abundance of *Staurosirella*.

Diatom Zone 3; The period from 12,200 to 11,800 cal a BP is marked by an abrupt change in the diatom assemblage, with *A. ambigua* becoming dominant (up to 90%) (Fig. 3a). This marked shift (ca. 12,200 – 11,800 cal a BP) coincides with the later part of the YD chronozone and indicates a more profound change in regime than earlier in the YD interval. The detailed diatom record from the period encompassing the last glacial-interglacial transition is illustrated in Figure 3b. *A. ambigua* is a planktonic taxon and was moderately abundant in surface sediment samples from the modern lake; it was most abundant at the core site, where it formed 60% of the surface sediment assemblage (Whitney *et al.*, 2011). Gasse (1986) reports this species as being most abundant in lakes of pH 6.5 – 8 and EC 70 – 400 µS cm^{-1}, very like the modern La Gaiba. This seems to indicate that the lake became fresher, as well as deeper, compared with DZ1 and DZ2. In the modern samples, the distribution of *A. ambigua* was most strongly associated with water depth, confirming this interpretation of increasing water depth. It is also possible, however, that a reduction in nutrient availability drove a change in the dominant *Aulacoseira* species, away from the coarse-pored form (*A. granulata* var. *valida*) (Kilham *et al.*, 1986). *A. ambigua* has high light requirements, so less turbid conditions are indicated. It is interesting to note that over the same interval as these very high percentages of a planktonic diatom, there are also peaks in aerophilous taxa (*Eunotia camelus* and *Diadesmis confervacea*) (Velez *et al.*, 2006). *Diadesmis confervacea* peaks at 12,300 cal a BP at the transition of DZ2 to DZ3, and *Eunotia camelus* increasing up to 27% around 12,000 cal a BP. A seasonally dynamic environment may be indicated. *A. italica* makes its first notable appearance in this zone (up to 14 %). This species was not found in either sediment or water samples from the modern

Laguna La Gaiba and also appears to be quite rare in South American records. Velez *et al.* (2005a) report it from Colombia as occurring in very shallow water, with occasional desiccation. Gasse (1986) and Germain (1980) both record it as a littoral form. Taken together, these indicators may suggest that the later YD interval was a period of rapid change with strong flooding episodes (deep water) and erosion, punctuated by brief (possibly seasonal) dry periods. The mix of planktonic and littoral/aerophilous taxa might reflect the flooding of previously dry areas around the lake as the water level rose, stronger seasonality or a change in seasonality so that the offset between rainfall peak and inundation peak was reduced leading to drier conditions in the dry season than occurs today (Hamilton *et al*., 2002).

Diatom Zone 4; The transition into the Holocene (DZ4, ca. 11,800 to 10,000 cal a BP) is marked by another abrupt change in diatom assemblage, with *A. granulata* var. *valida* and *A. ambigua* var. *robusta*, both important in the glacial sediments, dominating (Fig. 3a). A difference between DZ4 and DZ1 and DZ2 is the absence of *Staurosira* and *Staurosirella* species. In spite of this difference, the overall similarity to a glacial type assemblage is illustrated by their overlapping position on axis 1 of the DCA (Fig. 4). As described above, *A. granulata* var. *valida* was only present in low percentages in the modern sediment samples from the lake, although it dominates here. It has, however, been reported in plankton samples from the Lago dos Tigres hydrological system in Brazil (Dunck *et al.* 2012) a similar mix of riverine (lotic) and lacustrine (lentic) environments. Based on the findings of Kilham *et al.* (1986), the shift from fine pored *A*. *ambigua* (dominant in DZ3) to the coarse pored forms *A. ambigua* var*. robusta* and *A. granulata* var. *valida* (DZ4) may indicate lower light levels and higher nutrient levels; an interpretation supported by the presence of some *A. granulata* varieties. The lake may also have shifted to higher pH and EC.

Over the period represented by DZ3 and DZ4, $\delta^{13}C$ moves abruptly to higher values (ca. -24‰) (Fig. 2) and these persist through much of the Holocene. There is also a small peak in Rb/K (Fig. 2) which may reflect higher levels of chemical weathering, although this trend started in the late glacial and may reflect warming.

Diatom Zone 5; The change in diatoms at around 10,000 cal a BP (Fig. 3a) is the most distinct in the entire sequence, being the first split in the zonation; the diatom DCA also clearly isolates the samples from 10,000 cal a BP on from the full glacial samples (Fig. 4). DZ5 covers the whole period from 10,000 cal a BP to ca. 2,100 cal a BP, with a flora dominated (> 60%) by *A. ambigua* (as the YD), accompanied by *A. italica* and forms of *Staurosira*. Unlike the glacial part of the core, *Staurosira* spp. are relatively uncommon. The DCA shows some overlap between this assemblage and that in DZ3, although the trend through DZ5 and into DZ6 separates the assemblage more distinctly from DZ3 along axis 2 (Fig. 4). *A. ambigua* were present (but rarely dominant) in the modern sediment samples, but its variety *robusta* were often dominant (see above and Whitney *et al.*, 2011). *A. italica* returns to levels at, or above, those in DZ3, peaking towards the top of this zone at 47%. Between about 9000 and 5000 BP there are small peaks in aerophilous (e.g. *Diadesmis confervacea*) and benthic taxa (e.g. *Navicula* and *Craticula* spp.). Small peaks in *S. construens* and *S. lapponica* f. *lanceolata* also occur. Both these taxa were present, but rare, in modern surface samples, being found mainly in sites in the shallower northern sub-basin. Overall, rather variable conditions are indicated, perhaps with distinct seasonal drying and fall in water levels. The period between about 5000 and 2100 BP was particularly stable in respect of the diatom flora, which reflects deep water conditions.

Although the core stratigraphy indicates little or no visible change over this period (organic matter and clay throughout), the geochemical and other data show two discrete phases. The earlier phase, prior to 4000 cal yr BP, is marked by (i) the highest TOC values of the entire sequence; (ii) evidence for the presence of carbonate (LOI 1000^{o}C); (iii) the highest Ca/Ti of the whole sequence; (iv) persistent high δ^{13}C that reached the highest values of the entire record (-21‰) (Fig. 2). These geochemical and sedimentological indicators, together with peaks in benthic/aerophilous taxa, provide clear evidence of drying in the early to mid Holocene. Concurrent with these indicators, peaks in both particle size and in magnetic susceptibility (χ) may reflect periods of high variability with increased inwash from the catchment, perhaps associated with flood pulses. Hamilton et al. (1997) suggest that organic matter (OM) in the Pantanal wetlands may be derived from flood events and it is notable that %TOC in our La Gaiba core also peaks in this period (see Fig. 2).

Diatom zone 6; At the top of the core (the last 2,100 years), the diatom assemblages are dominated by *A. ambigua* (> 60%), *A. granulata* (up to 20%) and *A. ambigua* var. *robusta*. The shift in *Aulacoseira* spp. probably reflects a return to more turbid (low light) conditions and increased nutrient levels (Kilham *et al.* 1986). *A. granulata* has been recorded in percentages similar to those found here in shallow lakes in Colombia (Velez *et al.*, 2005a and b), but is also reported as being very common in South American flood plain rivers (e.g. the Parana, Orinoco, Amazon and Paraguay), so it is possible that its increasing abundance here reflects more fluvial input (De Oliviera and Calheiros, 2000). The diatom assemblages in the samples from the top of the core are similar to those in the modern surface sediment samples (Whitney *et al*., 2011), suggesting near modern conditions over the last ca. 2,100 years. This part of the core sequence shows a drop in TOC and C/N (to 8, the lowest values in the record), a fall in $\delta^{13}C_{organic}$ (to ~ -28‰ at the top of the core) and a sharp decline in carbonate as recorded by LOI at 1000^{o}C (Fig. 2). The C/N and $\delta^{13}C_{organic}$ values here are distinct from the rest of the sequence and appear to reflect algal dominance of organic matter which is distinctive from the rest of the core where a mix of terrestrial and algal sources is demonstrated. Unfortunately, there are no χ or XRF scanner data for this part of the core, but generally more stable and perhaps increasingly lacustrine (wetter) conditions, may be indicated. The most recent changes in diatom assemblage (e.g. *Cyclostephanos* sp.) may reflect further increases in nutrient input.

