Response to reviewer #1

General:

Merz et al. present an interesting study that for the first time quantifies the possibly important role of North Atlantic sea-ice changes, and there with the sea-ice sensitivity, in the last interglacial. This sea-ice sensitivity could to a large extend explain the model data mismatch in terms of last interglacial Greenland temperatures, as well as explain large inter-model differences in simulated last interglacial climate changes at the high latitudes of the Northern Hemisphere. The methodology and analysis are well thought through and the manuscript well written. I suggest publishing this manuscript in climate of the past after minor revisions.

We thank the referee for the careful review and the constructive comments. Please find the answers to all specific comments below. We have not responded yet to the technical corrections (wording etc.) but will do so when preparing a revised manuscript.

Main comment 1:

The manuscript shows that differences in simulated North Atlantic SST and sea-ice cover patterns are important to explain reconstructed Greenland temperature anomalies as well as inter-model differences in terms of simulated last interglacial temperatures. It does not attempt to explain the origin of these SST and sea-ice cover differences, which would likely be a whole study on its own. However, in my view this topic cannot be fully ignored and should at least be introduced and its potential implications discussed. Questions that arise are for instance:

What are the causes of the large SST and sea ice differences between the two versions of CCSM3? Yeager et al. show that under pre-industrial boundary conditions there are important differences in the simulated northward oceanic heat transport between the low and high resolution versions of CCSM3. These findings could be shortly summarized here. Can it be deduced which model version is closer to observations in terms of the simulated pre-industrial North Atlantic ocean circulation?

Both the low and the high resolution versions of CCSM3 have known deficiencies in its representation of Arctic sea ice and heat transport in the Atlantic Ocean (Collins et al, 2006 and Yeager et al., 2006). In particular, the low resolution CCSM3 has a too extensive sea ice cover and an underestimated ocean heat transport. The sea ice cover is smaller and thinner in the high resolution version, which is closer to observations. On the other hand, the high resolution CCSM3 still has a pronounced cold anomaly in the subpolar North Atlantic compared to observations (Collins et al., 2006).

Large and Danabasoglu (2006) devote a whole study to the attribution and impacts of upper-ocean biases in the high (and medium) resolution CCSM3. The study shows that too strong surface winds are likely one reason. Besides, the biases in upper-ocean temperature and salinity along ocean basin boundaries relate to problems in the representation of ocean upwelling.

We agree that these are important points and we will include this information in the revised manuscript.

Are the inter-model differences also visible in figure 4 of Lunt et al.? And is the cold bias described here for the low resolution version also the cause of the comparatively low CCSM3 temperatures (winter and annual mean) in the transient last interglacial results (see Bakker et al. 2013, 2014) for the Northern Hemisphere?

The “error” of the high and low resolution pre-industrial control simulations compared to NCEP (Fig. 4 in Lunt et al., 2013) shows a cold bias in the North Atlantic for both cases. Partly due to the chosen color scale in Fig.4 in Lunt et al., 2013 it is not apparent which of the cold bias is stronger but the high resolution bias seems more spatially extensive. Nevertheless, Fig. 4 in Lunt et al., 2013 nicely illustrates that the high and low resolution versions of CCSM3 produce quite different SAT patterns (globally) and thus should be regarded as different climate models even though they base on some common model physics.

We will make an effort to make this last point clearer in the manuscript

Furthermore, we don’t’ believe that the cold bias described for the low resolution version necessarily is the cause of the comparatively low CCSM3 temperatures (winter and annual mean) in the transient last interglacial results (see Bakker et al. 2013, 2014). Note that the latter are low CCSM3 temperatures for the last interglacial with respect to pre-industrial. Hence, this “relative” cooling of the last interglacial CCSM3 has to be clearly distinguished from the cold model biases found for absolute present-day/pre-industrial temperatures.

