

1 **Reply to Emilie Capron**

2
3 **Comment:**

4 Having reviewed an earlier version of the manuscript, I have evaluated the paper in its current form as
5 such and in view of the author's response to the review comments. I would like to thank the authors for
6 all the work and efforts they put in the preparation of this revised version of their manuscript.

7 Many of my earlier comments have been addressed with the revised version of the manuscript and as
8 far as I can see, that also holds for many of the comments of the other reviewer too. The clarity and the
9 structure of the paper have improved in several sections but unfortunately not everywhere. Therefore,
10 before accepting the manuscript for publication, I still have some important comments that I would like
11 to see being addressed.

12 **Reply:**

13 We thank Emilie Capron very much for the in-depth revision of the revised version of the manuscript
14 and for all the valuable suggestions and comments that again help to further improve the manuscript.
15 We appreciate the referee's efforts to provide a detailed review of our paper.

16
17 **Comment:**

18 First, there are still two important remaining issues that need to be addressed:

19 1- Although I really appreciate the fact that the authors shortened and clarified some sections, I still
20 believe that more is necessary. Especially, there are several places where information is redundant (e.g.
21 in the introduction) and where it is really hard to extract what is the main message the authors want to
22 get across (e.g. results):

23 → One of my main concerns is about the introduction. I think it could be written much more to the
24 point and ideas need still to be reorganised as well to appear in a more logical order. I have made some
25 suggestions below.

26 **Reply:**

27 We would like to thank for the detailed suggestions on how to restructure the Introduction section. We
28 have closely followed the suggestions and reorganized the Introduction. We have removed redundant
29 information, for example, we have removed the information related to the astronomical parameters
30 during the LIG, since this information is given later in the Data & Methods section. We have rephrased
31 some sentences to make it more to the point. Also the paragraph from Page 3 Line 17 has been

1 shortened, synthesized, and reorganized as suggested.

2

3 **Comment:**

4 → I still think that the result section is too long and very hard to follow and to extract the main
5 message. There are still some very long descriptions that could certainly be synthesised and written in a
6 more concise way. Especially, Sections 3.4 and 4.3 are still very long and would benefit from being
7 shortened : the text can be written in a more concise way but also only the most important observations
8 and patterns should be kept.

9 **Reply:**

10 In the latest version of the manuscript, we have further shortened the Results section, especially the
11 sections 3.4 and 4.3, and aimed for a more synthesized description of results.

12

13 **Comment:**

14 2- Several sentences that have been added in the revised version convey incorrect information and they
15 absolutely need to be rephrased. I have highlighted them below.

16 **Reply:**

17 We have corrected these sentences as suggested below.

18

19 **Comment:**

20 Second, still for the purpose of clarity I believe that the readability of the various maps showing model
21 simulations displayed in the figures (both in the main manuscript and the Suppl. Material) should be
22 further improved. It would make it much clearer if the authors were adding short title above each of
23 them indicating the acronym of the simulation displayed (as well as the reference). Similarly “annual
24 mean “, “local winter”, etc... should be added on the side of each panel in Figure 5 and it should
25 indicated on the top of the panel that simulations are for the Northern high latitudes (60-90 degrees
26 lat.). I would thus ask the authors to modify the figures (both in the main manuscript and the SM)
27 accordingly.

28 **Reply:**

29 In the latest version of the manuscript as well as the supplementary material, we have added in all
30 figures titles and additional necessary information that helps distinguish between different maps/graphs
31 on each figure.

1

2 I list below more specific changes that I would like to see considered in the next version of the
3 manuscript.

4 **P1**

5 **Comment:**

6 Line 23: write instead: “...of the timing are estimated from NEW transient model simulation...”

7 **Reply:**

8 We have modified accordingly. Now **Page 1 Line 21**.

9

10 **Comment:**

11 Line 25: write instead: “...when PROXIES ARE INTERPRETED AS REPRESENTING ANNUAL
12 MEANS rather than RECORDING summer temperature

13 **Reply:**

14 For clarification, we have rephrased the whole sentence and wrote:

15 now **Page 1 Line 22**: “The model-data comparison improves for proxies that represent annual mean
16 temperatures when GIS is reduced and when we take into account the local thermal maximum during
17 the LIG (130-120 kyr BP). For proxy data that represent summer temperatures, changes in GIS are of
18 minor importance for sea surface temperatures.”

19

20 **Comment:**

21 Line 26: this is a strong statement, I suggest you’d rather write: “Additionally, THE COMPARISON
22 BETWEEN OUR MODEL RESULTS AND TEMPERATURE RECONSTRUCTIONS SUGGEST that
23 the GIS elevation.....”

24 **Reply:**

25 | For clarification, we have replaced the following sentence:

26 “Additionally, by comparing our model results to temperature reconstructions we can conclude that the
27 GIS elevation was not as low as prescribed in our simulations, but potentially lower than prescribed in
28 other studies.”

29 with:

30 now **Page 1 Line 25**: “However, the temperature change over Greenland in the reduced GIS
31 simulations seems to be overestimated as compared to the local data, which could be related to the

1 interpretation of the recorder system and/or the assumptions of GIS reduction.”

2

3 **P2**

4 **Comment:**

5 Line 5: you should remove the sentence segment “this is necessary since...”; this is not needed.

6 **Reply:**

7 Done.

8

9 **Comment:**

10 Line 13: remove the sentence segment “represents.....and” and write directly “the last interglacial is
11 considered to be” And move the dates for the holocene at the end of this sentence.

12 **Reply:**

13 Done. Now **Page 2 Line 9.**

14

15 **Comment:**

16 Line 22: the sentence “According...” should be removed, you already refer to this paper above.

17 **Reply:**

18 Done.

19

20 **P3**

21 **Comment:**

22 Line 8: you should not refer to Dahl-Jensen et al 2013 in this bracket since you mention the actual
23 result of this study after; Also please change the reference, it should be refer as NEEM Community
24 members 2013 and not Dahl-Jensen et al. 2013.

25 **Reply:**

26 Done. We have changed to NEEM Community Members (2013) everywhere where Dahl-Jensen et al.
27 (2013) was cited in the manuscript.

28

29 **Comment:**

30 Line 11: please see and refer to Dutton et al. Science 2015 for the latest sea level variations assessment
31 over the LIG.

1 **Reply:**

2 Now **Page 2 Line 28**. We have rephrased this sentence and added the suggested reference as follows:
3 “An increase in sea level during the LIG is estimated to be of about 7 m (Kopp et al., 2009; Dutton et
4 al., 2015), with a possible contribution of 3 to 4 m from Antarctica (Sutter et al., 2015).”
5

6 **Comment:**

7 From line 2 to line 13: I feel that this could be shortened as somehow the information are redundant,
8 you may consider shortening the very first sentence that is relatively vague, you should go straight by
9 mentioning the numbers proposed for the contribution of the Greenland ice sheet.

10 **Reply:**

11 Now **Page 2 Line 22**. We have completely removed the first sentence and started the paragraph more to
12 the point. Furthermore, we have shortened and aimed to avoid redundant information. We have
13 reorganized as follows:

14 - first, we mention that studies suggest a partial or complete absence of GIS or a modest change:

15 “Studies based on reconstructions and climate model simulations suggest a partial or complete
16 absence of the Greenland Ice Sheet (GIS) during the LIG, and that the sea level was higher than the PI
17 (Veeh, 1966; Stirling et al., 1998; Cuffey and Marshall, 2000; Otto-Bliesner et al., 2006; Overpeck et
18 al., 2006; Jansen et al., 2007; Kopp et al., 2009, 2013; Alley et al., 2010; van de Berg et al., 2011;
19 Robinson et al., 2011; Dutton and Lambeck, 2012; Quiquet et al., 2013; Church et al., 2013; Stone et
20 al., 2013), while a more recent study based on ice core data proposes only a modest GIS change (i.e.
21 equivalent to a contribution to sea level rise of ~2 m, NEEM Community Members, 2013).”

22 - second, we give numbers on sea level rise during the LIG:

23 “An increase in sea level during the LIG is estimated to be of about 7 m (Kopp et al., 2009; Dutton
24 et al., 2015), with a possible contribution of 3 to 4 m from Antarctica (Sutter et al., 2015).”

25 - third, we give numbers on the contribution of GIS to sea level rise during the LIG:

26 “The contribution of a partially melted GIS to LIG sea level rise is however not yet well
27 determined; various studies suggest a sea level rise due to meltwater from Greenland of +0.3 to +5.5 m
28 (Cuffey and Marshall, 2000; Tarasov and Peltier, 2003; Lhomme et al., 2005; Otto-Bliesner et al., 2006;
29 Colville et al., 2011; Quiquet et al., 2013; Stone et al., 2013).”
30

31 **Comment:**

1 Line 29: remove “even when taking into account...”.

2 The sentence referring to the work by Bakker and Renssen should arrive later: after you have listed all
3 the studies that show mismatch between model and data. For instance, please consider moving it after
4 the sentence that currently finishes at line 11; This same sentence referring to the work by Bakker and
5 Renssen also needs to be re-written has at the moment the formulation could lead to misunderstanding.
6 Here is a proposition: “... may stem from the fact that commonly-used climate syntheses represent a
7 single time-slice assuming synchronous LIG thermal maximum in space and in time”.

8 **Reply:**

9 Done.

10 We have moved and rephrased the sentence with Bakker and Renssen (2014) as suggested.

11 We have reorganized as follows:

12 “Other model-data comparison studies for the LIG (Lunt et al., 2013; Otto-Bliesner et al., 2013), based
13 on AOGCMs (but with no changes in GIS elevation or extent) also show an underestimation of global
14 temperature reconstructions (Turney and Jones, 2010; McKay et al., 2011). Bakker and Renssen
15 (2014), who perform an analysis of transient simulations for the LIG, provide a partial explanation for
16 the model-data mismatch, proposing that such large differences between the reconstructed and
17 simulated LIG temperatures may stem from the fact that commonly-used climate syntheses represent a
18 single time-slice assuming synchronous LIG thermal maximum in space and time. Their study suggests
19 that global compilations of reconstructed LIG thermal maximum overestimate the warming. However,
20 different studies (modelling as well as proxy-based) indicate that the maximum LIG warmth occurred
21 at different times throughout the LIG in dependence of the geographical location (Bakker et al., 2012;
22 Govin et al., 2012; Langebroek and Nisancioglu, 2014). The lack of climate synthesis for the LIG
23 going further than proposing a single snapshot on LIG maximum warmth and thus accounting for
24 asynchronous changes across the globe is due to the difficulty in building robust and coherent age
25 models for different climatic archives during the LIG (Govin et al., 2015). Recently, Capron et al.
26 (2014) propose a new climate synthesis for the high latitude regions based on a coherent temporal
27 framework between ice and marine archives. This allows for the first time to assess both the temporal
28 and the spatial evolution of the climate throughout the LIG (Capron et al., 2014).”

29

30 **P4**

31 **Comment:**

1 Line 11: “The lack of ...” this statement is somehow incorrect.

2 If you want to mention the issue with the dating of paleoclimatic records, you need to say something
3 along the lines suggested below and also change the reference for a more appropriate paper that has just
4 been published: “The lack of climate synthesis for the LIG going further than proposing a single
5 snapshot on LIG maximum warmth and thus accounting for asynchronous changes across the globe is
6 due to the difficulty in building robust and coherent age models for different climatic archives during
7 the LIG (Govin et al. 2015)”

8 **Reply:**

9 Now **Page 3 Line 27**. We have replaced the sentence with the one suggested above.

10

11 **Comment:**

12 Line 13: you should remove the sentence “for example....”

13 **Reply:**

14 Done.

15

16 **Comment:**

17 Line 16: with the sentence I propose above, you don’t need this exact sentence, however you could
18 present the Capron et al new data synthesis with a sentence as such: Recently, Capron et al. propose a
19 new climate synthesis for the high latitude regions based on a coherent temporal framework between
20 ice and marine archives. This allows for the first time to assess both the temporal and the special
21 evolution of the climate throughout the LIG (Capron et al. 2014).”

22 **Reply:**

23 Now **Page 3 Line 30**. Done as suggested.

24

25 **Comment:**

26 Line 20: I suppose that this paragraph should appear beforehand; here is a possible order to follow that
27 seems to be more logical.

28 i- you should listed all the studies showing model-data mismatch,

29 ii- then you should mention the fact that the issue is due to the fact that data synthesis assume
30 synchronous changes and that is an issue because other studies show that the peak warmth likely occurs
31 at different time across the globe;

- 1 iii- you should then explain that the difficulty on producing more than one snapshot on maximum
2 warmth is due to the fact that it is hard to define robust age models and thus robust chronologies for
3 multiple archives;
4 iv- finally you should present the latest synthesis that able to solve this issue for the high latitudes.

5 **Reply:**

6 Now **Page 3 Line 17**. We have restructured the paragraph as suggested.

- 7 i- you should listed all the studies showing model-data mismatch,

8 “[...]

9 Other model-data comparison studies for the LIG (Lunt et al., 2013; Otto-Bliesner et al., 2013),
10 based on AOGCMs (but with no changes in GIS elevation or extent), also show an underestimation of
11 global temperature reconstructions (Turney and Jones, 2010; McKay et al., 2011).”

- 12 ii- then you should mention the fact that the issue is due to the fact that data synthesis assume
13 synchronous changes and that is an issue because other studies show that the peak warmth likely occurs
14 at different time across the globe;

15 “ Bakker and Renssen (2014), who perform an analysis of transient simulations for the LIG, provide a
16 partial explanation for the model-data mismatch, proposing that such large differences between the
17 reconstructed and simulated LIG temperatures may stem from the fact that commonly-used climate
18 syntheses represent a single time-slice assuming synchronous LIG thermal maximum in space and
19 time. Their study suggests that global compilations of reconstructed LIG thermal maximum
20 overestimate the warming. However, different studies (modelling as well as proxy-based) indicate that
21 the maximum LIG warmth occurred at different times throughout the LIG in dependence of the
22 geographical location (Bakker et al., 2012; Govin et al., 2012; Langebroek and Nisancioglu, 2014).”

- 23 iii- you should then explain that the difficulty on producing more than one snapshot on maximum
24 warmth is due to the fact that it is hard to define robust age models and thus robust chronologies for
25 multiple archives;

26 “ The lack of climate synthesis for the LIG going further than proposing a single snapshot on LIG
27 maximum warmth and thus accounting for asynchronous changes across the globe is due to the
28 difficulty in building robust and coherent age models for different climatic archives during the LIG
29 (Govin et al., 2015).”

- 30 iv- finally you should present the latest synthesis that able to solve this issue for the high latitudes.

31 “ Recently, Capron et al. (2014) propose a new climate synthesis for the high latitude regions based on

1 a coherent temporal framework between ice and marine archives. This allows for the first time to assess
2 both the temporal and the spatial evolution of the climate throughout the LIG (Capron et al., 2014).”
3

4 **P5** (We assume it was meant P5 and not P4 because there is no “of” in the Line 7 of P4)

5 **Comment:**

6 Line 7: replace “of” by “on”.

7 **Reply:**

8 Done.

9

10 **P6**

11 **Comment:**

12 “The latter simulation ... model-data agreement”: which model-data agreement? when? Please clarify
13 this new sentence.

14 **Reply:**

15 Now **Page 5 Line 16**. We have compared the simulation for the 125 kyr BP time slice with all three
16 datasets (CAPE Last Interglacial Project Members (2006) in Fig. S10; Turney and Jones (2010) in Fig.
17 S11; Capron et al. (2014) in Fig. S15), therefore we did not mention which model-data agreement since
18 it refers to all three datasets. But for clarification, we have added this information in the sentence to
19 clarify that from Capron et al. (2014) we have used the 125 kyr BP time slice. Now is rephrased as
20 follows:

21 “ The latter simulation is performed in order to assess whether a reduction in GIS at 125 kyr BP
22 improves the agreement between the model and the three proxy compilations considered in this study
23 (CAPE Last Interglacial Project Members, 2006; Turney and Jones, 2010; 125 kyr BP time slice by
24 Capron et al., 2014).”
25

26 **P9**

27 **Comment:**

28 Line 23: “the data...”: this sentence is very confusing; please reformulate as such: “The high latitude
29 climate synthesis by Capron et al. (2014) provides temporal air and sea surface temperature
30 reconstructions based on ice core and marine records respectively, across the interval 115 to 130 ka.
31 They also propose snapshots of surface temperature anomalies and associated quantitative uncertainties

1 at 115, 120, 125 and 130 ka.

2 **Reply:**

3 Now **Page 9 Line 1**. We have reformulated as suggested. However, in order to clarify that we haven't
4 used all the snapshots in our study we have rephrased as follows:

5 “The high latitude climate synthesis by Capron et al. (2014) provides temporal air and sea surface
6 temperature (SST) reconstructions based on ice core and marine records respectively, across the
7 interval 130 to 115 kyr BP (in our study covering the period between 125 and 115 kyr BP). They also
8 propose snapshots of surface temperature anomalies and associated quantitative uncertainties at 115,
9 120, 125, and 130 kyr BP, but here we use the last two snapshots.”

10

11 **Comment:**

12 Line 25: maybe the sentence starting with “this...” is not necessary anymore if you mention this
13 already in the introduction.

14 **Reply:**

15 We have removed this sentence.

16

17 **P10**

18 **Comment:**

19 Line 24: please refer to Table 2 for this paragraph. It will be most helpful for the reader.

20 **Reply:**

21 Now **Page 9 Line 27**. Done.

22

23 **P11**

24 **Comment:**

25 Line 26: please remove the sentence starting with “the TS anomalies...” I find this very confusing since
26 after that, you come back to the other simulation you want to focus one. You already mention that you
27 focus on this specific one.

28 **Reply:**

29 We have removed that sentence.

30

31 **Comment:**

1 Line 30: what do you consider “high latitudes” , 60-90degrees of latitudes ? please clarify.

2 **Reply:**

3 Now **Page 10 Line 19**. We have added the exact information.

4

5 **P12**

6 **Comment:**

7 Line 14: “considering Table 2” : please be more specific than that.

8 **Reply:**

9 Now **Page 11 Line 4**. We have added: “Considering the TS values from Table 2, [...]”

10

11 **P14**

12 **Comment:**

13 Section 3.4 is still far too long and needs to be shortened with a text written in a more concise way and

14 that also be going straight to the most important observations and patterns

15 **Reply:**

16 Now **Page 12 Line 18**. We have shortened the section further. We have removed some unnecessary

17 descriptions and synthesized some information. As a result, the Results section is 3 pages shorter in the

18 latest manuscript version.

19

20 **P16**

21 **Comment:**

22 Line 24: explicitly mention at the beginning of this paragraph that you use the Turney and Jones data

23 synthesis.

24 **Reply:**

25 Now **Page 14 Line 11**. Done:

26 “Both reconstructed (Turney and Jones, 2010) [...]”.

27

28 **P19**

29 **Comment:**

30 Line 14: “...is used FOR A model-data...”

31 **Reply:**

1 Now **Page 23 Line 8**. We have moved this paragraph to the Discussion section, thus to fit it with the
2 rest of the text, we rephrased as follows:

3 “The proxy data compilation by Capron et al. (2014) used in our study is also compared to two
4 different climate models, namely CCSM3 and HadCM3.”

5

6 **Comment:**

7 Line 17: be careful to not create misunderstanding: CCSM3 is FORCED with higher GHG
8 concentrations, it does not simulate GHG, they are prescribed.

9 You should mention the bipolar seesaw pattern!

10 **Reply:**

11 Now **Page 23 Line 11**. We have corrected the information and wrote:

12 “ For 130 kyr BP, a model-data mismatch is found in both cases, as most of the records indicate strong
13 negative anomalies, while the models simulate strong positive anomalies (Capron et al., 2014),
14 especially CCSM3 which was run with higher GHG concentrations than HadCM3 and COSMOS.”

15 In the latest manuscript version, we have mentioned the bipolar seesaw, which is actually captured by
16 COSMOS. In Fig. 10, for example, it is shown that in the North Atlantic Ocean (south of Iceland and
17 Greenland) there is a cooling (marked in white, but there the anomalies are actually negative), while in
18 the South a warming is found. There is an AMOC response, but is partly masked by the stronger
19 insolation (and also Greenland) effect. Thus, we have added the following lines:

20 **Page 23 Line 16:** “Another cause may be the decrease in AMOC at the LIG with respect to PI leading
21 to the bipolar seesaw, a pattern that is also observed in the proxy data at 130 kyr BP. We note a relative
22 cooling in both LIG simulations south of Iceland and Greenland. This region is very sensitive to
23 changes in the AMOC as shown in observational and numerical studies (Knight et al., 2005; Latif et al.,
24 2006; Dima and Lohmann, 2009).”

25

26 **Comment:**

27 Line 14-26: this is some discussions, not really a result, please move this paragraph to the discussion
28 section. I’m actually surprised you don’t mention here and in the discussion more explicitly the fact
29 that your model does not reproduce the bipolar seesaw pattern observed in the 130 ka data based
30 timeslices.

31 **Reply:**

1 We have moved this paragraph to the Discussion section and also wrote a few lines about the seesaw
2 pattern, which is actually simulated by COSMOS.

3 Now **Page 23 Line 8**.

4 “The proxy data compilation by Capron et al. (2014) used in our study is also compared to two
5 different climate models, namely CCSM3 and HadCM3. For 130 kyr BP, a model-data mismatch is
6 found in both cases, as most of the records indicate strong negative anomalies, while the models
7 simulate strong positive anomalies (Capron et al., 2014), especially CCSM3 which was run with higher
8 GHG concentrations than HadCM3 and COSMOS. With respect to the difference between model and
9 data, COSMOS simulates TS closer to the temperatures derived from marine-based records, since it
10 indicates nearly no change rather than a strong opposite signal. One cause for this modest change in the
11 North Atlantic Ocean may be related to vegetation changes, which may lead to a cooling as suggested
12 above. Another cause may be the decrease in AMOC at the LIG with respect to PI leading to the
13 bipolar seesaw, a pattern that is also observed in the proxy data at 130 kyr BP. We note a relative
14 cooling in both LIG simulations south of Iceland and Greenland. This region is very sensitive to
15 changes in the AMOC as shown in observational and numerical studies (Knight et al., 2005; Latif et al.,
16 2006; Dima and Lohmann, 2009).”

17

18 **Comment:**

19 Results Section: I still find it still long and hard to read.

20 **Reply:**

21 We have shortened further the Results section, removed some unnecessary description and aimed for a
22 more synthesized text.

