

## ***Interactive comment on “Effects of orbital forcing on atmosphere and ocean heat transports in Holocene and Eemian climate simulations with a comprehensive Earth system model” by N. Fischer and J. Jungclaus***

**N. Fischer and J. Jungclaus**

nils.fischer@zmaw.de

Received and published: 9 February 2010

We would like to thank the two anonymous referees for their productive comments and suggestions that helped to improve the manuscript. Especially for bringing to our attention a shortcoming in the discussion concerning the relationship between temperature and ocean circulation changes in the Arctic region.

Responses to referee 1:

1/ Many studies have been devoted to the response of the Arctic to a warming in  
C1156

the framework of the recent and future rise in greenhouse gas concentration in the atmosphere. The forcing is different compared to the mid-Holocene and Eemian but comparing the mechanisms involved would be very interesting. In particular, I have in mind the paper of Bitz et al. (2006) that also analyzes changes in heat transport when the ice edge is retreating.

Bitz CM, Gent PR, Woodgate RA, Holland MM, Lindsay R. The influence of sea ice on ocean heat uptake in response to increasing CO<sub>2</sub>. JOURNAL OF CLIMATE 19 (11) 2437-2450, 2006

Answer: We added the following text to the corresponding paragraph in the Discussion section:

"Bitz et al. 2006 investigate changes in the ocean in a coupled AO-GCM (CCSM3) under increasing CO<sub>2</sub> forcing. They also find increased circulation and thus heat transport in the Arctic region comparable to the changes we find in our paleo-simulations. They attribute the this increase to increased convection along the Siberian Shelf."

2/ All the figures are very small so it is often hard to see the signals described by the authors.

Answer: We have asked the editors to increase the size of the pictures.

3/Page 2314, line 17. To my knowledge, the model used by Renssen et al. (2006) does not include heat flux corrections.

Answer: According to Table 2 in Braconnot et al. 2007a and the ECBILT-CLIO web page the model does apply basin wide corrections of fresh water fluxes, but apparently indeed no heat flux corrections are applied. The sentence in the manuscript has been corrected accordingly.

4/ Page 2318, line 4. I see well the decreased of 1 K south of Iceland in the Eemian simulation on Fig. 2b but not on Fig 1a. I see no blue patch in the Atlantic in the latter figure. Is it the same field that is plotted on the 2 figures as suggested by the text?

C1157

Answer: There has been a mix-up. Has been corrected.

5/ Page 2318, line 5-10. The explanation attributing the temperature decrease to a reduction in albedo is a bit short for me. Without additional effects, I would expect a warming associated with a reduced albedo. I imagine that we also have to take into account hydrological changes but the authors must at least mention their impact on temperature (related to clouds, latent heat flux ?).

Answer: It was not our intention to relate the decreased albedo to the cooling signal, but rather to state that the changes in vegetation cover also affect the soil albedo. We agree that the paragraph as it was might be confusing. The paragraph has been reformulated:

"We attribute the temperature decrease in the tropics to an intensification of the African monsoon system. With increased cloud cover over the Sahel region shielding the land surface from direct insolation. Sensible heat flux from the land surface to the atmosphere is thus reduced by up to  $30 \text{ W/m}^2$  and  $60 \text{ W/m}^2$  in the Holocene and Eemian, respectively, whereas latent heat flux increases by similar amounts. The hydrological cycle is further increased by an increase in vegetation cover. The subsequent decrease in surface albedo (see below) however is not able to counterbalance the cooling effect. The temperature increase in the Arctic is due to a reduction in sea-ice cover in the Arctic and changes in atmospheric and oceanic circulations and heat transports which will be discussed in further detail in the following sub-sections. Changes in precipitation in the Holocene and the Eemian (Fig.1b) are qualitatively similar but more enhanced in the Eemian simulation, with the strongest increase of up to 2.5 mm per day over the Sahel region and the western Indian ocean. Over the Sahel this increase is mainly due to an increase in convective rain since evaporation increases by similar amounts (not shown). The latitudinal precipitation maximum over the region between  $10^\circ\text{S}$  and the Equator reduces (not significantly) by 0.2 mm/day to 6.0 mm/day. In the northward direction the latitudinal band between  $15^\circ\text{N}$  and  $30^\circ\text{N}$  with no precipitation has almost vanished to a small band around  $30^\circ\text{N}$  with less than 1/day precipitation."