Comparison with other published La Gaiba records

This reconstruction of the last ca. 25,000 years needs to be put into the wider context of the full core record, especially that provided by pollen (Whitney *et al.*, 2011), the alga *Pediastrum* (Whitney and Mayle, 2012) and an independent Holocene record from the same lake (McGlue *et al.*, 2012).

Zonation of the pollen record (Whitney *et al.*, 2011) indicated the presence of only three major pollen zones. Of these zone boundaries, only one from 12,200 cal a BP coincided with a zone boundary in the diatom record. Evidently, these two palaeoecological proxies are responding in slightly different ways to changes in the climate of the Pantanal and its wider region. Unlike the diatoms, the pollen record extends through the whole period of the core, with zone one extending up to 19,500 BP. This glacial part of the record shows an open landscape with fewer trees and cooler temperatures. Higher magnetic susceptibility (χ), C/N values and the presence of wood fragments and charcoal at the base of the core (ca. 42,000 to 38,000) probably indicate catchment disturbance and inputs of terrestrial material. Peaks in Fe, Al, Mn and Fe/K from XRF analysis support this interpretation (Fig. 2), as do the slightly higher C/N and higher $\delta^{13}C_{organic}$ values. The vegetation, however, shows no response at this point. The abundance of herbs through this part of the pollen record (see Whitney *et al.*, 2011) may explain the higher values of $\delta^{13}C_{organic}$ over this interval. The diatom record is consistent with this interpretation of drier conditions.

The pollen record shows a marked change at 19,500 cal a BP (Fig. 5) with the expansion of two distinctive tropical forest formations: seasonally inundated forest onto the exposed margins of the lake and the establishment of seasonally dry tropical forest (SDTF) on the surrounding hills (Fig. 5). This expansion of floodplain trees corresponds to a shift in $\partial^{13}C_{organic}$ to lower values (consistent with an increase in C3 plants). Warming and periodic inundation of the seasonally dry shallows are indicated. There is no clear evidence in the diatom record for the shift at around 19,500 indicated by the pollen record, perhaps supporting the interpretation of Whitney *et al.* (2011) that this change in vegetation is primarily a response to temperature. The diatom record indicates shallower water after the LGM than before, which may be a response to increasing evaporation over this period (although not enough to affect water chemistry significantly). The effects of post-glacial warming may also be seen in the increasing values of Rb/K, possibly as weathering increased. Overall, however, the diatom and pollen records are consistent. In contrast to the pollen record, there is a change in the diatoms at ca. 13,100 cal a BP (just prior to the start of the YD) when conditions shallower than previously are indicated. This is different from the previously published coarser resolution diatom analysis (using the pollen zones) that suggested water levels may have started to rise from 12,800 (see Whitney *et al.*, 2011).

As described above, the change in Laguna La Gaiba at around 12,200 cal a BP is clear in both the pollen and diatom records (Fig. 5), when rising water levels apparently eliminated the floodplain forest due to permanent inundation of low-lying habitat around the lake shore. Peaks in aerophilous diatom taxa within a period otherwise dominated by the planktonic *A. ambigua*, may indicate more variability in the inundated area over the period up to ca. 11,800 BP (DZ3) than is suggested by the pollen data and may be reflected by the spike in LOI at 550^{o}C (Fig. 2). More stable, deeper water conditions are then indicated in DZ4 and apparently also recorded by *Pediastrum* species (Whitney and Mayle, 2012). After 12,000 cal a BP, there is a return to higher values of $\delta^{13}C_{organic}$ that persisted into the late Holocene. An expansion of C4 terrestrial vegetation is probably not the explanation for this (see Whitney *et al.*, 2011) so it may reflect high algal productivity or an expansion of C4 aquatic Poaceae. There is no major change in C/N that might help to shed further light on this.

The change at 10,000 cal a BP is more pronounced in the diatom record than the pollen record. In the early to mid Holocene (ca. 10,000 to 6,400 cal a BP), the pollen record has been interpreted as recording a drier, more seasonal precipitation regime, with the expansion of drought adapted SDTF. This is entirely consistent with diatom and sediment chemistry data for this period and with changes in the species of *Pediastrum* found in the core. It is also consistent with the reconstruction of McGlue *et al.* (2012) for the period between 9000 and 6200 cal a BP, although we see no evidence for their proposed mid Holocene (6200 to 5300 cal a BP) lake expansion. There is no evidence in our record for the major drought and possible desiccation of Laguna la Gaiba in the later Holocene (5300 to 2600 cal a BP), when the diatom record shows stable, deeper water conditions and the *Pediastrum* record also indicates wetter conditions after about 4000 cal a BP. The occurrence of modern conditions over the last ca. 2000 years is consistent across the records. Although it is interesting to speculate that the occupation of basin shorelines (indicated by the presence of ceramics and stone carvings) as reported by McGlue *et al.* (2012) might help to explain the changes in diatoms at the very top of the core as additional nutrients entered the system, no maize or other cultivated plant pollen has been found in these sediments to support this contention.

Discussion

The diatom and sediment chemistry records from a core from Laguna La Gaiba offer new insights in system change over the late Pleistocene and Holocene, particularly the LGIT. This record is generally consistent with that based on the pollen record and the palaeoclimatic conclusions drawn by Whitney *et al.* (2011) are generally confirmed, including drier conditions around the LGM, a relatively dry early – mid Holocene (but with no evidence for extreme mid-Holocene drying) and the onset of modern, wet conditions thereafter. A complex response to insolation driven change in the SASM is demonstrated, with La Gaiba being relatively dry at the time of the insolation peak near the LGM, but wet in the late Holocene (Fig. 5). Differences in records of SASM strength around the LGM between records from western Amazonia and the Altiplano have also been noted by Mosblech *et al.* (2012). Variability along this W-E transect across South America is discussed further below.

The impact of the Younger Dryas, originating in the North Atlantic, on the climate of tropical South America is confirmed. The higher-resolution record and independent diatom zonation presented here (compared to previous pollen and diatom analyses) results in a distinct difference in the interpretation of conditions in the transition into the early part of the YD chronozone. The diatom record (DZ2) shows shallow conditions until ca. 12,200 cal a BP, not the onset of rising water levels at 12,800 cal a BP originally suggested by Whitney *et al.*, (2011). Corroborated by the rapid decline in floodplain forest pollen, in DZ3 (the later part of the YD chronozone) the diatoms do seem to indicate an abrupt increase in water levels, even if punctuated by periods of very low water, perhaps driven by changes in seasonality. The nature of change across the YD interval inferred here is different from the classic pattern of reversion to glacial conditions. Instead, we demonstrate that this period experiences a highly variable precipitation regime, with the onset of a wetter climate in the later part of the YD. The two stage nature of change across the YD interval indicated here is also of interest. A similar structure to the YD has been reported elsewhere including Lea *et al.* (2003) from the Cariaco Basin; Sifeddine *et al*. (2003) from Lake

Caçó, Brazil; Flower *et al.* (2004) from the Gulf of Mexico and Rein *et al.* (2005) based on a marine record from coastal Peru. Unfortunately, integrating these patterns (warmer/cooler, wetter/drier) in terms of coherent climatologies seems impossible at this stage.