23

24 **P20**

25 **Comment:**

26 Typo in the title of Section 4.1. (insolation)

27 **Reply:**

28 Done.

29

30 **Comment:**

31 Line 24: Check typo at the end of the sentence.

1 **Reply:**

2 Done.

3

4 **P23**

5 **Comment:**

6 The section on model-data comparison is very long, you should consider writing it much more to the
7 point. However, I think that here you should add a few sentences of discussion regarding the model-
8 data comparison with the new 130 ka data based time-slice and the fact that your new simulation do not
9 reproduced the bipolar seesaw and possible explanation for that.

10 **Reply:**

11 We have shortened subchapter 4.3 and wrote it more to the point.

12 We have also added the paragraph from the Results section to the Discussion section, which discusses
13 the new proxy dataset, and a few lines on the bipolar seesaw pattern, which is simulated by COSMOS:

14 **Page 23 Line 8:** “The proxy data compilation by Capron et al. (2014) used in our study is also
15 compared to two different climate models, namely CCSM3 and HadCM3. For 130 kyr BP, a model-
16 data mismatch is found in both cases, as most of the records indicate strong negative anomalies, while
17 the models simulate strong positive anomalies (Capron et al., 2014), especially CCSM3 which was run
18 with higher GHG concentrations than HadCM3 and COSMOS. With respect to the difference between
19 model and data, COSMOS simulates TS closer to the temperatures derived from marine-based records,
20 since it indicates nearly no change rather than a strong opposite signal. One cause for this modest
21 change in the North Atlantic Ocean may be related to vegetation changes, which may lead to a cooling
22 as suggested above. Another cause may be the decrease in AMOC at the LIG with respect to PI leading
23 to the bipolar seesaw, a pattern that is also observed in the proxy data at 130 kyr BP. We note a relative
24 cooling in both LIG simulations south of Iceland and Greenland. This region is very sensitive to
25 changes in the AMOC as shown in observational and numerical studies (Knight et al., 2005; Latif et al.,
26 2006; Dima and Lohmann, 2009).”

27

28 **P24**

29 **Comment:**

30 Line 31: you need to refer to NEEM c.m 2013 instead of the two references that you propose.

31 **Reply:**

1 We have removed the first part of this paragraph and wrote directly about the results from NEEM
2 Community Members (2013).
3 Now **Page 21 Line 6**: “A warming as high as $+8 \pm 4^{\circ}\text{C}$ is proposed by NEEM Community Members
4 (2013) for the peak LIG warmth at 126 kyr BP, based on North Greenland Eemian Ice Drilling
5 (NEEM) ice core. They propose that the northwest GIS is characterized only by a modest reduction of
6 400 ± 250 m between 128 and 122 kyr BP. In our study, we find at the location of the NEEM ice core
7 an annual mean warming of $+9.6^{\circ}\text{C}$ at 125 kyr BP at a GIS height of 553 m, a warming that is within
8 the temperature range proposed by NEEM Community Members (2013).”
9

10 **P25**

11 **Comment:**

12 Line 1: please use the NEEM ice core site rather than the Renland and the NGRIP sites site as a
13 reference site in Greenland having some LIG quantitative temperature reconstruction. Be careful please
14 also when using the NGRIP ice core for the LIG: the record stops at about 123 ka and it very likely
15 doesn't record the LIG maximum warmth; NEEM is the only Greenland ice core providing a
16 quantitative estimate of surface temperature change of $8 \pm 4^{\circ}\text{C}$.

17 **Reply:**

18 We have removed the first part of this paragraph and left out the Renland and NGRIP sites, and focused
19 only on the NEEM ice record:

20 Now **Page 21 Line 6**: “A warming as high as $+8 \pm 4^{\circ}\text{C}$ is proposed by NEEM Community Members
21 (2013) for the peak LIG warmth at 126 kyr BP, based on North Greenland Eemian Ice Drilling
22 (NEEM) ice core. They propose that the northwest GIS is characterized only by a modest reduction of
23 400 ± 250 m between 128 and 122 kyr BP. In our study, we find at the location of the NEEM ice core
24 an annual mean warming of $+9.6^{\circ}\text{C}$ at 125 kyr BP at a GIS height of 553 m, a warming that is within
25 the temperature range proposed by NEEM Community Members (2013). [...]”
26

27 **Comment:**

28 Line 10: this sentence needs to be rewritten, it is not correct to say that the reconstructions overestimate
29 the simulated temperature, but you can say that the reconstructions suggest stronger warming than the
30 one simulated.

31 **Reply:**

1 We have rephrased as suggested and wrote:

2 Now **Page 21 Line 11**: “Antarctic ice cores indicate positive temperature anomalies of up to +3.5°C
3 (Capron et al., 2014), suggesting stronger warming than the simulated TS. However, a reduction in GIS
4 reduces the model-data disagreement.”.

5

6 **P28**

7 **Comment:**

8 Section 4.4. You need to be careful here as there is a lot of slightly inexact information that are given in
9 this section:

10 **Reply:**

11 We have corrected as suggested below.

12

13 **Comment:**

14 Line 8: For over a decade, paleoceanographers mostly use the benthic d18O stack from Lisiecki and
15 Raymo 2005 rather than the SPECMAP curve; you should refer to this curve as well and maybe be
16 more general in your statement:

17 “the dating of ...by lining up their benthic d18O signal to a dated benthic d18O stack...”

18 I can refer you to the Govin et al. 2015 paper, it explains this in details.

19 As a consequence, you need to remove “which is tuned...”.

20 **Reply:**

21 We have replaced the SPECMAP with the method suggested above and the corresponding reference.

22 Now **Page 23 Line 29**: “ The dating of most of the records is derived by lining up their benthic $\delta^{18}\text{O}$
23 signal to a dated benthic $\delta^{18}\text{O}$ stack (Lisiecki and Raymo, 2005). This strategy allows a relative dating
24 of sediment cores beyond the time limit of radiocarbon dating (Fairbanks et al., 2005; Chiu et al., 2007;
25 Reimer et al., 2009; Shanahan et al., 2012; Reimer et al., 2013), but it may lead to an artificial
26 synchronization of all records and therefore dampen regional differences in climate records with
27 respect to the LIG chronozone.”.

28

29 **Comment:**

30 Line 13: “A relatively...” this is the wrong reference, the method we used in Capron et al. 2014 was
31 originally developed by Govin et al. CP 2012; Also the rest of the sentence is

1 very unprecise. Also, you should rather talk about “an alternative” method, rather than “new”
2 - The next sentence “...allowing for consideration of dating uncertainties”: this is an incorrect
3 formulation: the method doesn’t not allow use to estimate uncertainties more than another alignment
4 strategies. This is only that we made the decision to provide such a quantitative estimate, which was
5 not something done previously. Please rephrase.

6 **Reply:**

7 We have replaced the reference as suggested and also rephrased:

8 Now **Page 24 Line 3**: “An alternative method for synchronizing different types of proxies is used in
9 Govin et al. (2012), by aligning proxy records to the AICC2012 ice core chronology. Their study shows
10 that the maximum temperature changes during the LIG is different between the two hemispheres, the
11 records from Southern Ocean and Antarctica showing an early maximum compared to the records from
12 northern high latitudes. This method is used by Capron et al. (2014) in their proxy data compilation,
13 thus allowing for one less uncertainty in the model-data comparison.”

14
15 **Comment:**

16 Line 21: from the sentence starting with “furthermore” until the end of the section: this should greatly
17 be shortened: you are repeating information that you already describe in the introduction. Also, since
18 you now consider a time-evolving data synthesis, your statements are not always relevant.

19 You should instead discuss whether by comparing with the Capron et al synthesis, there is an
20 improvement in the model data comparison (or not) compared to when you do the comparison with
21 climate synthesis that give a unique time slice.

22 **Reply:**

23 Now **Page 24 Line 13**: We have shortened and wrote: “Furthermore, defining the timing of the
24 maximum warmth during the LIG represents as well a challenge. Bakker and Renssen (2014) show that
25 the calculation of the maximum LIG temperature is largely model-dependent, indicating also
26 geographical- and time-dependency (retrieved values differ between the annual mean and warmest
27 month temperature anomalies). They propose that the time-dependency originates from the dependency
28 of the time evolution of orbital forcing on latitude and seasons, as well as from the thermal inertia of
29 the oceans and from different feedbacks in the climate system. Our model results indicate that the
30 timing of maximum LIG warmth is indeed regionally dependent (Fig. 9).”

31 Now **Page 24 Line 8**: We have also added a few words on the comparison with the new dataset.

1 “[...]. However, using such a time-resolved temperature compilation does not improve our model-data
2 comparison, as when compared to the other proxy-based datasets that represent the maximum LIG
3 warmth.”

4

5 **P29**

6 **Comment:**

7 Line 6: replace “proxy reconstruction” by “LIG climate data synthesis”

8 **Reply:**

9 Now **Page 24 Line 24:** Done.

10

11 **Comment:**

12 Line 7: remove “a compilation of synchronised records by”.

13 **Reply:**

14 Done.

15

16 **Typographic comments:**

17 **Comment:**

18 P4, line 29: missing space between two sentences.

19 **Reply:**

20 Done.

21

22 **Comment:**

23 P6, line 21: missing space between two sentences.

24 **Reply:**

25 Done

26

27 **Comment:**

28 P9, line 1: missing space between two sentences.

29 **Reply:**

30 Done.

31

1 **Comment:**

2 P11, line 24: missing space between simulation and (.
3

3 **Reply:**

4 Done.
5

6 **Comment:**

7 P29, line 13: double space before the start of the sentence I think.
8

8 **Reply:**

9 Done.
10

11 **Comment:**

12 P29, line 29: a “.” is missing between “considered” and “At”.
13

13 **Reply:**

14 In order to write also the Conclusions more to the point, we have removed that part of the paragraph.
15

16 **Comment:**

17 P20, line 10: I don't understand this sentence, it needs to be re-written or removed.
18

18 **Reply:**

19 We assume that it was meant P30, because there is no sentence starting at line 10 from P20.
20

20 Now **Page 25 Line 19**: We have rephrased the sentence as follows:
21

21 “The missing exact time constrain in CAPE Last Interglacial Project Members (2006) and Turney and
22 Jones (2010) provides therefore an additional uncertainty and complicates direct model-data
23 comparisons.”.
24

25 **Comment:**

26 Figure 10: Please indicate clearly which time slice from Capron et al. you are using in the caption (130
27 ka).
28

28 **Reply:**

29 Done.
30

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1 Abstract

2 During the Last Interglacial (LIG, ~130–115 kiloyear (kyr) before present (BP)), the northern high
3 latitudes were characterized by higher temperatures than those of the late Holocene and a lower
4 Greenland Ice Sheet (GIS). However, the impact of a reduced GIS on the global climate has not yet
5 been well constrained. In this study, we quantify the contribution of the GIS to LIG warmth by
6 performing various sensitivity studies based on equilibrium simulations, employing the Community
7 Earth System Models (COSMOS), with a focus on height and extent of the GIS. We present the first
8 study on the effects of a reduction in GIS on the ~~global~~ surface temperature (TS) anomalies on a global
9 scale and separate the contribution of different forcings to LIG warmth. The strong Northern
10 Hemisphere warming is mainly caused by increased summer insolation. Reducing the height by ~1300
11 m and the extent of the GIS does not have a strong influence during summer, leading to an additional
12 global warming of only +0.24°C. The effect of a reduction in GIS is strongest during local winter, with
13 up to +5°C warming ~~in the northern and southern high latitudes~~ and with an increase in global average
14 temperature of +0.48°C. ~~Furthermore, the method by which GIS configuration is changed influences~~
15 ~~the results.~~

16 In order to evaluate the performance of our LIG simulations, we additionally compare the simulated
17 TS anomalies with marine and terrestrial proxy-based LIG temperature anomalies derived from three
18 different proxy data compilations. Our model results are in good agreement with proxy records with
19 respect to the warming pattern, but underestimate the reconstructed temperatures, suggesting a potential
20 misinterpretation of the proxy records or deficits of our model ~~such as low resolution, lack of~~
21 ~~biogeochemistry feedback, of lithosphere, or of a coupled ice sheet model~~). However, we are able to
22 partly reduce the mismatch between model and data by additionally taking into account the potential
23 seasonal bias of the proxy record and or the uncertainties in the dating of the proxy records for the LIG
24 thermal maximum. The seasonal bias and the uncertainty of the timing are estimated from ~~our own~~ new
25 transient model simulations covering the whole LIG ~~(130–115 kyr BP)~~. The model-data comparison
26 improves for proxies that represent annual mean temperatures when GIS is reduced and when we take
27 into account the local thermal maximum during the LIG (130–120 kyr BP). For proxy data that
28 represent summer temperatures, changes in GIS are of minor importance for sea surface temperatures.
29 However, the temperature change over Greenland in the reduced GIS simulations seems to be
30 overestimated as compared to the local data, which could be related to the interpretation of the recorder
31 system and/or the assumptions of GIS reduction. ~~Additionally, by comparing our model results to~~

temperature reconstructions we can conclude that the GIS elevation was not as low as prescribed in our simulations, but potentially lower than prescribed in other studies. Changes in GIS improve the model-data agreement when annual mean proxies are considered rather than proxies that record summer temperatures. Thus, the question regarding the real size of the GIS during the LIG has yet to be answered.

1. Introduction

One important application of atmosphere-ocean general circulation models (AOGCMs) is the computation of future climate projections (Collins et al., 2013; Kirtman et al., 2013). These projections which allow insight into possible future climate states that may be notably different from present day. In order to ensure the reliability of such climate projections, the climate models' ability to replicate climate states that are different from the present needs to be tested (e.g. Braconnot et al., 2012; Flato et al., 2013). This is necessary since model development is biased towards present climate states as a result of the tuning of various physical parameterizations towards modern observations. Past time periods provide the means for evaluating the performance of general circulation models (e.g. Dowsett et al., 2013; Lohmann et al., 2013; Lunt et al., 2013).

In particular, the simulation of interglacial climates provides an example of how models can respond when strong changes in the forcing are applied (Mearns et al., 2001). For a better understanding and assessment of potential future climate change it is necessary and the possibility to analyze the main drivers leading to an interglacial climate that was warmer than the present interglacial. The Last Interglacial (LIG, ~130–115 kiloyear (kyr) before present (BP)) represents the penultimate interglacial before the Holocene (10–0 kyr BP), and is considered to be on average warmer than the Holocene (10–0 kyr BP) (CLIMAP Project Members, 1984; Martinson et al., 1987; Kukla et al., 2002; Bauch and Erlenkeuser, 2003; Felis et al., 2004; Kaspar et al., 2005; Jansen et al., 2007; Turney and Jones, 2010; Masson-Delmotte et al., 2013). Model simulations indicate a pronounced warming during boreal summer in northern high latitudes (Harrison et al., 1995; Kaspar et al., 2005; Otto-Bliesner et al., 2006; Lohmann and Lorenz, 2007; Stone et al., 2013). Proxy records located in the Northern Hemisphere indicate also that LIG climate is characterized by temperatures that are several degrees Celsius above preindustrial (PI) values (Kaspar et al., 2005; CAPE Last Interglacial Project Members, 2006; Turney and Jones, 2010; McKay et al., 2011). According to climate reconstructions, Arctic summer temperatures were about +2 to +4°C warmer than those of the late Holocene (CAPE Last Interglacial Project Members, 2006). Winter in high latitudes is considered to be warmer during

the LIG due to sea ice feedbacks (Montoya et al., 2000; Kaspar et al., 2005; Yin and Berger, 2010). One cause for LIG summer warmth ~~in summer~~ was increased summer insolation at middle to high latitudes. ~~Enhanced seasonality in the Northern Hemisphere is attributed to larger obliquity (ϵ) and eccentricity (e) relative to today (Berger, 1978), with Earth's orbital eccentricity being more than twice the PI value (Berger and Loutre, 1991), and boreal summer coinciding with the Earth passing the perihelion (Laskar et al., 2004; Yin and Berger, 2010).~~ Greenhouse gas (GHG) concentrations during the LIG were similar to the preindustrial (PI). ~~Changes in the insolation forcing determine feedbacks in the ocean, atmosphere, vegetation, and sea ice, which further influence the climate (e.g. Berger and Loutre, 1991; Braconnot et al., 2012).~~

~~According to different studies, the Greenland Ice Sheet (GIS) was lower during the LIG compared to PI, but the magnitude of reduction of elevation and area of the GIS has yet to be determined.~~ Studies based on reconstructions and climate model simulations suggest a partial or complete absence of the Greenland Ice Sheet (GIS) during the LIG, and that the sea level was higher than the PI (Veeh, 1966; Stirling et al., 1998; Cuffey and Marshall, 2000; Otto-Bliesner et al., 2006; Overpeck et al., 2006; Jansen et al., 2007; Kopp et al., 2009, 2013; Alley et al., 2010; van de Berg et al., 2011; Robinson et al., 2011; Dutton and Lambeck, 2012; ~~Dahl-Jensen et al., 2013~~; Quiquet et al., 2013; Church et al., 2013; Stone et al., 2013), while a more recent study based on ice core data proposes only a modest GIS change (i.e. equivalent to a contribution to sea level rise of ~ 2 m, ~~Dahl-Jensen et al.~~ NEEM Community Members, 2013). An increase in sea level during the LIG ~~as high as 8 m is proposed by~~ is estimated to be of about 7 m (Kopp et al., (2009; Dutton et al., 2015), with a possible contribution of 3 to 4 m from Antarctica (Sutter et al., 2015) ~~based on sea level data synthesis which may imply a large contribution from the GIS and the Antarctic Ice Sheet~~. The contribution of a partially melted GIS to LIG sea level rise is however not yet well determined; ~~various studies suggest a sea level rise due to meltwater from Greenland of +0.3 to +5.5 m (Cuffey and Marshall, 2000; Tarasov and Peltier, 2003; Lhomme et al., 2005; Otto-Bliesner et al., 2006; Colville et al., 2011; Quiquet et al., 2013; Stone et al., 2013).~~

Existing studies on the effects of a reduced GIS during the LIG have been centered mostly on the Northern Hemisphere and focused on implications related to sea level rise (Stone et al., 2013) and Atlantic Meridional Overturning Circulation (AMOC) (Bakker et al., 2012). The studies by Bakker et al. (2012) and Stone et al. (2013) assume a relatively modest reduction of the GIS and find a mismatch between the simulated and the proxy-based temperature anomalies with respect to PI (CAPE Last Interglacial Project Members, 2006). Otto-Bliesner et al. (2006) find that a GIS elevation reduced by

500 m leads to a pronounced warming of up to +5°C in middle to high latitude summer. However, they find as well a mismatch between model and data, with the model underestimating the temperature anomaly indicated by the proxy record. In an LIG study based on transient climate model simulations performed with an earth system model of intermediate complexity, Loutre et al. (2014) find that changes in the Northern Hemisphere ice sheets configuration (extent and albedo) have only a small impact on the climate at the beginning of the LIG. They find as well an underestimation of the reconstructed temperatures by the model, ~~even when taking into account several uncertainties. Bakker and Renssen (2014), who perform an analysis of transient simulations for the LIG, provide a partial explanation for the model-data mismatch, proposing that such large differences between the reconstructed and simulated LIG temperatures may stem from the assumption in temperatures reconstructions that the LIG thermal maximum occurred synchronously in space and time. Their study suggests that global compilations of reconstructed LIG thermal maximum overestimate the warming.~~

~~Another~~ Other model-data comparison studies ~~(Otto-Bliesner et al., 2013)~~ for the LIG ~~(Lunt et al., 2013; Otto-Bliesner et al., 2013)~~, based on ~~an~~ AOGCMs (but with no changes in GIS elevation or extent), also shows an underestimation of global temperature reconstructions ~~by (Turney and Jones, 2010;) and McKay et al., (2011). Lunt et al. (2013) compare global terrestrial and marine proxy-based temperature anomalies with respect to PI by Turney and Jones (2010) to an ensemble of equilibrium simulations for the LIG performed with different state-of-the-art climate models. Even when considering a multi-model and a multi-proxy approach, they also find a pronounced disagreement between model and data, with the model underestimating the reconstructed temperature. Bakker and Renssen (2014), who perform an analysis of transient simulations for the LIG, provide a partial explanation for the model-data mismatch, proposing that such large differences between the reconstructed and simulated LIG temperatures may stem from the fact that commonly-used climate syntheses represent a single time-slice assuming synchronous LIG thermal maximum in space and time. Their study suggests that global compilations of reconstructed LIG thermal maximum overestimate the warming. However, different studies (modelling as well as proxy-based) indicate that the maximum LIG warmth occurred at different times throughout the LIG in dependence of the geographical location (Bakker et al., 2012; Govin et al., 2012; Langebroek and Nisancioglu, 2014). The lack of accurate and independent age models for most paleoclimatic record during the LIG could be one cause for the observed model-data discrepancy (e.g. Drysdale et al., 2009; Govin et al., 2012; Capron et al., 2014). The lack of climate synthesis for the LIG going further than proposing a single~~

1 snapshot on LIG maximum warmth and thus accounting for asynchronous changes across the globe is
2 due to the difficulty in building robust and coherent age models for different climatic archives during
3 the LIG (Govin et al., 2015). For example, the compilation of LIG temperature reconstructions
4 included in this study (CAPE Last Interglacial Project Members, 2006) represents one single snapshot
5 on the LIG thermal maximum, with the assumption that maximum warmth occurred synchronously
6 across the globe. This assumption has to be made when compiling reconstructed LIG temperatures as it
7 is difficult to align time series from different types of paleoclimatic archives since they do not benefit
8 from robust absolute timescale allowing precise temporal comparison between different regions and
9 between different archives. Recently, Capron et al. (2014) propose a new climate synthesis for the high
10 latitude regions based on a coherent temporal framework between ice and marine archives. This allows
11 for the first time to assess both the temporal and the spatial evolution of the climate throughout the LIG
12 (Capron et al., 2014). Moreover, different studies (modelling as well as proxy-based) indicate that the
13 maximum LIG warmth occurred at different times throughout the LIG in dependence of the
14 geographical location (Bakker et al., 2012; Govin et al., 2012; Langebroek and Nisancioglu, 2014).
15 Additionally, some proxy records may be seasonally biased (Lohmann et al., 2013, and references
16 therein). Still, the models used by Lunt et al. (2013) and Otto-Bliesner et al. (2013) do not capture the
17 magnitude of change recorded by the proxies, even when simulated summer mean temperature
18 anomalies are considered.