The CCSM3 EEM-PI cooling found in Bakker et al., 2013/2014 bases on the same simulation (conducted by people from University of Bremen) as the the low resolution CCSM3 simulations shown in our manuscript. Hence, our analysis of those simulations shows that the atmospheric cooling in the last interglacial is explained by concurrent sea ice growth and cooling SSTs (see Fig. 3) which likely bases on a reduced oceanic heat transport. The latter seems to be the model’s response to the Eemian external forcing (we cannot think of a mechanism why it should link to the model bias, i.e., an already underestimated ocean heat transport simulated for present-day/pre-industrial). Reviewer # 2 correctly pointed out that the CCSM3 low resolution pre-industrial run by Merkel et al. (2010) has higher GHG concentrations than the transient Eemian simulation (in particular CH4), which likely fosters the relatively cold Eemian temperatures. Further, one can speculate that the model might be more sensitive than other models (including the high resolution CCSM3) to the decrease in winter insolation resulting from the Eemian orbital forcing.

If so, both could be pointed out in the manuscript. One could think that a bias in the climate can be accounted for by looking at the anomaly of last interglacial temperatures with respect to a pre-industrial simulation. How does the bias impact the last interglacial climate? Is also the sensitivity of the overturning more sensitivity to global warming, thus leading to cooling in the North Atlantic under last interglacial forcings?

Please see the answers above.

We will provide more details on the biases of the two versions of CCSM3 in the revised manuscript. We will also clarify our motivation to investigate the impact of these biases on the uncertainty of last interglacial temperatures over Greenland. With regard to further interpretation of the origin of the biases and implications for the stability of the overturning circulation during the last interglacial or under global warming, we feel that this would probably be too speculative and that a comprehensive discussion exceeds the scope of this study.

Main comment 2:

The experiments successfully show the role of sea ice and SSTs in explaining the differences between two versions of the CCSM3 model, and provide a potential mechanism that can yield additional warming over Greenland. However, it does not give more warming over Europe, something that is mentioned a couple of times in the manuscript. Please come back to this point at the end of the manuscript. Questions that come to mind are for instance:

What does it imply that the model-data temperature mismatch over Europe is not improved when using a model with a more sensitive sea-ice cover? Is there another mechanism or feedback missing? Maybe even a mechanism that can explain both the warming over Greenland and Europe without the need for a larger sea-ice retreat? Please shortly discuss this in the manuscript.

We believe that a retreating sea ice cover is one important mechanism to explain the Eemian warmth but it does not exclude other influences. The finding that temperatures over Europe are largely insensitive to changes in the sea ice cover illustrates this point well. We will revise the manuscript to clarify that the large biases in the representation of sea ice in CCSM3 and other climate models complicate the quantification of the impact of other variations.

Main comment 3:

An important difficulty of last interglacial climate research is the relatively small number of well resolved temperatures and, especially, sea-ice reconstructions. Does the Holocene thermal maximum possibly provide an analogue that can inform us about what happened during the last interglacial because of higher data availability and the existence of sea-ice reconstructions?

Reconstructions of sea ice are generally rare for all paleoclimatic epochs including the mid Holocene. The intent of our study was not to propose the most likely sea ice simulation for the last interglacial, but to highlight how the uncertainty in the ice cover of periods in the past propagates into the estimates of Greenland temperatures.

Minor comments:

General 1: It is a rather long manuscript, so perhaps the reader can be helped a little more to keep track of the aims and line of the manuscript by shortly repeating those aims and or by providing sort summaries at different points in the manuscript.

We agree with the referee that we should help the reader not to lose track in the rather long manuscript. We thus intend to include short repetitions of the study aims at the beginning of Sections 4.1, 4.2 and 5.

General 2: The potentially important role of sea-ice changes in the North Atlantic in the last interglacial climate have been suggested previously, in relation with observations from Greenland ice cores (Sime et al., 2013) and with large inter-model differences in simulated annual mean and winter temperatures (Bakker et al., 2013). It would be good to mention this in the introduction.

Thank you for bringing these papers to our attention. We will investigate their findings in detail and include respective references in the revised manuscript if applicable.

Line 7 page 1: ‘thus’, not everyone is familiar with this model-data mismatch, shortly introduce it in the abstract.

The abstract will be revised to make this clearer.

Line 12 page 1: ‘accumulation’, this is not mentioned before in the abstract and thus appears a little disconnected from the previously discussed issues.

We consider revising the abstract to better introduce moisture and accumulation processes.

Page 2: More work on the last interglacial and simulated temperatures over Greenland has been done previously, consider discussing that work, for instance by Loutre et al., Goelzer et al., Bakker et al. and Sanches-Goni et al. and Govin et al.

We will revise the introduction to account for these studies.

