Anthony J. Coletti
11/6/2014
Responses to Anonymous Reviewer #1

Reviewer's comments in **black**
Authors' comments in red

***** As of 2/25/2015*****

Dear Reviewer,

Thank you very much for your comments and suggestions. All of your suggestions (in both text and figures) have been used. Thank you. You should see a new version of our manuscript with changes. Please see the markuped version.

Changes:

- Title changes more relative to what we were discussing in the body of the text.
- Re-done figure showing Lake E temperature and precipitation values with corresponding model data (see Figure 5).
- Table corresponding to temperature and precipitation values for clarity (Table 2)
- Table corresponding to all model simulations for clarity and less confusion (Table 1).
- Various grammar and wording changes in the body of the text to ensure clarity and avoid confusion.
- Removed section on "Modern" control to avoid confusion. The control simulation is the Pre-Industrial simulation.
- Re-ran model simulations (including vegetation) out to ~80 years to ensure equilibrium. Differences between periods are now shown to be significant at the 95% confidence interval with a very low p-value (~0.29). (See Figures 2 and 3)
- Additional references added to support statements.
- Removed section on glaciation at 2.7 Ma.

Comments:

The description of experiments is not sufficiently complete and precise. For example, it is not clear whether the same Greenland ice sheet (altitude,extent,…) is used for PI, Modern, MIS1, MIS5e,MIS11c,MIS31. In the case of MIS5e, the description of this interglacial states that Greenland ice core records suggest a modern reduction in the size of the GIS. In the discussion, the authors wrote 'our simulations of MIS-5e with a near-modern GIS'. However, it is not clearly mentioned whether a reduction of the size (or any other change) of the GIS compared to present-day (pre-industrial or modern) is applied for the simulation. Is the same GIS used for PI and Modern simultations? How realistic is it? As far as the orbital forcing is concerned, the authors stated that Earth's orbital configuration has changed little in 120 years (from PI to Modern, I guess). Has this modern change been taken into account? The authors should also check the orbital parameters for MIS31.

Description of the experiments have been fixed and made clearer for the audience. Thank you for your suggestions throughout the comments. The same Greenland Ice Sheet (modern; same elevations and extent) is used for our modern, pre-industrial, MIS-1, MIS-5e and MIS11GIS simulations. No GIS is used in our MIS11NG and MIS-31 simulations. In regards to Earth's orbital configuration since pre-industrial, this is a great question. Precession has changed within the time from of ~120 years (from PI to modern) which accounts for ~ 1% change in the orbital configuration. However, Berger's astronomical solutions are calculated for every 1000 years. To keep within his solutions, we used his values. This is a great question - the orbital parameters for MIS-31 are correct. The values of precession in the table are our GCM precessional values. They are slightly different than Berger's astronomical solutions. The GCM reads precession as the prograde angle from perihelion to the vernal equinox. To avoid future confusion for the reader, we have changed the precession value in our table to omega defined by Berger.

There are major defects all throhgout the text. Very regularly, the authors forgot to mention their reference, which is either PI or Modern. I agree that the problem would not exist if there were only one reference! Very regularly, the authors forgot to mention the time in the year (Summer, July, Annual, …) that applied on the provided values. Very regularly, the authors forgot to mention the region (Lake E, Beringia, Arctic) that applied to the provided values. This issue must be solved.

Thank you for your very detailed comments. We have fixed most of these issues and have done a very thorough editing of our manuscript.

Several authors, including Yin and Berger (2011) that the authors quoted, selected peak interglacial for their study. However, they do not agree on the date corresponding to this peak interglacial. For example, for MIS1, Yin and Berger (2011) selected 12ka, Lisiecki and Raymo (2005) pointed towards 6ka and Melles et al (2012) choose 9ka. Could the authors elaborate on the reason for the difference (as well as for the other interglacials) and explain how they make their choice? By the way, peak of summer warmth may be different from peak of boreal summer insolation.

This is a great question. Unfortunately, an in-depth discussion regarding the definition of the defined timing of the interglacials is beyond the scope of this study. We agree there is some community disagreement regarding what defines early Holocene warmth however, for simplicity, we follow the same protocols of Melles et al., 2012 (9ka is the time of peak boreal warmth and insolation at the lake).

The authors do not seem to be aware of other modeling studies performed from the Eemian, such as…

Thank you very much for a listing of these references. We will take a look and add them appropriately.

Detailed comments

Page (P.)3128 line(l.)18 - 'A prescribed enhancement of oceanic heat transport into the Arctic ocean has some effect on Beringian climate, suggesting intrahemispheric coupling seen in comparisons between Lake El'gygytgyn and Antarctic sediment records might be related to linkages between Antarctic ice volume and ocean circulation.' I do not understand this sentence.

Thank you very much. This has been fixed and the sentence is clearer.

P.3129 l.13 - I suggest using Lake E everywhere throughout the main text (from section 1 to section 4-included).

Thank you. We agree and this has been changed.

P.3131 l.19 – The authors should define **summer** insolation. The value they are giving for summer insolation seems rather large. However, it may be correct depending on their definition of summer insolation. A reference for the insolation should be provided in the text (and not only in the table).

This citation has been added in the text and table. Citation is as follows:

Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A. C. M., & Levrard, B. (2004). A long-term numerical solution for the insolation quantities of the Earth. *Astronomy and Astrophysics*, *428*(1), 261–285.

Summer insolation is defined at latitude 67.5°N using the astronomical, long-term solution of (see reference above).

P.3132 l.6 – '(Dahl-Jensen et al., 2013) suggest warm conditions throughout the Arctic'. I think that Dahl-Jensen et al. (2013) suggest warm conditions recorded at NEEM site. How is it extrapolated for the whole Arctic?

You are correct in questioning whether the NEEM record can be extrapolated for the entire Arctic. I do agree the sentence is improperly worded and it is indeed hard to assume this one record can be a circum-Arctic imprint of temperature. We have fixed this sentence so it is clearer.

P.3132 l.16 – 'insolation plays a dominant role on the on precipitation'. Something is going wrong in this sentence.

Fixed.

P.3132 l.21 – 'The simulation of LIG shown here is used to compare with the paleoenvironmental conditions in the Arctic during this period of and investigate temperature, vegetation and precipitation and correlate the data to pollen proxy analysis.' Something is going wrong in this sentence.

