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Climate of the Past Discussions

Interactive comment on "Two-signed feedback of cross-isthmus moisture transport on glacial overturning controlled by the Atlantic warm pool" *by* H. J. de Boer et al.

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We kindly thank Ref #2 for critically reading and commenting the discussion paper. In the following reply we will first clarify and address the key points raised by Ref #2 and then address the specific points. For clarity, the comments of Ref #2 will be numbered and repeated before they are addressed.

Key points Ref #2

The main message of the study, i.e. a two-signed feedback of the cross-isthmus moisture transport, is based on highly speculative assumptions regarding the dynamics of the AWP during glacial slowdowns of the AMOC.

Our assumptions regarding the dynamics of the Atlantic Warm Pool (AWP) during the glacial are a key concern to Ref #2. Part of this concern may have been related to the Sea Surface Temperature (SST) threshold of 28.5 deg.C which defines the (modern) AWP. The SST proxy data reviewed in section 2 of the discussion paper show values in the range of 21-27 deg.C for the Gulf of Mexico (Ziegler et al., 2008) and 25-27 deg.C for the Caribbean Sea (Schmidt et al., 2004), which may have been interpreted by Ref #2 to indicate that no AWP existed during the last glacial. However, the AWP is a typical summer phenomenon while the Mg/Ca derived SSTs from the Gulf of Mexico and Caribbean Sea reflect a more annual averaged signal (Anand et al., 2003). For example, present annual average SSTs in the Gulf of Mexico are around 24-25 deg.C while summer SSTs may surpass 29 deg.C when the AWP expands well into the Gulf of Mexico. The absence of a clear SST cooling in the Gulf of Mexico during extratropical North Atlantic cold events therefore led Ziegler et al. (2008) to propose that the AWP persisted to expand into the Gulf of Mexico during summer throughout most of the last glacial. Further evidence for consistently warm glacial SSTs in the region of the modern AWP is available from the Gulf of Mexico (Flower et al., 2004) and Caribbean Sea (Rühlemann et al., 1999; Schmidt et al., 2006). The data from Rühlemann et al. (1999) and Flower et al. (2004) even suggest SST warming at the onset of Heinrich event 1, which was interpreted to reflect low-latitude heat retention during periods with diminishing northward heat transport. Another interpretation, as put forward by Ziegler et al. (2008), involves increased seasonality during Heinrich events. We therefore argue that the proxy data reviewed in section 2 of the discussion paper provide ample evidence for a role of the AWP during glacial summers. Yet, we realize that the offset between summer SSTs defining the (seasonal) AWP and annual average SSTs typically reflected in proxy data may have been confusing. We therefore propose to revise section 2 by emphasizing that paleo-SSTs in the range of modern annual average SSTs may be indicative of the presence of an AWP during glacial summers. Further we propose to adapt Figure 1a to show modern annual average SSTs rather than summer SSTs to facilitate comparison with the proxy data. The extent of the modern summer-time AWP will then be indicated by a line.

Another concern of Ref #2 regarding the dynamics of the AWP may have been related to our assumptions on its spatial extent beyond the Caribbean Sea and Gulf of Mexico. We are aware of the limitations of available empirical evidence to constrain the spatial extent of the glacial AWP and therefore understand this concern. However, we like to stress that it is exactly this uncertainty which inspired us to perform the atmospheric sensitivity analysis presented in the discussion paper. Key here is that we realized that the AWP affects Atlantic-Pacific moisture transport trough its influence on the Caribbean Low Level Jet. This insight came from the work of Wang and co-workers who show that the size of the modern AWP is inversely related to the strength and moisture transport of the Caribbean Low Level Jet (CLLJ) (Wang and Lee, 2007; Wang et al., 2008b) due to the effect of diabatic heating on tropical low-level flow (Gill, 1980). Following a recent publication aiming to understand inferred changes in Atlantic-Pacific moisture transport during Heinrich stadial 1 (Prange et al., 2010), we were inspired to involve the AWP as a potential mechanism for altering cross-isthmus moisture transport during periods of rapid glacial climate change. Owing to the uncertainty regarding the dynamics of the glacial AWP, we aimed to study the sensitivity in cross-isthmus moisture transport to hypothesized variations in the AWP following the approach of Wang et al. (2008b). As this goal of the discussion paper may not have been explained clear enough we propose to emphasize that we performed a sensitivity study in the introduction. Also we propose to formulate the three hypotheses that were implemented in our experiments in section 2 of the discussion paper: (1) coeval extratropical and subtropical North Atlantic cooling during AMOC collapse without an AWP; (2) extratropical North Atlantic cooling during AMOC collapse with persistent AWP expansion, and (3) inhibited AWP expansion after AMOC collapse. The model results based on these hypotheses will then be compared with reconstructed paleo-salinities from the Atlantic and Pacific sides of the Central American isthmus in section 5.2. Also we propose to alter the title of the discussion paper to: "The role of the Atlantic Warm Pool in controlling atmospheric moisture transport across the Central American Isthmus during the last glacial: a climate model sensitivity study".