Line 19 page 1: As you are probably aware, the term Eemian is used to describe a pollen-based warm period in Europe, the regional continental equivalent of the general last interglacial period. Consider using last interglacial instead of Eemian throughout the manuscript.

We consider replacing the term „Eemian" by last interglacial although we feel that „Eemian" is a widely accepted term in the paleoclimate scientific community. Using the term "Eemian" is more in line with our previous studies (Merz et al., 2014a,b) which can be regarded as companion papers also focusing on the climate in/around Greenland during this time period.

Lines 3-6 page 2: These lines seem to suggest that proxies can resolve, annual, summer and winter temperature changes for the last interglacial. Please clarify.

We will revise the aforegoing sentence to make this clear. The seasonality issue rather relates to the models than to the proxies which can provide information about the temperature seasonality of the Eemian.

Line 7 page 2: What 'Eemian proxies' is referred to here? From what region? Please provide references.

We will add references to Turney & Jones (2010) and Capron et al., 2014.

Line 31 page 2: Consider referring to Capron et al. and Govin et al.

We will add the according references.

Lines 29-33 page 2: What season is discussed here? Is it possible that the ~~winter~~ summers? where warmer, but still the winters were not and neither was the accompanying sea-ice cover decreased?

Axford et al., 2011 refers to summer temperatures whereas Bauch et al. 2012 does not refer to a single season. We are further not aware of temperature reconstructions for the winter season for the last interglacial in this area. In the low resolution CCSM3 we see that Eemian winters were colder and sea ice was rather expanding (likely due to the negative orbital forcing in NH winters) but again this model seems in contrast with many other climate models which generally show a stronger warming for the last interglacial (e.g., see Bakker et al., 2013, Lunt et al., 2013). Hence, we can hardly do more than speculate on the last interglacial state of the NH sea ice, particularly for the winter season.

Line 3 page 6: Why is a 2m thick sea-ice cover used? What are the potential implications of this assumption, please discuss.

2 meter sea ice thickness is standard for all CCSM3/CCSM4 atmospheric simulations with prescribed sea ice cover and there is no choice on that in the state-of-the art configurations of the (atmospheric) CCSM simulations. We cannot really comment on this standard but it corresponds to the observed sea ice thickness in the NH although there is quite a range in sea ice thickness (0-5m), e.g., based on recent CryoSat-2 measurements.

Hence, we haven't tested the sensitivity of sea ice thickness on the Arctic climate. Please refer to Holland et al., 2006 for a respective study. We will add this reference and a statement that the sea ice thickness is not tested in this study.

Line 3 page 9: It would be helpful for the reader if the 125ka external forcings (GHG and orbital) and their impacts are shortly described (perhaps in the method section), in terms of their annual mean and also seasonal impact.

We agree that this information should be included in the manuscript and we will revise the text accordingly.

Line 13-14 page 9: Perhaps an order of magnitude difference can be given to illustrate the dominant role of the turbulent fluxes over the radiative fluxes.

We will add respective estimates which are of the order of 10-20 W/m^2 (LWnet) and up to 150 W/m^2 for SHF and LHF.

Line 4 page 10: Perhaps at this point come back to the large inter-model spread suggested by previous work (Lunt et al., Otto-Bliesner et al., Nikolova et al. and others) to put the findings in a bigger picture as an introduction to the next section.

As stated above we will add some sentences here (at the beginning of Section 5) to remind the reader of the goals of the study and the initial problem with the large inter-model spread.

Line 21 page 11: So what are the SATs discussed before if not 'lowest terrain-following level?

The SAT refers to the 2m temperature which is state of the art in most climate models. The 2m temperature is an interpolated diagnostic measure whereas temperature at the lowest terrain-following level conforms to the temperature in the lowest layer of the atmospheric grid. We consider taking out the sentence at (page 11, line 22) as it might confuse the reader.

Line 13 page 12: Is the feedback by clouds also small over the Nordic Seas?

We do find some moderate increase in cloud cover directly above the main SHFLX anomalies in the Nordic Seas. However, we find that all changes in cloud cover and do not lead to significant radiation anomalies and hence are not of crucial importance for the temperature response.

Line 3 page 14: Earlier on, when winter changes are discussed, mention that seasonality will be covered later.