This now reads: 'The simulation of LIG shown here is used to compare paleoenvironmental conditions in the Arctic, such as, temperature, vegetation and precipitation, to Lake-E pollen proxy analysis. Orbital and GHG values are estimated for 127 ka; peak warmth during MIS 5e.'

P.3133 l.1 – I am not sure that the paper (Miller et al., 2010) is dealing with MIS11.

You are absolutely correct. This was the wrong citation. It has now been fixed. See below:

See the section on MIS 11 -

Miller, G. H., Brigham-Grette, J., Alley, R. B., Anderson, L., Bauch, H. A., Douglas, M. S. V., … Wolff, E. W. (2010). Temperature and precipitation history of the Arctic. *Special Theme: Arctic Palaeoclimate Synthesis (PP. 1674-1790)*, *29*(15–16), 1679–1715. doi:10.1016/j.quascirev.2010.03.001

P.3133 l.1 – 'insolation forcing ... was remarkably long'. I do not understand what this mean. Does it mean that the insolation (which one?) remains high over a long time interval?

I have changed the wording of the sentence to be clearer. This now reads:

Unlike the other interglacials, MIS-11c was remarkably long, with two insolation maxima anomalies at ~ 409 ka and 423 ka, apparently creating extensive warmth throughout the Arctic (Melles et al., 2012).

P.3133 l.28 – 'distributions of are used' a word is missing preventing the understanding of the sentence.

Fixed

'Furthermore, simulations using prescribed distributions of biome flora are used to quantify the local effect of changing vegetation cover around the region.'

P.3134 l.13 – What is 'MIS model'?

Removed "MIS"

P.3135 l.23 – 'the GCM is only +0.5 °C warmer than the modern reanalysis data' When? In Summer? In July? In annual mean?

Fixed – this is a mean July temperature difference.

"The difference indicates that mean July GCM temperatures are only + 0.5 °C warmer than the modern mean July reanalysis data in the Lake-E region, signifying relatively reliable temperature results."

P.3136 l.10 – 'precipitation is rather dry'. I am sorry! This does not make sense to me. Please clarify what you mean.

Thank you for catching this. This part of the sentence is not clear. However, it is supposed to mean "precipitation is rather low…" I have changed the word "dry" to "low"

P.3136 l.27 – Please avoid to write that temperatures are cooler/colder/warmer. Indeed a region can be cooler/colder/warmer than another but temperatures can only be larger/smaller/lower ...

Thank you. Noted.

P.3137 l.20 – Is this for Lake E or for Beringia or for the Arctic?

This is for Lake-E. I added the location within that sentence.

P.3137 l.7 – When? In summer or in July or in annual mean?

Summer = mean JJA precipitation. This has been fixed and made clearer.

P.3138 l.12 – ppmv instead of ppm_V.

Thank you. Noted.

P.3138 l.15 - Is this for Lake E or for Beringia or for the Arctic? As long as there is a 2°C difference between PI and Modern simulation, it is difficult to understand that the comparisons to PI and to Modern are similar. Please explain.

Added that the location of this comparison is Lake-E.

P.3138 l.20 - Is this for Lake E or for Beringia or for the Arctic?

This is for Lake-E as well. This has been cleared up.

P.3138 l.26 – The reference to Fig4c is not correct.

Fixed. This should have read Fig 3c.

P.3139 l.14 – What does 'mean annual summer temperature' refer to?

This represents JJA averaged temperatures. This has been fixed.

P.3140 l.9 – Is modern value 478mm yr^{-1}?

Modern values are 475 mm yr^{-1}. Thank you. This has been corrected.

P.3140 l.11 – The reference to Fig4d is not correct.

This has been corrected to Fig 3D.

P.3141 l.2 - Is this for Lake E or for Beringia or for the Arctic?

This is for Lake-E. Thank you. This has also been fixed.

P.3141 l.7 – Is it really for the Arctic? I thought that it was for Lake E.

This is for Lake-E. This has been fixed.

P.3141 l.21 – 'more than' instead of 'more then'. What is the reference here? 150mm yr^{-1} decrease compare to what?

This was not made clear but has been fixed. The comparison was with respect to the integration without large NH ice sheets.

P.3142 l.13, l.16 – This seems to contradict numbers previously given. I am sure that this will be immediately clarified with the revised tables. There are three MIS-11c simulations. Which one is referred to here?

Revised tables will clear this up. This sentence refers to the MIS 11c runs w/o a Greenland Ice Sheet (MIS11NG).

P.3142 l.21-22 – What do the authors mean with 'thermal maximum are variable'? Does it mean that thermal maximum has a large variability measured with a large standard deviation? In that case, why could the authors conclude that it is large? What is their reference for such a conclusion? 'smaller anomalies reconstructed ...' Which anomalies are the authors discussing? What is the reference, i.e smaller than what? Why is it so?

Great questions. We have revised this sentence to make it clearer. Thank you.

P.3143 l.3 – 'a reduction in the Greenland Ice Sheet adding 1.6 to 2.2 m of equivalent sea level rise'. Adding water to what? To which reference sea level?

Colville et al., 2011 states that analysis of sediment sources during the LIG relative to the early Holocene denote greater southern GIS retreat during the LIG. This is consistent with a suite of GIS models and a GIS contribution of 1.6 to 2.2 meters to the >= 4-meter LIG sea level global highstand.

P.3143 l.6 – 'the thickness decreased by '. Once more, what is the reference? A decrease from what?

NEEM concluded the decrease of 400 ± 250 meters reached surface elevations of 130 ± 300 meters lower than present ~ 122 ka years ago. Therefore, surface elevations 122,000 years ago were anywhere from +170 m higher than modern to 430 meters lower than modern surface GIS elevations. This was fixed and made clearer in the manuscript.

P.3144 l.5 – In this simulation, the authors increased the heat flux convergence under sea ice in the Arctic Ocean. I assume that the reduction in sea ice fraction and the summer warming are not prescribed but rather a consequence of the increased heat flux. This should be made clear. The reference to Fig3a is not correct.

Excellent suggestion. This has been fixed.

P.3144 l.21 – Is this statement valid for MIS11 (i.e. deduced from the comparison between MIS11GIS and MIS11NG) or is it more general (deduced maybe from additional simulations not shown)?