Conditions in low latitude South America during the YD remain rather uncertain. In the northern part of South America, Van der Hammen and Hooghiemstra (1995) and Rull et al. (2010) describe a cool and dry YD in the Colombian and Venezuelan Andes respectively and there is reduced continental runoff recorded in the Cariaco Basin. In a record from the Amazon Fan Maslin *et al.* (2000) also report a dry YD, but with a short lived major peak in Amazon discharge around 11,400 BP, which the authors associate with Termination 1B. In contrast, the Botuvera stalagmite record (Wang *et al.*, 2007) and lake records from the Bolivian Altiplano (Baker *et al.*, 2001) show wet conditions. Ledru *et al.* (2006) suggest that the apparent contrast in conditions in north east Brazil between inland and northern locations (dry YD) and coastal locations (wet YD) might reflect a greater influence of winter precipitation along the coast. This, however, seems a very unlikely explanation for wet conditions in the Bolivian Altiplano. Another explanation may be a difference between regions more directly affected by the ITCZ (e.g. north east Brazil) and areas where convection (more monsoon-type) dominates (Garreaud *et al.*, 2009). Such an explanation might also explain the contrast in full glacial conditions between Laguna la Gaiba and NE and SE Brazil noted by Whitney *et al.* (2011). A similar mechanism has been suggested by Bush and Silman (2004). Again, it is difficult to place the Altiplano sites into this framework as convection over Amazonia is usually identified as the main moisture source for this area, although Vizy and Cook (2007) have suggested that a delayed onset of the SASM at the LGM with reduced convection over Amazonia (weaker Chaco Low and low level jet) could have led to enhanced easterly flow from Amazonia to the Andes causing the wetter conditions recorded by the Altiplano lakes and the drier conditions over Amazonia. Cooling early in the YD could have had the same effect, but the expression of the later YD is different. Some of the complexity of the YD across the tropical Americas is discussed by Bush and Metcalfe (2012). It is increasingly evident that the structure of Greenland ice core $\delta^{18}O$ records is not a straightforward template for hydroclimatic change in the tropics (Deplazes *et al*., 2013).

The Holocene sequence from La Gaiba shows the persistence of generally wet conditions, but with evidence of drying in the early to mid Holocene. This drying is very muted compared with that in other records from the southern hemisphere neotropics (e.g. Baker *et al.*, 2001), although it may reflect differential sensitivity between tropical forest pollen and diatoms in response to drying. The strengthening of the SASM in the later Holocene has been widely reported as a response to insolation forcing, with southward expansion of the Amazon rainforest (Mayle *et al.* 2000; Burbridge *et al.*, 2004) and SDTF (Taylor *et al.*, 2010) in more southerly locations and wetter conditions recorded by speleothems east and west of Amazonia (Wang *et al*., 2006; Mosblech *et al*., 2012). As Mosblech *et al.* suggest this more uniform and predictable monsoon response to insolation may reflect the different boundary conditions of the Holocene compared with the full glacial period. The diatom record shows no major change in the late Holocene, with changes apparently being driven more by changes in nutrients than available moisture. The additional insights into change over the last 25,000 years afforded by studying the diatom record at Laguna La Gaiba emphasise the potential importance of extending diatom-based reconstructions across this region.

Acknowledgements

Funding for this research was provided as a NERC (UK) PhD studentship to KAF (DTG NE/H526794/1), an NSERC (Canada) PGS-D studentship grant to BSW, as well as additional financial support provided by the School of Geosciences, University of Edinburgh. Fieldwork was supported by National Geographic (ref. No. 6953-01) and Carnegie Trust research grants to FEM. Radiocarbon dating support was granted by the NERC radiocarbon facility to FEM (allocation numbers 966.0402, 1149.1005, 1225.0407). Fieldwork logistical support was provided by the ‘Noel Kempff Mercado’ Natural History Museum, Santa Cruz, Bolivia and we thank the authorities of San Matias National Park and Otuquis National Park for permission to core LAGUNA LA GAIBA. William Gosling, Mike Burn, Huw Jones, Philip Metcalfe, Eric de Boer, Ezequiel Chavez and René Guillén aided in the field, and we thank

Don Chango and family for their continued hospitality on the shores of Laguna La Gaiba. Alayne Street-Perrott is thanked for her support in the early stages in the La Gaiba work and NJL and FASP thank the Climate Change Consortium for Wales (C3W) for research support.

References

Alho, C.R.J. 2005. The Pantanal. In *The World's Largest Wetlands: Ecology and Conservation,* Fraser, L.H. and Keddy, P.A. (eds). Cambridge University Press: Cambridge.

Baker, P.A., Seltzer, G.., Fritz, S.C., Dunbar, R.B., Grove, M.., Tapia, P.M., Cross, S.L., Rowe, H.D. and Broda, J.P. 2001. The history of South American tropical precipitation for the past 25,000 years. *Science* **291**: 640-643.

Bennett, K. (2007) http://chrono.qub.ac.uk/psimpoll/psimpoll.html

Berger, A. and Loutre, M.F., 1991. Insolation values for the climate of the last 10 million years. *Quaternary Science Reviews* **10**: 297-317

Burbridge, R.E., Mayle, F.E. and Kileen, T.J. 2004. Fifty-thousand-year vegetation and climate history of Noel Kampff Mercado National Park, Bolivian Amazon. *Quaternary Research* **61**: 215-230.

Bush, M.B. and Silman, M.R. 2004. Observations on Late Pleistocene cooling and precipitation in the lowland Neotropics. *Journal of Quaternary Science* **19**: 677-684.

Bush, M.B. and Metcalfe, S.E. 2012. Latin America and the Caribbean. In *Quaternary Environmental Change in the Tropics*, Metcalfe, S.E. and Nash, D.J. (eds.). Wiley-Blackwell: Chichester; 263-311.

Bush, M.B., De Oliveira, P.E., Colinvaux, P.A., Miller, M.C. and Moreno, J.E. 2004. Amazonian paleoecological histories: one hill, three watersheds. *Palaeogeography, Palaeoclimatology, Palaeoecology* **214***: 359-393.*

Colinvaux, P.A., De Oliviera, P.E. and Bush, M.B. 2000. Amazon and Neotropical plant communities on glacial time scales: the failure of the aridity and refuge hypotheses. *Quaternary Science Reviews* **19**: 141-169.

Cordeiro, R.C., Turcq, B., Sifeddine, A., Lacerda, L.D., Silva Filho, E.V., Gueiros, B., Potty, Y.P., Santelli, R.E., Papua, E.O. and Patchinelam, S.R. 2011. Biogeochemical indicators of environmental changes from 50Ka to 10Ka in a humid region of the Brazilian Amazon. *Palaeogeography, Palaeoclimatology, Palaeoecology* **299**: 426-436.

Croudace, I.W., Rindby, A. and Rothwell, R.G. 2006. ITRAX: description and evaluation of a new multi-function X-ray core scanner: Geological Society of London, Special Publication **267**: 51-63.

Cruz, F.W., Burns, S.J., Karmann, I., Sharp, W.D., Vuille, M. and Ferrari, J.A. 2006. A stalagmite record of changes in atmospheric circulation and soil processes in the Brazilian subtropics during the Late Pleistocene. *Quaternary Science Reviews* **25**: 2749-2761.

de Oliviera, M.D. and Calheiros, D.F. 2000. Flood pulse influence on phytoplankton communities of the south Pantanal floodplain, Brazil. *Hydrobiologia* **427**: 101-112.

D'Apolito, C., Absy, M.L. and Latrubesse, E.M. 2013. The Hill of Six Lakes revisited: new data and re-evaluation of a key Pleistocene Amazon site. *Quaternary Science Reviews* **76**: 140-155.

Deplazes, G., Luckge, A., Peterson, L.C., Timmermann, A., Hamann, Y., Hughen, K.A., Rohl, U., Laj, C., Cane, M.A., Sigman, D.M. and Haug, G.H. 2013. Links between tropical rainfall and North Atlantic climate during the last glacial period. *Nature Geoscience* 6: 213-217, doi:10.1038/ngeo1712.

Dunck, B., de Souza Nogueira, I. and das Graças Machado, M. 2012. Planktonic diatoms in lotic and lentic environments in the Lago dos Tigres hydrologic system (Britânia, Goiás, Brazil): Coscinodiscophyceae and Fragilariophyceae. *Brazilian Journal of Botany* **35**: 181-193.

Fairbanks, R.G., Mortlock, R.A., Chiu, T-C., Cao, L., Kaplan, A., Guilderson, T.P., Fairbanks, T.W. and Bloom, A.L. 2005. Marine radiocarbon calibration curve spanning 0 to 50,000 years BP based on paired ^{230}Th/^{234}U/^{238}U and ^{14}C dates on pristine corals. *Quaternary Science Reviews* **24**: 1781-1796.

Flower, B.P., Hastings, D.W., Hill, H.W. and Quinn, T.M. 2004. Phasing of deglacial warming and Laurentide Ice Sheet meltwater in the Gulf of Mexico. *Geology* **32**: 597-600.