C1158

6/ Page 2318, line 18. Would it be possible to diagnose the shifts in the ITCZ?

Answer: We diagnosed the ITCZ as proposed in Braconnot et al. 2008 (as suggested also by referee #2). We observe northward shift over Africa of  $1.5^\circ$  ( $3^\circ$ ) over western and central Africa to  $9^\circ\text{N}$  ( $10^\circ\text{N}$ ) in the Holocene (Eemian) simulation compared to the pre-industrial one. (Added to the manuscript) Since we are not yet fully content with the dynamic vegetation module of the surface component regarding the albedo effects (see discussion), we would like to improve this before looking into low latitude effects more detailed and rather focus on the northern hemisphere in this study. We added the following to the manuscript.

"Following the ITCZ-definition given in Braconnot et al. 2008 we observe northward shift over Africa of  $1.5^\circ$  ( $3^\circ$ ) over western and central Africa to  $9^\circ$  ( $10^\circ$ ) over eastern Africa in the Holocene (Eemian) simulation compared to the pre-industrial one (not shown)."

7/ Page 2319, line 25. If the dry and moist components compensate each other, there is no net change in heat transport. Do the authors mean TEND TO compensate each other, or simply that these two components have opposite signs?

Answer: "Tend to" is indeed what we meant to say.

8/ Page 2322, line 4. The definition of the barotropic streamfunction is a bit strange to me. As I am reading it, because of the integration on both x and z, psi would be only a function of y. I guess I am wrong because if psi is only a function of y, it could not be used to describe ocean gyres.

Answer: The integral is the definition of the ocean gyres, not of the stream function. We hope to have formulated this more clearly now.

"Ocean gyres in the North Atlantic are derived from the vertically integrated horizontal barotropic stream function by integrating the water transports through a zonal plane from the coast to the grid box point ( $\psi(x, y) = \int v dx dz$ , with  $v$  meridional velocity,  $x$  and

C1159

z the zonal and vertical coordinates)."

In a more general way, the definition of all the integrals would be much clearer (and more precise) if the intervals on which the integral is computed were given.

Answer: We added the intervals in the text.

9/ Page 2323, line 24. I agree that for BAR, "the relative increase in heat transport is larger than (not then I guess) the increase in volume transport (in absolute values)". However, this is not the case for ISR as claimed in the manuscript. This is indeed consistent with the explanation given page 2324 lines 1-2.

Answer: There was indeed an inconsistency in the corresponding paragraph. The paragraph has been reformulated.

"In the Holocene and more enhanced in the Eemian simulation the volume transports through all passages increase due to enhanced circulation. Nevertheless, this increase in volume transport is not sufficient to explain the changes in heat transport. In case of ISR and BAR the increase in volume transport has the same sign as the increase in heat transport. In case of the BAR, the relative increase in heat transport is larger than the increase in volume transport. Thus the heat transport increase is also due to an increase of 5% in heat content of the Nordic Seas basin for the Holocene and the Eemian simulation compared to the pre-industrial. This increase in heat content also contributes to the increase of effective heat transport to the Arctic through FRAM due to the increased temperature difference between the two basins. The temperature difference between the Nordic Seas and the North Atlantic on the other hand decreases and so, despite the increase in volume transport, the effective heat transport into the Nordic Seas via DEN and ISR decreases."

10/ Page 2324, line 17-18. For me, it is not straightforward that the increase in the heat flux is associated with a northward shift of deep convection. It could be due to the reduction of the ice cover only (see line 11-12, same page). If a link is seen in the

C1160

model between heat flux and deep convection this must be shown or at least discussed more precisely.

Answer: The comment is valid and connected comment #13. We decided to omit the sentence in the results section and refer to the issue in the Discussion section (see Answer #13).