These statements are valid for MIS11 numerical model simulations

P.3145 l.13 – 'atmospheric CO_2 was higher'. Higher than what? I suggest that the authors explain in more details what they have in mind with this sentence.

The sentence is comparing the MIS 31 with the late Pleistocene interglacials, which start at the Eemian. The sentence should say:

"Elevated GHG concentrations and a very warm orbit with a large precession can explain much of the warmth during MIS-31, assuming atmospheric CO_2 was higher than MIS-11 and the late Pleistocene interglacials (Hönisch et al., 2009)."

P.3145 l.23 – It was stated that PANN for the Modern simulation was 475mm yr^{-1}. This is NOT 350mm yr^{-1}less than 600mm yr^{-1}. This should be clarified.

Fixed. This has been clarified.

P.3146 l.6 – Starting from here, the discussion focuses on the 116K simulations. This should appear more clearly in the text.

We will use a heading to differentiate the discussion topics.

P.3146 l.19 – The authors seems to explain the aridity during the 116K simulations with more frequent storms. Actually, I would guess that more frequent storms would drive more precipitation. Can this be clarified?

Storm track during this period has been shifted south along the southern coast of west and east Beringia. The storms, due to synoptic changes attributed to the ice sheets, never make it more northward than the southern coast of Beringia essentially drying out the Lake-E region and the Arctic interior.

P.3146 l.26 - The reference to Fig6a and b is not correct, at least if the discussion is still about July. If not, this must be clearly stated.

This section has been removed from our paper. We had difficulty making this section fluid with the rest of the paper.

P.3147 l.8 - Is this for Lake E or for Beringia or for the Arctic?

Clarified this point. It was in relation to Lake-E.

P.3148 l.1-4 – I assume that this comes from data (observation) or did one/several of the simulation account for changes in the GIS?

This is demonstrated in our model simulations where when the GIS is removed, Greenland surface temperatures increase but Lake-E regional temperatures are not affected.

P.3153 - I already made suggestions and comments about table1. Here are a few additional ones. It is written that 'precession is Ω'. Ω must be defined and the units must be provided. It is written that 'temperatures are mean July temperatures'. I assume that they are for Lake E. There is no explanation about Prec in the caption. The reader can but assume that it is annual mean precipitation simulated at Lake E. Is this correct? The obliquity at MIS1 may be 24.229 instead of 24.29. This should be checked.

Precession is now defined in the table (degrees). Precession is also no defined for the reader. Obliquity of MIS-1 is 24.229 – this has been corrected. Thank you.

P.3155 - Which calendar is used for this plot? Orbital calendar? Present-day calendar (360 or 365 days)? The resolution of the plot seems to be better than 'monthly' or is it the interpolation from the graphic tool?

The calendar used in this plot is a normal present-day calendar with monthly data averaged over latitude. Contour intervals are in 10's therefore contour distribution looks rather dense.

P.3156 – Are these plots for annual, summer or July temperature? 'Area of no shading (white)'. I am sorry, I do not understand what this mean. Actually the white shading, according to the color bar, corresponds to zero warming. It is therefore difficult to imagine how it also represents statistically significant anomalies. At last it is surprising to label these figures as **warming** relative to PI while there is also cooling.

The difference with respect to Pre-Industrial is mostly red indicating temperatures that are warmer than Pre-Industrial simulations. There is some blue shading along the eastern Beringia coast, but it is on the order of >1 °C. These cooling areas could be noise in the model data making them insignificant. Most of the circum-Arctic is warmer by a few degrees.

P.3157 – Figure A is most probably pre-industrial vegetation rather than modern vegetation. It should be mentioned if figure D is MIS11GIS or MIS11NG.

Thank you for your suggestion; this has been fixed.

P.3159 – What is Polar MM5 regional climate model? It is not discussed in the main text.

*****This section has been removed from our paper*****

The polar MM5 is a regional atmospheric model, with high spatial resolution and multiple options for physical parameterizations. Polar MM5 is the Pennsylvania State University-National Center for Atmospheric Research (PSU-NCAR) Mesoscale Model (MM5; Dudhia 1993; Grell et al., 1994) adapted for simulations over Polar Regions (Bromwhich et al., 2001; Cassano et al., 2001). We did not go into depth about the Polar MM5 model because it was not fundamental to our simulations.

P.3161 – The caption indicates that figures show anomalies with respect to the simulations without NH ice sheet. Actually, anomalies can be computed with respect to one simulation (at least one at a time). Which simulation (name) is used here? Strictly speaking 'MTCM temperature' is a bit awkward, indeed when the acronym is expanded it reads Mean Temperature of the Coldest Month temperature.

*****This section has been removed from our paper*****

Thank you. This caption has been fixed. Simulations with northern hemisphere ice sheets and without northern hemisphere ice sheets are now correctly named with their experimental name.

"MTCM temperatures" has been changed. We removed the word "temperatures".

Responses to Anonymous Reviewer #2

Reviewer's comments in **black**
Authors' comments in red

***** As of 2/25/2015*****

Dear Reviewer,

Thank you very much for your comments and suggestions. All of your suggestions (in both text and figures) have been used. Thank you. You should see a new version of our manuscript with changes. Please see the markuped version.

Changes:

- Title changes more relative to what we were discussing in the body of the text.
- Re-done figure showing Lake E temperature and precipitation values with corresponding model data (see Figure 5).
- Table corresponding to temperature and precipitation values for clarity (Table 2)
- Table corresponding to all model simulations for clarity and less confusion (Table 1).
- Various grammar and wording changes in the body of the text to ensure clarity and avoid confusion.
- Removed section on "Modern" control to avoid confusion. The control simulation is the Pre-Industrial simulation.
- Re-ran model simulations (including vegetation) out to ~80 years to ensure equilibrium. Differences between periods are now shown to be significant at the 95% confidence interval with a very low p-value (~0.29). (See Figures 2 and 3)
- Additional references added to support statements.
- Removed section on glaciation at 2.7 Ma.

Comments:

The text needs to be more precise and focused as at the moment it feels somewhat rushed. Furthermore, it is not at all obvious what is new analysis compared with the Melles et al. (2012) paper. Many of the statements/conclusions are very similar to this paper. Figure 2 has already been published in almost identical form in Melles et al. (2012) for example. It is important that the authors make it clear what new analysis they have performed for this work to be publishable. In addition, I was often confused whether the authors were discussing comparisons in relation to E-Lake, Beringia or the Arctic and relative to what reference? Modern or pre-industrial?