Garreaud, R.D., Vuille, M., Campagnucci, R. and Marengo, J. 2009. Present day South American climate   *Palaeogeography, Palaeoclimatology, Palaeoecology* **281**: 180-195.

Gasse, F. 1986. East African Diatoms. Taxonomy, ecological distribution. Bibliotheca Diatomologica Band 11.

Germain, H. 1980. *Flore des diatomées Diatomophycees.* Societé Nouvelle des Editions Boubeé : Paris.

Haberzettl, T., Fey, M., Lücke, A., Maidana, N., Mayr, C., Ohlendorf, C., Schäbitz, F., Schleser, G.H., Wille, M. and Zolitscka, B. 2005. Climatically induced lake level changes during the last two millennia as reflected in sediments of Laguna Potrok Aike, southern Patagonia (Santa Cruz, Argentina). *Journal of Paleolimnology* **33**: 283-302.

Hamilton, S.K. 2002. Hydrological controls of ecological structure and function in the Pantanal wetland (Brazil). In *The Ecohydrology of South American Rivers and Wetlands*, McClain, M.E. (ed). IAHS Press, Centre for Ecology and Hydrology: Wallingford.

Hamilton, S.K., Sippel, S.J. and Melack, J.M. 2002. Comparison of inundation patterns among major South American floodplains. *Journal of Geophysical Research* **107**, D20, 8038, doi: 10.1029/2000JD000306.

Jacob, J., Disnar, J-R., Boussafir, M., Sifeddine, A., Turcq, B. and Spadano Albuquerque, A.L. 2004. Major environmental changes recorded by lacustrine sedimentary organic matter since the last glacial maximum near the equator (Lagoa do Caco, NE Brazil). *Palaeogeography, Palaeoclimatology, Palaeoecology* **205**: 183-197.

Juggins, S. 2003. User guide C2. Software for ecological and palaeoecological data analysis and visualisation. User Guide version 1.3 University of Newcastle.

Kilham, S.S. and Kilham, P. 1975. *Meloseira granulata* (Ehr.) Ralfs: morphology and ecology of a cosmopolitan freshwater diatom. *Verhandlungen des Internationalen Verein Limnologie* **19**: 2716-2721.

Kilham, P., Kilham, S.S. and Hecky, R.E. 1986. Hypothesized resource relationships among African planktonic diatoms. *Limnology and Oceanography* **31**: 1169-1181.

Krammer, K. and Lange-Bertalot, H. 1986. Bacillariophyceae. 1. Teil: Naviculaceae. *Susswasserflora von Mitteleuropa* 2/1. Gustav Fischer Verlag: Jena.

Krammer, K. and Lange-Bertalot, H. 1988. Bacillariophyceae. 2. Teil: Bacillariaceae, Epithemiaceae, Surirellaceae. *Susswasserflora von Mitteleuropa* 2/2. Gustav Fischer Verlag: Stuttgart.

Krammer, K. and Lange-Bertalot, H. 1991a. Bacillariophyceae. 3. Teil: Centrales, Fragilariaceae, Eunotaciaceae. *Susswasserflora von Mitteleuropa* 2/3. Gustav Fischer Verlag: Stuttgart

Krammer, K. and Lange-Bertalot, H. 1991b. Bacillariophyceae. 4. Teil: Achnanthaceae. *Susswasserflora von Mitteleuropa* 2/4. Gustav Fischer Verlag: Stuttgart

Lea, D.W., Pak, D.K., Peterson, L.C. and Hughen, K.A. 2003. Synchroneity of tropical and high-latitude Atlantic temperatures over the Last Glacial Termination. *Science* **301**: 1361-1364.

Ledru, M-P., Cecantini, G., Gouveia, S.E.M., López-Sáez, J.A., Pessendda, L. C.R. and Ribeiro, A.S. 2006. Millennial-scale climatic and vegetation changes in the northern Cerrado (Northeast, Brazil) since the Last Glacial Maximum. *Quaternary Science Reviews* **25**: 1110-1126.

Maslin, M.A., Durham, E., Burns, S.J., Platzman, E., Grootes, P., Greig, S.E.J., Nadeau, M-J., Schleicher, M., Pflaumann, U., Lomax, B. and Rimington, N. 2000. Palaeoreconstruction of the Amazon River freshwater and sediment discharge using sediments recovered at Site 942 on the Amazon Fan. *Journal of Quaternary Science* **15**: 419-434.

Mayle, F.E., Burbridge, R. and Killeen, T.J. 2000. Millennial-scale dynamics of southern Amazonian rain forests. *Science* **290**: 2291-2294.

McGlue, M.M., Silva, A., Corradini, F.A., Zani, H., Trees, M.A., Ellis, G.S., Parolin, M., Swarenski, P.W., Cohen, A.S. and Assine, M.L. 2011. Limnogeology in Brazil's 'forgotten wilderness': a synthesis from the large floodplain lakes of the Pantanal. *Journal of Paleolimnology* **46**: 273-289.

McGlue, M.M., Silva, A., Zani, H., Corradini, F.A., Parolin, M., Abel, E.J., Cohen, A.S., Assine, M.L., Ellis, G.S., Trees, M.A., Kuerten, S., dos Santos Gradella, F., Rasbold, G.G. 2012. Lacustrine records of Holocene flood pulse dynamics in the Upper Paraguay River watershed (Pantanal Wetlands, Brazil). *Quaternary Research* **78**: 285-294.

Metzeltin, D. and Lange-Bertalot, H. 1998. Tropical Diatoms of South America I. *Iconographia Diatomologica. Annotated Diatom Micrographs vol. V.* Koeltz Scientific Books: Königstein.

Metzeltin, D. and Lange-Bertalot, H. 2007. Tropical Diatoms of South America II. *Iconographia Diatomologica. Annotated Diatom Micrographs vol. XVIII.* Koeltz Scientific Books: Königstein.

Meyers, P.A. and Teranes, J.L. 2001. Sediment organic matter. In *Tracking Environmental Change using Lake Sediments. Vol. 2 Physical and Geochemical*

Methods, W.M. Last and J.P. Smol (eds). Kluwer Academic Publishers; Dordrecht, Boston, London; 239-269.

Mosblech, N.A.S., Bush, M.B., Gosling, W.D., Hodell, D., Thomas, L., van Calsteren, P., Correa-Metrio, A., Valencia, B.G., Curtis, J. and van Woesik, R. 2012. North Atlantic forcing of Amazonian precipitation during the last ice age. *Nature Geoscience* doi:10.1038/ngeo1588.

Patrick, R. and Reimer, C.W. 1966. *The Diatoms of the United States exclusive of Alaska and Hawaii. Vol. 1.* Monographs of the Academy of Natural Sciences of Philadelphia No. 13.

Peterson, L.C., Haug, G.H., Hughen, K.A., Rohl, U. 2000. Rapid changes in the hydrological cycle of the tropical Atlantic during the Last Glacial. *Science* **290**: 1947-1951

Rasmussen, S.O., Andersen, K.K., Svensson, A.M., Steffensen, J.P., Vinther, B.M., Clausen, H.B., Siggaard-Andersen, M-L., Johnsen, S.J., Larsen, L.B., Dahl-Jensen, D., Bigler, M., Röthlisberger, R., Fischer, H. Goto-Azuma, K., Hansson, M.E. and Ruth, U. 2006. A new Greenland ice core chronology for the last glacial termination. *Journal of Geophysical Research* **111**, D06102, doi:10.1029/2005JD006079.

Rein, B., Lückge, A., Reinyhardt, L., Sirocko, F., Wolf, A. and Wolf-Christian, D. 2005. El Nino variability off Peru during the last 20,000 years. *Paleoceanography* 20, PA4003, doi:10.1029/2004PA001099.

Ruiz Pessenda, L.C., de Oliveira, P.E., Mofatto, M., de Medeiros, V.B., Francischetti Garcia, R.J., Aravena, R., Bendassoli, J.A., Zunga Leita, A., Saad, A.R. and Lincoln Etchebehere, M. 2009. The evolution of a tropical rainforest/grassland mosaic in southeastern Brazil since 28,000 14C yr BP based on carbon isotopes and pollen records. *Quaternary Research* **71**: 437-452.