11/ Page 2325, line 23. In winter, at high latitudes the insolation is very low (and even equal to zero at many places) and its changes are thus low too.

Answer: This is correct, but low insolation prevails longer at high latitudes in the Holocene and the Eemian. This has been added in the manuscript.

"The heat flux from the ocean to the atmosphere increases in the Holocene and the Eemian simulation enhancing the overall warming signal in high northern latitudes counterbalancing the decrease in winter insolation due to the prolonged winter season."

12/ Page 2325, line 28. If I understand well, it is said that the oceanic heat loss to the atmosphere increases in the Nordic Seas (mentioning in the manuscript "increased heat flux" is not very clear) while the numbers given page 2324 give a decrease in the heat flux. Is this compatible?

Answer: As mentioned in the discussion, the overall heat flux over the Nordic Seas basin is reducing slightly and changing in terms of distribution, i.e. a northward shift of heat flux over the Nordic Seas basin. The corresponding paragraph has been modified to be more clear.

"The heat flux from the ocean to the atmosphere increases over the Barents Shelf and shifts further north over the Nordic Seas in the Holocene and the Eemian simulation enhancing the overall warming signal in high northern latitudes counterbalancing the decrease in winter insolation due to the prolonged winter season."

13/ Page 2326, line 1-2. I must admit that I am not at all convinced by this feedback

C1161

loop. First, I do not understand the argument related to the increased heat loss (see above). Second, if deep water formation were more active and the AMOC more vigorous at the Iceland-Scotland ridge, we should see that on Fig. 7 but this is not the case. Only a very small increase in the AMOC is seen close to the surface, northward of 70°S, if I am right. The authors do not mention the role of the winds in the increased transport which appears to be a much more likely candidate to explain the changes in ocean currents to my point of view.

Answer: We admit that the proposed feedback loop is indeed debatable. We are thankful to both referees for pointing at this and for proposing alternative explanations. We investigated the wind fields over the Nordic Seas basin and found no clear picture as to how they influence the Nordic Seas gyre. The northward shift in storm tracks observed leads to an increase in wind stress curl over the eastern margin of the basin along the Norwegian coast and could thus contribute to the strengthening of the gyre circulation. On the western margin, however, wind and wind stress curl reduces and can not explain the increase. We therefore investigated the water density structure in the Nordic Seas basin in all three simulations and found less dense water masses on the basin's margins more enhanced along the Greenland coast than long the Norwegian coast in the Holocene and Eemian simulations. This leads to the geostrophic response in circulation also favored by the increase in convection in the Nordic Seas basin seen in the simulations.

The following has been added/reformulated to the revised manuscript:

In the Ocean circulation (Results) section:

"The Nordic Seas gyre maximum intensity increases by up to 1 Sv in the Holocene simulation and by 1.5 Sv in the Eemian (pre-industrial maximum: 16 Sv) and it expands further north due to the retreat of sea ice and an increasing density gradient with relatively dense water at the center and less dense water at the margins. An investigation of wind stress over the Nordic Seas basin does not show a clear influence

C1162

on the gyre circulation. Wind stress curl slightly increases along the Norwegian coast, but decreases along the Greenland coast."

In the Discussion section:

"In high northern latitudes the increase in summer insolation influences the sea ice coverage in the Arctic. The sea-ice melt in the summer months due to the increased insolation is enhanced by the sea ice-albedo feedback (Harvey 1988) and cannot be counterbalanced by sea-ice built-up in winter. In the absence of sea ice over the Barents Shelf and along the east coast of Greenland sea-ice cover cannot act as an insulator between the ocean and the atmosphere. The heat flux from the ocean to the atmosphere increases in the Holocene and the Eemian simulation enhancing the overall warming signal in high northern latitudes counterbalancing the decrease in winter insolation due to the prolonged winter season. The heat is transported by the relatively warm and saline water coming from the North Atlantic over the Iceland-Scotland-Ridge into the Nordic Seas. The volume transport and thus the heat transport consists of vertical overturning circulation and horizontal gyre circulation contributions. The increase in heat transport to high northern latitudes is mainly due to strengthened gyre circulation in the Nordic Seas that is caused geostrophically by an increase of the density gradient in the basin and to some extent by an increase in wind stress at the eastern margin of the basin along the Norwegian coast. The strengthening of the gyre is favored by increased convection at its center visible in the local increase in the vertical stream function at 75°N in the Holocene and the Eemian simulation."