Thank you for your detailed and constructive comments. The text has been made more precise and clear in many parts of the manuscript. A very thorough and in-depth review is being made to ensure the revised manuscript does not cause any confusion. Additionally, tables have been re-done to also avoid or clear up any confusion readers may have. References in the body of the manuscript (with respect to anomalies) have also been made clearer.

Where is the E-lake record? There should at least be a figure showing this data for the relevant time relevant time periods as it so central to the paper. Furthermore, a separate map include the location would also be very useful.

Thank you for your suggestions. We will include temperature and precipitation reconstructions from the Lake-E core in our paper. A star on all figures denotes the location of Lake-E.

A table of temperature changes for different time periods at E-Lake/Beringia etc. from data and model would be useful. It is somewhere confusion what is being compared with what in the text. For example, temperatures are quoted for different months regions etc. There does not appear to be a direct focus on E-Lake, which the title of the article implies – perhaps the title should be more general.

A new, revised table with temperature at Lake-E during our different time periods (simulations) has been made and will be in the new revised document. This table should now address many aspects that cause confusion in the manuscript. A more direct focus on Lake-E has been made clearer in the revised manuscript. Thank you for your suggestions.

The analysis of NH glaciation has no context as there is a sudden jump from discussion super interglacials to glacials and feels as if it has been appended at the end. Could this be revised so it fits better?

NH hemisphere glaciation was another simulation performed during our study to simulate temperatures and precipitation of NH glaciation and relate them to the Lake-E core. However, we agree that there it has little context with regards to the scope of this manuscript. We also found it difficult to tie in this section with the rest of the paper. Therefore, we have removed this section from our manuscript.

It would be beneficial to include spin-up plots of the simulations as this paper is focused on the modeling aspect of this work. Ten years is a short average time and may not be capturing the overall signal, as decadal variability is not taken into account. Furthermore, the slow components of the land surface (i.e. trees) often require > 1000 years to reach equilibrium. Is there some sort of acceleration forcing for the vegetation component?

This is a great comment and is very much appreciated. In response to your comment and question, the GCM is running with a 50m-slab ocean component. The slab ocean GCM spins up within the first few decades. The same can be said for the vegetation model. Our vegetation model is an interactive vegetation model as opposed to a dynamical vegetation model. Based on my experience with this GCM in slab ocean mode, it spins up rather quickly. Ttest done on 11 years of annual temperatures at the lake show that the values are significant at the 95% confidence interval with a $p<0.05$. The vegetation model calculates the biome distribution in each grid cell relative to last years (model time) climatology (temp, precip, humidity etc.) and picks the appropriate biome based on a biome ranking system in the vegetation model instead of actually growing trees. Therefore, the vegetation model does have an acceleration-type feature component.

Please be consistent with the use of acronyms. Once stated use the abbreviation. Also some have been stated twice.

Thank you. This has been noted.

The introduction states that the results are assessed in terms of teleconnections implied by other far field records including Antarctica. However, I see very little evidence for this type of analysis with the only mention of Antarctica in terms of previous studies and the conclusions presented in Melles et al. (2012). If this is to be included there should be a more thorough examination of these teleconnections with the SH and not just a repetition of what is written in Melles et al. (2012).

Thank you for your comments. You are correct and we have edited these statements so that they fit into the scope of our manuscript.

Although the authors have included the yin & Berger (2012) reference other references such as Lunt et al. (2013) and Bakker et al. (2013) could be included when discussing the results in comparison to other studies.

Thank you for the suggestion. We will insert these references to further solidify our findings.

Detailed comments

P3128, line 7: is the temperature for MIS 11c (0.5˚C) correct? Why have you only quoted three temperatures and not four corresponding to the four interglacials?

We have added the comparison for MIS-1 vs. modern temperature. Noted. Thank you.

P3128, line 10: "extraordinary warmth compared with other interglacials" – not according to the value stated on line 7. Also, this is not very clear. I assume you mean extraordinary warmth considering the moderate orbital forcing and GHG concentrations compared with other interglacials?

Here, the extraordinary warmth refers to the Lake-E core proxy reconstructions of temperature. This has been made clearer.

P3129, line 6: What do you mean by "long" terrestrial archives? Context might be useful.

"Long terrestrial archives" refer to temporally long terrestrial archives.

P3129, line 11: Current trends in what? Temperature, precipitation?

This refers to climate trends such as temperature and precipitation. This has been fixed and made clearer. Thank you.

P3131, line 6-7: 30 to 40 year equilibrium run is very short as is the ten year average (please see comment above).

Please see comment above.

P3131, line 9-10: Warmest monthly mean climate (July). Is this always July for all simulations?

Yes. When referring to temperature of the warmest month, it is July for all simulations.

P3131, line 19: Younger-Dryas –state when the end of this event occurred.

Noted. Thank you.

P3132, line 7: the 8˚C warming at NEEM actually has a large uncertainty of ±4˚C. Please include this.

Noted. Thank you.

P3132, line 16: Please remove "on" from "on the on"

Fixed. Thank you.

P3132, line 17: Insert "extent" after "sea ice"

Fixed. Thank you.

P3132, line 21-24: This paragraph needs re-writing as it is not at all clear. For example the orbital parameters are calculated from the Berger solution and not estimated and GHG concentrations are measured.

Fixed. Thank you.

P3133, line3: Please be more precise. The phrase "apparently" implies that you are not sure the statement you are making is true or not.

Fixed. Thank you.

P3133, line 27-28: Please modify to include what the prescribed distributions are of.

Fixed. Thank you.

P3135, line 10: Insert "air" in front of "temperature".

Fixed. Thank you.

P3135, line 11: Insert rate after "precipitation".

Fixed. Thank you.

P3136, line 19: Please be more precise –either the mixed forest types dominate further south or they do not in the simulation ("not seem to dominate…")

Fixed. Thank you.

P3136, line 16: Remove the capital "S" from "South"

Fixed. Thank you.

P3137, line 3: Remove "the" from "…for the most…"

Fixed. Thank you.

P3137, line 8: The minus signs in front of 2 and 20 are not necessary.

Fixed. Thank you.