Rull, V., Stansell, N.D., Montoya, E., Bezada, M. and Abbott, M.B. 2010. Palynological signal of the Younger Dryas in the tropical Venezuelan Andes. *Quaternary Science Reviews* **29**: 3045-3056.

Rumrich, U., Lange-Bertalot, H. and Rumrich, M. 2000. Diatomeen der Anden von Venezuela bis Patagonia/Tierra del Fuegao und zwei weitere Beiträge. *Iconographia Diatomologica. Annotated Diatom Micrographs vol. IX.* Koeltz Scientific Books: Königstein.

Sifeddine, A., Spadano Albuquerque, A.L., Ledru, M-P., Turcq, B., Knoppers, B., Martin, L., Zamboni de Mello, W., Passenau, H., Landim Dominguez, J.M., Campello

Cordeiro, R., Joao Abrao, J. and da Silva Pinto Bittencourt, A.C. 2003. A 21,000 cal years paleoclimatic record from Caçó Lake, northern Brazil: evidence from sedimentary and pollen analyses. *Palaeogeography, Palaeoclimatology, Palaeoecology* **189**: 25-34.

Schmidt, A., Schmidt, M., Fricke, F., Heiden, H., Müller, O. and Hustedt, F. 1874–1959. *Atlas der Diatomaceenkunde*. R. Reisland, Leipzig.

Stone, J.R., Westover, K.S. and Cohen, A.S. 2011. Late Pleistocene paleohydrology and diatom paleoecology of the central basin of Lake Malawi, Africa. *Palaeogeography, Palaeoclimatology, Palaeoecology* **303**: 51-70.

Taylor, Z.P., Horn, S.P., Mora, C.I. Orvis, K.H. and Cooper, L.W. 2010. A multi-proxy palaeoeclogical record of late-Holocene forest expansion in lowland Bolivia. *Palaeogeography, Palaeoclimatology, Palaeoecology* **293**: 98-107.

Train, S. and Rodriques, L.C. 1998. Temporal fluctuations of the phytoplankton community of the Baía River, in the upper Parana River floodplain, Mato Grosso do Sul, Brazil. *Hydrobiologia* **361**: 125-134.

Van der Hammen, T. and Hooghiemstra, H. 1995. The El Abra stadial, a Younger Dryas equivalent in Colombia. *Quaternary Science Reviews* **14**: 841-851.

Velez, M.I., Hooghiemstra, H., Metcalfe, S., Martínez, I. and Mommersteeg, H. 2003. Pollen and diatom based environmental history since the Last Glacial Maximum from the Andean core Fúquene-7, Colombia. *Journal of Quaternary Science* **18**: 17-30.

Velez, M.I., Wille, M., Hooghiemstra, H. and Metcalfe, S. 2005a. Integrated diatom-pollen based Holocene environmental reconstruction of lake Las Margaritas, eastern savannas of Colombia. *The Holocene* **15**: 1184-1198.

Velez, M.I., Hooghiemstra, H. and Metcalfe, S. 2005b. Fossil and modern diatom assemblages from the savanna lake El Piñal, Colombia: an environmental reconstruction. *Diatom Research* **20**: 387-407.

Vélez, M.I., Hooghiemstra, H., Metcalfe, S.E., Berrío, J. and Wille, M. 2006. Lateglacial and Holocene palaeolimnological records from four lakes in Colombia, northern South America. *Palaeogeography, Palaeoclimatology, Palaeoecology* **234**: 81-96.

Vizy, E.K. and Cook., K.H. 2007. Relationship between Amazon and high Andes rainfall. *Journal of Geophysical Research* **112**, D07107, doi:10.1029/2006JD007980.

Wang, X., Auler, A.S., Edwards, R.L., CHaeng, H., Ito, E. and Solheid, M. 2006. Interhemispheric anti-phasing of rainfall during the last glacial period. *Quaternary Science Reviews* **25**: 3391-3403.

Wang, X., Auler, A.S., Edwards, R.L., Cheng, H., Ito, E., Wang, Y., Kong, X., Solheid, M. 2007. Millennial-scale precipitation changes in southern Brazil over the past 90,000 years. *Geophysical Research Letters* 34, L23701, doi: 10.1029/2007GL031149

Whitney, B.S. and Mayle, F.E. 2012. *Pediastrum* species as potential indicators of lake-level change in tropical South America. *Journal of Paleolimnology* **47**: 601-615.

Whitney, B.S., Mayle, F.E., Punyasena, S.W., Fitzpatrick, K.A., Burn, M.J., Guillen, R., Chavez, E., Mann, D., Pennington, R.T. and Metcalfe, S.E. 2011. A 45 kyr palaeoclimate record from the lowland interior of tropical South America. *Palaeogeography, Palaeoclimatology, Palaeoecology* **307**: 177-192.

Zhou, J.Y. and Lau, K.M. 1998. Does a monsoon climate exist over South America? *Journal of Climate* **11**: 1020-1040.

Figures

Fig. 1. Location of Laguna La Gaiba within the Pantanal Basin and its relationship to major features of the atmospheric circulation.

Fig. 2 Selected physical, isotopic and elemental data from the full Laguna La Gaiba core. XRF data normalised.

Fig. 3. Diatom abundance (%) of taxa present at >1% in three or more samples from the La Gaiba core. Top panel (3a) = entire record. Bottom panel (3b) = detail of the last glacial-interglacial transition. Both panels zoned according to diatoms.

Fig. 4. DCA of fossil diatoms based on all taxa present in at least three samples. Open circles indicate taxa of minor significance.

Fig. 5. Overall summary showing grouped pollen types (Whitney et al., 2011), Austral summer insolation at 15°S (Berger and Loutre, 1991; Berger, A., 1992, Orbital Variations and Insolation Database, IGBP PAGES/World Data Center for Paleoclimatology, Data Contribution Series # 92-007. NOAA/NGDC Paleoclimatology Program, Boulder CO, USA), Cariaco reflectance data (Peterson et al., 2000; Peterson, L.C. et al., 2001, Cariaco Basin ODP1002 Color Reflectance

and Bulk Elemental (Fe, Ti, Ca) Data, IGBP PAGES/World Data Center A for Paleoclimatology Data Contribution Series #2001-020.NOAA/NGDC Paleoclimatology Program, Boulder CO, USA or http://hurricane.ncdc.noaa.gov/pls/paleox/f?p=519:1::::P1_STUDY_ID:2544)), Botuvera δ^{18}O speleothem data (Wang et al., 2007; http://hurricane.ncdc.noaa.gov/pls/paleox/f?p=519:1::::P1_STUDY_ID:8635) and diatoms grouped by ecological preference (this study).