20 Transient LIG climate simulations provide the possibility to determine when and where maximum
21 LIG warmth occurred, and whether a given record may be seasonally biased or rather represents annual
22 mean temperatures. Therefore, transient climate simulations may help to clarify the origin of the
23 disagreement between model and data. In this study, we analyze the effect of a reduced GIS on LIG
24 global climate with a focus on surface temperature (TS) at 130 kyr BP. The TS is derived from
25 equilibrium simulations performed with ~~thean~~ AOGCM-COSMOS. We perform several sensitivity
26 simulations with different boundary conditions and use three different methods of reducing GIS
27 elevation to half its preindustrial elevation and/or extent. This approach enables us to determine what
28 GIS configuration has the strongest impact on the global temperature. Additionally, we assess the
29 importance of additional forcings like insolation and albedo. Furthermore, in order to validate our
30 results, we perform a model-data comparison using three different proxy-based temperature
31 compilations by CAPE Last Interglacial Project Members (2006), Turney and Jones (2010), and

1 | Capron et al. (2014). For model-data comparison, we additionally consider the timing uncertainty of
2 the maximum LIG warmth as determined from our transient simulations as well as the potential
3 seasonal bias of the proxy record.

4 **2. Data and methods**

5 **2.1 Model description**

6 The Community Earth System Models (COSMOS) consist of the general atmosphere circulation model
7 ECHAM5 (5th generation of the European Centre Hamburg Model; Roeckner et al., 2003), the land
8 surface and vegetation model JSBACH (Jena Scheme of Atmosphere Coupling in Hamburg; Raddatz et
9 al., 2007), the general ocean circulation model MPIOM (Max-Planck-Institute Ocean Model; Marsland
10 et al., 2003), and the OASIS3 coupler (Ocean-Atmosphere-Sea Ice-Soil; Valcke et al., 2003; Valcke,
11 2013) that enables the atmosphere and ocean to interact with each other. COSMOS is mainly developed
12 at the Max-Planck-Institute for Meteorology in Hamburg (Germany). The atmospheric component
13 ECHAM5 is a spectral model, which is used in this study at a horizontal resolution of T31
14 ($\sim 3.75^\circ \times 3.75^\circ$) with a vertical resolution of 19 hybrid sigma-pressure levels, the highest level being
15 located at 10 hPa. The JSBACH simulates fluxes of energy, momentum, and CO₂ between land and
16 atmosphere and comprises the dynamic vegetation module by Brovkin et al. (2009), which enables the
17 terrestrial plant cover to explicitly adjust to variations in the climate state. MPIOM is formulated on a
18 bipolar orthogonal spherical coordinate system. We employ it at a horizontal resolution of GR30
19 (corresponding to $\sim 3^\circ \times 1.8^\circ$) with 40 vertical levels. MPIOM includes a Hibler-type zero-layer
20 dynamic-thermodynamic sea ice model with viscous plastic rheology (Semtner, 1976; Hibler, 1979).
21 No flux correction is applied (Jungclaus et al., 2006). Model time steps are 40 min (atmosphere) and
22 144 min (ocean). This COSMOS configuration has been applied for the mid- and early Holocene (Wei
23 and Lohmann, 2012), glacial conditions (Gong et al., 2013; Zhang et al., 2013, 2014), the Pliocene
24 (Stepanek and Lohmann, 2012), the Miocene (Knorr et al., 2011; Knorr and Lohmann, 2014), future
25 climate projections (Gierz et al., 2015), and the LIG (Lunt et al., 2013; Pfeiffer and Lohmann, 2013;
26 Bakker et al., 2014; Felis et al., 2015; Gong et al., 2015; Jennings et al., 2015).

27 **2.2 Experimental setup**

28 | As control climate, we use a PI simulation described by Wei et al. (2012). Greenhouse gas
29 concentrations and astronomical forcing of the PI simulation are prescribed according to the

1 Paleoclimate Modelling Intercomparison Project Phase 2 (PMIP2) protocol (Braconnot et al., 2007).
2 Several equilibrium simulations covering the LIG are performed using fixed boundary conditions for
3 130 and 125 kyr BP time slices. The latter simulation is performed in order to assess whether a
4 reduction in GIS at 125 kyr BP improves the ~~model-data~~ agreement between the model and the three
5 proxy compilations considered in this study (CAPE Last Interglacial Project Members, 2006; Turney
6 and Jones, 2010; 125 kyr BP time slice by Capron et al., 2014). Astronomical parameters for the time
7 slices considered in this study have been calculated according to Berger (1978) and are given in Table
8 1. It is known that one main driver for LIG climate is the Earth's astronomical parameters (Kutzbach et
9 al., 1991; Crowley and Kim, 1994; Montoya et al., 2000; Felis et al., 2004; Kaspar and Cubasch, 2007).
10 During the early part of the LIG, the axial tilt (obliquity) was higher which caused stronger summer
11 insolation at high latitudes of the Northern Hemisphere, while the low latitudes received less insolation;
12 this effect manifests in enhanced seasonality (i.e. warmer summers and cooler winters) in the early LIG
13 climate. The Earth's orbital eccentricity was more than twice the present-day value (Berger and Loutre,
14 1991), and boreal summer coincided with the Earth passing the perihelion (Laskar et al., 2004; Yin and
15 Berger, 2010).

16 Our main focus is the effects of height and extent of the GIS and of insolation changes on climate;
17 consequently, GHG concentrations are prescribed at mid-Holocene levels (278 parts per million by
18 volume (ppmv) CO₂, 650 parts per billion by volume 10 (ppbv) CH₄, and 270 ppbv N₂O, Table 1). An
19 additional simulation is performed using values for GHG concentrations proposed in the Paleoclimate
20 Modelling Intercomparison Project Phase 3 (PMIP3) for the 130 kyr BP time slice (e.g. Lunt et al.,
21 2012) and corresponding to 257 ppmv for CO₂, 512 ppbv for CH₄, and 239 ppbv for N₂O (LIG-GHG,
22 Table 1, Fig. S1). This simulation is included in the Supplementary material as a control run for the
23 GHG concentrations used in our LIG sensitivity simulations, in order to show that there is no large
24 scale impact of lower GHG concentrations relative to our LIG control simulation (Fig. S1). Another
25 LIG simulation is forced with increased CH₄ (760 ppbv) and slightly increased CO₂ (280 ppmv) in
26 order to have one LIG simulation that has identical GHG concentrations to the ones prescribed in the PI
27 simulation (Wei et al., 2012) (Table 1).

28 The size of the GIS during the LIG is not well constrained by reconstructions (Koerner, 1989;
29 Koerner and Fisher, 2002; NGRIP members, 2004; Johnsen and Vinther, 2007; Willerslev et al., 2007;
30 Alley et al., 2010; ~~Dahl-Jensen et al.~~ NEEM Community Members, 2013). We take this uncertainty into
31 account and perform sensitivity simulations with three different elevations and two different ice sheet

1 areas of the GIS (Fig. 1). An LIG simulation (~~LIG-ctl~~) with a preindustrial GIS elevation (~~(LIG-ctl~~,
2 Table 1, Fig. 1a) is used as control run for our LIG simulations, which allows us to quantify the
3 exclusive effects of Greenland elevation on climate. Four simulations (~~Table 1~~) are performed using a
4 modified GIS (~~Table 1~~). We consider (1) a GIS lowered to half its presentindustrial elevation (~~LIG-~~
5 ~~$\times 0.5$~~) with unchanged GIS area (~~LIG- $\times 0.5$~~ , Fig. 1b); (2) a GIS lowered by 1300 m (LIG-1300m); at
6 locations where the preindustrial Greenland elevation is below 1300 m, we set LIG orography to zero
7 meters, but define the ground to be ice covered and keep the albedo at values typical for the GIS (Fig.
8 1c); (3) a GIS similar to ~~simulation~~ LIG-1300m, but with albedo adjustment at locations where
9 prescribed LIG orography is zero meters (LIG-1300m-alb); at such locations the land surface is defined
10 as being ice-free and the background albedo is reduced from 0.7 to 0.16 (Fig. 1d), an albedo value that
11 is typical for tundra (Fitzjarrald and Moore, 1992; Eugster et al., 2000) – this simulation, in
12 combination with ~~simulations~~ LIG-1300m and LIG-ctl, allows us to separate the climatic effects of a
13 lowered and spatially reduced GIS from those of changes in albedo; (4) a simulation similar to (3), but
14 with an atmospheric concentration of CH₄ that is increased to 760 ppbv (LIG-1300m-alb-CH₄, Fig. 1d);
15 this simulation enables us to quantify the combined effect of a lowered GIS elevation, changes in
16 albedo and insolation with respect to PI.

17 Such changes in GIS elevation and extent would lead to a sea level rise of about 3 m instead of 7 m
18 for the present situation due to the rebound effect (relaxation of the lithosphere). A sea level change of
19 +3 m is in agreement with other studies that suggest an increase in sea level of 0.3 to 5.5 m during the
20 LIG as a result of GIS melting (Cuffey and Marshall, 2000; Tarasov and Peltier, 2003; Lhomme et al.,
21 2005; Otto-Bliesner et al., 2006; Carlson et al., 2008; Colville et al., 2011; Quiquet et al., 2013; Stone
22 et al., 2013). Generally, other boundary conditions of the simulations are kept at their preindustrial
23 state, except for vegetation which is computed dynamically according to the prevailing climate
24 conditions (the only equilibrium simulation that considers fixed preindustrial vegetation is LIG-GHG).

25 Furthermore, we perform one transient model simulation that covers the Holocene (8–0 kyr BP) and
26 four transient simulations of the LIG (130–115 kyr BP). The Holocene transient simulation is included
27 in this study as a control run for the LIG transient simulations, in order to assess the differences and
28 similarities between the present and last interglacial. For the LIG, we apply orography configurations
29 of ~~simulations~~ LIG-ctl, LIG- $\times 0.5$, LIG-1300m-alb, and LIG-GHG, respectively. These LIG transient
30 simulations enable us to extract the temperatures at the LIG thermal maximum. The transient
31 simulations are started from a near-equilibrium state, meaning that the climate system is already

adjusted to the prescribed forcings, except for the ocean which needs about 3000 years in order to reach an equilibrium state. Performing such long equilibrium simulations is not feasible due to the involved computational effort. Each transient simulation is accelerated by a factor of ten in order to reduce the computational expense. To this end, astronomical forcing is accelerated following the method of Lorenz and Lohmann (2004). The astronomical parameters are calculated after Berger (1978). During the simulations, the trace gas concentrations remain fixed – except for the LIG-GHG-tr~~run~~^{simulation}, where a timeseries is prescribed according to Lüthi et al. (2008) for CO₂, Loulergue et al. (2008) for CH₄, and Spahni et al. (2005) for N₂O, as proposed for PMIP3. The respective values are interpolated to a 0.01 kyr resolution that corresponds to the accelerated model time axis. A fixed preindustrial vegetation is considered only in the LIG-GHG-tr~~simulation~~^{simulation}, in the other transient simulations vegetation is computed dynamically. For the Holocene run, the orography is identical to preindustrial conditions.

In order to determine whether TS anomalies between simulations are statistically significant or rather caused by internal variability (noise), we perform an independent two-tailed Student's t test t following Eq. (1). For each grid cell, it relates time averages \bar{X} and standard deviations σ of model output time series of two given model simulations X_1 and X_2 of a length of n timesteps, in dependence of the effective degrees of freedom (DOF_{eff}). The DOF_{eff} are calculated considering the lag-1 autocorrelation acf (von Storch and Zwiers, 1999):

$$\text{DOF}_{\text{eff}} = n(1 - \text{acf}) / (1 + \text{acf}) \quad \text{with} \quad \text{acf} = \max(\text{acf}, 0),$$

meaning that the DOF_{eff} cannot be higher than 50, as the last 50 model years of each simulation are used for the analysis. For each grid point from X_1 and X_2 simulations, the smaller DOF_{eff} value is used for calculating the significance value with a 95% confidence interval.

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{\sigma^2(X_1)}{n} + \frac{\sigma^2(X_2)}{n}}} \quad (1)$$

Surface temperature at locations where the t test t of two data sets indicates a significance value below the critical value is considered to be statistically insignificant and is marked by hatches on geographical maps presented throughout this study.

For the analysis of time slice simulations, we define winter and summer as the mean of the 50 coldest and warmest months, respectively, for each grid cell, as we are mainly interested in local seasons. In all performed simulations, a modern calendar is assumed. Although in reality the definition of seasons changes over time due to orbital precession, taking this calendar shift into account would

only have a minor influence on our results since we calculate the summer and winter seasons by extracting the warmest and coldest month, respectively. Maximum and minimum LIG TS are calculated from the transient simulations considering the time interval between 130 and 120 kyr BP. In order to filter out internal variability, a 100-point running average representing the average over 1000 calendar years is applied. Maximum and minimum LIG warmth of the summer are defined as the warmest and coldest average of 100 warmest months, respectively, which reflects the warmest or coldest 1000 summer seasons with respect to the astronomical forcing. For the maximum and minimum LIG warmth of annual mean, we consider the warmest and coldest average of 100 model years, respectively. The seasonality range is defined by calculating the summer maximum LIG warmth (warmest average of 100 warmest months of the model years) and winter minimum LIG TS (coldest average of 100 coldest months of the model years).

2.3 Temperature reconstructions

In order to test the robustness of our simulations, we additionally perform a model-data comparison using proxy-based temperature anomalies that are available for the northern high latitudes (CAPE Last Interglacial Project Members, 2006), across the globe (Turney and Jones, 2010), and in ~~the northern and southern~~ middle to high latitudes (Capron et al., 2014). The temperature reconstructions from CAPE Last Interglacial Project Members (2006) are based on terrestrial and marine proxy records and estimate summer temperatures for maximum LIG warmth relative to PI. The global dataset by Turney and Jones (2010) comprises terrestrial and marine proxy records and estimates annual mean temperatures for maximum LIG warmth (terrestrial) and for the period of plateaued $\delta^{18}\text{O}$ (marine), relative to present day (PD, 1961–1990; Smith and Reynolds, 1998; New et al., 1999). ~~The dataset by Capron et al. (2014) used in our study comprises marine and ice core-based temperature reconstructions at the 130 and 125 kyr BP, as well as covering the LIG (125–115 kyr BP). The high latitude climate synthesis by Capron et al. (2014) provides temporal air and sea surface temperature (SST) reconstructions based on ice core and marine records respectively, across the interval 130 to 115 kyr BP (in our study covering the period between 125 and 115 kyr BP). They also propose snapshots of surface temperature anomalies and associated quantitative uncertainties at 115, 120, 125, and 130 kyr BP, but here we use the last two snapshots. This temperature compilation is the first one to comprise temperature reconstructions associated with a coherent temporal framework built between the ice core and marine sediment records (Capron et al., 2014).~~ Detailed information regarding the proxy data is given in CAPE Last Interglacial Project Members (2006), Turney and Jones (2010), and Capron et al.

1 (2014), respectively.

2 In order to quantify the agreement between model and data, we calculate the root-mean-square
3 deviation (RMSD) which is a measure of the differences between an estimator (y_{model}) and estimated
4 parameter (y_{data}) (Gauss and Stewart, 1995; Mudelsee, 2010). RMSD is defined in Eq. (2):

$$\text{RMSD} = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_{\text{model}} - y_{\text{data}})^2} \quad (2)$$

6 where y_{model} is the simulated TS anomaly at the location of the proxy record, y_{data} indicates the
7 reconstructed TS anomaly, and n is the number of data samples.

8 **3. Results**

9 In the first part of this section, we present results from our LIG GIS sensitivity simulations, focusing on
10 TS anomalies. Afterwards, a short description of results from the transient simulations is presented,
11 followed by the model-data comparison and consideration of potential uncertainties in the ~~model~~
12 ~~and data~~.

13 **3.1 Greenland Ice Sheet elevation and albedo influence on global surface** 14 **temperature**

15 **3.1.1 Annual mean anomalies**

16 ~~We first focus on annual mean TS anomalies.~~ Figure 2 presents the effect on the global TS of lowering
17 the GIS by half its preindustrial elevation by various methods. We observe the strongest warming over
18 Greenland (of up to +12.5°C) in the ~~simulation with a reduction in GIS of 1300 m and albedo changes~~
19 ~~wherever the land surface is changed from ice-covered to tundra (LIG-1300m-alb; (Figs. 1c and 2c).~~
20 ~~When reducing GIS by half its preindustrial elevation applying the first method described in Data and~~
21 ~~Methods section (LIG-×0.5 simulation, Figs. 1a and 2a), Greenland warms by up to +11.1°C.~~ Northern
22 North America and the Arctic Ocean warm by up to +2°C in all GIS sensitivity simulations. ~~The most~~
23 ~~widespread warming is simulated in LIG-×0.5 (Fig. 2a), while the LIG-1300m-alb simulation presents~~
24 ~~a less widespread warming but a higher increase in TS over the Arctic Ocean, where anomalies of +2°C~~
25 ~~are simulated (Fig. 2e).~~ A pronounced warming is found over the southernmost Southern Ocean of up
26 to +4°C (Fig. 2a–c).

27 The highest global mean (Southern Hemisphere) TS anomaly is simulated in LIG-1300m-alb
28 ~~simulation~~ with an average of $\Delta\text{TS} = +0.37^\circ\text{C}$ ($\Delta\text{TS} = +0.31^\circ\text{C}$), ~~though is higher by only +0.01°C than~~

the average derived from $LIG-\times 0.5$ simulation, and by $+0.07^{\circ}\text{C}$ than $LIG-1300\text{m}$ simulation (Table 2). Changes in GIS configuration lead to strongest anomalies in However, for the Northern Hemisphere, with the highest average TS anomaly changes of $\Delta\text{TS} = +0.47^{\circ}\text{C}$ is found in $LIG-\times 0.5$ simulation (Table 2), $\Delta\text{TS} = +0.38^{\circ}\text{C}$ in $LIG-1300\text{m}$, and $\Delta\text{TS} = +0.43^{\circ}\text{C}$ in $LIG-1300\text{m}-\text{alb}$ simulation. The highest average TS changes in the Southern Hemisphere are simulated in $LIG-1300\text{m}-\text{alb}$ with $\Delta\text{TS} = +0.31^{\circ}\text{C}$, while in $LIG-1300\text{m}$ and $LIG-\times 0.5$ simulations the average TS anomalies are $\Delta\text{TS} = +0.20^{\circ}\text{C}$ and $\Delta\text{TS} = +0.24^{\circ}\text{C}$, respectively. Consequently, the exact method of changing GIS configuration influences the hemispheric temperature anomalies.

The most affected areas by changes in GIS configuration are the northern high latitudes, which experience a warming of $\Delta\text{TS} = +1.45^{\circ}\text{C}$ in $LIG-1300\text{m}-\text{alb}$ simulation, and $\Delta\text{TS} = +1.07^{\circ}\text{C}$ and $\Delta\text{TS} = +1.03^{\circ}\text{C}$ in $LIG-\times 0.5$ and $LIG-1300\text{m}$ simulations, respectively. This indicates that albedo plays a significant role in the northern high latitude temperature changes, causing an average temperature anomaly of $\Delta\text{TS} = +0.42^{\circ}\text{C}$. A local cooling of up to -1.60°C is limited to the Barents Sea in $LIG-\times 0.5$ and $LIG-1300\text{m}$ simulations (Fig. 2a, b), south-west of Greenland in $LIG-1300\text{m}$ simulation (Fig. 2b), and a cooling of up to -2.30°C over the Sea of Okhotsk (western Pacific Ocean) in $LIG-1300\text{m}-\text{alb}$ simulation caused by a reduction in albedo in the prescribed ice-free areas (Fig. 2c, d). In the latter simulation, the Barents Sea cooling is counteracted by a warming caused by changes in albedo (Fig. 2d).

At 130 kyr BP, the AMOC was reduced by 3.5 Sv as compared to the PI (Table 2). However, a reduction in GIS partly counteracts the negative anomaly and leads to an increase in the AMOC of up to 2.2 Sv relative to the control simulation $LIG-\text{ctl}$. The applied method of changing GIS configuration has an influence also on the simulated changes in AMOC. In the $LIG-\times 0.5$ simulation, there is rather a minor increase in AMOC of 0.5 Sv, while in $LIG-1300\text{m}$ simulation AMOC is increased by 2 Sv. In the $LIG-1300\text{m}-\text{alb}$, AMOC is enhanced by 2.2 Sv, meaning that changes in albedo further contribute an increase of 0.2 Sv (Table 2).

3.1.2 Winter and summer mean anomalies

The seasonal effect of a reduced GIS elevation is strongest during local winter in both hemispheres in all GIS sensitivity simulations (Table 2). However, for simplicity we focus here only on the GIS sensitivity simulation that includes changes in GIS elevation and corresponding changes in albedo ($LIG-1300\text{m}-\text{alb}$, Fig. 3). The TS anomalies between the LIG control simulation $LIG-\text{ctl}$ and the other two GIS sensitivity simulations ($LIG-\times 0.5$ and $LIG-1300\text{m}$) can be calculated from the TS averages

given in Table 2. In the Northern (Southern) Hemisphere, winter TS changes by $\Delta TS = +0.57^{\circ}\text{C}$ ($\Delta TS = +0.39^{\circ}\text{C}$). The corresponding change in the Southern Hemisphere winter is $\Delta TS = +0.39^{\circ}\text{C}$ and the global average is $\Delta TS = +0.48^{\circ}\text{C}$ (Fig. 3a). The changes in GIS elevation and albedo lead to a winter warming of $\Delta TS = +2.08^{\circ}\text{C}$ in, with the northern high latitudes (60–90°N) experiencing the highest positive anomalies of $\Delta TS = +2.08^{\circ}\text{C}$ (Fig. 3a, Table 2).

During summer, the TS anomaly is also positive but of lower magnitude, with an average of $\Delta TS = +0.24^{\circ}\text{C}$ for Northern Hemisphere, Southern Hemisphere, and globally (Fig. 3b, Table 2). The northern high latitudes warm during summer by $\Delta TS = +0.46^{\circ}\text{C}$, which is a modest change compared to winter warming. Relatively strong cooling occurs over the Sea of Okhotsk and south-west of Greenland (Fig. 3), again with the strongest effect being present during winter. The sea ice edge and 50 %-compactness isolines are subject to local poleward retreat in the case of changed GIS and albedo.