P3138, line 17-19: Firstly, the uncertainty of the NEEM ice core measurement puts the value of 5˚C within the measured range of temperature change for MIS5e. Secondly, the comparison with modern day suggests that the temperature difference over Greenland relative to preindustrial is 4˚C which seems very high. Could this be an artefact of your averaging time period for the simulations? Otherwise, I have misinterpreted your sentence.

Thank you for this point. The sentence is not clearly articulated. MIS-5e summer temperatures (JJA) with respect to Pre-Industrial (JJA temperatures) show a warming of +5 °C over GIS and the same comparison with respect to Modern (JJA temperatures) only shows a ~2 °C warming over the GIS. Modern simulation with respect to Pre_Industrial simulation in our model only shows a 1.8°C difference in summer temperatures. We have edited this statement so that it is clearer to the audience.

P3139, line 8: Change "replace" to "replaced"

Fixed. Thank you.

P3139, line 9: "Additional experiments involving sea ice extent…" This is unclear. Please be more explicit and state that it is the sub-sea ice heat flux you are changing which affects the sea ice extent.

Fixed. Thank you.

P3139, line 11-15: It is unclear whether you are referring to the data or the model. Please make sure you state what source you are talking about.

Fixed. Thank you.

P3139, line 26: Remove “an” before 2a mostly ice-free…”

Fixed. Thank you.

P3140, line 6: The Arctic Ocean is dry compared with what?

Compared with modern observations.

P3140, line 9: I suggest not using the phrase “exactly matching…”

Noted. Thank you.

P3140, line 28: change “record” to “records”

Fixed. Thank you.

P3143, line 3: Please update the current estimate of Greenland ice sheet contribution to sea level rise in line with the IPCC (2013) report (1.4 to 4.3 m). References such as Stone et al. (2013), Robinson et al (2011), Quiquet et al. (2013) should be included.

Thank you for this suggestion. We have addressed these citations.

P3145, line 15: What do you mean by “thick” needle-leaf and deciduous forests?

Thick should mean dense. This has been fixed. Thank you.

P3145, line 29: You have already used the acronym WAIS previously so do not need to define again.

Thank you. Fixed.

Figure 1: Are these plots using a fixed month calendar?

Yes. This is a fixed month calendar.

Figure 2: Do you mean areas of no shading are NOT statistically significant at the 95% level. Also do they represent annual, July, summer anomalies?

Yes, this is what we mean. We have clarified this. Thank you.

Figure 3: please state that D is with the ice sheet removed.

Fixed. Thank you.

Figure 4: What is the reference for the summer sea surface temperature anomalies? Also state the time period these plots represent.

The temperature difference is with respect to the same run with the default sub-surface heat flux.

A GCM Comparison of Plio-Pleistocene SuperInterglacial Periods in Relation to Lake El’gygytgyn, NE Arctic Russia

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Abstract

Until now, the lack of time-continuous, terrestrial paleoenvironmental data from the Pleistocene Arctic has made model simulations of past interglacials difficult to assess. Here, we compare climate simulations of four warm interglacials at Marine Isotope Stage (MIS) 1 (9ka), 5e (127 ka), 11c (409 ka), and 31 (1072 ka) with new proxy climate data recovered from Lake El’gygytgyn, NE Russia. Climate reconstructions of the Mean Temperature of the Warmest Month (MTWM) indicate conditions up to 0.4, 2.1, 0.5 and 3.1 ºC warmer than today during MIS 1, 5e, 11c, and 31, respectively. While the climate model captures much of the observed warming during each interglacial, largely in response to boreal summer orbital forcing, the extraordinary warmth of MIS 11c relative to the other interglacials in the Lake El’gygytgyn temperature proxy reconstructions remains difficult to explain. To deconvolve the contribution of multiple influences on interglacial warming at Lake El’gygytgyn, we isolated the influence of vegetation, sea ice, and circum-Arctic land ice feedbacks on the modeled climate of the Beringian interior. Simulations accounting for climate-vegetation-land surface feedbacks during all four interglacials show expanding boreal forest cover with increasing summer insolation intensity. A deglaciated Greenland is shown to have a minimal effect on Northeast Asian temperature during the warmth of stage 11c and 31 (Melles et al., 2012). A prescribed enhancement of oceanic heat transport into the Arctic Ocean

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does have some effect on Lake El’gygytgyn regional climate, but the exceptional warmth of MIS-11c remains enigmatic relative to the modest orbital and greenhouse gas forcing during that interglacial.

1. Introduction

Knowledge of Pleistocene climate history has increased dramatically over the past three decades, however existing records remain strongly biased toward an oceanic viewpoint, due to the lack of long terrestrial archives. In the context of future warming, it is clearly important to understand the effects of warming on the terrestrial Arctic, the strength of polar amplification, and systemic teleconnections to and from other latitudes. Past warm periods known as Interglacials, over the past 2.8 million years, provide a means of studying climates warmer than today.

In 2009, a multinational team drilled a sediment core from a 25 km wide impact crater lake named “Lake El’gygytgyn” (alternatively, Lake “E”), in northeast Siberia (Brigham-Grette et al., 2013; Melles et al., 2012). The core contains the longest Arctic terrestrial record ever recovered, extending back ~3.5 million years, and provides evidence for periods of exceptional warmth during Pleistocene interglacials as defined by marine benthic $\delta^{18}O$ records (Lisiecki and Raymo, 2005) (Figure 5A&B). It has been shown that Marine Isotope Stage(s) 1, 5e, 11c and 31 were among the warmest interglacials in the Pleistocene Arctic (Melles et al., 2012).

To explore the sensitivity of northwestern Beringia to interglacial forcing and the mechanisms responsible for the observed climate changes, we use a Global Climate Model coupled to an interactive vegetation model to simulate the terrestrial Arctic’s response to the greenhouse gas and astronomical forcing associated with specific interglacial (e.g., Yin and Berger, 2011). A range of sensitivity tests were performed and a range of changes in boundary conditions are imposed to test the response of the region to changes in circum-Arctic ice sheets and possible changes of ocean heat transport into the Arctic Ocean. The results are then compared to the Lake E multi-proxy reconstructions.

