

Interactive comment on “Terrigenous input off northern South America driven by changes in Amazonian climate and the North Brazil Current retroflexion during the last 250 ka” by A. Govin et al.

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Comments from Reviewer 2 (M. Maslin)

We thank Paul Baker for his constructive review. His comments are in plain text. Our reply is in italic. Text modifications in the manuscript are in blue.

Govin et al. present palaeoclimate records from a transect of four marine cores along the North East Brazilian coast ranging from 5 deg to 12 deg N. One site extends back

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to 150 ka while the other two sites extend further back to 250 ka. The authors have reconstructed the terrigenous input at each site and interpreted them in terms of both terrestrial input and oceanic deposition. The authors have produced excellent rigorous manuscript. The Introduction is clear, however there are a few points that they might like to include for completeness, which are listed below.

We thank the Reviewer for his enthusiastic review. We completed the Introduction, as suggested. Please see our reply to specific comments below.

The regional setting section is clear though the authors may like to include some details on modern rainfall over South America as it is relevant to their discussion section.

The beginning of the Regional setting section summarizes modern rainfall patterns in northern South America: precipitation driven by the ITCZ seasonal migrations over the Orinoco basin (i.e. high rainfall in JJA when the ITCZ has a northern position and low rainfall in DJF when the ITCZ has a southern position), precipitation connected to the Southern American monsoon system over most of the Amazon basin, with intense rainfall during austral summer (DJF). This is described in lines 2-11 of page 5859 and illustrated in Figure 1 (both DJF and JJA situations). We are hence unsure which additional information the Reviewer actually meant.

For more clarity, we added the word “modern” at the beginning of this paragraph. Page 4, line 29 of the revised manuscript: “Modern precipitation in northern South America exhibits strong seasonal patterns”

Material and Methods are very clear. My only comment is that ‘Age Models’ might be better as 3.3 following directly from the Stable isotopes section.

We followed the Reviewer’s suggestion and modified the text outline accordingly: 3.3 Age models, 3.4 Major element composition and 3.5 Endmember unmixing analysis.

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I am impressed with the endmember unmixing analysis and it seems to have worked extremely well at these sites. In the Discussion section is comprehensive and the authors investigate all the potential mechanisms that could be influencing the terrestrial inputs and deposition. This thoroughness lends much greater credibility to their final conclusions.

Thanks.

I cannot fault the final interpretation that the Sites at 5 deg N and 8 deg N are controlled by precessional modulated Amazon rainfall and thus sediment discharge. While the 12 deg N Site is strongly influenced by the duration of the NBCC retroflexion. The only part that I might suggest a slightly different interpretation is that I would suggest that precession influence could be through increased convection strength and not movements of the ITCZ. While the retroflexion would be more influenced by wind direction and hence the position of the northern arm of the ITCZ, which is in turn strongly influenced by the Equator-Temperate Northern Hemisphere temperature gradient.

Here we fully agree with the Reviewer's interpretation. We also think that precession driven changes in Amazonian rainfall are not modulated by latitudinal shifts in the ITCZ position. We propose that enhanced land-ocean thermal contrast during periods of high DJF insolation strengthened the NE trade winds, increased the transport of moisture to the continent and intensified the South American monsoon. This was included in the original version of the paper (p. 5871, line 27 to p. 5872, line 4) and remains in the revised manuscript (page 17, lines 16-20). In the manuscript, the only place where we invoke changes in the ITCZ position to explain South American rainfall variations is in the discussion of the 12° N record in section 5.3, where we investigate whether %-Amazon variations could be driven by changes in Orinoco rainfall and input (controlled by ITCZ shifts, as in the modern climatology). This is present in p. 5875, lines 4-10 of the original paper and p. 21, lines 9-12 of the revised manuscript.

To avoid confusion on the drivers (i.e. changes in convection strength vs. shifts in the
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position of the ITCZ) of enhanced Amazonian rainfall during periods of high DJF insolation, we slightly modified the Conclusions and the Abstract.

In the Conclusions (page 23, lines 10-12): "Increased Amazonian rainfall reflects the intensification of the South American monsoon in response to enhanced land-ocean thermal gradient and moisture transport during periods of high austral summer insolation."

In the Abstract (page 1, line 28 to page 2, line 2): "Increased Amazonian rainfall reflects the intensification of the South American monsoon in response to enhanced land-ocean thermal gradient and moisture convergence."

We also fully agree with the Reviewer that the proposed intensification or prolongation of the NBC retroflexion is driven by strengthened trade winds in response to enhanced meridional thermal gradient in the northern hemisphere.

We slightly modified the text in section 5.3 in the light of the Reviewer's comment #4 (please see details in our reply below).

Conclusions are short concise and reflect the outcomes of the Discussion section. Overall this is an excellent manuscript and my comments are minor and are intended only to help the authors to improve it further.

Thank you.