14/ Page 2326, line 9. Do you mean Eastern Europe or Northern Europe? For me Romania, for instance, is part of Eastern Europe while the influence of the Barents Sea in this region is probably weak.

Answer: We mean northeastern Europe.

15/ Page 2326, line 18. What do you mean by "multimodel mean does not display regional amplification in high northern latitudes"? The majority of the models have a clear

C1163

polar amplification of temperature changes (see for instance figure 6a of Braconnot et al. 2007).

Answer: We mean to say that the PMIP2-model mean does not show regional differences at the same latitude.

"The surface temperature obtained from multi-model ensemble means in PMIP2 (Braconnot et al. 2007) does not show zonal regional amplifications in high northern latitudes."

16/ Page 2327, line 12-14. In the introduction, the authors mention that the maximum temperature is delayed compared to the maximum in insolation because of the inertia of the climate system. Here, the authors said that the response in previous study (Schurgers et al. 2007) is larger than in their study because they analyzed an earlier period. Is this compatible?

Answer: It is compatible in so far as in the study by Schurgers et al. the transient run was started from a 1000 year spin-up experiment under the orbital forcing for 128-129ka, the effects of the preceding glacial conditions (melting continental ice sheets, etc. ) were not taken into account. We reformulated the corresponding paragraph to be more precise.

"The global temperature, precipitation and albedo changes shown in transient experiments of the Eemian performed with an earlier generation of the model set-up used in this study Schurgers et al. 2007 are in good agreement with the results presented here. The changes in their study of the Eemian period from 127,000 yBP - 125,000 yBP are larger than in this study where we only consider a time-slice at 125,000 yBP conditions because of the initial conditions of their transient experiment that were obtained from an equilibrium experiment run under orbital forcing corresponding to the insolation maximum in the Eemian which was at 128,000 yBP and declined thereafter, not taking into account melting continental ice sheets, etc. of the preceding glacial period."

C1164

17/ Page 2327, line 18. Adding references for the temperatures on the western coast of Europe and Northern Africa would be helpful. In addition, precisising which part of Western Europe is discussed would clarify the discussion.

Answer: We added references (Rimbu et al. 2004, Lorenz et al. 2006) and specified the exact locations (coast near Portugal and near Morocco) in the manuscript.

Responses to referee #2:

Major concerns: 1) The discussion is not very convincing. The feedback loop (page 2325 / line 25 and following) is not really supported by the results shown within the text. Most of the transport and transport changes in the Nordic seas are due to the gyre component rather than MOC. Is the MOC change really impacting the heat transport ? Over the ISR, MOC increase is not clear. The existence of the alleged feedback loop need to be clarified. Some quantification is needed. A feedback due to the northward shift of wind and storm tracks could be, and probably is, active in the simulations, through the gyre heat transport in North Atlantic. This should be clarified.

Answer: We admit that the proposed feedback loop is indeed debatable. We are thankful to both referees for pointing at this and for proposing alternative explanations. We investigated the wind fields over the Nordic Seas basin and found no clear picture as to how they influence the Nordic Seas gyre. The northward shift in storm tracks observed leads to an increase in wind stress curl over the eastern margin of the basin along the Norwegian coast and could thus contribute to the strengthening of the gyre circulation. On the western margin, however, wind and wind stress curl reduces and can not explain the increase. We therefore investigated the water density structure in the Nordic Seas basin in all three simulations and found less dense water masses on the basin's margins more enhanced along the Greenland coast than long the Norwegian coast in the Holocene and Eemian simulations. This leads to the geostrophic response in circulation also favored by the increase in convection in the Nordic Seas basin seen in the simulations.