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2. Model and experimental design

All global climate simulations discussed herein were performed using the current version of the Global ENvironmental and Ecological Simulation of Interactive Systems (GENESIS) Global Climate Model (GCM) version 3.0 (Alder et al., 2011; Thompson and Pollard, 1997). GENESIS is an atmosphere, land-surface, ocean, snow, sea ice, ice sheet and vegetation coupled model. As used here, spectral resolution of the atmosphere GCM is T31 resolution (approximately 3.75° resolution) with 18 vertical levels (Thompson and Pollard, 1997). The AGCM is coupled to 2°x2° soil, snow, vegetation, ocean, and sea ice model components. The GCM is interactively coupled to the BIOME4 (Kaplan, 2003) vegetation model that predicts equilibrium vegetation distribution, structure and biogeochemistry using monthly mean climatologies of precipitation, temperature and clouds simulated by the GCM. Vegetation distributions take the form of 27 plant biomes including 12 plant functional types (PFTs) that represent broad, physiologically distinct classes (Kaplan, 2003). GENESIS includes options for coupling to an Ocean General Circulation Model (Alder et al., 2011) or a non-dynamical, slab ocean model that incorporates heat transfer, calculations of sea-surface temperatures (SST) and feedbacks operating between ocean surface and sea ice. The slab mixed layer ocean model is used here to allow multiple simulations to be performed with and without imposed perturbations of surface ocean conditions. This version of the GCM has a sensitivity of 2.9 °C, without GHG, vegetation or ice sheet feedbacks. Greenhouse gasses and orbital parameters for each interglacial simulation were prescribed according to ice core records (Loulergue et al., 2008; Lüthi et al., 2008; Schilt et al., 2010) and standard astronomical solutions (Berger, 1978).

The strategy adopted here was to target Marine Isotope Stage (MIS) 1 (11 ka), 5e (127 ka), 11c (409 ka) and 31 (1072 ka), corresponding to the timing of peak summer warmth observed at Lake E and identified as "super-interglacials" by Melles et al., (2012). Equilibrium simulations were performed at the time of peak boreal summer insolation at 67.5°N (Laskar et al., 2004) assuming the real climate system equilibrated within a half-precession cycle. Model temperature and precipitation values were calculated from 20-year averages taken from the 60 to 80-year equilibrated simulations.

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Preliminary analysis of pollen assemblages in the Lake E core is assumed to provide a record of peak summer temperatures, so our data-model comparisons focus on warmest monthly mean climate (July). A simulation of pre-industrial climate (280 ppmv $p\mathrm{CO}_2$) was run as a control experiment to evaluate the model's representation of Beringian climate and to provide a baseline for comparing super-interglacial simulations. A modern Greenland Ice Sheet (GIS) is prescribed unless otherwise noted. In simulations without a GIS, the ice sheet is replaced with ice-free, isostatically equilibrated land surface elevations.

2.1 MIS 1, 9 ka

MIS-1 represents the last 11,000 years and its onset roughly coincides with the end of the Younger-Dryas (~11,500 ka). Peak boreal summer insolation occurs ~9 ka, when summer insolation was ~510 Wm^{-2} at 65 °N, relative to 446 Wm^{-2} today. Proxy indicators suggest conditions were warmer than present (+1.6 °C over western Arctic and +2 to 4°C in circum-Arctic) with lush birch and alder shrubs (Melles et al., 2012) dominating the vegetation around the lake. This period, known as the Holocene Climate Optimum (HCO), was spatially variable, with most warming in the high latitudes, and minimal warming in the mid-latitudes and tropics (Kitoh and Murakami, 2002).

2.2 MIS-5e, 127 ka

MIS-5e, also known as the Last InterGlaciation (LIG), is one of the warmest interglacials of the Pleistocene and lasted roughly ~12-10 kyr (130 to 116 ka). High obliquity, eccentricity and the timing of perihelion (precession) combined to produce high intensity boreal summer insolation at around 127 ka. Greenland ice core records (Dahl-Jensen and NEEM community members, 2013) suggest summer warming up to 8±4 ºC over northeast Greenland, but only a modest reduction in the size of the Greenland Ice Sheet (GIS). Studies involving Sr – Nd – Pb isotope ratios of silt-sized sediment discharged from southern Greenland suggest that no single southern Greenland geologic terrain was completely deglaciated during the LIG, however, some southern GIS retreat was evident (Colville et al., 2011). A previous model study of MIS-5e by (Yin and

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Berger, 2011) involved running a model of intermediate complexity to test relative contributions of Greenhouse Gas (GHG) and insolation forcing on LIG warmth. They found that GHGs play a dominant role on the variations of the annual mean temperature of both the globe and the southern high latitudes, whereas, insolation plays a dominant role on precipitation, northern high latitude temperatures, and sea ice extent (Yin and Berger, 2011). Similarly, model simulations have shown that insolation anomalies during MIS-5e likely caused significant summer (JJA) warming throughout the Arctic (Bakker et al., 2013; Lunt et al., 2013; Otto-Bliesner et al., 2006).

The LIG simulation shown here is used to compare paleoenvironmental conditions in western Beringia, including, temperature, vegetation and precipitation, to Lake E pollen proxy analysis. Orbital parameters and greenhouse gas concentrations are set at their 127 ka values to represent peak boreal warmth during MIS-5e.

2.3 MIS-11c, 409 kyr

MIS-11c is another exceptionally warm interglacial (Howard, 1997) that lasted from 428 to 383 ka (~45 ka). Sediment records from the Arctic containing information on MIS-11 are generally lacking (Miller et al., 2010b). Unlike the other interglacials, MIS-11c was remarkably long, with two boreal insolation maxima at ~409 ka and 423 ka, creating extensive warmth throughout the Arctic (Melles et al., 2012). Unlike MIS-5e, there is evidence that the GIS may have been much reduced in size (Raymo and Mitrovica, 2012; Willerslev et al., 2007), with lush boreal forest covering most of southern Greenland (de Vernal and Hillaire-Marcel, 2008). Particularly warm conditions are also suggested by pollen records analyzed from Lake Biwa (Tarasov et al., 2011) located in Shiga Prefecture, Japan. Likewise, a study from Lake Baikal also indicates warmer than modern temperatures with a "conifer optimum" suggesting warmer conditions, and less aridity, perhaps influenced by higher sea levels and reduced continentality (Prokopenko et al., 2010).