We will add a respective statement at the end of section 4 to advertise the seasonality section:

Line 12 page 15: Are these SATs for Greenland averages over the whole of Greenland (and also in Figure 11E)?

Yes. We add the following statement to the caption of Fig. 11:

[The Greenland mean SAT refers to the area-averaged SAT of whole Greenland.]

Line 21-23 page 16: Consider repeating what EEM-PIdiff stands for to make this point more clear.

We revise this paragraph to clarify this issue:

Line 15 page 17: Consider giving the ages covered by the NEEM core.

We don’t feel that this adds much clarification here as the full NEEM core actually extends beyond the Eemian but its information from the penultimate glacial is disturbed by folding effects etc. Moreover, our simulations are rather generally valid for an Eemian optimum but do not refer to a specific time period or a transient evolution of the Greenland temperature.

Line 17 page 17: Give distance between NEEM and pNEEM to give the reader an idea of the difference.

We will add the respective information, i.e. that pNEEM is located ca. 300km upstream of NEEM relatively close to the summit of the ice sheet.

Lines 29-32 page 17: It is not clear how this connects to the topic of this manuscript, please clarify.

This statement is included to provide some perspective on our results in the context of contemporary climate change. We also think that the previous sentence that our results are “not limited to the Eemian but very likely valid for any interglacial and glacial climate period” requires this specification to not mislead the reader.

Line 7 page 18: Give range of temperature estimate. Is this number altitude corrected? This seems relevant with the discussion later on.

We prefer to just mention the upper limit of the temperature estimate as we focused on the maximum temperature response in Merz et al., 2014a, i.e. for the simulated minimum in the Eemian Greenland ice sheet volume/extent. Further, the number (3.1K) is altitude corrected what will be clarified in the revised statement (see next point).

Line 15 page 18: Is this 3.1K because of elevation changes, circulation changes? Please shortly summarize. What about other work on this topic by for instance Stone et al., Langebroeck et al. and Fyke et al.?

The full warming effect to explain the 3.1K is due to a series of changes in the low-level winds and eventually the surface energy balance following a change in the Greenland ice sheet topography as discussed in full details in Merz et al., 2014a. We will extend the sentence at page 18, line 15 to make this clearer.

However, we prefer to guide the reader to the reference rather than giving a full summary of the topography-effects as this would further lengthen the already rather extensive discussion section. To our knowledge, the studies mentioned above investigate possible changes in the Greenland ice sheet topography during the Eemian but do not estimate/simulate the associated climate/temperature effect.

Line 34 page 18: Be more specific about what ‘climate change’ means here.

“Eemian climate change” is changed to “Eemian warming”

Line 2 page 19: What about changes in the seasonality of precipitation?

In Merz et al., 2014b we show that Greenland precipitation is more biased towards the summer season in the Eemian compared to PI. However, Sime et al., 2013 states that uncertainty about local interglacial sea surface conditions, rather than precipitation intermittency changes, may lead to the largest uncertainties in interpreting temperature from Greenland ice cores.

Line 11 page 19: Is this for specific regions? Please clarify.

We revise the statement as follows:

[These simulations are in better agreement with Eemian SST and SAT proxy records from the NH extratropics.]

Lines 24-26 page 19: Make clear that this combined experiment has in fact not been performed.

We will revise the statement to make this clear.

Figure 2: So does this indicate that the atmosphere is of little importance in determining the LIG climate response to the orbital forcing? What about the role of vegetation?

Fig. 2 does imply that the ocean and sea ice component are most likely responsible for the spread among different EEM-PI simulations. This does not mean that the atmosphere itself is not reacting to the anomalous orbital forcing but in both CCSM3 model simulations in a rather consistent way. However, as always the pure sensitivity of a single component of the climate system is only to guess from a fully-coupled setup. An experiment with an atmospheric model simulation forced by the anomalous Eemian orbital forcing but pre-industrial sea ice/SSTs might be a possible experiment to answer this question in detail. The vegetation is held to modern values in all CCSM3 experiments (our initial statement that the CCSM3 EEM_{lowRes} simulation used a dynamic vegetation model was actually wrong as correctly pointed out by Reviewer #2 – we will revise it accordingly). Hence, in the CCSM3 simulations shown here vegetation processes are not taken into account and therefore cannot be responsible for the temperature spread seen in $EEM\text{-}PI_{diff}$ (Fig. 2).