3.2 Combined effects of LIG forcings on global surface temperature

The combined effects on TS of reducing the GIS by 1300 m, adjusting albedo, and applying astronomical changes that represent an LIG climatic setting are presented in Fig. 4. Assuming linearity of the different climatic drivers, we can additionally split the anomaly of simulations PI and LIG-1300m-alb-CH₄ (equivalent to simulation LIG-1300m-alb, but with a CH₄ concentration adjusted to PI simulation) into the isolated contributions of changes in elevation and albedo and in astronomical forcing. The anomaly caused by the astronomical forcing is (calculated as the difference between the anomaly of LIG-1300m-alb-CH₄ and PI, and the anomaly of LIG-1300m-alb and LIG-ctl).

Considering the TS values from Table 2, we find that the magnitude of the astronomical forcing influence is stronger than the effects of lowering the GIS and respective adjustment of the albedo in the global average of annual mean TS, as well as the annual mean average over Northern Hemisphere (Fig. 4a). In the Southern Hemisphere, both forcings have equal contributions to changes in annual mean TS (Fig. 4a). During winter, changes in GIS have the strongest influence globally and in the Northern Hemisphere, while in the Southern Hemisphere changes in astronomical forcing are dominant (Fig. 4b). During summer, there is an opposite pattern. Insolation changes are dominant globally and in the Northern Hemisphere, while the Southern Hemisphere is mostly influenced by changes in GIS and albedo (Fig. 4c). The strongest combined effect of insolation and changes in GIS and albedo occurs in the Northern Hemisphere during summer with an anomaly of $\Delta TS = +2.51^{\circ}\text{C}$. Globally, the combined effect leads to a warming of $\Delta TS = +1.34^{\circ}\text{C}$ during summer. In the Southern Hemisphere, the strongest combined effect is simulated during winter with $\Delta TS = +1.08^{\circ}\text{C}$. The highest annual mean average TS

anomaly due to the combined forcing is found over Greenland with up to $\Delta TS = +13.9^\circ\text{C}$, while the strongest cooling caused by insolation is located over central Africa, the Arabian Peninsula, and India (locally $\Delta TS = -5.3^\circ\text{C}$, Fig. 4a).

The winter (local minimum TS) of the LIG is in general cooler than the PI at northern low to middle latitudes, while at northern high latitudes and Southern Hemisphere winter is warmer (Fig. 4b). If we separate the astronomical effect from the GIS lowering and albedo changes, we can attribute to insolation a cooling of $\Delta TS = -0.52^\circ\text{C}$ in Northern Hemisphere, and a warming of $\Delta TS = +0.69^\circ\text{C}$ in Southern Hemisphere. Due to warmer high latitudes, the sea ice edge and 50 % sea ice compactness isolines are located closer to the continents in LIG relative to PI (Fig. 4b).

Summer (local maximum TS) anomalies of the LIG with respect to PI are stronger than winter anomalies in the Northern Hemisphere (Fig. 4c). Strongest continental summer TS anomalies are located in the Northern Hemisphere (up to $\Delta TS = +16.7^\circ\text{C}$). Locations where the LIG is cooler than PI are found at $\sim 10^\circ\text{N}$ over Africa and at $\sim 25^\circ\text{N}$ over India. Figure 4e also depicts the locations of the sea ice edge and the 50 % sea ice compactness isolines, which indicate that, in the Arctic Ocean, LIG summer sea ice is more strongly reduced compared to PI than winter sea ice. The summer LIG Arctic Ocean sea ice cover does not exceed 50 % compactness anywhere. In the Southern Ocean there is no such clear seasonal bias.

3.3 Surface temperature evolution during the present and Last Interglacial

In Figs. 5, S2, and S3, a comparison of transient TS derived from the five transient simulations (Table 1) is shown. The LIG transient simulations are important for determining when the maximum LIG warmth occurred in dependence of the location as well as seasons. For simplicity, we display here only the TS evolution in the northern high latitudes ($60\text{--}90^\circ\text{N}$), is displayed in Fig. 5). All LIG (130–115 kyr BP) simulations (LIG-ctl-tr, LIG- $\times 0.5$ -tr, LIG-1300m-alb-tr, and LIG-GHG-tr) indicate a similar annual mean trend, starting with a plateau until mid-LIG (around 123 kyr BP). After mid-LIG, there is followed by a pronounced cooling trend in all LIG transient simulations (Fig. 5a). The control simulation LIG-ctl-tr starts at a slightly higher TS than the LIG-GHG-tr, but although the trace gas concentrations are mostly lower throughout the latter, the LIG-GHG-tr simulates higher TS throughout the LIG. This indicates that changes in the vegetation which are simulated in the LIG-ctl-tr simulation lead to a cooling in the Northern Hemisphere, partly counteracting the warming induced by higher GHG concentrations. Even warmer TS are observed in the LIG- $\times 0.5$ -tr, due to the changes in GIS elevation. The most extreme case is represented by the simulation LIG-1300m-alb-tr, which shows

predominantly the highest TS relative to TS of other LIG transient simulations. ~~When calculating the linear TS trends over 15 kyr covering the LIG (130–115 kyr BP), simulation LIG- $\times 0.5$ -tr presents the steepest trend with a value of -3.97°C . LIG-GHG-tr represents the weakest trend, namely -2.95°C . The Holocene (8–0 kyr BP) transient simulation (HOL-tr) starts also with a warming ($+1.45^{\circ}\text{C}$) until around mid-Holocene (6 kyr BP), followed by a cooling trend. The trend over the last 8 kyr is negative, with a value of -1.76°C .~~

During winter, all LIG simulations indicate a positive trend in the early LIG, with maximum TS at around mid-LIG (Fig. 5b), followed by a strong cooling. The relative order of magnitudes of TS trends during different simulations is the same as for annual mean TS, but with a relatively larger offset in between simulations. ~~The strongest winter TS trend during the LIG is present in simulation LIG- $\times 0.5$ -tr, with a cooling of -2.47°C . The smallest trend is simulated in LIG-GHG-tr simulation, namely -1.08°C . Simulation HOL-tr shows a warming of $+0.8^{\circ}\text{C}$, followed by a cooling trend that starts at mid-Holocene (Fig. 5b). Overall, the Holocene TS trend is -1.73°C .~~ Winter TS are characterized by stronger temporal variability than summer TS (Fig. 5b, c). Summer TS in all LIG simulations indicate a slight warming trend until around 128 to 126 kyr BP, followed by a pronounced cooling. ~~The strongest trend during summer is present in simulation LIG-ctl-tr (-6.26°C), while the smallest is derived from LIG-GHG-tr simulation (-5.94°C).~~ The offset between transient TS is smaller than for annual mean and winter, but with the same order on the temperature scale. A dramatic cooling is also present in the Holocene simulation, ~~which shows a trend of -2.28°C~~ starting at mid-Holocene (Fig. 5c). Furthermore, the timing of the maximum LIG warmth does not occur simultaneously between the winter and summer seasons, the winter season indicating a later peak than summer (Figs. 5, S2, and S3).

3.4 Comparison of model results to temperature reconstructions

Due to the large amount of simulated data, we display in the model-data comparison simulated LIG TS derived from only one equilibrium simulation with changes in GIS, namely LIG-1300m-alb. For the calculation of the maximum LIG warmth, we consider the corresponding ~~LIG-1300m-alb-tr~~ transient simulation (LIG-1300m-alb-tr). However, the comparison of the proxy-based temperatures with the other GIS sensitivity simulations is considered in Table S1 in the Supplementary material, which gives the RMSD values between temperature reconstructions and simulated TS extracted at the location of each given proxy record and derived from simulations with different GIS boundary conditions. Furthermore, we display also results from ~~LIG-ctl equilibriumcontrol~~ simulation for 130 kyr BP (LIG-ctl) and ~~LIG-ctl-tr the corresponding~~ transient simulation (LIG-ctl-tr) for maximum LIG warmth, in

1 order to determine if and where GIS changes lead to an increase in model-data agreement.

2 **3.4.1 Proxy-based summer temperature reconstructions**

3 Figures 6, 8a, and S4a present a model-data comparison that consider LIG terrestrial and marine proxy-
4 based summer temperature anomalies relative to PI derived by CAPE Last Interglacial Project
5 Members (2006). Simulated and reconstructed temperature anomalies agree reasonably well with
6 respect to the sign of the change, in the simulation with a reduction in GIS ([LIG-1300m-alb](#), Fig. 6a)
7 and with preindustrial GIS configuration ([LIG-ctl](#), Fig. 6c). The best agreement between model and
8 proxy reconstructions occurs over northern Asia and Europe. In the North Atlantic Ocean and the Arctic
9 Ocean, the model underestimates marine-based temperature reconstructions (Fig. 6a, c). ~~There is~~
10 ~~nearly no TS change present in the model, while the marine records indicate anomalies of +1 to +4°C.~~
11 However, a reduction in GIS and albedo leads to slightly higher summer temperature anomalies at the
12 location of some marine proxies in the North Atlantic Ocean, partly reducing the model-data mismatch
13 (Fig. 6a).

14 Over Greenland, the elevation changes lead to an overestimation of the reconstructed temperature
15 anomalies – proxy records show anomalies of +4 to +5°C, while the simulated TS anomalies are above
16 +7°C (Fig. 6a). ~~However, in the control simulation, LIG-ctl, there is an underestimation of the~~
17 ~~reconstructed temperatures (Fig. 6c). An overestimation of the proxy reconstruction by the model is~~
18 ~~present over Alaska, where the simulated TS changes in the LIG-1300m-alb simulation are within +3 to~~
19 ~~+4°C, while the terrestrial proxy-based temperature anomalies are between +0 and +2°C. However, in~~
20 ~~the LIG-ctl simulation, the differences between model and data are smaller.~~

21 ~~LIG-1300m-alb-tr (Fig. 8a). transient simulation~~In addition to the 130 kyr BP LIG simulation ([LIG-](#)
22 ~~1300m-alb~~), for each given core location we also consider TS anomalies relative to PI calculated at the
23 ~~minimum and maximum LIG summer warmth as derived from the~~In the case of the terrestrial proxies,
24 the temperature span covers +2 to +6°C, but 0 to +10°C (Fig. 8a) if we consider the uncertainty
25 ~~temperature intervals from which we chose the values closest to corresponding model results. while~~
26 ~~t~~The corresponding ~~respective~~ simulated anomalies cover +1 to +11°C, the largest anomalies being
27 ~~located over Greenland (Fig. 6a). In addition to the 130 kyr BP simulation (LIG-1300m-alb), for each~~
28 given core location we also consider TS anomalies relative to PI calculated at the minimum and
29 maximum LIG summer warmth as derived from the LIG-1300m-alb-tr (Fig. 8a). ~~When we consider also~~
30 ~~the simulated TS anomalies at the summer minimum and summer maximum LIG warmth for each~~
31 ~~record, i~~In about half the cases (14 records out of 27), the error bars touch the 1 : 1 line, possibly

indicating better agreement than when compared to LIG-summer TS anomalies at 130 kyr BP (Fig. 8a). ~~However, the number of 13 unresolved records can be reduced to 11, when the terrestrial proxy-based temperature anomalies are compared to the simulated TS anomalies that are derived from the simulation with PI-GIS elevation (LIG-ctl-tr; (Fig. S4a). Marine-based temperature anomalies and the corresponding simulated anomalies (from LIG-1300m-alb) are of lower magnitude than their terrestrial counterparts, with a marine-based temperature anomaly cover temperature spans of 0 to +3°C (and 0 to +4°C temperature uncertainty) and simulated TS anomaly span of ~0 to +4°C, respectively (Fig. 8a). Only one marine record, located on the eastern coast of Greenland, shows an underestimation of at least 6°C (Fig. 6). Seven out of thirteen marine records cannot be reconciled with the simulations when considering maximum and minimum summer TS anomalies during the LIG (Figs. 8a and S4a). The LIG-ctl-tr simulation as well can resolve only 6 records (Fig. 6d and S4a). When the reconstructed data is compared to simulated annual mean TS anomalies at 130 kyr BP (Figs. S5a, c and S6) and at annual mean minimum or maximum LIG warmth (Figs. S5b, d and S6), we find an even higher discrepancy than when compared to the summer average, implying that the reconstructed records are indeed biased towards summer. Furthermore, there are 20 terrestrial and 8 marine records that cannot be resolved by using annual mean minimum or maximum LIG warmth in the LIG-1300m-alb-tr (Figs. S5b and S6a); and 21 terrestrial and 8 marine records in the LIG-ctl-tr (Figs. S5d and S6b).~~

The proxy dataset by CAPE Last Interglacial Project Members (2006) is considered to represent summer temperatures at the maximum LIG warmth. Thus, we additionally include in the model-data comparison the simulated maximum LIG warmth calculated from our transient LIG simulations (Fig. 6b, d). We find that the agreement between model and data increases in some cases. ~~Over northern Asia, for example, highest simulated summer TS anomalies occur between 126.5 and 129.5 kyr BP (Fig. 9a), and are in better agreement with the proxy records than when simulated anomalies at 130 kyr BP are considered.~~ For the northern North Atlantic Ocean, for example, marine records agree best with simulated TS anomalies at the maximum LIG warmth (between 121.5 and 124.5 kyr BP, Fig. 9a) in the LIG-1300m-alb simulation (Fig. 6b). However, the RMSD between the simulated TS and reconstructed temperature anomalies reveals that the best agreement occurs with TS anomalies at maximum LIG warmth in the LIG-ctl-tr simulation (Table S1 in Supplementary material). A reduction in GIS, thus, does not improve in general the model-data agreement when the dataset by CAPE Last Interglacial Project Members (2006) is considered. However, changes in GIS lead to high temperature anomalies during local winter (Fig. 3a), while summer season is not strongly influenced (Fig. 3b). Therefore, in a

comparison with proxy reconstructions that represent summer temperature anomalies, changes in GIS do not have a significant impact on model-data agreement.

3.4.2 Proxy-based annual mean temperature reconstructions

Both reconstructed (Turney and Jones, 2010) and simulated global annual mean temperature anomalies (Fig. 7) indicate that the high latitudes experienced warmer temperatures during the LIG than in the PI, with strongest anomalies being present in the northern high latitudes (Fig. 7). However, the model underestimates the strong positive anomalies derived from proxy records, and in low and middle latitudes the model cannot capture the magnitude of the cooling that the proxy records show (Figs. 7a, c, 8b, and S4b).

Changes in GIS have no significant influence in low to middle latitudes but cause strong positive anomalies in the northern high latitudes thus improving the model-data comparison (Fig. 7a, Table S2), although the model still underestimates the proxy reconstructions. Terrestrial proxy records indicate stronger anomalies with $\Delta TS = +2.21^\circ\text{C}$ (globally), $\Delta TS = +2.21^\circ\text{C}$ (Northern Hemisphere), and $\Delta TS = +2.11^\circ\text{C}$ (Southern Hemisphere). The corresponding simulated anomalies at locations of terrestrial records indicates a global average of $\Delta TS = +1.44^\circ\text{C}$, underestimating the records by $\sim 1^\circ\text{C}$. The Northern Hemisphere and Southern Hemisphere average TS anomalies are $\Delta TS = +1.48^\circ\text{C}$ and $\Delta TS = +0.92^\circ\text{C}$, respectively. Marine records capture lower anomalies than their terrestrial counterparts but still larger anomalies than the corresponding simulated anomalies.

The majority of the terrestrial records shows a stronger signal than the simulated anomalies (Fig. 8b). The temperature anomaly range in the terrestrial reconstructed data covers -5 to $+15^\circ\text{C}$, while the model covers 0 to $+12^\circ\text{C}$. The proxy records that indicate the most extreme negative temperature anomalies (31 records out of 100) are not fully reconciled with simulations by considering the minimum LIG values derived from the model. For positive temperature anomalies, there are 36 records that agree better with the model simulation when the maximum LIG warmth is considered, but the error bars do not touch the $1:1$ line indicating as well a persistent deviation (Fig. 4b). The remaining Out of 100 terrestrial records, 33 terrestrial records agree with the model data simulated TS anomalies somewhere between the annual mean minimum and maximum LIG warmth derived from LIG-1300m-alb-tr (Fig. 8b). This is a slightly better result than for simulation LIG-ctl-tr, in which case only 19 terrestrial records can be resolved by considering minimum and maximum TS intervals (with simulated TS anomalies derived from LIG-ctl-tr, (Fig S4b). When we consider marine proxy-based temperature anomalies, the model-data agreement is lower than in the case of their terrestrial counterparts.

1 | The reconstructed marine temperature anomalies cover a range of -6 to $+11^{\circ}\text{C}$ compared to 0 to
2 | $+3^{\circ}\text{C}$ in the model, indicating pronounced underestimation of the marine proxy-based anomalies by the
3 | model. ~~Low temperature anomalies are mostly located at low latitudes, where the magnitude of~~
4 | ~~temperature change is higher in the reconstruction than in the model~~ (Figs. 7a and 8b). When we
5 | consider both annual mean minimum and maximum LIG warmth, the simulated TS span increases by
6 | $\sim 1^{\circ}\text{C}$ (-0.5 to $+3.5^{\circ}\text{C}$). ~~Considering the annual mean maximum LIG warmth, 71 (out of 162) marine~~
7 | ~~records that show positive anomalies cannot be reconciled with the simulation. From the records that~~
8 | ~~show negative anomalies, 71 cannot be resolved by TS anomalies at minimum LIG. The remaining~~
9 | ~~20~~ Twenty records (out of 162) agree with the model data somewhere between the minimum and
10 | maximum LIG warmth with respect to annual mean derived from LIG-1300m-alb-tr, and. ~~The marine~~
11 | ~~records are slightly better reconciled when LIG-ctl-tr is considered, with 25 records being reconciled~~
12 | ~~with the simulation by the minimum and maximum LIG warmth (when LIG-ctl-tr is considered;~~ (Fig.
13 | S4b).

14 | The proxy records derived by Turney and Jones (2010) are considered to record an annual mean
15 | temperature signal. Nevertheless, some records may be biased towards a specific season. Therefore, we
16 | also consider the minimum winter and maximum summer TS during the LIG (Fig. 4c). Seasonality
17 | increases the span of the vertical bars, providing the possibility of a better agreement with the
18 | reconstructed temperature anomalies. The agreement between proxy records and model simulations
19 | increases, with 51 (69) terrestrial and 53 (51) marine records being reconciled by considering
20 | seasonality derived from LIG-1300m-alb-tr (LIG-ctl-tr) (Figs. 4c and S4c). ~~An even better agreement is~~
21 | ~~found when the terrestrial proxy-based temperature anomalies are compared to the simulated~~
22 | ~~seasonality range derived from simulation LIG-ctl-tr. In this case, for 69 terrestrial records the vertical~~
23 | ~~bars touch the 1 : 1 line (Fig. 4c). For the marine proxies a number of 51 records can be reconciled~~
24 | ~~with the simulation by considering seasonality as derived from simulation LIG-ctl-tr.~~

25 | As already mentioned, the terrestrial proxy records by Turney and Jones (2010) are considered to
26 | record annual mean temperature anomalies at the maximum LIG warmth. Therefore, we additionally
27 | compare the terrestrial records with the simulated annual mean at the LIG thermal maximum (Fig. 7b,
28 | d). Over Europe, the agreement between model and data is increased for those records that indicate a
29 | warming, sinceas the simulatedmodelled anomalies derived from LIG-1300m-alb-trsimulation indicate
30 | a warming at the maximum LIG warmth, while presenting nearly no change at 130 kyr BP (Fig. 7a).
31 | ~~Over northern Europe, maximum LIG warmth occurs at mid-LIG between 122.5 and 123.5 kyr BP.~~

(Fig. 9b). There is a slightly better agreement for the records located in northern Asia. At these locations, the highest TS anomalies are found towards the first part of the LIG (between 126.5 and 129.5 kyr BP). A better agreement is found also over northern Asia. According to Table S2 in the Supplementary material, the terrestrial proxy-based temperature anomalies indicate the best agreement with the simulated annual mean TS at the maximum LIG warmth derived from the LIG-1300m-alb simulation. The annual mean anomalies are influenced by winter temperatures, the season during which GIS leads to strong positive anomalies. Therefore, a model-data comparison with proxy reconstructions that represent an annual mean signal shows a better agreement than when summer proxies are considered.

3.4.32 Time resolved proxy-based summer temperature reconstructions

For a more robust model-data comparison, we additionally compare our simulated TS to a compilation of high-latitude LIG temperature anomalies derived from synchronized records representing 130 kyr BP (Figs. 10 and S12, Capron et al., 2014). The synchronization is performed by aligning marine sediment records onto the recent AICC2012 ice chronology (Capron et al., 2014 and references therein). This method reduces the uncertainty in relative dating of the proxy reconstructions. ~~The temperature reconstructions are mostly located in the North Atlantic Ocean and Southern Ocean.~~ The marine records from the North Atlantic Ocean indicate mostly negative anomalies, while the model simulates nearly no changes. As shown above, GIS reduction leads to a small increase in summer TS anomalies, thus increasing the model-data disagreement (Figs. 10a and S12a). A warming in the Southern Ocean is captured by both the model and proxies, though the model underestimates the reconstructions. Reducing the GIS and albedo leads to an increase in local summer TS anomalies in the Southern Ocean bringing the model and data in slightly closer agreement (Figs. 10b and S12b).

Considering Table S3 ~~in Supplementary material~~, the reconstructed temperatures agree best with the simulated summer TS at 125 kyr BP in ~~simulation~~ LIG-125k (Fig. S15), which considers a reduced GIS configuration (as in the LIG-1300m-alb ~~simulation~~), both indicating a warming. However, this result is not conclusive with respect to the GIS elevation, as a simulation with preindustrial GIS elevation has not been yet performed for this particular time slice. For 130 kyr BP, the best agreement occurs for the LIG-ctl ~~simulation~~ but for annual mean rather than summer, since the model simulates an annual mean cooling in the North Atlantic Ocean (Fig. S5c).