Three different simulations (Table 1, 2) were run to test the sensitivity of the lake region to MIS-11c forcing. The first simulation uses default boundary conditions, including a modern GIS (MIS11GIS). The second simulation tests the sensitivity of the

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Lake E region to an ice-free Greenland (MIS11NG). In this simulation, the entire GIS was removed and topography of Greenland was corrected for glacial isostatic adjustment. The final sensitivity experiment includes an increase in sub-sea ice surface heat flux from 2 Wm^2 in our modern control, to 10 Wm^2 (additional +8 Wm^2) to test the Beringian sensitivity to a mostly ice-free Arctic Ocean. The increased heat flux assumes an extreme ~3 Sverdrup (Sv) increase in Bering Strait through flow and a 4 °C temperature contrast between North Pacific and North Polar surface water (Melles et al., 2012, supplemental). The additional heat flux convergence is used to crudely mimic the influence of a wider and deeper Bering Strait during times of higher sea level. Using the predictive BIOME4 interactive vegetation model, direct comparisons of observed and modeled Arctic vegetation within the Lake E region can be made. Furthermore, simulations using prescribed distributions of biome flora can be used to quantify the local effect of changing vegetation cover around the region.

2.4 MIS-31, 1072 ka

MIS-31 (~1062-1082 ka) (Lisiecki and Raymo, 2005) has only been identified in a few Arctic records prior to Lake E. The Interglacial represents one of the last 41-kyr glacial cycles and is best known for extreme warmth in circum-Antarctica ocean waters induced by a deterioration of the Polar Front (Scherer et al., 2008) and the collapse of the marine based West Antarctic Ice Sheet (WAIS) (DeConto et al., 2012; Pollard & DeConto, 2009), by intrusion of warm surface waters onto Antarctic continental shelves. On Ellesmere Island, Fosheim Dome includes terrestrial deposits that date to ~1.1 Ma, which contains fossil beetle assemblages dated within MIS-31, suggesting temperatures of 8 to 14 °C above modern values (Elias and Matthews Jr., 2002). It is speculated, like MIS-11c, that the Arctic may have been too warm to support a GIS which may have been substantially reduced in size, or possibly nonexistent (Melles et al., 2012; Raymo and Mitrovica, 2012). Therefore, simulations of MIS-31 are run both with and without a GIS (Table 1, 2).

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3. Results

3.1 Control Simulations

3.1.1 Pre-Industrial

Simulations of preindustrial 2-m mean annual temperature (MAAT) and MTWM at Lake E are -12 and 10.3 °C respectively, -3 °C and -1.7 °C lower than the modern simulations. Preindustrial summer temperatures (8 °C) are -2.2 °C lower than modern. GHG radiative forcing from a combination of CO_2, CH_4, and N_2O atmospheric mixing ratios implies a 1.8 Wm^{-2} reduction relative to modern, accounting for most of the cooling in the preindustrial simulation. Generally, mean annual precipitation (PANN) values in the cooler, preindustrial simulation are slightly lower than modern precipitation. At Lake E, preindustrial annual precipitation was 438 mm $year^{-1}$, substantially wetter than observations (+122 mm $year^{-1}$). Winter (DJF) precipitation in the preindustrial simulation was ~24 mm $month^{-1}$, while mean summer (JJA) precipitation was 43 mm $month^{-1}$.

Simulated pre-industrial vegetation distributions are assumed to be in equilibrium (Fig. 3A). In the preindustrial simulation, shrub tundra dominates the Lake E region, with evergreen taiga and deciduous forests maintained in interior Siberia and Yukon. Simulated Siberian biome distributions are similar to modern day vegetation described by Kolosova (1980) and Viereck & Little Jr (1975). Shrub tundra in the preindustrial simulation can be attributed to cool and dry Arctic conditions in the preindustrial run.

3.2 Paleoclimate simulations

3.2.1 MIS-1 (9 ka); Holocene Thermal Maximum

July temperatures at Lake E in the MIS-1 simulation (12.4 °C) are ~2.1 °C warmer than preindustrial (10.3 °C) and summer (JJA) temperatures are 1.6 °C warmer (Fig. 2A). Overall, the Siberian interior warms > 5 °C in July, relative to preindustrial. Simulated MTWM exceed > 2 °C around Lake E.

Simulated MIS-1 PANN values at the lake (~438 mm $year^{-1}$) are close to preindustrial values, although somewhat drier conditions dominate further inland, possibly as a result attributed increased proximity away from a moisture source.

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Simulated vegetation around Lake E is close to the transition between dominant shrub tundra to the east and deciduous forest to the west (Fig. 3B).

3.2.2 MIS-5e (127 ka)

Overall warming of the Beringian interior in the MIS-5e simulation is > 2 °C relative to preindustrial temperatures (Fig. 2B). Most of this warming can be attributed to the direct effects of the MIS-5e orbit (Groll et al., 2005; Langebroek and Nisancioglu, 2014), which produces an Arctic summer insolation anomaly of >50 Wm^{-2} at the top of the atmosphere, relative to a pre-industrial (modern) orbit (Fig. 1B). According to ice core records, carbon dioxide (CO$_2$) concentrations during this period were about 287 ppmv, contributing 0.132 Wm^{-2} more surface radiative forcing than preindustrial, but the combination of CO$_2$, CH$_4$, and N$_2$O attributes just -0.0035 Wm^{-2} forcing relative to preindustrial GHG mixing ratios.

Comparing MIS-5e with respect to the preindustrial control simulation at Lake E shows differences in summer (JJA) and MTWM temperatures of +2.5 and +4.2 °C, respectively (Fig. 2B). Summer warming over the GIS is +5 °C relative to preindustrial, which is comparable to the LIG warming reported in a recent Greenland ice core study (Dahl-Jensen and NEEM community members, 2013). Mean annual precipitation at Lake E (~401 mm year^{-1}), is 37 mm year^{-1} less than pre-industrial levels, and the difference is statistically significant at the 95% confidence level with a p-value of 0.029. Overall, similar precipitation patterns are seen at Lake E, relative to MIS-5e and the pre-industrial control scenario, which reflects both the overall wet bias in the GCM and the similar continental/ice sheet boundary conditions, in both simulations.

A less moist, but warm high latitude environment produces deciduous taiga and evergreen taiga biome distributions around Lake E (Fig. 3C), with evergreen taiga being the most dominant in eastern Beringia and deciduous taiga being more dominant around the Lake E region and most of western Beringia.