Fig 1

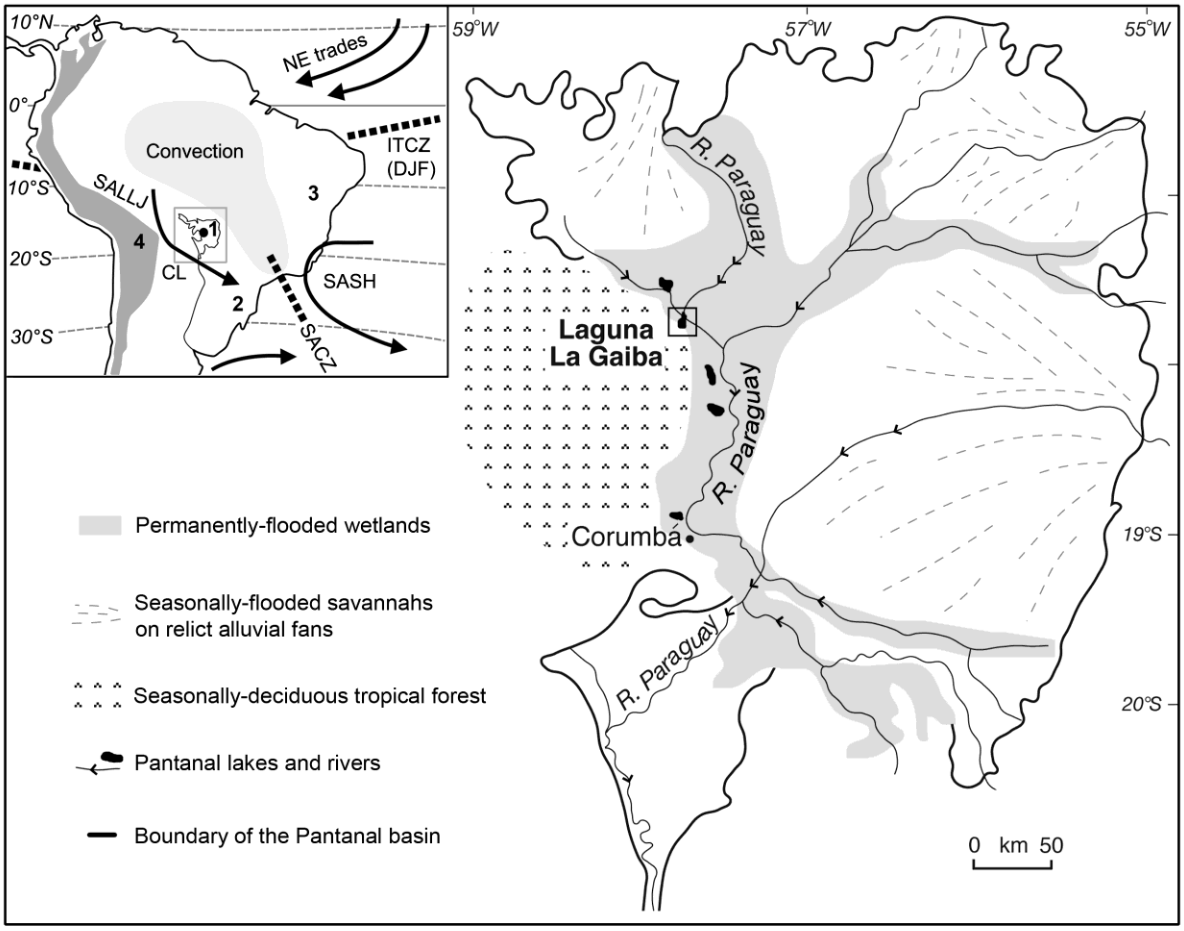

10°N
0°
10°S
20°S
30°S
NE trades
Convection
ITCZ
(DJF)
SALLJ
1
2
3
4
CL
SASH
SACZ
59°W
57°W
55°W
19°S
20°S
R. Paraguay
R. Paraguay
R. Paraguay
Laguna
La Gaiba
Corumbá
Permanently-flooded wetlands
Seasonally-flooded savannahs
on relict alluvial fans
Seasonally-deciduous tropical forest
Pantanal lakes and rivers
Boundary of the Pantanal basin
0 km 50

Fig 2

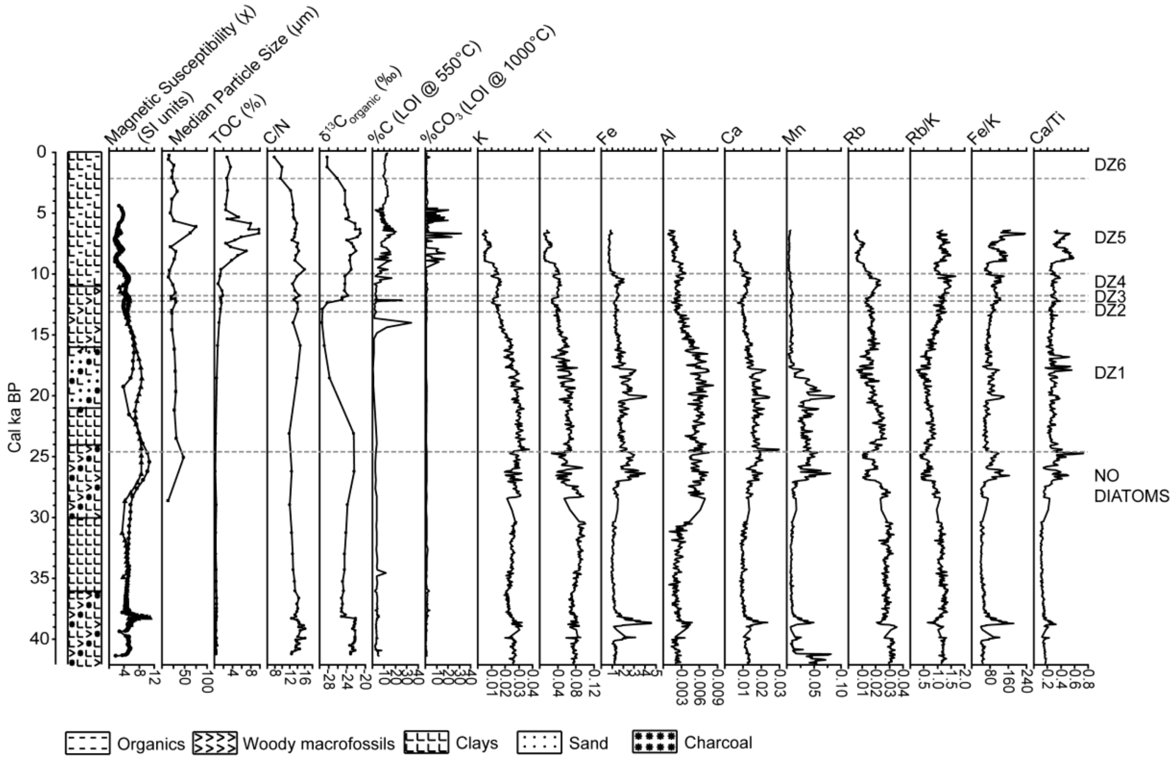

Magnetic Susceptibility (χ) (SI units)
Median Particle Size (μm)
TOC (%)
C/N
δ13C organic (‰)
%C (LOI @ 550°C)
%CO3 (LOI @ 1000°C)
K
Ti
Fe
Al
Ca
Mn
Rb
Rb/K
Fe/K
Ca/Ti
Cal ka BP
0
5
10
15
20
25
30
35
40
4 8 12
50 100
4 8
8 12 16
-28 -24 -20
10 20 30 40
10 20 30 40
0.01 0.02 0.03 0.04
0.04 0.08 0.12
1 2 3 4 5
0.003 0.006 0.009
0.01 0.02 0.03
0.05 0.10
0.01 0.02 0.03 0.04
0.5 1.0 1.5 2.0
80 160 240
0.2 0.4 0.6 0.8
DZ6
DZ5
DZ4
DZ3
DZ2
DZ1
NO DIATOMS
Organics
Woody macrofossils
Clays
Sand
Charcoal