The second key point of Ref #2 regarding our integrated moisture transport calculations is discussed in our response to specific comment #3.

Specific comments Ref #2:

1) PUMA is a relatively simple coarse-resolution atmosphere model. The model's skill in simulating the (present-day) regional precipitation and wind systems (in particular the Caribbean Low Level Jet) needs to be assessed before any conclusions for glacial climate dynamics can be drawn.

We agree that the atmosphere module of the Planet Simulator (PUMA version 2) is relatively simple in comparison to the atmosphere models currently used for modern climate simulations. However, in comparison to the quasigeostrophic atmosphere component of LOVECLIM (EC-Bilt) which is commonly used in paleo-climate modelling, PUMA-2 simulates the atmospheric circulation in the tropics more realistically. We therefore used PUMA-2 instead of EC-Bilt to perform the atmospheric sensitivity simulations. We note that the atmospheric response of PUMA-2 has previously been evaluated, for example a detailed comparison between the Planet Simulator (with PUMA-2 as dynamical core) and the ERA-40 reanalysis was performed by the University of Hamburg (Haberkorn et al., 2009) and a comparison between PUMA-2 and ECHAM4 was performed by Grosfeld et al. (2007). The response of PUMA-2 to variations in Atlantic SSTs was analyzed by Grosfeld et al. (2008). The seasonality in the position of maximum moisture transport by the CLLJ as simulated by PUMA-2 in the LGMN simulation (Fig. 3a-c) is comparable to the ERA-40 reanalysis as shown by Muñoz et al. (2008). Also, the atmospheric response of PUMA-2 shows the same inverse relation between the size of the AWP and the strength of the CLLJ as the NCAR CAM3 model (Wang et al., 2008b). Wang et al. (2008b) discuss that this inverse relation is consistent with the theory on heat-induced tropical circulation of Gill (1980). Our results are therefore consistent with this previous work although, to our knowledge, the role of the AWP in altering the atmospheric circulation during periods of rapid glacial climate change has not been considered before. We propose to cite these studies in a revised version of the manuscript and discuss the potential model biases more elaborately in the discussion of a revised version of the manuscript.

2.1) The final conclusions, i.e. the existence of a two-signed feedback, relies on highly speculative assumptions regarding changes in AWP area during Heinrich events.

We agree with Ref #2 that our conclusions depend on hypothesized dynamics of the AWP during the last glacial. However, because coupled ocean-atmosphere models do not accurately simulate the AWP in the modern climate due to a cold SST bias (Breugem et al., 2008; Misra et al., 2009), we argue that our approach using hypothesized AWP dynamics in the framework of a sensitivity study is a valid starting point to foster further research towards unravelling the role of the AWP in the glacial climate. In a revised version of the manuscript we therefore propose to explain more clearly that our paper presents sensitivity experiments following the approach of Wang et al. (2008b) within the context of proxy based evidence of the AWP during the glacial (Schmidt et al., 2004; Ziegler et al., 2008). To achieve this, we propose to explicitly state the 3 hypotheses that were considered in our simulations and adjust the title of the discussion paper, as discussed in our response to the key concerns of Ref #2. Because the SST reconstructions on which we based these hypotheses are not conclusive in the spatial dynamics of the glacial AWP, we propose to revise the conclusions accordingly. Our main conclusion will then state that our results indicate that changes in (sub)tropical and extratropical SSTs have an opposite effect on cross-isthmus moisture transport by the CLLJ. We will also emphasize the importance to accurately constrain changes in the spatial extent of the AWP during the last glacial.

2.2) What is the reason for assuming that the AWP was 1/3 smaller than the average modern AWP? In this respect, Section 2 is very confusing since the presented proxy records do not provide any support for this assumption.