~~The proxy record compilation is used in the model-data comparison by Capron et al. (2014), using two different climate models, namely CCSM3 and HadCM3. For 130 kyr BP, a model-data mismatch is~~

found in both cases, as most of the records indicate strong negative anomalies at 130 kyr BP, while the models simulate strong positive anomalies, especially CCSM3 which simulates higher GHG concentrations than HadCM3 and COSMOS. With respect to difference between model and data, COSMOS simulates TS closer to the temperatures derived from marine-based records, since it simulates nearly no change rather than a strong opposite signal. One cause for this modest change in the North Atlantic Ocean may be related to vegetation changes, which may lead to a cooling as suggested above. For 125 kyr BP, COSMOS simulates higher anomalies in the North Atlantic Ocean than at 130 kyr BP, but lower than CCSM3 and HadCM3 which simulate SSTs closer to the reconstructed temperatures. Note that the definition of summer is different in our study than in the study by Capron et al. (2014), as they calculate it as the average of July-August-September, while we consider the warmest month.

A model-data comparison of LIG temperature trends is also considered in our study (Figs. S13 and S14). The proxy-based temperature trends by Capron et al. (2014) is compared to the temperature evolution derived from our transient simulations (LIG-ctl-tr and LIG-1300m-alb-tr), between 125 and 115 kyr BP. An underestimation of the proxies by the model is again found, as well as an overestimation depending on the locations (Figs. S13 and S14). Changes in GIS do not strongly influence the results, with the exception of a few locations where such changes lead to a less pronounced warming simulated in LIG-ctl-tr, thus reducing the mismatch.

4. Discussion

4.1 Effects of insolation and Greenland Ice Sheet elevation on surface temperature

The main focus of our study is to quantify the possible contribution of reduced GIS elevation in comparison with the contribution of insolation forcing to the climate of the LIG.

We can confirm the importance of insolation for the Northern Hemisphere, especially for the northern middle to high latitudes (Figs. 4, 6, 7, 10). The belt of decreased TS, observed around 10°N over Africa and 25°N over Arabian Peninsula and India (Figs. 4a, b and 7a), is related to increased cloud cover (Fig. S9) and increased summer precipitation of up to +6 mm d⁻¹ (not shown). This effect has been described by Herold and Lohmann (2009), who propose a mechanism for the temperature anomalies that relies on changes in insolation in conjunction with increased cloud cover and increased evaporative cooling.

1 In general, and independent of GIS elevation we observe an annual mean global warming of $\Delta TS =$
2 $+0.44^{\circ}\text{C}$ in our LIG simulations relative to PI, hinting to positive feedbacks (such as sea ice-albedo)
3 that amplify the high latitude insolation signal (Fig. 4).

4 In Section 3.1.2, we have shown that the most pronounced impact of reduced GIS elevation (in
5 LIG-1300m-alb-simulation) occurs during local winter in both hemispheres (Fig. 3a). The winter
6 warming of up to $+3^{\circ}\text{C}$ over the Arctic Ocean may be linked to a decrease in sea ice and a delayed
7 response to a warming occurring in October (not shown), which is caused by positive sea-ice-albedo
8 feedbacks. A decrease in albedo over Greenland has the strongest influence during summer especially
9 over the southernmost region (Figs. 2d and 3b), caused by insolation absorption by the ice-free land
10 surface. Furthermore, we note cold annual mean anomalies in the Barents Sea (Fig. 2a, b) and Sea of
11 Okhotsk (Fig. 2c) caused by an increase in sea ice cover.

12 The change in the GIS elevation leads also to a relatively strong warming in the southern high
13 latitudes, mainly off the coast of Antarctica, with the strongest positive anomaly occurring during local
14 winter (Fig. 3a) that coincides with a heat flux transfer anomaly from the ocean to the atmosphere (not
15 shown). Increased ocean heat flux during winter leads to a warming of the atmosphere. The Antarctic
16 warming is most likely related to warmer deep water as well as subsurface warming poleward of 50°N
17 in the North and South Atlantic Ocean. The warming may be attributed to enhanced AMOC (Table 2),
18 which plays an important role in the exchange of heat between the hemispheres and between
19 atmosphere and ocean. Our results indicate a weaker AMOC during the LIG as compared to the PI of
20 up to 3.5 Sv, but changes in GIS lead to an increase of up to 2.2 Sv (Table 2). The simulated increase in
21 AMOC in the sensitivity simulations may be triggered by increased salinity of up to + 1 psu in the
22 northern North Atlantic Ocean. Increased salinity cannot be explained by changes in precipitation
23 minus evaporation, which show positive anomalies in this area (not shown). Another contributing
24 factor to the enhanced AMOC may be an increase in the atmospheric flow due to a reduction in GIS
25 elevation. The low pressure system over Greenland and the high pressure system above Europe become
26 more extreme, enhancing the north-eastward air circulation (Fig. 11). We find that the higher the sea
27 level pressure (SLP) anomaly (Fig. 11), the stronger the AMOC (Table 2, Fig. 11). This change could
28 also explain the positive TS anomalies of up to $+1^{\circ}\text{C}$ in the northern North Atlantic Ocean, with more
29 heat being transported poleward from the low latitudes (Fig. 2a–c). However, convection cannot be the
30 only explanation for the southern high latitudes warmth, since the heat would be dispersed towards the
31 Southern Hemisphere. We however note a large scale warming in the subsurface of the Southern Ocean

1 which is probably caused by positive feedbacks. This warming may be related to changes in the water
2 stratification. We observe an invigorated vertical mixing in the northern North Atlantic Ocean and a
3 suppressed vertical mixing in the Southern Ocean (not shown), the latter causing the heat at subsurface
4 to be preserved. The Southern Ocean has a large heat capacity leading to a long memory of the system.
5 Lags of up to three months occur in the surface layer including sea ice (amplifying factor via positive
6 ice-albedo and ice-insulation feedbacks), while long-term lags occur in deeper levels below the summer
7 mixed layer that store seasonal thermal anomalies (Renssen et al., 2005).

8 In contrast to our results that show an increase in the AMOC relative to GIS elevation changes,
9 Otto-Bliesner et al. (2006) and Bakker et al. (2012) find a weakening of the AMOC. Bakker et al.
10 (2012) infer that the AMOC is weaker by up to 14 % in a regional study of LIG climate of the North
11 Atlantic Ocean, prescribing a reduction of GIS elevation (by 700 m) and extent (reducing the ice
12 volume by 30%). The weakening of the AMOC is caused by additional freshwater runoff resulting
13 from a melting GIS, a factor that is not considered in our study and that would probably cancel out or
14 reduce the effect of changes in the atmospheric transport on the AMOC. In the study by Bakker et al.
15 (2012), reducing GIS elevation and extent leads to changes in the atmospheric flow pattern and creates
16 a special pattern of surface pressure anomalies. In particular in the Norwegian Sea, Barents Sea, and
17 south-east of Greenland, the low pressure system is weaker inhibiting the overturning circulation.

18 The reduction of the GIS elevation and albedo alone leads in the study by Bakker et al. (2012) to a
19 local warming of up to +4°C in July, a substantially lower anomaly (factor of ~3) than simulated in our
20 model for local summer when reducing both GIS and albedo. However, when comparing their
21 simulated data to proxy-based temperature anomalies relative to PI (CAPE Last Interglacial Project
22 Members, 2006), Bakker et al. (2012) find an overestimation of the temperature reconstruction over
23 Greenland, and an underestimation at eastern Europe and Baffin Island – locations where we find a
24 similar temperature tendency (Fig. 6a).

25 Another climate model study that considers a reduction in GIS topography by various methods has
26 been performed by Merz et al. (2014). In their GIS sensitivity simulations, performed with the
27 Community Climate System Model (version 4; (CCSM4), they find a rather mixed signal in
28 temperature anomalies over Greenland relative to the predominant warming found in our simulations
29 with changes in GIS. During local winter, their model simulates a warming of up to +5°C in central
30 Greenland and a cooling of up to -12°C in areas that become flat and ice-free. However, changes in
31 topography of GIS do not have a significant influence on climate in the surrounding areas in the study

1 by Merz et al. (2014). This may be caused by the fact that in their simulations SSTs are prescribed,
2 while in our study the atmosphere model is interactively coupled to an ocean general circulation model.
3 However, in their study the GIS is reconstructed by means of high resolution ice sheet models, while
4 we consider a relatively simplistic representation of the GIS. Differences are found also with respect to
5 changes in low-level winds. They find a rather local influence of the GIS changes and no major effect
6 on the large-scale atmospheric circulation. Our model simulates an enhancement of low-level winds
7 around GIS and on SLP (Fig. 11). As such, the methods of reducing GIS and the model used have a
8 strong influence on the local and large-scale climate. Note, however, that the aims of our study and the
9 study by Merz et al. (2014) are different, since the latter focuses on local effects above Greenland,
10 while our main focus is on the GIS effects on large-scale climate.

11 **4.2 Surface temperature evolution during the Last Interglacial and the** 12 **Holocene**

13 Although our results are not directly comparable to those derived by Bakker et al. (2013), who analyze
14 transient LIG January and July temperature anomalies (simulated by seven different models) with
15 respect to PI while we use transient absolute TS for coldest and warmest month, the pattern of the
16 temperature evolution remains the same. We observe similarities in middle latitudes and in winter
17 temperatures at high latitudes characterized by a large variability, and also note a clear cooling trend for
18 summer caused by a decrease in summer insolation. At northern high latitudes, Bakker et al. (2013)
19 find July maximum LIG warmth at 128.4–125.1 kyr BP, while in middle latitudes the maximum occurs
20 at 129.4–126.3 kyr BP. We also observe a warmest month maximum at around 128 kyr BP for high and
21 middle latitudes. A July maximum LIG warmth is found in the study by Loutre et al. (2014) at 128 kyr
22 BP. They find that the summer SST during the LIG is smaller in the model than in the reconstructed
23 temperatures, especially in the North Atlantic Ocean, but taking into account the evolution of the
24 Northern Hemisphere ice sheets reduces the disagreement between model and data.

25 During winter, our simulations produce a clear high latitude TS maximum around mid-LIG, while
26 the middle latitudes experience peak warmth around 121–117 kyr BP. Bakker et al. (2014) compare
27 transient LIG and Holocene (8–0 kyr BP) temperature trends simulated by different models (including
28 our COSMOS LIG-GHG-tr and HOL-tr simulations). They find negative warmest month temperature
29 trends for both LIG and Holocene in the Northern Hemisphere, ~~and they propose that the climate reacts~~
30 ~~linearly to changes in insolation.~~ Bakker et al. (2013) find a linear relation between changes in
31 insolation and temperatures for both summer and winter and for all latitudes. There are however some

exceptions. In northern high-latitudes, the winter temperature changes result mainly from sea-ice related feedbacks and are described as highly model-dependent. In southern middle to high latitudes, winter temperatures are strongly affected by changes in GHG concentrations. Comparing all LIG transient simulations with the Holocene in the three considered latitudinal bands, we observe that the Holocene experiences mostly lower TS than during the LIG, and is characterized by smaller trends.

In our LIG transient simulations, we find that the differences in TS between the different model simulations at the beginning of the LIG (130 kyr BP) are higher than during the late LIG (115 kyr BP), indicating that the impact of a reduced GIS is stronger at the beginning of the LIG as compared to glacial inception (GI, 115 kyr BP). By using different approaches to simulate the LIG evolution, we offer a bandwidth of possible temperatures at each given time.

4.3 Model-data comparison

In combination with changes in the GIS elevation and lower albedo, the insolation effect ~~causes~~ leads to ~~high~~ strong positive ~~summer~~ TS anomalies in the Northern Hemisphere, ~~especially during summer~~ (Figs. 4c and 6a). The pattern of these changes is observed also in a ~~another~~ model study of the LIG that includes ~~changes~~ a reduction in GIS elevation of 500 m (Otto-Bliesner et al., 2006). The study shows that the June-July-August (JJA) temperature anomaly with respect to PI is positive in the Northern Hemisphere, especially over the continents – yet, the magnitude of these changes is smaller than in our study. ~~The Barents Sea experiences no temperature change in Otto-Bliesner et al. (2006), compared to a warming of +2 to +4°C simulated by our model. The only location in simulations by Otto-Bliesner et al. (2006) that is notably warmer than in our simulations is at the western side of Greenland – the high decrease in GIS elevation prescribed in our simulation is accompanied by modest TS anomalies at the western side of Greenland, which may be related to an increase in the sea ice.~~ In order to validate their results, Otto-Bliesner et al. (2006) compare the simulated temperature anomalies to proxy-based temperature anomalies by CAPE Last Interglacial Project Members (2006), ~~the same temperature reconstruction data that we use in our model-data comparison (Figs. 6, 8a, S4a, S5, S6, and S10).~~ Comparing our model results ~~with the marine and terrestrial reconstruction temperatures by CAPE Last Interglacial Project Members (2006) to the same proxy compilation,~~ we see most similarities ~~with respect to temperature~~ in the ~~local~~ summer anomalies of LIG relative to PI, although at some locations the magnitude differs. ~~At the western side of Greenland, our model underestimates the terrestrial proxy-based temperature anomalies by at least 2°C, while in Alaska there is an overestimation, making the model-data agreement of Otto-Bliesner et al. (2006) better.~~ Over Greenland, the warming reaches +5°C

1 according to the proxy reconstructions, while our results show a higher warming caused by the
2 reduction of the GIS. However,
3 ~~Over Greenland, the model overestimates the proxy-based temperature anomalies, while~~ the results
4 from Otto-Bliesner et al. (2006) indicate an underestimation. This suggests that the GIS elevation
5 during the LIG may have not been so drastically reduced as prescribed in our model setup, but was still
6 reduced by at least 500 m. This conclusion is supported ~~also~~ by another model-data comparison study
7 (Stone et al., 2013) that ~~compares simulated LIG TS anomalies relative to PI to anomalies derived from~~
8 ~~the reconstruction by~~ uses the same data compilation (CAPE Last Interglacial Project Members,
9 ~~(2006). In their simulation, which was produced using the coupled atmosphere-ocean general~~
10 ~~circulation model HadCM3 (Hadley Centre Coupled Model, version 3) with an AOGCM,~~ Stone et al.
11 (2013) find a good agreement between model and reconstruction as well, but cannot capture the
12 reconstructed strong warming over Greenland, their simulation indicating a warming of up to +3.5°C.
13 They imply that the GIS was reduced in the LIG as compared to PI, but not completely deglaciated – in
14 the simulation with a completely removed GIS, they find much stronger temperature anomalies over
15 Greenland of up to +16°C, higher than in our findings when GIS is reduced to half its present elevation
16 (Fig. 2). A high overestimation of reconstructed temperatures by the model is found also by Otto-
17 Bliesner et al. (2006) for a deglaciated Greenland, with summer temperature anomalies being higher
18 than +10°C. Although in our simulations we do not completely remove the ice sheet, we find strong TS
19 anomalies of up to +11°C.

20 ~~Proxy records based on ice cores indicate over Greenland positive summer anomalies of up to +5°C~~
21 ~~at the maximum LIG warmth (Johnsen et al., 2001; NGRIP members, 2004). The corresponding~~
22 ~~simulated temperature anomalies at Renland ice core site (Johnsen et al., 2001) are +4.93°C in the LIG-~~
23 ~~etl simulation and +8.71°C in the LIG-1300m-alb simulation, indicating that in eastern Greenland, the~~
24 ~~height of the ice sheet was probably similar to preindustrial elevation. An overestimation by the model~~
25 ~~occurs at NGRIP ice core location (NGRIP members, 2004), whether changes in GIS are taken into~~
26 ~~account or not, the LIG-etl and LIG-1300m-alb simulations indicating a warming of +7.46°C and of~~
27 ~~+11.13°C, respectively. A warming as high as $+8 \pm 4^\circ\text{C}$ is proposed by Dahl-Jensen et al.~~ NEEM
28 Community Members (2013) for the peak LIG warmth at 126 kyr BP, based on North Greenland
29 Eemian Ice Drilling (NEEM) ice core. They propose that the northwest GIS is characterized only by a
30 modest reduction of 400 ± 250 m between 128 and 122 kyr BP. In our study, we find at the location of
31 the NEEM ice core an annual mean warming of +9.6°C at 125 kyr BP at a GIS height of 553 m, a

warming that is within the temperature range proposed by NEEM Community Members (2013). Antarctic ice cores indicate positive temperature anomalies of up to +3.5°C (Capron et al., 2014), overestimating suggesting stronger warming than the simulated TS. However, a reduction in GIS reduces the model-data disagreement. only modest changes in temperature, mostly underestimating the marine data. The discrepancy is partly removed by considering simulated TS anomalies for maximum summer warmth during the LIG (Fig. 6d), in both Otto-Bliesner et al. (2006) and this publication, The Arctic Ocean and the North Atlantic Ocean show A high overestimation of reconstructed temperatures by the model is found also by Otto-Bliesner et al. (2006) for a deglaciated Greenland, with summer temperature anomalies being higher than +10°C. Although in our simulations we do not completely remove the ice sheet, we find strong TS anomalies of up to +11°C. The Siberia region experienced similar anomalies in the reconstruction, with records showing +4 to +8°C warming, slightly overestimating our model results. LIG-ctl is of a lower magnitude. simulation LIG-ctl (Figs. 6c and S4a). We find a better agreement for some records, especially over Greenland where the warming in the simulation

In order to determine whether a lowered GIS creates a better agreement with the data, we compare the proxy records derived by CAPE Last Interglacial Project Members (2006) to

We go one step further and perform an additional model-data comparison with global coverage (Turney and Jones, 2010). This proxy compilation is included in another model-data comparison study for the LIG (Lunt et al., (2013) performed a model-data comparison for the LIG, using a multi-model approach including the our LIG-GHG simulation. None of the model simulations, used in their study, consider a reduction of the GIS elevation or albedo. As in our simulations, Lunt et al. (2013) find as well that the models fail to capture the magnitude of the temperature anomaly change suggested by the proxy data. In their study, the model-data difference is slightly higher than in our study when comparing simulations to terrestrial data, as none of the simulations manage to capture a strong high latitude annual mean warming indicated by the terrestrial proxy data in the high latitudes. In fact, most of the models suggest a slight cooling over Europe and northern Asia at the beginning of the LIG (130 kyr BP) and only a slight warming over Greenland, at 130 kyr BP. Over Alaska, the proxy records show a strong warming, which is not captured by any simulation analyzed by Lunt et al. (2013). The Our reduced GIS simulation (LIG-1300m-alb) also presents indicates a relatively higher warming, but of a slightly higher magnitude, reducing the disagreement between model and data. Most of the temperature records in Europe indicate a positive LIG temperature anomaly, whereas the multi-model

analysis by Lunt et al. (2013) captures a slight cooling. Another region where reconstructions agree better with our simulated TS is situated over Antarctica, where the simulated and reconstructed temperature anomalies indicate a warming of similar magnitude, in contrast to the simulations performed by Lunt et al. (2013), where most of the models indicate a slight cooling. These results imply that a reduced GIS during the LIG ~~may have contributed to an increase in temperature~~ improves the model-data comparison. — in our study, the difference between the terrestrial proxy-based temperature anomalies and the anomalies of LIG simulation that implies a PI-GIS configuration is higher than when reduced GIS is considered (Fig. 7). The RMSD values support this assumption (Table S2), although differences between the considered cases (i.e. with or without a reduction in GIS) are relatively small. ~~The differences are small because —~~ in the calculation of the RMSD, all the proxy records by Turney and Jones (2010) are considered, including a large number of records in the low latitudes where a change in GIS has no influence. Yet, i

In all considered simulations, the models does not capture the magnitude of the SST anomalies derived from marine records. Such underestimation of proxy data by the models is also found in model-data comparison studies for the Holocene (Masson-Delmotte et al., 2006; Brewer et al., 2007; Sundqvist et al., 2010; Zhang et al., 2010; O'ishi and Abe-Ouchi, 2011; Braconnot et al., 2012; Lohmann et al., 2013; Bakker et al., 2014). Lohmann et al. (2013) show that the simulated SST trends systematically underestimate the marine proxy-based temperature trends, and suggest that such discrepancies can be caused either by too simplistic interpretations of the proxy data (including dating uncertainties and seasonal biases) or by underestimated long-term feedbacks in climate models, a feature which is probably also valid for the LIG. Such long-term feedbacks missing in our model is for example the lithosphere-soil which has ~~not~~ been recently yet implemented in COSMOS (Stärz et al., 2016). A coupled ice sheet model ~~and biogeochemistry are~~ already implemented in the COSMOS (Barbi et al., 2014; Gierz et al., 2015), but ~~are~~ is a relatively new tools. We did not consider ~~them~~ is in our simulations, although potential effects of the ice sheets during the LIG exist (e.g. Sutter et al., 2015) ~~because running the carbon cycle and the ice sheet into equilibrium would take a very long computational time. Additionally, other factors like glacial memory effect is not well represented and cannot be fully reproduced by the models.~~

~~Our reduced GIS simulation (LIG-1300m-alb) indicates a strong annual mean warming in the high latitudes with respect to PI (Fig. 7a). These changes are in accordance with the terrestrial proxy-based temperature anomalies by Turney and Jones (2010), although at northern high latitudes the order of~~

magnitude differs between model and reconstruction, with the model underestimating the
 reconstructions. As shown above, the ocean surface TS in and middle the low to middle latitudes
 experiences mostly no TS change in our simulation, in contrast to the proxy-based SST anomalies that
 indicate strong positive or negative temperature changes. Our results partly contradict results from
 another early LIG (130 kyr BP) model simulation study performed by (Otto-Bliesner et al., (2013).
 Their Community Climate System Model 3 (CCSM3) used in their analysis simulates mostly a cooling
 in the ocean, with the exception of the North Atlantic Ocean south of Greenland, where the anomalies
 have the same sign as proxy-based SSTs by Turney and Jones (2010). The terrestrial proxy-based
 temperatures records located in the high latitudes indicate however a better agreement with our
 simulation, especially over northern Asia, Alaska, and Antarctica at the LIG-1300m-alb. Even when
 considering mid-LIG (125 kyr BP), in both studies (see Figs. S11 for our study), the terrestrial data can
 be better reconciled with the simulation in which GIS elevation and albedo are reduced, especially over
 Antarctica where Otto-Bliesner et al. (2013) find a cooling. Nevertheless, the difference between the
 magnitude of change in model and reconstruction is still large. One contributing factor to warmer
 temperatures in the high latitudes in our study may be (as also proposed by Otto-Bliesner et al., 2013)
 the vegetation feedback, which is considered included in our simulations. Over Greenland, the CCSM3
 model underestimates the ice record data, while our model simulations LIG- $\times 0.5$, LIG-1300m, and
 LIG-1300m-alb with reduced GIS capture an overestimation. Otto-Bliesner et al. (2013) propose that
 the Greenland ice records may capture temperatures associated with a reduction in GIS elevation. This
 suggests again that the LIG GIS was lower, but possibly not as low as prescribed in our study. Otto-
 Bliesner et al. (2013) take into account also possible seasonal biases considered by Lohmann et al.
 (2013). To this end, they compare the proxy data to simulated JJA temperature anomalies for which
 they find the best fit, suggesting that the proxies record boreal summer temperatures. In our study,
 however, we find the best overall fit for simulated annual mean rather than summer TS (Figs. S11a and
 S12a) in all three cases: reduced GIS and albedo for beginning of the LIG at 130 kyr BP (LIG-1300m-
 alb, 130 kyr BP, Figs. 7a and 8b), for and at 125 kyr BP mid-LIG (LIG-125k, 125 kyr BP, Figs. S11a,
 c), and for the control run with prescribed preindustrial PI GIS at 130 kyr BP (LIG-ctl, 130 kyr BP, Figs.
 6c and S4b), with the best agreement between model and data in the first case (Table S2). This could
 indicate that the proxies may indeed record annual mean temperatures, but in a warmer climate caused
 by a reduced GIS (Fig. 7a). While the simulated summer TS are closer to the proxies at some locations
 (e.g. Northern Asia and Europe, Figs. S7a, S8), there are still more records that agree best with the

1 simulated annual mean TS (Fig. 7a). ~~Otto-Bliesner et al. (2013) include in their study also a mid-LIG~~
2 ~~simulation performed by Gordon et al. (2000) with the HadCM3 model. Their simulation indicates an~~
3 ~~even lower agreement between model and data.~~

4 The proxy data compilation by Capron et al. (2014) used in our study is also compared to two
5 different climate models, namely CCSM3 and HadCM3. For 130 kyr BP, a model-data mismatch is
6 found in both cases, as most of the records indicate strong negative anomalies, while the models
7 simulate strong positive anomalies (Capron et al., 2014), especially CCSM3 which was run with higher
8 GHG concentrations than HadCM3 and COSMOS. With respect to the difference between model and
9 data, COSMOS simulates TS closer to the temperatures derived from marine-based records, since it
10 indicates nearly no change rather than a strong opposite signal. One cause for this modest change in the
11 North Atlantic Ocean may be related to vegetation changes, which may lead to a cooling as suggested
12 above. Another cause may be the decrease in AMOC at the LIG with respect to PI leading to the
13 bipolar seesaw, a pattern that is also observed in the proxy data at 130 kyr BP. We note a relative
14 cooling in both LIG simulations south of Iceland and Greenland. This region is very sensitive to
15 changes in the AMOC as shown in observational and numerical studies (Knight et al., 2005; Latif et al.,
16 2006; Dima and Lohmann, 2009).