Figure 3: The patterns are very different for the high and low resolution model runs. Does this point to an important role of differences in ocean dynamics?

Yes, very likely. Unfortunately, we didn't have the model output available to properly analyse this aspect. Furthermore, a comprehensive analysis of the different ocean dynamics might likely be beyond the scope of this paper. An indication for the cooling North Atlantic in the lowRes CCSM3 experiments stems from the comparison of the AMOC during the LIG (Bakker et al., 2013) compared to PI (Yeager et al., 2006), which we will acknowledge with a statement (Page 7, line 13): We are not aware of comparable AMOC diagnostics for the highRes CCSM3 model.

Figure 3: Why is there no EEM-PI-diff row in this figure?

We prefer to show the EEM-PI-diff of SST and sea ice in Fig. 5 (for DJF) together with the resulting heat flux anomalies and hence we have omitted a EEM-PI-diff row in Fig. 3.

Figure 3: Why are the patterns in SST so different from the SAT (Figure 4) patterns for, for instance, the Arctic region?

In all CCSM3 simulations the Arctic ocean is covered by sea ice throughout the year and hence the SSTs are constantly set to the freezing point temperature of -1.8°C which is the standard for ocean cells fully covered by sea ice. However, EEM-PI changes in the amount of snow falling on sea ice and the resulting changes in insulation of the cold winter atmosphere from the ocean below, explains the SAT pattern over the Arctic ocean in Fig. 4 (most distinctively in autumn).

Figure 8d-e: There appears to be a dipole kind of structure over Greenland for HTdyncore and HTpar. Why is that and how are they related to the large scale wind changes?

The change in surface winds in the NordS-shift experiment indicates anomalous flow above Greenland in the southwest to northeast direction. This likely relates to the observation that the advective transport (Fig. 8d) fosters warming in northeastern Greenland at the expense of a cooling southwestern Greenland building this dipole pattern. This dipole is compensated by the heat transport associated with HTpar, which due to the fact that it represents parameterized (subgrid) processes is much harder to link with other changes in atmospheric circulation.

Figure 12: Indicate on a map (perhaps in figure 1) where the NEEM or pNEEM site is located.

Will be added to Fig.1

Figure 12: Indicate significance of simulated temperature changes.

Will be added.

Table 1: Why are the other sensitivity tests not included?

As mentioned on page 4, line 15 we only list the six (out of 12) CCSM4 simulations which build the core of the study. We prefer doing so, as the other 6 simulations use the same setup as EEMLabs and EEMNordS except for SST/sea ice, so only little additional info would be displayed by adding those 6 simulations to Table 1.

Table 3: Perhaps a printing issue on my side, but the bold letters are very difficult to distinguish.

We have checked this issue but it indeed seems to be a printing issue on your side.

Table 3 and 4: Using different regions for Greenland (whole island, central Greenland or pNEEM) is a little confusing and perhaps not necessary.

Table 4 has the purpose of displaying the results for the key region of the ice core community and hence can be regarded as an additional service. Table 3 focusing on Greenland as a whole is complementing Figure 11 and corresponds to the overall analysis with a general focus on Greenland as a whole. We, thus, prefer to keep both tables.

Additional references used in response (and not yet included in manuscript)

Bakker, P., Stone, E. J., Charbit, S., Gröger, M., Krebs-Kanzow, U., Ritz, S. P., Varma, V., Khon, V., Lunt, D. J., Mikolajewicz, U., Prange, M., Renssen, H., Schneider, B., and Schulz, M.: Last interglacial temperature evolution – a model inter-comparison, Clim. Past, 9, 605-619, doi:10.5194/cp-9-605-2013, 2013.

Bakker, P. and Renssen, H.: Last interglacial model–data mismatch of thermal maximum temperatures partially explained, Clim. Past, 10, 1633-1644, doi:10.5194/cp-10-1633-2014, 2014

Large, W. G., and Danabasoglu, G. Attribution and Impacts of Upper-Ocean Biases in CCSM3, Journal of Climate,19:11, 2325-2346, 2006

Holland, M., Bitz, C. M., Hunke, E.C., Lipscomb, W. H., and Schramm, J.L. Influence of the Sea Ice Thickness Distribution on Polar Climate in CCSM3, Journal of Climate,19:11, 2398-2414, 2006