We intended to investigate the atmospheric sensitivity to variations in AWP area during the glacial and thereby followed an approach comparable to Wang et al. (2008b). As discussed in our response to the key points of Ref #2 we are aware of the uncertainties regarding the spatial extent of the glacial AWP, which inspired our research in the first place. Despite this uncertainty, the SST reconstructions from the Gulf of Mexico (Ziegler et al., 2008) and Caribbean Sea (Schmidt et al., 2004) indicate that an AWP was present during glacial summers. These records reveal SST changes at timescales distinct of the SST changes in the extratropical North Atlantic. We therefore did not, as suggested by Ref #2, assume that the glacial AWP was 1/3 smaller than the average modern AWP. Rather we performed 6 atmospheric sensitivity simulations with AWPs ranging from almost non-existent to an AWP with the approximate size of a large modern AWP (as shown in Fig. 2a of the discussion paper). These simulations were inspired by the approach of Wang et al. (2008b) who simulated the atmospheric response to a small and a large AWP (defined as 1/3 smaller and larger than average) in the modern climate. Novel to our approach was that we applied the SST anomalies related to modern AWP size variations to the surface ocean output of glacial simulations performed with LOVECLIM. Because coupled ocean-atmosphere models typically do not accurately resolve the AWP in the modern climate (Breugem et al., 2008; Misra et al., 2009), we argue that our approach is a reasonable starting point for a sensitivity analysis with a focus on the glacial climate. Moreover, cross-isthmus moisture transport simulated by our atmospheric CGM responds approximately linear to changes in AWP area (as shown by the regression model in Fig. 5d in the discussion paper). Our assumptions regarding the absolute extent of the AWP are therefore not crucial to our main conclusions. However, to prevent confusion regarding our assumptions we propose to more clearly state the hypotheses considered in a revised version of the manuscript.

2.3) Moreover, why are records from the Iberian margin and the tropical east Atlantic presented? These sites are far beyond the reach of the AWP.

We presented SST records from the Iberian margin because these data, in contrast to the data from the Caribbean Sea and Gulf of Mexico, do show SST cooling during Heinrich events. Based on this evidence we hypothesized that cold surface waters were advected southward beyond the Iberian Margin via the Canary Current after AMOC collapse (Zhao et al., 1995; Bard et al., 2000). Although we are aware of the uncertainty regarding how far these cold water may have reached into the subtropical North Atlantic, we think that in absence of further evidence we should at least consider the possibility that these cold surface water may have hindered eastward expansion of the AWP beyond the Caribbean Sea and Gulf of Mexico in the period following AMOC collapse. For this reason we also included the SST record from the tropical east Atlantic, which shows a warming during Heinrich events and allows constraining the southward extent of North Atlantic cooling. We will clarify this in a revised version of the manuscript.

3) The calculation of the atmospheric moisture transport is wrong. Equation (3) does not make any sense if the authors want to calculate the moisture flux through the given line segments. This is easy to see even for a nonmathematician as the integrand is always positive, independent of the wind direction. Moreover, it is unclear why the vertical integration stops at 700 hPa and whether the moisture flux calculation is based on 6-hour, daily, monthly or whatever model output. Also note that dP is not a pressure difference but a differential, and g is not the gravitation constant but the acceleration due to gravitation.

We thank Ref #2 for noting these inconsistencies in the discussion paper. We should have been clearer in noting that the wind speed was calculated normal to each line segment over the isthmus and multiplied with the moisture content at each pressure level using monthly averaged model output. Because Richter and Xie (2010) state that cross-isthmus moisture transport calculations based on daily values differed by only 0.2% from calculations using monthly values, we argue that our approach using monthly values is proficient. Our focus on the low-level flow up to the 700hPa pressure

level is related to our focus on the Caribbean Low Level Jet (CLLJ), which typically resides below 700 hPa. This approach followed Muñoz et al. (2008). Further, equation (3) is indeed not an accurate representation of our calculations. We therefore propose the following correction to lines 1-8 on page 3868 of the discussion paper:

Correction to lines 1-8 on page 3868 We calculated vertically integrated moisture transport over the Central American isthmus across the line segments 1-4 (noted in Fig. 3a) and between the surface and 700 hPa pressure level following Xu et al. (2005) and Richter and Xie (2010) using monthly averaged model output:

(Due to limited typesetting options, the correct equation 3 is included in the supplemental PDF)

in which QCLLJ is the low-level moisture transport across the line segments, g is the acceleration due to gravity, ps and p700 are the surface pressure and the pressure at the top of the 700 hPa pressure level, l1 and l4 are the line segments 1 and 4, uist is the flow velocity normal to each line segment, qist is the specific humidity, p denotes the atmospheric pressure and l denotes the distance along the line segment. The moisture transport calculation is limited to the lower atmosphere in order to single out the response of the CLLJ. Using monthly averaged model output instead of daily output to compute cross-isthmus moisture transport only marginally affects results (Richter and Xie, 2010).

4) Why does extratropical cooling of the North Atlantic result in a weakening of the CLLJ? Usually, models predict a strengthening of the northeasterly trade winds in response to North Atlantic cooling.