17 For 125 kyr BP, COSMOS simulates higher anomalies in the North Atlantic Ocean than at 130 kyr
18 BP, but lower than CCSM3 and HadCM3 which simulate SSTs closer to the reconstructed
19 temperatures. Note however that the definition of summer is different in our study than in the study by
20 Capron et al. (2014), as they calculate it as the average of July-August-September, while we consider
21 the warmest month.

22 **4.4 Limitations of model-data comparison**

23 One challenge in an effective LIG model-data comparison is the difficulty to determine an absolute
24 dating of LIG marine paleo-proxy records (e.g. Drysdale et al., 2009), as few techniques exist for this
25 purpose. The dating of most of the records is derived by lining up their benthic $\delta^{18}\text{O}$ signal to a dated
26 benthic $\delta^{18}\text{O}$ stack (Lisiecki and Raymo, 2005)~~the climatic signal recorded in sediment cores to the~~
27 ~~SPECMAP (SPECTral MAPIng Project, Imbrie et al., 1984; Martinson et al., 1987) reference curve,~~
28 ~~which is tuned to the June insolation at 65°N.~~ This strategy allows a relative dating of sediment cores
29 ~~through global effects of glacial-interglacial climate changes~~ beyond the time limit of radiocarbon
30 dating (Fairbanks et al., 2005; Chiu et al., 2007; Reimer et al., 2009; Shanahan et al., 2012; Reimer et
31 al., 2013), but it may lead to an artificial synchronization of all records and therefore dampen regional

differences in climate records with respect to the LIG chronozone. ~~An alternative relatively new~~ method for synchronizing different types of proxies ~~from different regions~~ is used in ~~Capron~~ Govin et al. (2014), ~~by~~ They aligning proxy records to the AICC2012 ice core chronology ~~allowing for consideration of dating uncertainties~~. Their study shows that the maximum temperature changes during the LIG is different between the two hemispheres, the records from Southern Ocean and Antarctica showing an early maximum compared to the records from northern high latitudes. This method is used by Capron et al. (2014) in their proxy data compilation, thus allowing for one less uncertainty in the model-data comparison. However, using such a time-resolved temperature compilation does not improve our model-data comparison, as when compared to the other proxy-based datasets that represent the maximum LIG warmth.

Additionally, some proxy records that are considered as recording annual mean temperatures are seasonally biased, depending on the type of the proxy or on the region (Leduc et al., 2010; Schneider et al., 2010; Lohmann et al., 2013). Furthermore, defining the timing of the maximum warmth during the LIG represents as well a challenge. ~~Different studies (model as well as proxy-based) suggest that the maximum warmth occurred at different times throughout the LIG with regional dependency (Bakker et al., 2012; Govin et al., 2012; Langebroek and Nisancioglu, 2014). A study that involves transient LIG simulations performed with nine different models is presented by~~ Bakker and Renssen (2014), ~~showing~~ who-f that the calculation of the maximum LIG temperature is largely model-dependent, ~~and~~ indicating also ~~shows~~ geographical- and time-dependency (retrieved values differ between the annual mean and warmest month temperature anomalies). ~~Bakker and Renssen (2014)~~ They propose that the time-dependency originates from the dependency of the time evolution of orbital forcing on latitude and seasons, as well as from the thermal inertia of the oceans and from different feedbacks in the climate system, ~~such as the presence of remnant ice sheets from the preceding deglaciation, changes in sea-ice cover, vegetation, meridional overturning strength, and monsoon dynamics~~. Our model results indicate that the timing of maximum LIG warmth is indeed regionally dependent (Fig. 9).

5. Conclusions

In this study, we have analyzed data from several LIG sensitivity simulations performed with an ~~atmosphere-ocean general circulation model~~ AOGCM and have assessed the influence of the GIS on global climate. We have compared the simulated TS changes to anomalies as recorded by ~~proxy reconstructions~~ LIG climate data synthesis by of CAPE Last Interglacial Project Members (2006), Turney and Jones (2010), and ~~by a compilation of synchronized records of~~ (Capron et al., (2014).

We have shown that the exact method by which GIS configuration is changed has a significant influence on hemispheric temperature anomalies. A reduction in GIS by ~ 1300 m and changes in albedo (~~LIG-1300m-alb-simulation~~) enhance the warming caused by changes in the astronomical forcing by up to $+5^{\circ}\text{C}$. The LIG is much warmer than the PI, especially during summer in the Northern Hemisphere, and during winter in the Southern Hemisphere and in the well as northern high latitudes. The influence of astronomical forcing ~~influence~~ is dominant (relative to changes in GIS) in the global and Northern Hemisphere average of annual mean and local summer TS, and in the Southern Hemisphere winter. Changes in GIS have the strongest influence (relative to insolation changes) globally and in the Northern Hemisphere winter average TS, and in the Southern Hemisphere summer.

Modification of the GIS alone leads to a warming mostly in the northern and southern high latitudes. Cooling occurs locally in Barents Sea or Sea of Okhotsk (depending on the simulation). The warming caused by a reduced GIS has a winter ~~signal~~, rather than a summer signal at both hemispheres. ~~Winter TS over the Arctic Ocean is warmer by up to $+3^{\circ}\text{C}$ due to GIS changes, with an additional warming of $+1$ to $+2^{\circ}\text{C}$ caused by winter insolation changes, relative to PI.~~

The simulated TS underestimate the temperature changes indicated by the proxy reconstructions. However, a reduction in GIS elevation and extent improves the agreement between model and data by Turney and Jones (20106). In order to obtain the maximum LIG warmth, we perform and analyze transient model scenarios. ~~For terrestrial records, which represent annual mean temperature anomalies at maximum LIG warmth, the best agreement is found for annual mean TS anomalies at maximum LIG warmth derived from the simulation with changes in GIS and albedo (LIG-1300m-alb-tr simulation).~~ This result is in contrast to other model studies that find a best agreement when summer averages are considered. ~~At low latitudes the model does not capture the pronounced changes indicated by the marine proxies derived by Turney and Jones (2010). Most of the records derived by CAPE Last Interglacial Project Members (2006) and Capron et al. (2014) agree best with the model simulation that considers a preindustrial GIS configuration, as changes in GIS have the strongest influence during winter and the respective datasets represent summer temperatures.~~ For the proxy data by CAPE Last Interglacial Project Members (2006) that represent summer temperatures, changes in GIS are of minor importance for SSTs.

Throughout the LIG, winter in the northern high latitudes is characterized by high temporal variability, while summer TS indicate a clear cooling trend. By considering transient simulations with different boundary conditions (i.e. GIS elevation, albedo, insolation, GHG concentrations) we offer a

bandwidth of potential temperatures at each given time throughout the LIG, between 130 and 115 kyr BP. We reduce the mismatch between model and data by additionally considering uncertainties in absolute dating of the proxy reconstructions, and uncertainties in the timing of maximum LIG warmth (calculated in our study as the simulated maximum LIG warmth between 130 and 120 kyr BP at each given location). The ~~definition of maximum interglacial warmth~~missing exact time constrain in CAPE Last Interglacial Project Members (2006) and Turney and Jones (2010) provides therefore an additional uncertainty and ~~complicates direct model-data comparisons~~the LIG does not provide a strong constrain for estimating the amplitude of interglacial climate change. Future studies that provide a better multi-proxy interpretation and a better representation of the climate models are needed in order to reduce the model–data mismatch. Our sensitivity simulations represent a starting point for future studies on transient integrations of the LIG climate that include also transient changes in GIS elevation and extent, and for the comparison of such results to high-quality proxy data. More ~~climate model~~ sensitivity studies on the effects of a reduced GIS on global climate are ~~needed~~required in order to understand the response of different models to such changes, as the ability of the models to properly simulate future states of the GIS is critical.

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1 Table and Figure captions

2

3 **Table 1.** Overview of model configuration and climate forcings ~~for the COSMOS simulations~~
4 ~~presented in this study~~. PI = preindustrial, Veg. = vegetation; dyn. = dynamic; e = eccentricity; ϵ =
5 obliquity; ω = length of perihelion. The Greenland Ice Sheet (GIS) configurations ~~is~~ are displayed in
6 Fig. 1., in dependence of the simulation, as follows: PI—preindustrial GIS elevation and land ice mask;
7 $\times 0.5$ —preindustrial GIS elevation multiplied by 0.5 (at every grid point over Greenland) and
8 preindustrial land ice mask; -1300 m—preindustrial GIS elevation minus 1300 m (at every grid point
9 over Greenland; where preindustrial elevation is below 1300 m, the land is set to 0 m) and preindustrial
10 land ice mask; -1300 m+alb—preindustrial GIS elevation minus 1300 m (at every grid point over
11 Greenland; where preindustrial elevation is below 1300 m, the land is set to 0 m and albedo adjusted
12 accordingly) and adjusted land ice mask. The different GIS configurations are displayed in Fig. 1. *
13 Simulations ~~that are~~ presented in the supplementary material.

14

15 **Table 2.** Atlantic Meridional Overturning Circulation (AMOC) and absolute values of surface
16 temperature (TS) for global, Northern Hemisphere (NH), and Southern Hemisphere (SH) coverage,
17 calculated for annual mean, local summer mean (warmest month), and local winter mean (coldest
18 month).

19

20 **Figure 1.** Greenland Ice Sheet (GIS) elevation ~~(in m)~~ and land ice cover prescribed in our ~~COSMOS~~
21 model simulations: **(a)** preindustrial GIS and land ice mask, **(b)** $\times 0.5$ GIS and preindustrial land ice
22 mask, **(c)** -1300 m GIS and preindustrial land ice mask, **(d)** -1300 m and adjusted land ice mask. In
23 **(a)**, the preindustrial elevation and land ice mask are unchanged. In **(b)**, the preindustrial elevation over
24 the GIS area is multiplied by 0.5; the land ice mask is unchanged. In **(c)**, for each grid point over the
25 GIS, 1300 m are subtracted from preindustrial elevation; the land ice mask is unchanged. In **(d)**, for
26 each grid point over the GIS, 1300 m are subtracted from preindustrial elevation; at grid locations
27 where the elevation is lower than 1300 m, land ice is removed and albedo is adjusted accordingly.

28

29 **Figure 2.** Effect of **(a–c)** Greenland Ice Sheet elevation and **(c, d)** albedo in the 130 kyr BP
30 simulations. Annual mean surface temperature (TS) anomalies ~~(in $^{\circ}\text{C}$)~~ for ~~simulations~~: **(a)** $\text{LIG} \times 0.5$
31 minus LIG-ctl , **(b)** LIG-1300m minus LIG-ctl , **(c)** LIG-1300m-alb minus LIG-ctl , and **(d)** LIG-1300m-

1 alb minus LIG-1300m. Hatched areas mark statistically insignificant TS anomalies.

2

3 **Figure 3.** Effect of Greenland Ice Sheet elevation and albedo on surface temperature in the 130 kyr BP
4 simulation (LIG-1300m-alb-simulation). Same as Fig. 2c but for: (a) local winter mean (coldest month)
5 and (b) local summer mean (warmest month). Violet dashed lines represent the LIG-1300m-alb 50 %-
6 compactness sea ice isoline, violet continuous lines represent the LIG-1300m-alb sea ice edge. Green
7 dashed lines represent the LIG-ctl 50 %-compactness sea ice isoline, green continuous lines represent
8 the LIG-ctl sea ice edge.

9

10 **Figure 4.** Effect of Greenland Ice Sheet elevation, insolation, and albedo at 130 kyr BP relative to
11 preindustrial (PI). Surface temperature (TS) anomalies $(\text{in } ^\circ\text{C})$ between the Last Interglacial (LIG-
12 LIG-1300m-alb-CH₄-simulation) and PI (PI-simulation) for: (a) annual mean, (b) local winter mean (coldest
13 month), and (c) local summer mean (warmest month). Violet dashed lines represent the LIG 50 %-
14 compactness sea ice isoline, violet continuous lines represent the LIG sea ice edge. Green dashed lines
15 represent the PI 50 %-compactness sea ice isoline, green continuous lines represent the PI sea ice edge.
16 Hatched areas mark statistically insignificant TS anomalies.

17

18 **Figure 5.** Simulated surface temperature evolution $(\text{in } ^\circ\text{C})$ for the Last Interglacial (LIG-~~130-115~~
19 kyr BP, LIG-ctl-tr, LIG-x0.5-tr, LIG-1300m-alb-tr, and LIG-GHG-tr simulations) and the Holocene (8-
20 0 kyr BP, HOL-tr-simulation) in northern high latitudes (60-90°N) calculated as running average with a
21 window length of 21 model years representing 210 calendar years for: (a) annual mean, (b) local winter
22 mean (coldest month), and (c) local summer mean (warmest month). The lower x scale represents the
23 LIG time scale, the upper x scale indicates the Holocene time scale. The upper x scale is matched to the
24 time scale between 128 and 120 kyr BP, as [summing-Drysdale et al. \(2009\)](#) propose that Termination I and
25 Termination II are similar with respect to obliquity ([Drysdale et al., 2009](#)).

26

27 **Figure 6.** Effect of (a, b) Greenland Ice Sheet elevation, insolation, albedo, and atmospheric methane
28 concentration and (c, d) insolation and atmospheric methane concentration for the Last Interglacial
29 (LIG) relative to preindustrial (PI). Model-data comparison of mean local summer temperature
30 anomalies $(\text{in } ^\circ\text{C})$. The shading represents the simulated surface temperature (TS) anomalies at (a, c)
31 130 kyr BP derived from (a) LIG- 1300 m-alb-simulation and (c) LIG-ctl-simulation, and (b, d)

summer maximum LIG warmth (warmest 100 warmest months between 130 and 120 kyr BP) derived from (b) LIG-1300m-alb-tr-simulation and (d) LIG-ctl-tr, relative to PI. Hatched areas in (a, c) mark statistically insignificant TS anomalies. The squares and circles show marine and terrestrial proxy-based maximum LIG summer temperature anomalies relative to PI derived by CAPE Last Interglacial Project Members (2006). The colors inside the squares and circles represent the proxy-based temperature anomalies derived from the intervals provided by CAPE Last Interglacial Project Members (2006), that agree best with the simulated TS anomalies at the location of the proxies.

Figure 7. Effect of (a, b) Greenland Ice Sheet elevation, insolation, albedo, and atmospheric methane concentration and (c, d) insolation and atmospheric methane concentration for the Last Interglacial (LIG) relative to preindustrial (PI). Model-data comparison of mean annual temperature anomalies ($^{\circ}\text{C}$). The shading represents the simulated surface temperature (TS) anomalies at (a, c) 130 kyr BP derived from (a) LIG-1300m-alb-simulation and (c) LIG-ctl-simulation, and (b, d) maximum LIG warmth (warmest 100 model years between 130 and 120 kyr BP) derived from (b) LIG-1300m-alb-tr-simulation and (d) LIG-ctl-tr-simulation, relative to PI. Hatched areas in (a, c) mark statistically insignificant TS anomalies. The squares and circles show marine and terrestrial proxy-based LIG annual mean temperature anomalies relative to present-day (1961–1990) derived by Turney and Jones (2010).

Figure 8. Effect of Greenland Ice Sheet elevation, insolation, albedo, and atmospheric methane concentration for the Last Interglacial (LIG) relative to preindustrial (PI). (a) Proxy-based maximum LIG summer temperature anomalies ($^{\circ}\text{C}$) relative to PI derived by CAPE Last Interglacial Project Members (2006) plotted against simulated local summer surface temperature (TS) anomalies at 130 kyr BP (LIG-1300m-alb-simulation) relative to PI at the location of the proxies. The horizontal bars represent the proxy-based temperature intervals derived by CAPE Last Interglacial Project Members (2006). The vertical bars indicate the simulated TS anomalies at the maximum and minimum LIG TS with respect to local summer (i.e. the coldest and warmest 100 warmest months) derived from the time interval 130 to 120 kyr BP (LIG-1300m-alb-tr-simulation) relative to PI, for each given proxy record location. (b) Proxy-based LIG annual mean temperature anomalies relative to present-day (1961–1990) derived by Turney and Jones (2010), plotted against simulated annual mean TS anomalies at 130 kyr BP (LIG-1300m-alb-simulation) relative to PI at the location of the proxies. The vertical bars indicate

1 | the simulated -TS anomalies at the maximum and minimum LIG TS with respect to annual mean (i.e.
2 | the coldest and warmest 100 model years) derived from the time interval 130 to 120 kyr BP (LIG-
3 | 1300m-alb-tr-simulation) relative to PI, for each given proxy record location. (c) Same as b) but
4 | displaying vertical bars that represent local summer and local winter mean (i.e. the warmest 100
5 | warmest months and coldest 100 coldest months). The squares (red) and circles (black) represent
6 | marine and terrestrial proxy-based temperature anomalies, respectively. The solid thick lines represent
7 | the 1 : 1 line that indicates a perfect match of simulated and reconstructed anomalies.

8

9 | **Figure 9.** Timing of the maximum Last Interglacial warmth-(in kyr BP) for: (a) local summer (warmest
10 | 100 warmest months) and (b) annual mean (warmest 100 model years) derived from the LIG-1300m-
11 | alb-tr-simulation, between 130 and 120 kyr BP.

12

13 | **Figure 10.** Effect of (a, b) Greenland Ice Sheet elevation, insolation, albedo, and atmospheric methane
14 | concentration and (c, d) insolation and atmospheric methane concentration at 130 kyr BP relative to
15 | preindustrial (PI). Model-data comparison of mean local summer temperature anomalies-(in °C). The
16 | shading represents the simulated surface temperature (TS) anomalies derived from (a, b) LIG-1300-m-
17 | alb-simulation and (c, d) LIG-ctl-simulation. Hatched areas mark statistically insignificant TS
18 | anomalies. The squares show marine proxy-based LIG (130 kyr BP) summer temperature anomalies
19 | relative to present-day derived by Capron et al (2014).

20

21 | **Figure 11.** Effect of (a-c) Greenland Ice Sheet elevation and (c) albedo on sea level pressure (SLP) and
22 | surface winds in 130 kyr BP simulations. The shading represents December-January-February (DJF)
23 | mean SLP anomalies-(in Pa), superimposed by DJF mean surface wind anomalies (in ms⁻¹) for: (a)
24 | LIG-×0.5 minus LIG-ctl, (b) LIG-1300m minus LIG-ctl, and (c) LIG-1300m-alb minus LIG-ctl
25 | simulations. The vector length indicates the wind speed (in ms⁻¹).