Some specific comments are:

1. In the Introduction – there seems to be missing the debate concerning whether the Amazon was wetter or drier during glacial periods compared to Interglacial periods. It seems this should be discussed on page 5857 before Heinrich events are introduced. There is a good summary of the current state of knowledge in both Sylvestre (2009) and Maslin et al. (2011)

Agreed. We added in the Introduction a summary of the ongoing debate on how wet South American tropical climate was during the last glacial period.

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IPage 2, line 22 to page 3 line 2: "The ongoing debate on moisture availability in Amazonia during the Last Glacial Maximum (LGM) was relative to the Late Holocene reflects the incomplete character of our knowledge about South American tropical precipitation (Sylvestre, 2009). Recent data compilations seem to agree on the existence of drier conditions in northernmost South American regions and wetter conditions in the tropical Andes during the LGM compared to the present (Sylvestre, 2009; Maslin et al., 2011). Complex glacial patterns are, however, observed in tropical lowland regions, in particular over the Amazon Basin (Sylvestre, 2009). A recent compilation indicates more arid Amazonian conditions during the LGM than today (Maslin et al., 2011). Nevertheless, precisely dated speleothem records challenge this scenario and suggest more subtle changes, with a wetter LGM in western Amazonia while drier conditions prevailed in easternmost Amazonia in comparison to the late Holocene (Cheng et al., 2013)."

2. In the Introduction and also the Discussion it might be worth looking in more detail to the relative role of precessional driven austral summer convection which influences the strength of the monsoon versus the position of both the northern and southern ITCZ boundary. An attempt to try and look at these mechanisms is included in Maslin et al. (2011).

We thank the Reviewer for drawing our attention on this new dynamic boundary-monsoon intensity hypothesis. We do not think that we can disentangle the monsoon intensity vs. migrations of northern and southern boundaries of the ITCZ based on our %-Andes records, which integrate climatic changes occurring over the entire Amazon Basin. However, we can draw a parallel between our observations during periods of high DJF insolation (also low JJA insolation and cold substages) and the glacial situation proposed by Maslin et al. (2011). Intensified monsoon (due to enhanced trade winds and moisture transport) and latitudinal contraction of the South American rainbelt (due to increased meridional thermal gradient in both hemispheres) may both contribute to increase Amazonian precipitation.

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We added a paragraph to the Discussion in section 5.2.

Page 17, line 16 to page 18 line 2: "By analogy with the modern austral summer situation in South America (Grimm et al., 2005), high DJF insolation increased the land-ocean temperature contrast by enhancing heating over central South America. Strengthened NE trade winds transported an increased amount of moisture to the continent, which intensified the South American monsoon (Cruz et al., 2005) and increased Amazonian rainfall (Mosblech et al., 2012). Maslin et al. (2011) proposed that moisture availability over the Amazon Basin results from the combined effects of (1) precession-driven changes in the South American monsoon intensity (as described above) and (2) the position of both northern and southern boundaries of the ITCZ, which migrate according to the meridional thermal gradient of each hemisphere. We cannot disentangle these effects based on our %-Andes data, which integrate climatic changes over the entire Amazon Basin. However, periods of high DJF insolation are also intervals of low JJA insolation and correspond to cold substages of the last 250 ka (Figure 6). We can hence draw a parallel between our observations during periods of high DJF insolation and the glacial situation proposed by Maslin et al. (2011). Enhanced meridional thermal gradients in both hemispheres during glacial times tend to shift the northern and southern boundaries of the ITCZ towards the equator (e.g. Chiang and Bitz, 2005). Therefore, the resulting latitudinal contraction of the South American rainbelt and the intensification of the South American monsoon (driven by enhanced trade winds) may both contribute to increase Amazonian precipitation (Maslin et al., 2011) during the last glacial period and older cold substages."

In our discussion of the 12° N %-Amazon record (section 5.3), the southward shift of the ITCZ that we propose during periods of low JJA insolation (high DJF insolation) is in line with the contraction of the South American rainbelt proposed by Maslin et al. 2011. This shift resulted in decreased Orinoco precipitation, whereas the opposite pattern is observed in our data.

We slightly modified the Discussion in section 5.3.

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From page 21, lines 9-16: “By analogy with the modern situation, we expect reduced Orinoco precipitation during periods of low JJA insolation, when the ITCZ position is shifted to the south (Haug et al., 2001) in response to increased meridional temperature gradient in the northern hemisphere (e.g. Chiang and Bitz, 2005). This is in line with the latitudinal contraction of the South American rainbelt proposed by Maslin et al. (2011) during the last glacial period. The resulting reduction in Orinoco precipitation and sediment discharge during intervals of low JJA insolation (i.e. high DJF insolation, Figure 6A) would decrease the proportion of Orinoco material, i.e. increase %-Amazon values at the 12°N core site.”