C1165

The following has been added/reformulated to the revised manuscript:

In the Ocean circulation (Results) section:

"The Nordic Seas gyre maximum intensity increases by up to 1 Sv in the Holocene simulation and by 1.5 Sv in the Eemian (pre-industrial maximum: 16 Sv) and it expands further north due to the retreat of sea ice and an increasing density gradient with relatively dense water at the center and less dense water at the margins. An investigation of wind stress over the Nordic Seas basin does not show a clear influence on the gyre circulation. Wind stress curl slightly increases along the Norwegian coast, but decreases along the Greenland coast."

In the Discussion section:

"In high northern latitudes the increase in summer insolation influences the sea ice coverage in the Arctic. The sea-ice melt in the summer months due to the increased insolation is enhanced by the sea ice-albedo feedback (?) and cannot be counterbalanced by sea-ice built-up in winter. In the absence of sea ice over the Barents Shelf and along the east coast of Greenland sea-ice cover cannot act as an insulator between the ocean and the atmosphere. The heat flux from the ocean to the atmosphere increases in the Holocene and the Eemian simulation enhancing the overall warming signal in high northern latitudes counterbalancing the decrease in winter insolation due to the prolonged winter season. The heat is transported by the relatively warm and saline water coming from the North Atlantic over the Iceland-Scotland-Ridge into the Nordic Seas. The volume transport and thus the heat transport consists of vertical overturning circulation and horizontal gyre circulation contributions. The increase in heat transport to high northern latitudes is mainly due to strengthened gyre circulation in the Nordic Seas that is caused geostrophically by an increase of the density gradient in the basin and to some extent by an increase in wind stress at the eastern margin of the basin along the Norwegian coast. The strengthening of the gyre is favored by increased convection at its center visible in the local increase in the vertical stream function at 75°N

C1166

in the Holocene and the Eemian simulation."

2) Cooling in monsoon region is attributed to albedo changes (page 2318 / line 5). The vegetation is dynamic. This implied a possible change of the evaporation process between soil and atmosphere (page 2325 / line 10), which can impacts the simulated climate. The relative effect of the albedo feedback and the evaporation feedback should be quantified, even though the albedo is underestimated, the soil albedo being fixed.

Answer: We did not intend to attribute the cooling over the Sahel region to the reduced soil albedo. We merely added this information. However the corresponding paragraph was formulated misleadingly and has thus been reformulated including some further analysis as suggested by the referee:

"We attribute the temperature decrease in the tropics to an intensification of the African monsoon system. With increased cloud cover over the Sahel region shielding the land surface from direct insolation. Sensible heat flux from the land surface to the atmosphere is thus reduced by up to 30 W/m<sup>2</sup> and 60 W/m<sup>2</sup> in the Holocene and Eemian, respectively, whereas latent heat flux increases by similar amounts. The hydrological cycle is further increased by an increase in vegetation cover. The subsequent decrease in surface albedo (see below) however is not able to counterbalance the cooling effect."

3) The bibliography is missing some papers relevant to the subject : in the introduction, the paper reads that there is no bibliography about ocean dynamic change in simulations of these periods, except Rensen et al (2006). However, some references can be found in the literature about ocean dynamics change and its effects at the Holocene (the following list is probably not comprehensive) :

Change of global transport in atmosphere and ocean : Braconnot P., Joussaume S., Marti O and de Noblet N (2000). Impact of ocean and vegetation feedback on 6ka monsoon changes. Third PMIP Workshop, La Huardière, Canada, WCRP.

Change of deep temperature, vertical velocity, etc ... : Liu Z., E. Brady and J. Lynch-

C1167

Steiglitz, 2003b: Global ocean response to orbital forcing in the Holocene. *Paleoceanography*, 18 (2), 1041, doi:10.1029/2002PA000819. Liu Z., J. Kutzbach and L. Wu, 2000: Modeling climatic shift of El Nino variability in the Holocene. *Geophys. Res. Lett.*, 27, 2265-2268.