Fig 3 A and B

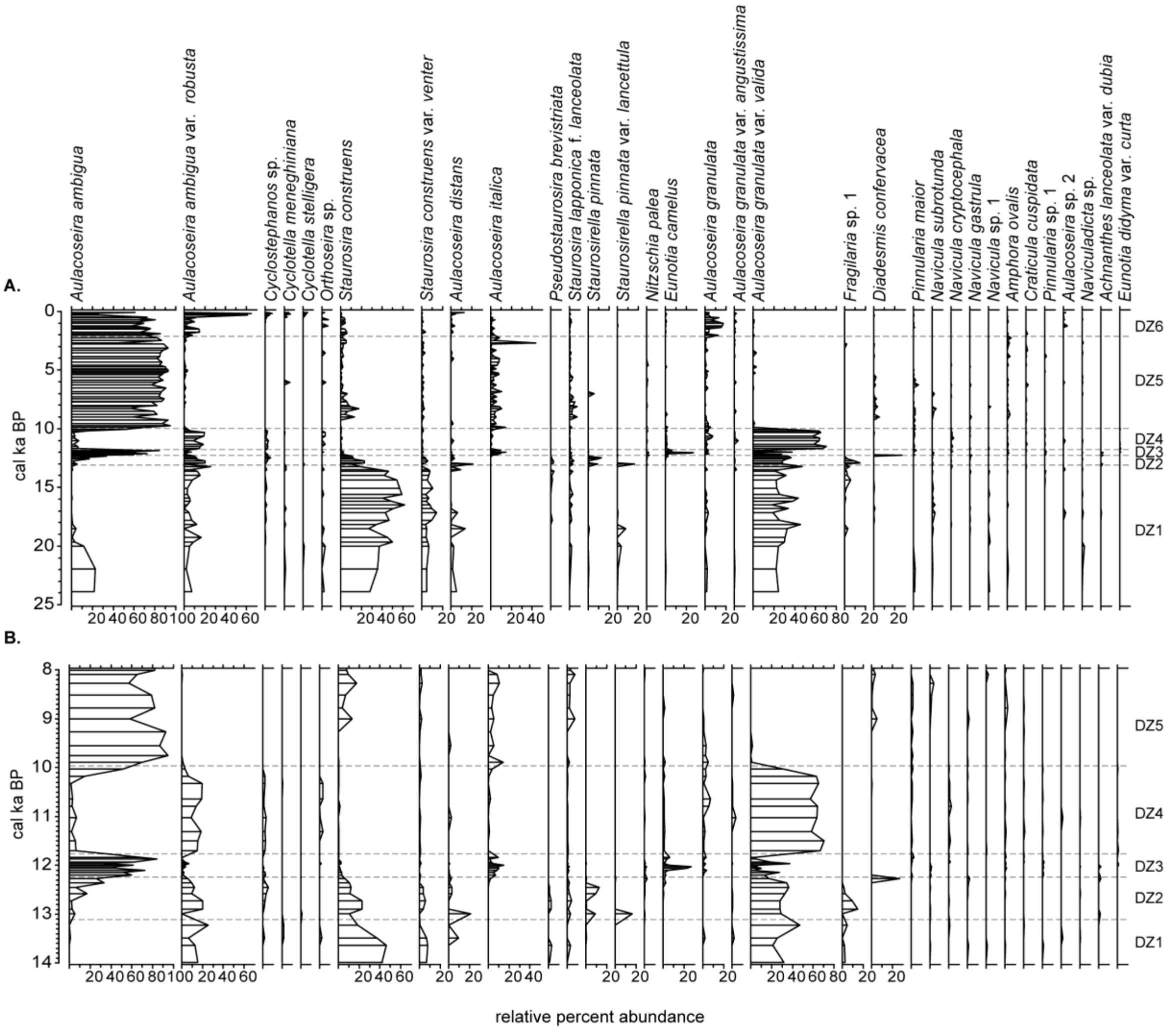
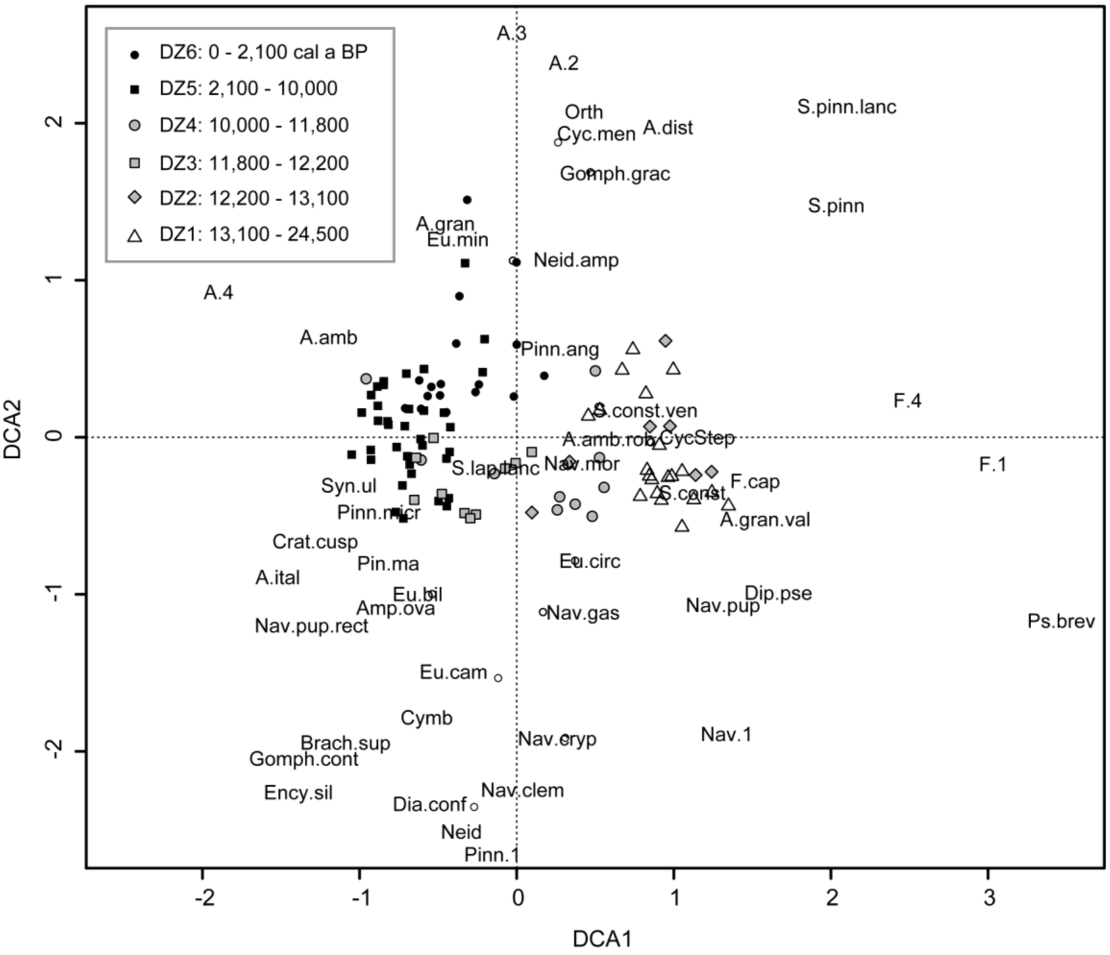

A.
B.
Aulacoseira ambigua
Aulacoseira ambigua var. robusta
Cyclostephanos sp.
Cyclotella meneghiniana
Cyclotella stelligera
Orthoseira sp.
Staurosira construens
Staurosira construens var. venter
Aulacoseira distans
Aulacoseira italica
Pseudostaurosira brevistriata
Staurosira lapponica f. lanceolata
Staurosirella pinnata
Staurosirella pinnata var. lancettula
Nitzschia palea
Eunotia camelus
Aulacoseira granulata
Aulacoseira granulata var. angustissima
Aulacoseira granulata var. valida
Fragilaria sp. 1
Diadesmis confervacea
Pinnularia maior
Navicula subrotunda
Navicula cryptocephala
Navicula gastrula
Navicula sp. 1
Amphora ovalis
Craticula cuspidata
Pinnularia sp. 1
Aulacoseira sp. 2
Naviculadicta sp.
Achnanthes lanceolata var. dubia
Eunotia didyma var. curta
cal ka BP
0
5
10
15
20
25
8
9
10
11
12
13
14
DZ6
DZ5
DZ4
DZ3
DZ2
DZ1
20 40 60 80 100
20 40 60
20 40 60
20
20
20 40
20
20
20
20
20 40 60 80
20
20
relative percent abundance

Fig 4



● DZ6: 0 - 2,100 cal a BP
■ DZ5: 2,100 - 10,000
● DZ4: 10,000 - 11,800
■ DZ3: 11,800 - 12,200
◆ DZ2: 12,200 - 13,100
△ DZ1: 13,100 - 24,500
A.3
A.2
Orth
Cyc.men
A.dist
S.pinn.lanc
Gomph.grac
S.pinn
A.gran
Eu.min
Neid.amp
A.4
A.amb
Pinn.ang
S.const.ven
F.4
A.amb.rob
CycStep
S.lap.lanc
Nav.mor
F.1
Syn.ul
F.cap
S.const
Pinn.micr
A.gran.val
Crat.cusp
Pin.ma
Eu.circ
A.ital
Eu.bil
Dip.pse
Amp.ova
Nav.pup
Nav.gas
Nav.pup.rect
Ps.brev
Eu.cam
Cymb
Nav.1
Nav.cryp
Brach.sup
Gomph.cont
Nav.clem
Ency.sil
Dia.conf
Neid
Pinn.1
DCA2
2
1
0
-1
-2
DCA1
-2
-1
0
1
2
3