Simulation	Time (kyr BP)	CO ₂ (ppmv)	CH ₄ (ppbv)	N ₂ O (ppbv)	Greenland Ice Sheet	Veg.	e	ε (°)	ω (°)
LIG-ctl	130	278	650	270	PI	dyn.	0.0382	24.24	49.1
LIG-×0.5	130	278	650	270	×0.5	dyn.	0.0382	24.24	49.1
LIG-1300m	130	278	650	270	-1300m	dyn.	0.0382	24.24	49.1
LIG-1300m-alb	130	278	650	270	-1300m+alb	dyn.	0.0382	24.24	49.1
LIG-1300m-alb-CH ₄	130	280	760	270	-1300m+alb	dyn.	0.0382	24.24	49.1
LIG-GHG*	130	257	512	239	PI	PI	0.0382	24.24	49.1
LIG-125k*	125	278	650	270	-1300m+alb	dyn.	0.0400	23.79	128.1
PI	0	280	760	270	PI	dyn.	0.0167	23.45	282.2
LIG-ctl-tr	130-115	278	650	270	PI	dyn.	varying	varying	varying
LIG-×0.5-tr	130-115	278	650	270	×0.5	dyn.	varying	varying	varying
LIG-1300m-alb-tr	130-115	278	650	270	-1300m+alb	dyn.	varying	varying	varying
LIG-GHG-tr	130-115	varying	varying	varying	PI	PI	varying	varying	varying
HOL-tr	8-0	278	650	270	PI	dyn.	varying	varying	varying

Table 1

Simulation	AMOC (Sv)	Annual mean TS (°C)			Winter mean TS (°C)			Summer mean TS (°C)		
		global	NH	SH	global	NH	SH	global	NH	SH
LIG-ctl	12.8	14.77	15.57	13.98	8.76	6.53	10.98	21.00	24.78	17.22
LIG- $\times 0.5$	13.3	15.13	16.03	14.22	9.19	7.12	11.25	21.25	25.09	17.41
LIG-1300m	14.8	15.07	15.95	14.18	9.14	7.05	11.22	21.17	24.96	17.39
LIG-1300m-alb	15.0	15.14	16.00	14.29	9.24	7.10	11.37	21.24	25.02	17.46
LIG-1300m-alb-CH ₄	14.4	15.32	16.34	14.29	9.40	7.49	11.31	21.43	25.35	17.50
LIG-GHG	12.8	14.65	15.50	13.80	8.69	6.56	10.82	20.82	24.64	17.00
LIG-125k	14.8	15.19	16.11	14.27	9.46	7.74	11.17	21.20	24.94	17.46
PI	16.3	14.51	15.35	13.67	8.84	7.44	10.23	20.09	22.84	17.33

Table 2

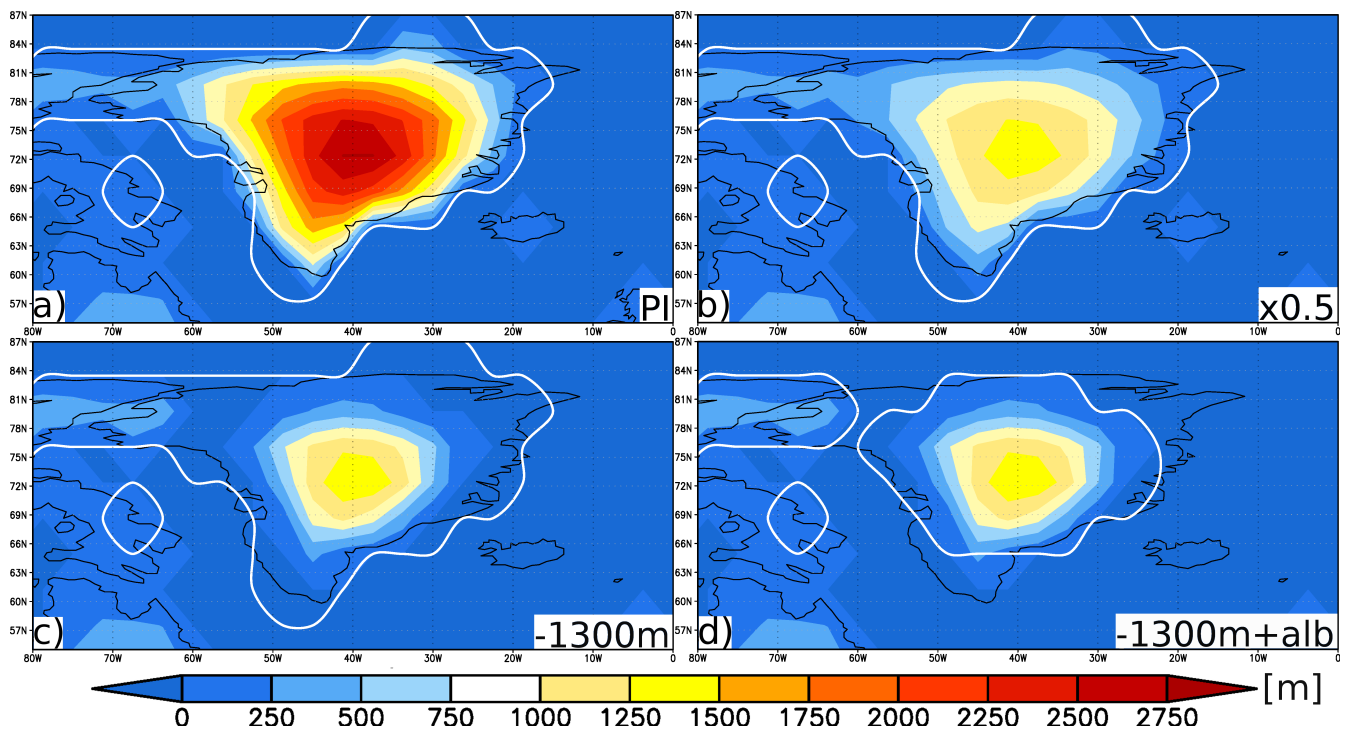


Figure 1

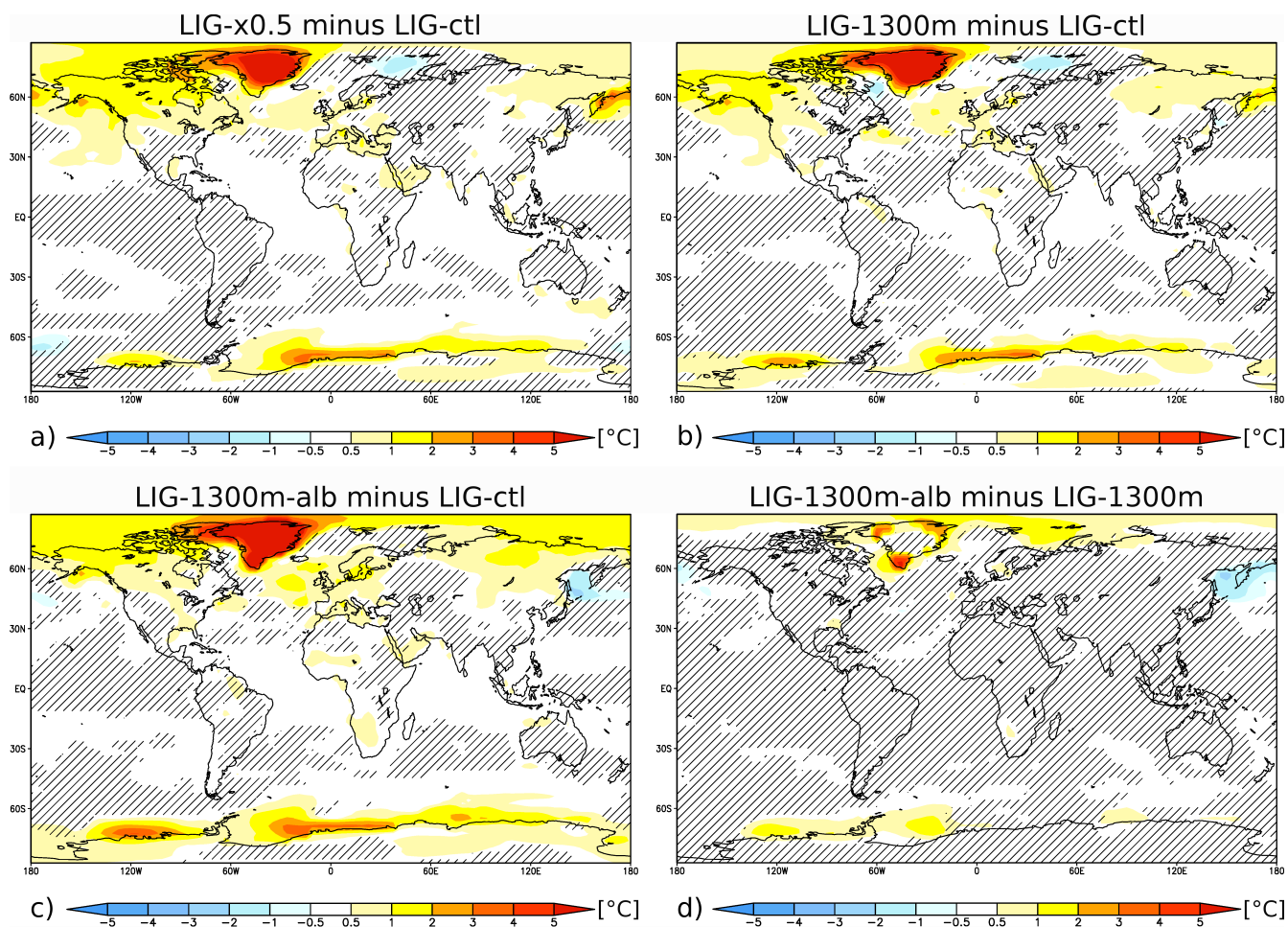


Figure 2

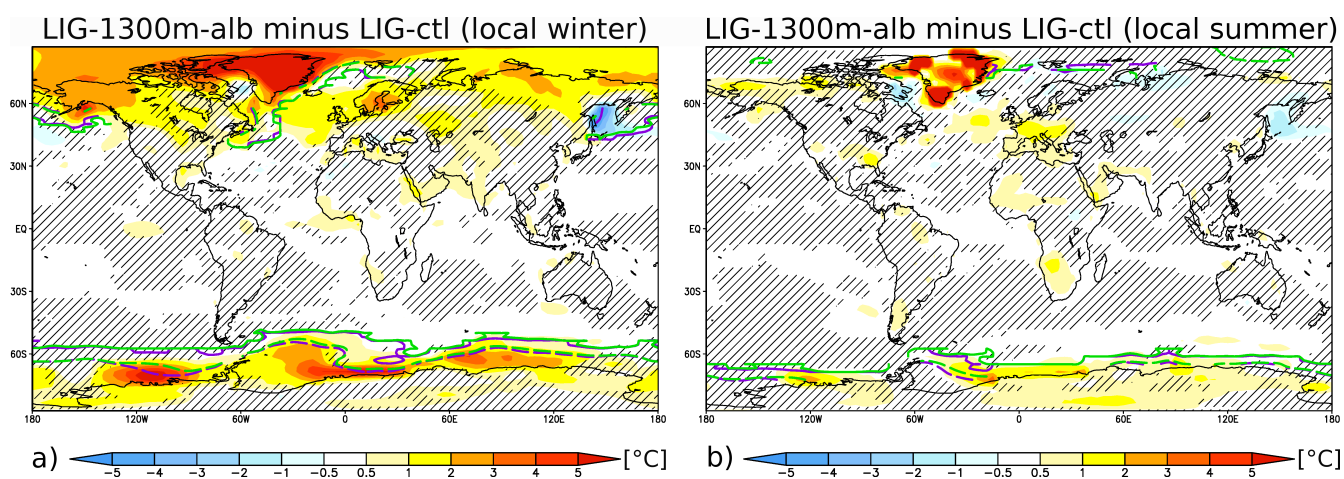


Figure 3

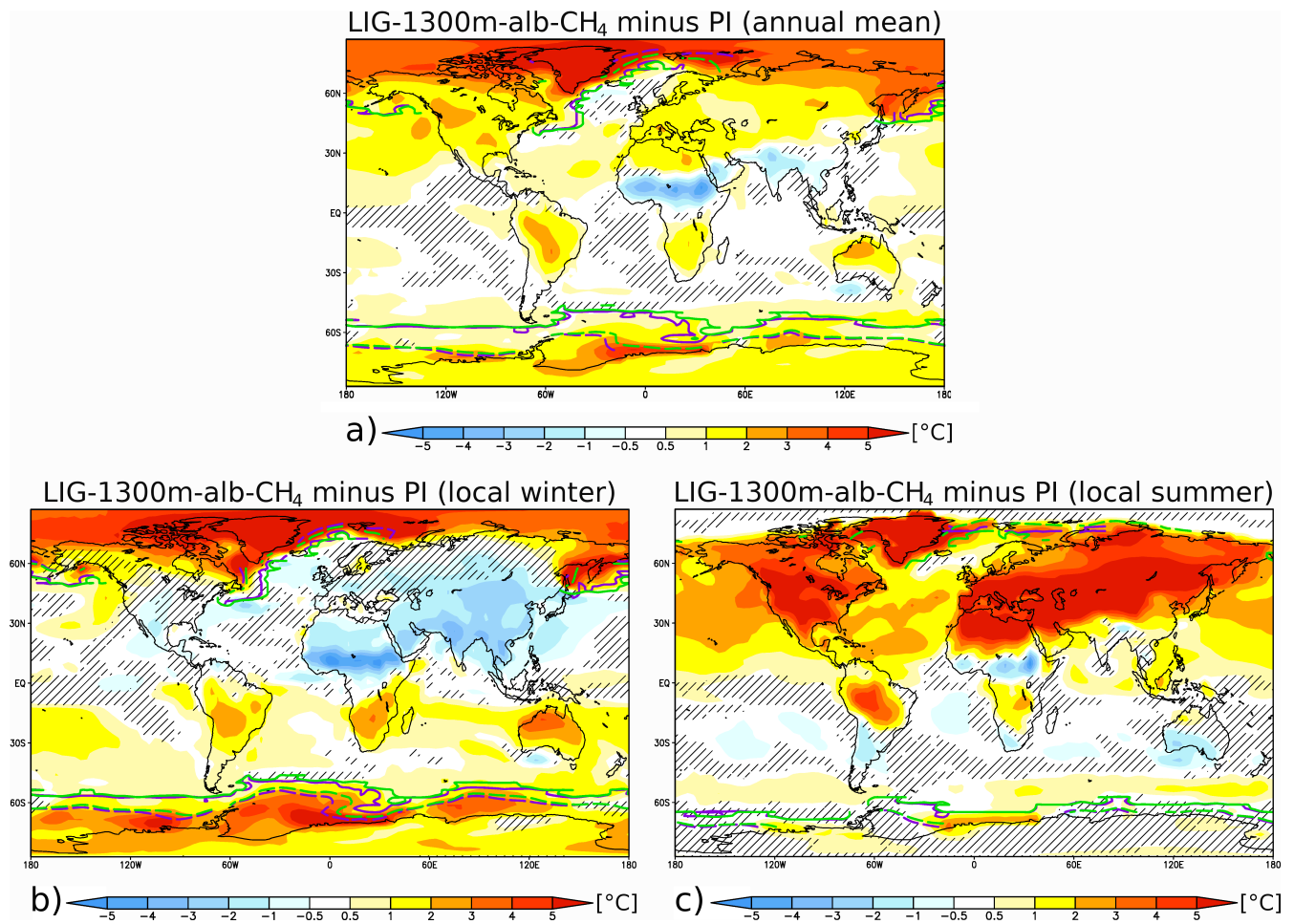


Figure 4

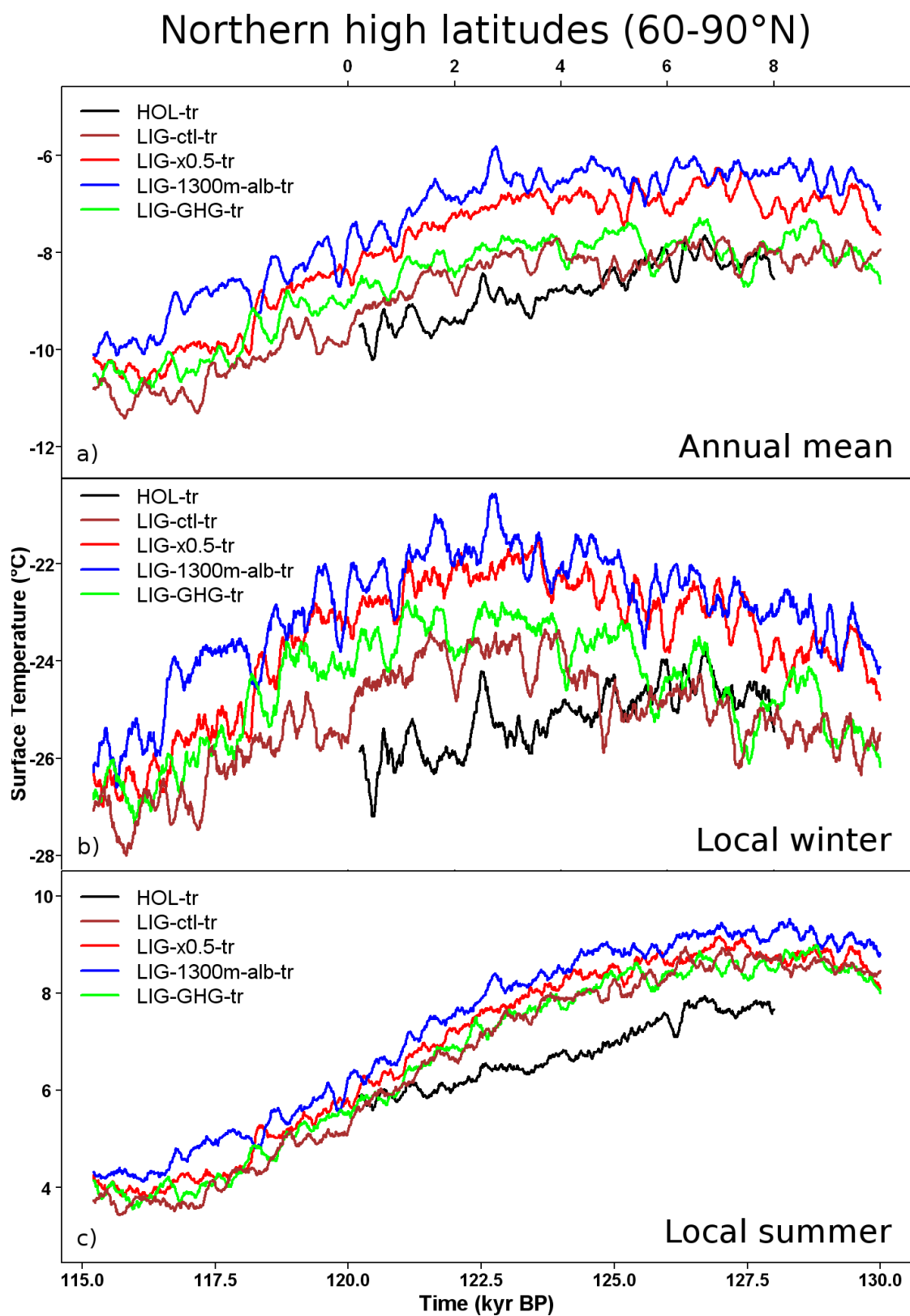
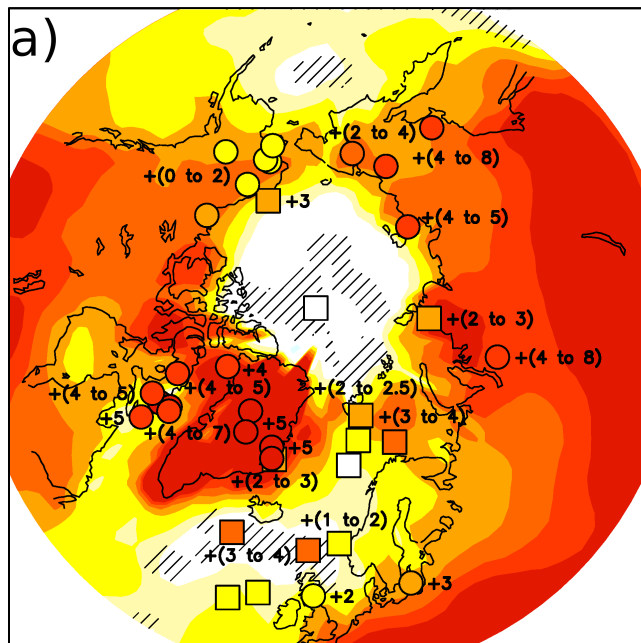


Figure 5

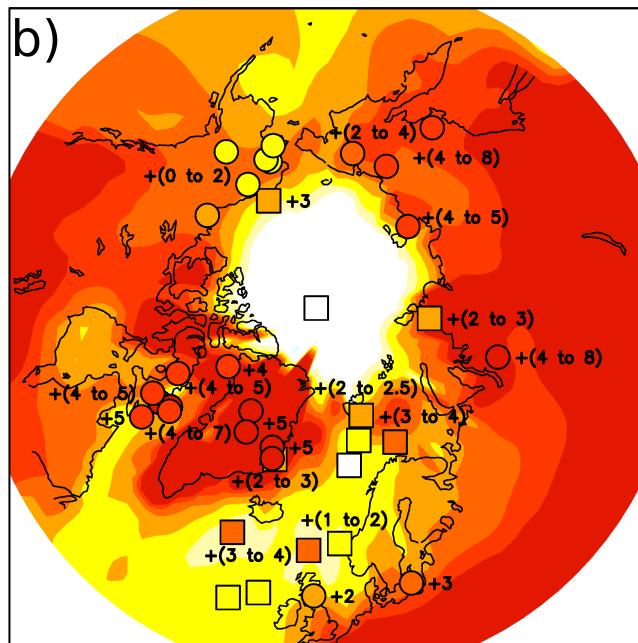
Local summer at 130 kyr BP

LIG-1300m-alb minus PI

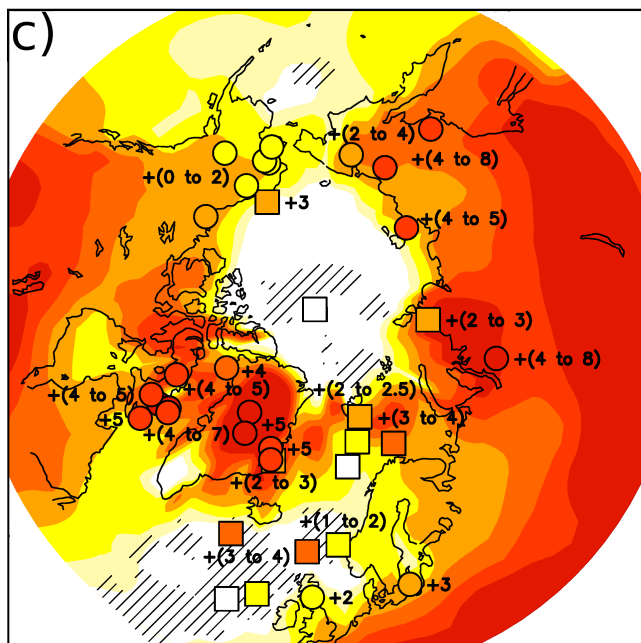


Local summer at maximum LIG warmth

LIG-1300m-alb-tr minus PI



LIG-ctl minus PI



LIG-ctl-tr minus PI

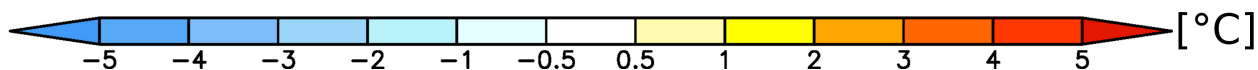
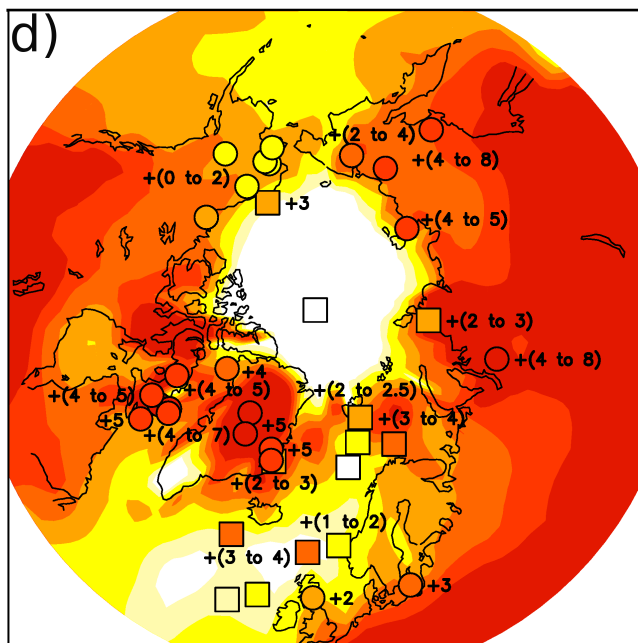