We are not exactly sure to what results Ref #2 refers in this comment. Fig. 3d of the discussion paper shows the anomalies between the OFFN and LGMN simulations and presents the atmospheric response to a typical "water-hosing" experiment with AMOC collapse. Comparable to other models, our results show an increase in surface pressure in the North Atlantic subtropical high which results in increased trade winds over the subtropical North Atlantic. This leads to increased easterly flow over line segments 3 and 4 (the southern part of the isthmus), as shown in more detail in Fig. 3e and 3f. Perhaps confusion arose because the vectors in Fig. 3d denote moisture transport and not wind speed.

If Ref #2 refers to the results presented in Fig. 4a-c with the anomalies between the OFFL and LGML simulations, we indeed reveal a strong decrease in speed and moisture transport of the CLLJ. This result is especially interesting because it suggests that if the extratropical North Atlantic cools without affecting the AWP, the CLLJ may be reduced substantially. We suggest that a cooling of the upper atmosphere over the persistent warm surface waters in the (sub)tropical North Atlantic may have resulted in increased atmospheric convection due an increased vertical temperature gradient. As shown by Johnson and Xie (2010), the tropical SST threshold for starting atmospheric convection decreases approximately linearly with a decrease in tropical 300 hPa temperature in climate models. Consequently, a cooling in the extratropical North Atlantic beside a persistent warm (sub)tropical North Atlantic may result in cooling of the upper atmosphere over these relatively warm (sub)tropical waters and thereby increase atmospheric convection. Hence, a persistent AWP beside a cooling extratropical North Atlantic may weaken the North Atlantic subtropical high and weaken the CLLJ. This atmospheric response may then reduce Atlantic-Pacific moisture transport across the Central American isthmus. We propose to discuss this potential mechanism in more detail in a revised version of the manuscript.

5) The authors discuss the case where the extratropical Atlantic cools without major changes in the AWP. This situation is actually hard to imagine given that the modern AWP correlates with the relatively small (compared to glacial millennial variability) variations of the Atlantic Multidecadal Oscillation (Wang et al., 2008).

We agree with Ref #2 that it is likely that summertime AWP expansion beyond the Caribbean Sea and Gulf of Mexico was inhibited during periods of intense extratropical North Atlantic cooling. We therefore explicitly stated in our hypothesis that AWP ex-

pansion was inhibited after AMOC shutdown. Because we performed an atmospheric sensitivity analysis to understand the individual effects of extratropical and (sub)tropical North Atlantic temperatures, we also explored the hypothetical situation that the extratropical North Atlantic cooled without affecting the AWP. To address this concern of Ref #2, we propose to explain more clearly that our work presents a sensitivity experiment in a revised version of the manuscript. Moreover, we argue that this sensitivity analysis is not unrealistic because extratropical North Atlantic cooling related to AMOC shutdown may have preceded the southward advection of cold surface water by the Canary Current (Zhao et al., 1995; Bard et al., 2000). As discussed in response to comment 4 of Ref #2, this situation may have resulted in an increased vertical temperature gradient in the atmosphere over the subtropical North Atlantic which may have reduced Atlantic-Pacific moisture transport across the isthmus. We therefore interpreted this situation to constitute an amplifying feedback with a slowdown of the AMOC. In agreement with the argumentation of Ref #2, we also hypothesized that eastward AWP expansion beyond the Caribbean Sea and Gulf of Mexico was inhibited in the period following AMOC collapse. Our simulations of the atmospheric response to this reduction in AWP area show an increase in flow and moisture transport by the CLLJ, comparable to the results of Wang et al. (2008b) for the modern climate. A combination of these atmospheric responses could lead to an initial reduction and later increase in cross-isthmus moisture transport during periods of rapid glacial climate change.

Further we like to note that Wang et al. (2008a) indeed reveal a bi-polar Atlantic SST pattern linked to the Atlantic Multidecadal Oscillation (AMOC). This result arose from the third EOF mode (with 5-11% variance explained depending on the area of reference). However, the first EOF mode (which explains 23-28% variance) shows a spatial pattern related to the global warming trend. The second EOF mode (7-15% variance explained) shows a spatial pattern related to ENSO. When Wang et al. (2008a) projected the AWP index on the EOFs, both the global warming trend and the AMO index were related to the AWP index. This suggests that different processes may control AWP expansion at distinct timescales. Different processes may therefore also have been relevant in controlling the dynamics of the AWP during the glacial. For example, the SST-proxy data from the Caribbean Sea (Schmidt et al., 2004) and Gulf of Mexico (Ziegler et al., 2008) indicate no cooling during Heinrich events while the temperature evolution shows a low-latitude summer insolation signal. In contrast, the records from Iberian margin show cooling during Heinrich events and (although less substantial) during cold D-O phases. Although an analysis of the processes that may have controlled AWP expansion during the glacial is beyond the scope of this discussion paper, it may be interesting to consider the possibility that subsurface Atlantic warming related to AMOC slowdown prior to a Heinrich event (Marcott et al., 2011) communicated upward to the surface in the region of the AWP. Especially as coupled ocean-atmosphere models exhibit a cold SST bias in the region of the modern AWP (Breugem et al., 2008; Misra et al., 2009), the relevance of the AWP for altering the glacial climate should not be discarded.