Change of transport and mixed layer depth in the Tropics : Zhao Y, Braconnot P, Marti O, Harrison SP, Hewitt C, Kitoh A, Liu Z, Mikolajewicz U, Otto-Bliesner B and Weber SL (2005). A multi-model analysis of the role of the ocean on the African and Indian monsoon during the mid-Holocene. *Clim Dyn* 25(7-8):777-800

Relation between mixed layer depth and monsoon : Braconnot P and Marti O (2003). Impact of precession on monsoon characteristics from coupled ocean atmosphere experiments: changes in Indian monsoon and Indian ocean climatology. *Marine Geology* 201(1-3):23-34 Braconnot P, Marzin C, Gregoire L, Mosquet E and Marti O (2008). Monsoon response to changes in Earth's orbital parameters: comparisons between simulations of the Eemian and of the Holocene. *Climate of the Past* 4(4):281-294

Answer: The publications brought to our attention are mentioned in the revised text in the corresponding sections. Although the monsoon and low latitude dynamics are very interesting, we do not intend to investigate them thoroughly in the present model set-up because of the mentioned shortcomings. We would rather like to focus on the effects on global atmospheric and oceanic heat transport and on ocean circulation and transport changes in the North Atlantic.

Minor concerns

The paper focuses on changes between pre-industrial and the paleo periods. Are changes significant ? As the simulations are quite long, I guess they are for most of the variables. I'm less certain about the change of 0.1 PW in heat transport at Eemian (page 2320 / line 5) ? But please give some indication on how significance has been checked.

C1168

Answer: The computation of the atmospheric transport components required 6 hourly output of the atmospheric variables and was therefore only written for 100 model years (12 hourly output otherwise). Significance of the changes in heat transport has been checked by computing the standard deviation of the implied total heat transport (available for the whole simulation period, i.e. 1000 years) as a function of latitude of 100-year-long sample periods. The changes mentioned in the text exceed the limit of two standard deviations. We added the following to the manuscript:

"Significance has been tested by comparing the changes computed from the total advective heat transport to changes computed from the total implied heat transports of the 1000 year investigation period divided in 100-year-periods. The changes discussed exceed two standard deviations."

Figures are small. I've looked at them by zooming on a big screen, but a paper reader could find them hard to understand. Color palette with one color per sign does not help to see details.

Answer: We asked the editors to increase the size of the pictures.

Page 2315 / Line 25 : the sentence suggests that the grid spacing is reduced in latitude, giving isotropic resolution. It is true ? Please be more specific.

Answer: The grid spacing is reduced in latitude and since we do not apply any grid refinement it is isotropic. We described the model grid more precisely in the model setup-section and refer to Marsland et al. 2003 for more information. We specified the corresponding paragraph:

"The ocean model uses a bipolar orthogonal spherical coordinate system and is based on an Arakawa C-grid and allows for an arbitrary placement of the poles. In the set-up applied here, the North Pole is shifted over Greenland to avoid numerical singularities combined with the advantage of relatively high resolution in the deep-water formation regions, around Greenland maintaining isotropic conditions."

C1169

Page 2316 / Line 14: coupling frequency should be specified (it is the actual time step of the whole model : the period at which all individual process are resolved at least once).

Answer: Has been added to the "Model setup" section.

"The coupling time-step between the atmosphere and ocean model is 24 hours."

Page 2317 / Line 5 and following. The control run is "assumed" to be in equilibrium. Please specify some quantitative indication of the model drift (deep ocean temperature and salinity are the relevant ones).

Answer: We added the deep ocean temperature and salinity trends of the control and the paleo runs to the manuscript.

"In all three experiments the drift of global ocean temperature at 2200 m over the investigated simulation period is 0.05 K, global salinity at 2200 m does not show a trend."

Page 2318 / Line 4. The cooling south of Iceland is not visible on the figure 1b. But is present in figure 2b. Is there a problem in the figures ?

Answer: There was indeed a mix-up in the figures - has been corrected.