Figure 6

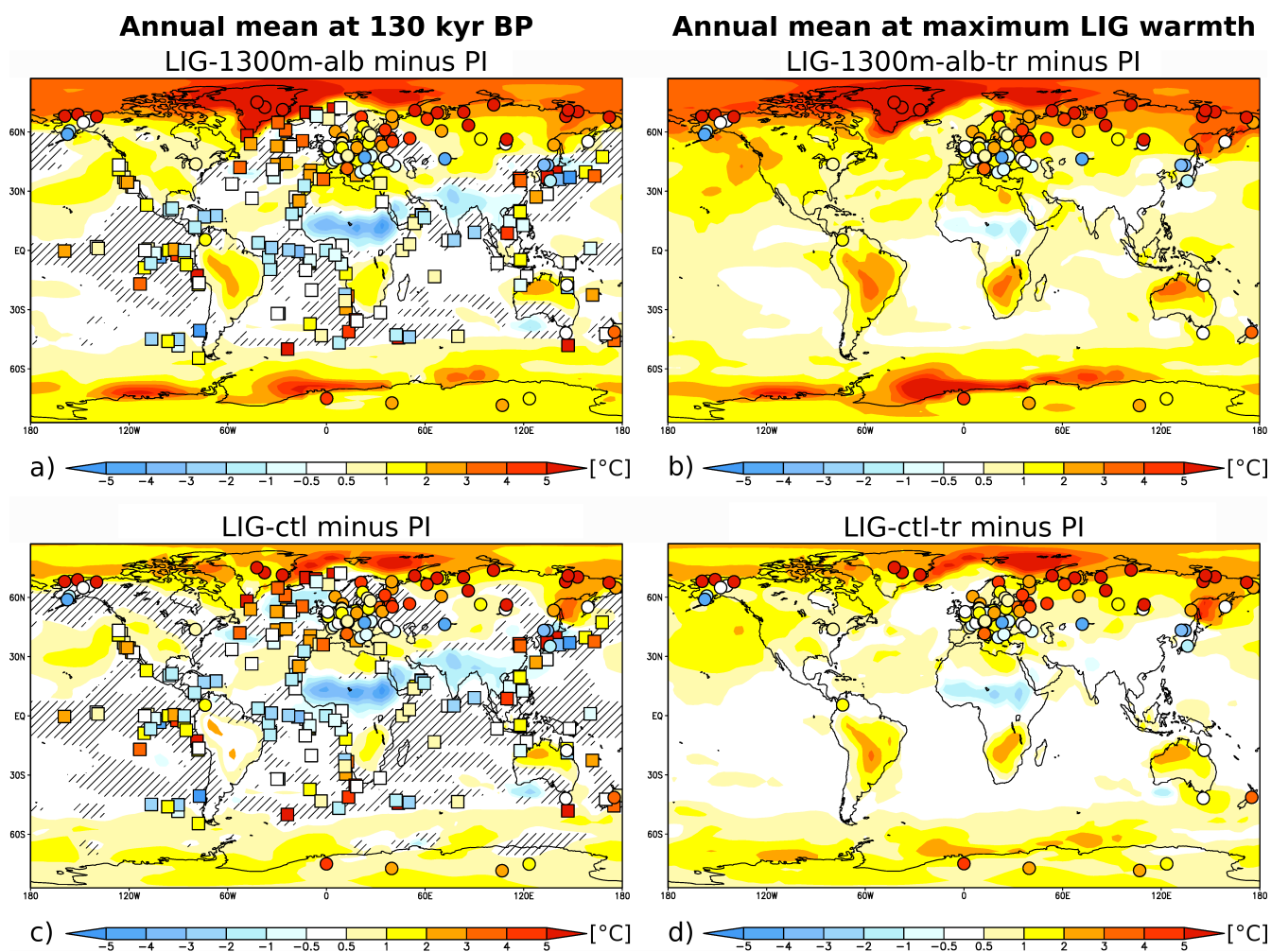
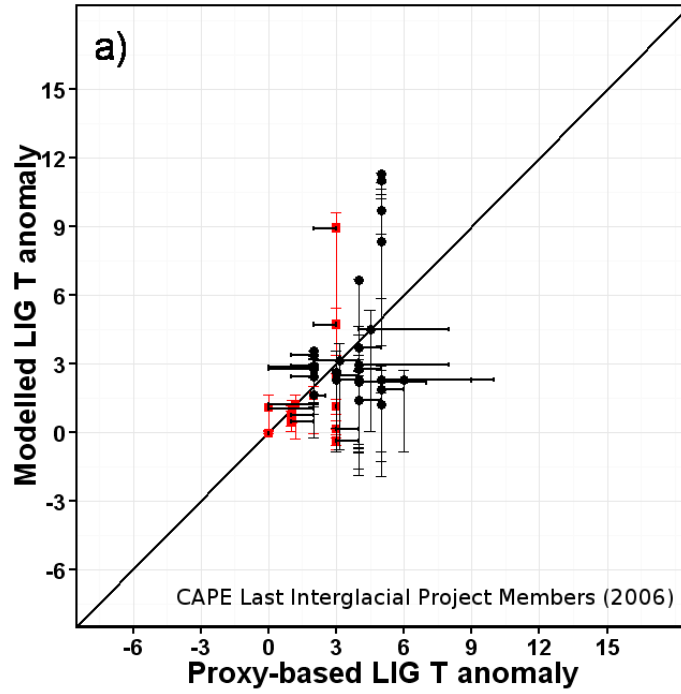


Figure 7

Proxy vs. simulated local summer [°C]



Proxy vs. simulated annual mean,
local winter and summer [°C]

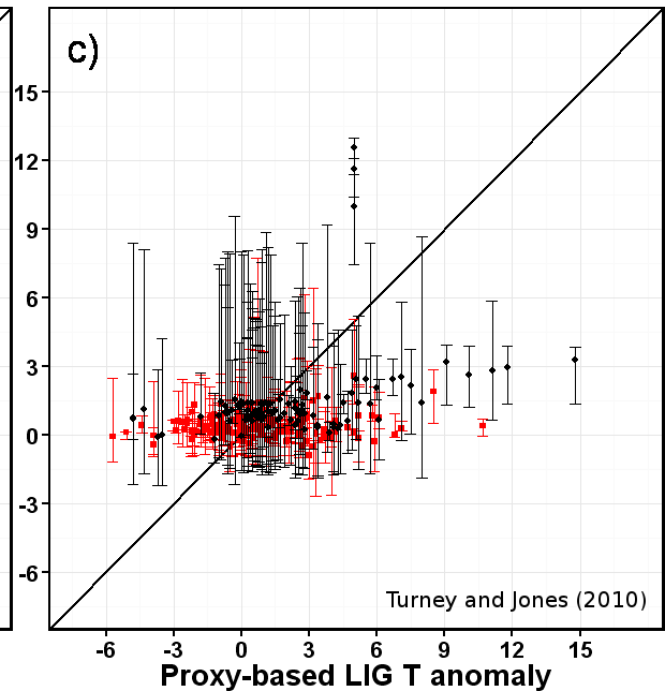
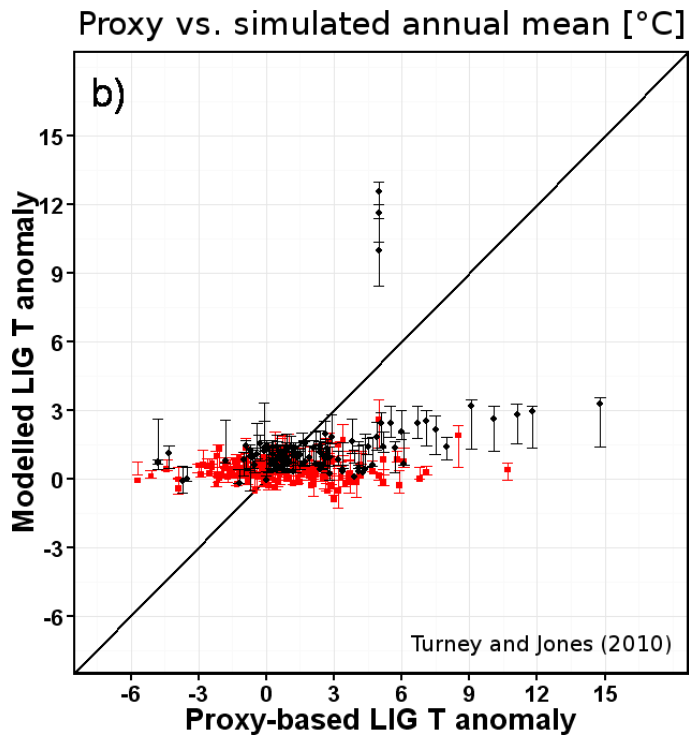


Figure 8

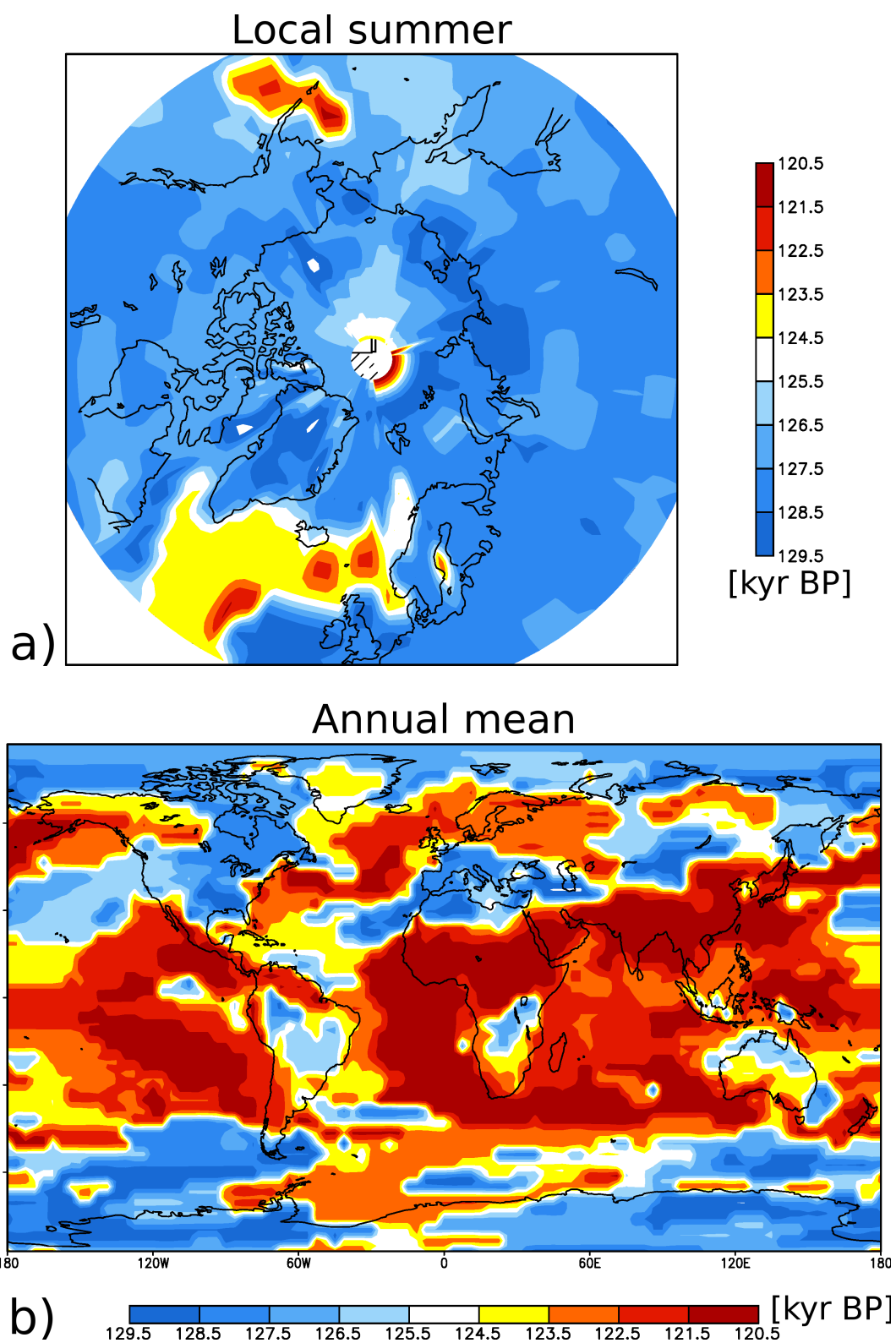
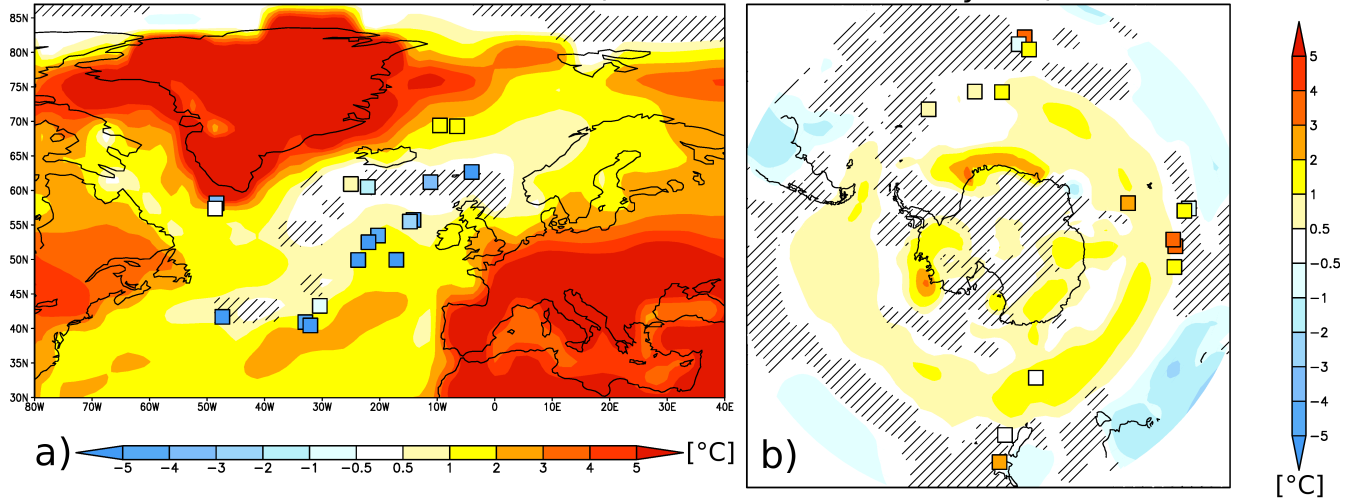


Figure 9

LIG-1300m-alb minus PI (local summer at 130 kyr BP)



LIG-ctl minus PI (local summer at 130 kyr BP)

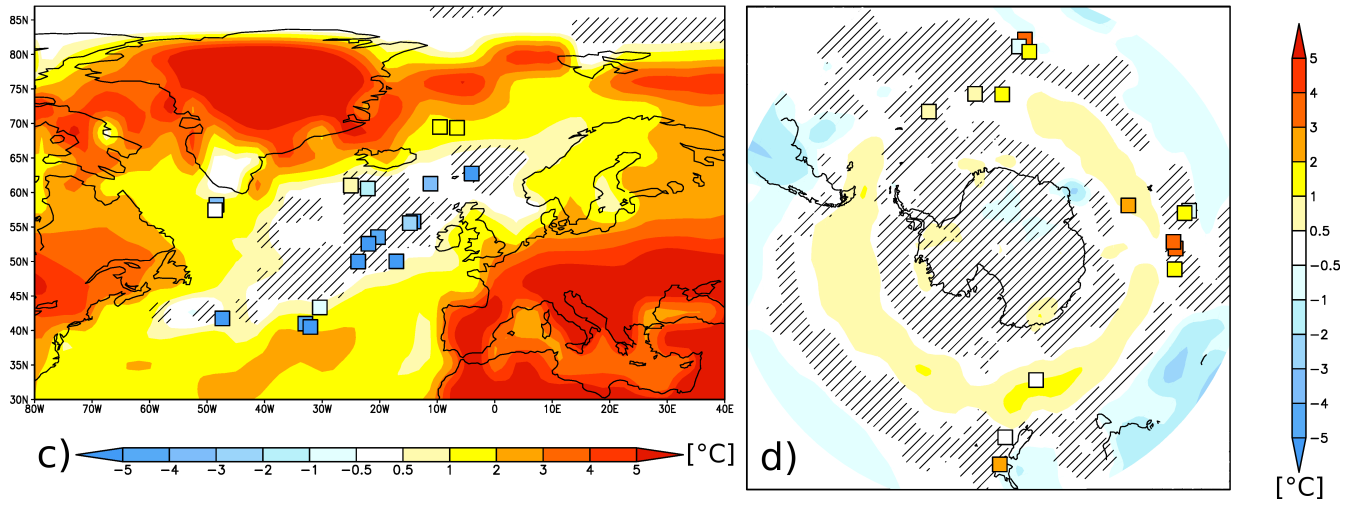


Figure 10

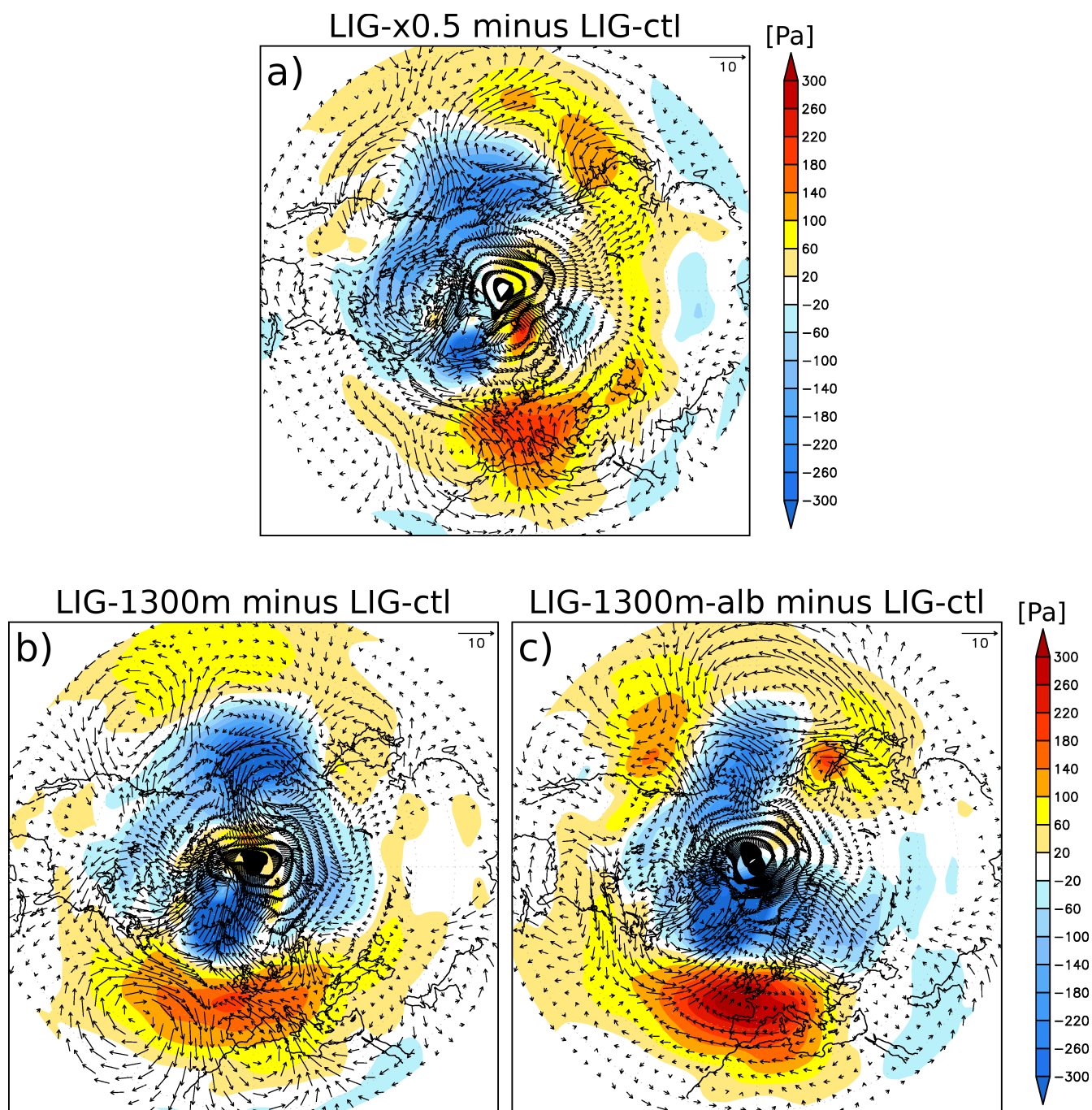


Figure 11