3. In the Discussion section Sea level is discussed – however the one key fact is missed in the discussion. The Amazon river sediment discharge is a threshold mechanism which occurs at about 80-100 m relative sea level drop. Before this drop is reached the sediment is deposited on the continental shelf and transported along the shelf. Once the sea level drop below this critical depth the sediments are funnel into the Amazon canyon and terrigenous sediments are pushed much further in to the Atlantic Ocean (see Milliman et al., 1979; 1983; Maslin et al. 2006).

Thanks for the more detailed information on sea level effect and additional references.

We modified accordingly the discussion on the effect of sea level changes on sediment discharge and deep-sea sedimentation. Please note the effect of sea level has been moved to the new Discussion section 5.1 “Factors controlling marine vs. terrigenous relative proportions”.

From page 11, line 27 to page 12, line 9: “Several studies suggest that past sea level variations influenced the amount and pathway of sediments delivered to the western tropical Atlantic (e.g. Schlünz et al., 2000; Rühlemann et al., 2001), in particular by the Amazon River (Milliman et al., 1975; Maslin et al., 2006). The discharge of Amazon sediments responds to a threshold mechanism driven by global sea level (Milliman et al., 1975). During interglacial highstands, Amazon sediments are deposited by long-

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shore currents along the continental shelf to the northwest of the river mouth. During glacial times when sea level falls 80-100 m below the present level, Amazon sediments are directly channelled down the continental slope (Milliman et al., 1975; Maslin et al., 2006). Increased glacial sediment delivery to the deep sea led to sedimentation rates in the Amazon Fan that were about 20 to 1000 times higher than during the Holocene (Milliman et al., 1975; Maslin et al., 2006). Therefore, sea level variations likely influenced the total amount of terrigenous material deposited at our core sites and explain the relative increases in terrigenous vs. marine biogenic endmember proportions observed during cold substages (Figure 5).”

4. The original work on which Wilson et al. (2011) is based is from an obscure paper Maslin (1998) in Geol Soc volume, which discusses the effects of glacial and Heinrich event conditions on the NBCC retroflexion. Though dated it might help the authors with their excellent discussion on the retroflexion.

We thank the Reviewer for making us aware of the paper by Maslin 1998, which first addressed changes in the NBC retroflexion during glacial times and Heinrich events.

In our discussion on the role of ocean surface currents (section 5.3), we added the reference to Maslin 1998 and slightly modified the text to include their findings. It can now be read in page 21, line 30 to page 22, line 9:

“This hypothesis is supported by the strengthening of the NBC retroflexion and oceanward deflection of Amazon freshwater plume suggested during past cold substages and Heinrich events (Maslin, 1998; Rühlemann et al., 2001; Wilson et al., 2011). Larger northern ice sheets during cold substages (or iceberg discharge during Heinrich events) enhanced the Atlantic meridional SST gradient, which strengthened trade winds, shifted the ITCZ southward (Chiang and Bitz, 2005) and curtailed the cross-equatorial export of the NBC (Maslin, 1998). Intensified trade winds also favoured the accumulation of surface waters in the western equatorial Atlantic, creating a W-E pressure gradient (Rühlemann et al., 2001). This gradient strengthened the North

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Equatorial Counter Current and the NBC retroflection, i.e. a more vigorous eastward flow of surface waters carrying freshwater and suspended particles delivered by the Amazon River (e.g. Maslin, 1998; Zabel et al., 1999; Rühlemann et al., 2001; Wilson et al., 2011).”

5. Figure 8 – I would be tempted to switch (F) 12 deg N upside down so that peak and trough matched with the other two record. Moreover it would be interesting to see if a cross plot of the 5 deg N and 12 deg N records clearly show the inverse relationship.

We reversed the scale of the 12°N core (panel F) in Fig 8, as suggested.

(Note that we did not reverse the scale of the Cariaco Basin record in panel G, initially plotted in the “wrong direction”. Low reflectance in the Cariaco Basin reflects increased terrestrial precipitation. This is now plotted in the same direction as increased Orinoco values in F.)

We also included a cross plot of 12°N %-Amazon vs. 5°N %-Andes records as new supplementary Figure 3. The obtained negative linear regression ($r = -0.21$) is significant at the 99% level, which supports the described inverse relationship at 5°N and 12°N. We added a sentence at the end of the Results section (page 11, lines 15-17) that refers to the new Supplementary Fig. 3:

“This inverse relationship is supported by the significant negative linear regression between the 12°N %-Amazon and 5°N %-Andes records (Supplementary Fig. 3).”

6. Figure 1 – It might be helpful if the core names were included either on the Figure or at the very least in the Figure caption for easy of reference.

Agreed. In order not to overload Figure 1 with text, we added the core names in the figure caption on lines 9-10 of page 33:

“Black dots mark the location of the studied sediment cores: GeoB3938-1 at 12°N, GeoB7010-2/GeoB7011-1 at 9°N and GeoB4411-2 at 5°N (Table 1).”

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Aline Govin, on behalf of all authors.

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