Fig 5

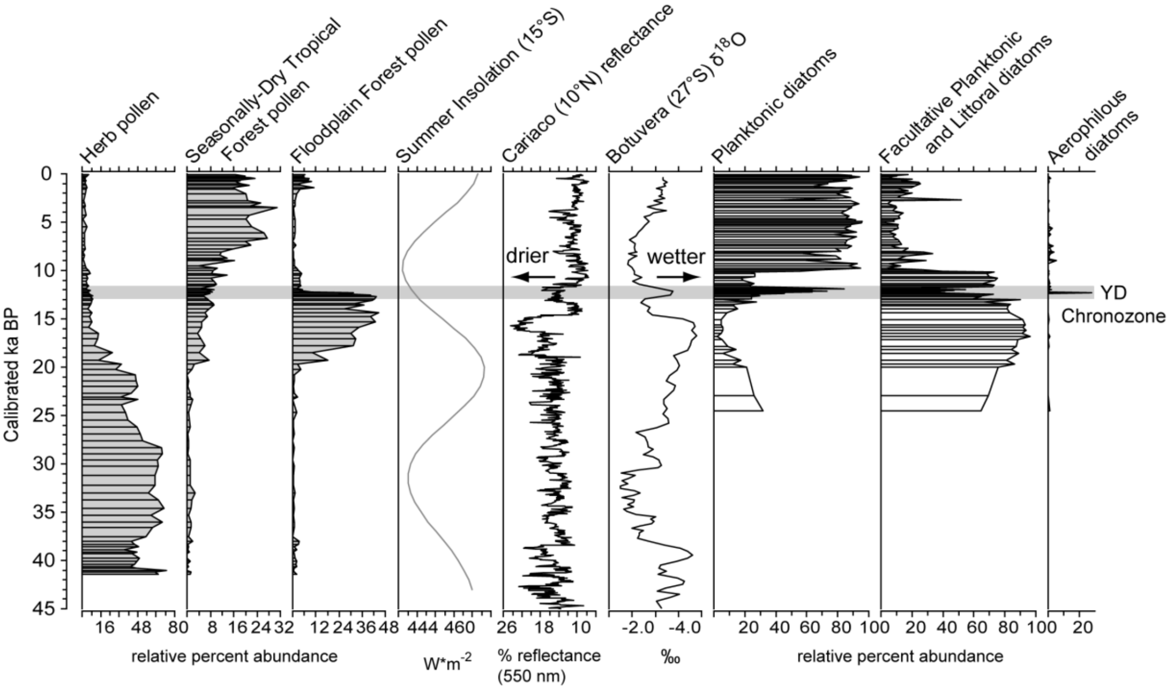

Herb pollen
Seasonally-Dry Tropical Forest pollen
Floodplain Forest pollen
Summer Insolation (15°S)
Cariaco (10°N) reflectance
Botuvera (27°S) δ18O
Planktonic diatoms
Facultative Planktonic and Littoral diatoms
Aerophilous diatoms
Calibrated ka BP
0
5
10
15
20
25
30
35
40
45
drier
wetter
YD
Chronozone
16 48 80
8 16 24 32
12 24 36 48
444 460
26 18 10
-2.0 -4.0
20 40 60 80 100
20 40 60 80 100
20
relative percent abundance
W*m-2
% reflectance (550 nm)
‰
relative percent abundance

Table 1

Publication Code	**Sampler Identifier (core : depth)**	**Material**	**Stratigraphic Position (cm)**	**^{14}C Enrichment (% modern)**	**Conventional ^{14}C Age (yrs BP ±1σ)**	**Carbon Content (% wt)**	**$\delta^{13}C_{VPDB}$ (‰ ±0.1)**	**Calibrated Age (yrs BP ±1σ)**
SUERC-11240	LLG surface: 49-50	Twig	44 - 45	72.79 ± 0.32	2552 ± 35	59	-26*	2701 ± 56
SUERC-16482	LLG1a: 92-94	Sediment	92 - 94	50.53 ± 0.24	5512 ± 38	10.5	-20.7	6298 ± 26
SUERC-16483	LLG1a: 124-126	Sediment	124 - 126	44.42 ± 0.22	6519 ± 40	8.9	-22.3	7431 ± 26
AA-51698	LLG1: 175-176	Twig	180 - 181	32.86 ± 0.23	8939 ± 56	18	-26.2*	10116 ± 101
SUERC-11241	LLG1: 194-195	Twig/bark	199 - 200	27.68 ± 0.15	10317 ± 43	50	-26.6	12104 ± 77
SUERC-11242	LLG1: 226-227	Twig/bark	231 - 232	25.43 ± 0.14	10999 ± 46	56	-28.1	12874 ± 49
SUERC-16748	LLG1: 236-238	Twigs/seed	241 - 243	24.17 ± 0.15	11408 ± 48	61	-26.3	13258 ± 72
SUERC-11251	LLG1: 249-251	Twig/bark	254 - 256	17.24 ± 0.13	14121 + 60	47	-27.2	16519 ± 142
SUERC-11704	LLG1: 256-257	Twig/wood	260.8 - 261.8	10.78 ± 0.12	17892 ± 91	67	-27.5	21211 ± 157
SUERC-11703	LLG1: 264-265	Twig/wood	267.2 - 268	10.33 ± 0.12	18236 ± 94	36	-27.2	21742 ± 180
SUERC-16749	LLG1: 268-271	Leaf/twig	268.8 - 272.8	9.41 ± 0.12	18983 ± 104	52	-26.5*	22557 ± 126
SUERC-11243	LLG1: 274-275	Twig/bark	275.2 - 276	5.87 ± 0.12	22771 ± 164	27	-28.2	27348 ± 230
†SUERC-16750	LLG1: 280-282	Leaf/bark	281.6 - 283.9	7.80 ± 0.12	20489 ± 122	12	-26.7	24397 ± 152
SUERC-11244	LLG1: 293-294	Bark/wood	296.3 - 297.4	2.99 ± 0.12	28185 ± 320	51	-24.6	33559 ± 370
SUERC-11245	LLG1: 306	Twig/bark	310.2 - 310.8	2.94 ± 0.12	28320 ± 326	47	-25.0*	33700 ± 373
AA-51699	LLG1a: 334	Twig	333.8 - 334.2	2.20 ± 0.11	30670 ± 390	36	-26.2	36042 ± 399
SUERC-16484	LLG1: 338	Twig	347 - 348.1	1.73 ± 0.12	32609 ± 556	56	-29.7	38002 ± 579
SUERC-16751	LLG1: 357-359	Leaf/twig	368.5 - 370.7	1.79 ± 0.12	32311 ± 535	43	-27.6	37701 ± 560
SUERC-11246	LLG1: 368	Wood	380 - 381.6	1.70 ± 0.13	32717 ± 564	47	-27.2	38110 ± 588

Table 2

List of diatom species assigned to the ecological groups presented in Fig. 5. Diatoms species not shown in the fossil diatom plot (Fig. 3) that were included in the ecological groups are marked here with (*). Taxa plotted in Fig. 3 but classified as epiphytic or benthic not listed here. Taxa only identified to generic level excluded.

Planktonic	Facultative Planktonic/Littoral	Aerophilous
Aulacoseira ambigua	*Aulacoseira italica*	*Diadesmis confervacea*
Aulacoseira ambigua var. *robusta*	*Aulacoseira distans*	*Eunotia bilunaris**
Cyclostephanos sp.	*Aulacoseira granulata*	*Eunotia circumborealis**
Cyclotella meneghiniana	*Aulacoseira granulata* var. *angustissima*	*Eunotia didyma* var. *curta*
Cyclotella stelligera	*Aulacoseira granulata* var. *valida*	*Eunotia gibbosa* var. *paraguayensis**
	Pseudostaurosira brevistriata	
	*Fragilaria capucina**	
	Staurosira construens	
	Staurosira construens var. *venter*	
	Staurosira lapponica f. *lanceolata*	
	Staurosirella pinnata	
	Staurosirella pinnata var. *lancettula*	
	*Gyrosigma acuminatum**	
	Nitzschia palea	
	Eunotia camelus	