6) Section 5.2 is very confusing. The authors argue that proxy evidence suggests reduced cross-isthmus moisture transport during Heinrich events and that this would agree with their modeling results. On the other hand, they argue that the AWP was strongly affected during AMOC collapse resulting in enhanced cross-isthmus moisture transport.

We thank Ref #2 for pointing out that our discussion in section 5.2 is not clear. Part of the confusion may have been related to the hypotheses underlying our sensitivity simulations. As discussed in our response to the key concern of Ref #2, we propose to rewrite section 5.2 and explicitly state the three hypotheses on which we based our sensitivity simulations. The model results related to these hypotheses may then be confronted with the reconstructed sea surface salinity changes from the Atlantic and Pacific sides of the Central American isthmus during Heinrich events (Schmidt et al., 2004; Leduc et al., 2007). Leduc et al. (2007) hypothesized that cross-isthmus moisture transport was reduced during Heinrich events because the reconstructed salinity increases were larger on the Pacific than at the Atlantic side of the isthmus. This result

is not consistent with our simulation of the first hypothesis which shows little change in cross-isthmus moisture transport. Our model result related to the hypothesis of a persistent AWP may explain reduced moisture transport at the onset of Heinrich events. However, as substantial cooling is observed in the subtropical Northeast Atlantic following AMOC collapse, we also considered the hypothesis that AWP expansion beyond the Caribbean Sea and Gulf of Mexico was inhibited after AMOC collapse. Our model response to this forcing shows an increase in cross-isthmus moisture transport. We agree with Ref #2 that we cannot differentiate between the two latter hypotheses based on the SST proxy data presented in section 2 of the discussion paper. We therefore propose to revise section 5.2 by noting that based on the substantial changes in reconstructed paleo-salinities we suggest a role for the glacial AWP in altering cross-isthmus moisture transport during periods of AMOC collapse.

7.1) The "statistics" presented in Fig. 7 is wishful thinking. Firstly, the correlation coefficient in Fig. 7c is statistically not significant at the 0.05 significance level;

We thank Ref #2 for noting this inconsistency. We propose to remove Fig. 7c and the Gulf of Mexico SSTs in Fig. 7b in a revised version of the manuscript.

7.2) secondly, there is obviously no temporal correlation between the Gulf temperature and the salinity records presented in Fig. 7a, which would be expected from a significant influence of Gulf temperature on cross-isthmus moisture flux.

We agree with Ref #2 that no temporal correlation is visible between the temperature in the Gulf of Mexico and the salinity difference between the Pacific and Caribbean records. We note however that this was also not expected based on our modeling results. We explicitly show that cross-isthmus moisture transport is controlled by an interplay between the temperature of the extratropical North Atlantic and the size of the AWP. For exactly this reason we focused on the difference in salinity change between the Atlantic and Pacific sides of the isthmus during period of AMOC collapse following Leduc et al. (2007). In addition to the analysis of Leduc et al. (2007) we involved a potential role for the AWP in altering moisture transport. Our reasoning was that, due to the opposing effects of AWP area and extratropical North Atlantic temperatures on cross-isthmus moisture transport, we may expect larger differences in salinity fluctuations during periods of AMOC collapse with a warmer Gulf of Mexico. Our modelling results, in line with those of Wang et al. (2008b) for the modern climate, do suggest that the AWP plays a crucial role in controlling moisture transport by the CLLJ. To explain the reconstructed salinity fluctuations on Pacific and Atlantic sides of the Central American isthmus we therefore argue that the atmosphere response to a combined forcing of the extratropical North Atlantic and the AWP should be considered.

8) Boundary conditions for ice-sheet cover and orography are taken from Paul and Schafer-Neth (2003)? This is probably not the right reference.

We thank Ref #2 for noting this error. The correct reference should cite Peltier (1994) for our boundary conditions on ice-sheet cover and orography.

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