Page 2318 / Line 17. The ITCZ shift is something that can be quantified in a GCM. Please give the ad hoc diagnosis. (e. g. : Results of PMIP2 coupled simulations of the Mid-Holocene and Last Glacial Maximum - Part 2: feedbacks with emphasis on the location of the ITCZ and mid- and high latitudes heat budget, Climate of the Past, Volume 3, Number 2, 279-296, 2007, P. Braconnot, B. Otto-Bliesner, S. Harrison, S. Joussaume, J.-Y. Peterschmitt, A. Abe-Ouchi, M. Crucifix, E. Driesschaert, Th. Fichet, C. D. Hewitt, M. Kageyama, A. Kitoh, M.-F. Loutre, O. Marti, U. Merkel, G. Ramstein, P. Valdes, S. L. Weber, Y. Yu, and Y. Zhao).

Answer: We diagnosed the ITCZ as proposed in Braconnot et al. 2008. We observe

C1170

northward shift over Africa of 1.5° (3°) over western and central Africa to 9° (10°) in the Holocene (Eemian) simulation compared to the pre-industrial one. (Added to the manuscript) Since we are not yet fully content with the dynamic vegetation module of the surface component regarding the albedo effects (see discussion), we would like to improve this before looking into low latitude effects more detailed and rather focus on the northern hemisphere in this study. We added the following to the manuscript.

"Following the ITCZ-definition given in Braconnot et al. 2008 we observe northward shift over Africa of 1.5° (3°) over western and central Africa to 9° (10°) over eastern Africa in the Holocene (Eemian) simulation compared to the pre-industrial one (not shown)."

Page 2318 / Line 23. Precip in Antarctica are small. A relative change could be important whereas change in mm/day is small, and not visible on the figures. Please give some precision.

Answer: We added the following to the manuscript.

"Most parts of Antarctica experience changes in precipitation below 10

Page 2320 / Line 13. hight -> height ?

Answer: Corrected.

Page 2323 / Line 7. Could you explain how Tref is used in the heat transport computation ? Have you a net volume transport through Bering ? If so, a reference temperature is probably also needed in equation 2 ?

Answer: The reference temperature is subtracted from the potential temperature in Eq. 2 (Has been added in the manuscript). There is a net volume transport through the Bering Strait into the Arctic Ocean of 0.4 Sv in all three experiments. Following the rules of procedure in computing latitudinal heat transport for the Atlantic basin (e.g. Hall and Bryden, 1982 and references therein) we assume the basin to be closed. The reference temperature is technically set to 0K. The manuscript has been added

C1171



accordingly.

Page 2323 / Line 20 and following. The heat transport change in BAR is larger than the volume transport, and the explanation is OK. But this is not true for ISR. Your explanation is not correct here. Heat transports leaving the basin are increased by the temperature effect. Transport entering the basin are more correlated to volume transport. Please correct this section, to be coherent with the explanation that follow.

Answer: There was indeed an inconsistency in the corresponding paragraph. The paragraph has been reformulated. "In the Holocene and more enhanced in the Eemian simulation the volume transports through all passages increase due to enhanced circulation. Nevertheless, this increase in volume transport is not sufficient to explain the changes in heat transport. In case of ISR and BAR the increase in volume transport has the same sign as the increase in heat transport. In case of the BAR, the relative increase in heat transport is larger then the increase in volume transport. Thus the heat transport increase is also due to an increase of 5% in heat content of the Nordic Seas basin for the Holocene and the Eemian simulation compared to the pre-industrial. This increase in heat content also contributes to the increase of effective heat transport to the Arctic through FRAM due to the increased temperature difference between the two basins. The temperature difference between the Nordic Seas and the North Atlantic on the other hand decreases and so, despite the increase in volume transport, the effective heat transport into the Nordic Seas via DEN and ISR decreases."

Bibliography

Page 2329 / Line. 2007 -> 2007b Berger (1978) is missing (cited page 2316 / line 18)

Answer: Has been added.

C1172

---

Interactive comment on Clim. Past Discuss., 5, 2311, 2009.

C1173