3.2.3 MIS-11c (409 ka)

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Due to an eccentricity minimum, MIS-11c is a longer interglacial than the other interglacials in this study (Howard, 1997). We assume an ice-free Greenland in our MIS-11c simulations, with the ice sheet removed and replaced with isostatically equilibrated (ice-free) land elevations. Additional experiments including an imposed increase in sub-sea ice heat flux in the Arctic Ocean basin will also be discussed.

Model simulations show summer insolation anomalies (relative to preindustrial) during MIS-11c ranging from +45 – 55 Wm^{-2} (Fig. 1C) allowing temperatures over the Lake E region during July (month of maximum insolation) to increase 2.2 °C relative to preindustrial. Overall, mean annual summer temperatures (JJA) over the circum-Arctic and Lake E are 2 to 4 °C warmer than pre-industrial temperatures, with the Siberian interior warming the most (Table 2).

In MIS-11c simulations performed with (MIS11GIS) and without a GIS (MIS11NG), the effect on temperature at the Lake E is shown to be small (~0.3 °C). Geopotential height anomalies at 500hPa (+4 – 10 meters) indicate upper-level warming east of Lake E, and cooling west of Lake E, but the net effect of ice sheet loss on surface air temperatures is mostly limited to Greenland itself and the proximal ocean, with little effect at the distance of Lake E, as shown in other modeling studies (Koenig et al., 2012; Otto-Bliesner et al., 2006).

The warmer MIS-11c climate and possible reductions of Greenland and West Antarctic ice sheet sheets are thought to have contributed to sea levels as much as >11 meters (Raymo and Mitrovica, 2012) higher than today. Arctic sea ice was also possibly reduced (Cronin et al., 2013; Polyak et al., 2010). In order to test the influence of high sea levels and a mostly ice-free Arctic Ocean on Lake E climate, heat flux convergence under sea ice was increased from 2 Wm^{-2} to 10 Wm^{-2} in the slab ocean/dynamic sea ice model. The resulting reductions in sea ice extent and warmer (~ 0.2 – 1.0 °C) (Fig. 4A) Arctic SST's produced negligible warming around Lake E (< 0.7 °C), suggesting the Lake E region was relatively insensitive to Arctic Ocean conditions.

Precipitation amounts at Lake E during MIS11GIS are close to modern values of 475 mm $year^{-1}$. Also, MIS11NG exhibits the same precipitation amounts as our pre-industrial control run (~438 mm $year^{-1}$) (Table 2). Simulated precipitation conditions in the Arctic Ocean basin are fairly dry, ~200 mm $year^{-1}$, comparable to reanalysis data sets

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(Serreze and Hurst, 2000). On the contrary, simulations of MIS11NG show reduced precipitation amounts by -37 mm year^{-1} relative to MIS11GIS. Runs with increased sub-ice oceanic heat flux reduced the drying seen in the MIS11NG simulation and produced values matching rainfall rates of modern control values (~475 mm year^{-1}).

A warmer and wetter MIS-11c places Lake E on the border of evergreen taiga and shrub tundra biomes (Fig. 3D). Vegetation limits, such as tree lines, are slightly changed during our simulations with increased heat flux and a warmer, open Arctic Ocean. Evergreen forests around the Lake E region extend poleward to the coast and slightly eastward.

3.2.4 MIS-31 (1072 ka)

An extreme warm orbit with high obliquity, high eccentricity and precession aligning perihelion with boreal summer allows insolation anomalies to be > 50 Wm^{-2} at the surface and + 60 – 80 W m^{-2} (Fig. 1D) at the top of the atmosphere at the latitude of Lake E. Average summer temperatures around the lake are about +3.6 °C warmer than preindustrial (Fig. 2D; Table 2). While MIS-31 is beyond the temporal range of ice core greenhouse gas records, proxy geochemical records imply MIS-31 has the highest $p\text{CO}_2$ (~325 ppmv) of the mid-Pleistocene (Hönisch et al., 2009), contributing ~+0.80 Wm^{-2} relative to pre-industrial values. As a result, modeled July temperatures at Lake E are >5 °C warmer than pre-industrial temperatures.

Simulated precipitation at Lake E during MIS-31 is ~438 mm year^{-1} (Table 2), similar to that in MIS-11c simulations Vegetation distribution is similar to the other interglacials described here (Fig. 3E). The Lake E region is dominated by deciduous taiga with evergreen forest dominating to the east.

4. Discussion

The warm periods of Marine Isotope Stage(s) 1, 5e, 11c and 31 show similar changes around Lake E. Temperature reconstructions during the Holocene Thermal Maximum (9 kyr) indicate +1.6 (±0.8) °C warming in the western Arctic (Kaufman and

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Brigham-Grette, 1993) with an overall warming of 1.7 (±0.8) °C in the circum-Arctic (Miller et al., 2010a), relative to modern temperatures. Though our model does not fully account for all the warming during this period, it does produce the warming in the western Arctic as documented by Kaufman and Brigham-Grette (1993). With the decrease in Arctic moisture and low CO_2, deciduous and evergreen forests dominate the Arctic in the model, matching the dominant vegetation such as *Alnus, Betula* (nut bearing trees and fruits), *Poaceae* (grasses) and some birch and alder seen in the Lake E record (Melles et al., 2012).

Marine Isotope Stage 5e produced the greatest summer warming among the four interglacials simulated here. Comparisons with a preindustrial control run show that differences in MTWM at Lake E during MIS-1 and 5e (+2.1 and +4.2 °C) are similar to the changes seen in MIS11NG and 31 (+2.2 and +3.5 °C) (Table 2). Similar warming has been seen in other modeling studies showing that a high obliquity and high eccentricity with precession aligning perihelion with boreal summer will yield the warmest boreal summer temperatures (Koenig et al., 2011; Lunt et al., 2013; Otto-Bliesner et al., 2006; Yin and Berger, 2011). Strong insolation forcing at these latitudes cause July maximum temperatures to exceed pre-industrial temperatures by >2 °C. The 2–4 °C simulated MIS-5e warming in Siberia and Lake E has also been seen in proxy data compilations (CAPE, 2006; Lozhkin and Anderson (1995); Lozhkin et al. (2006)) and in simulations using a GCM without vegetation feedbacks. Most of the warming has been linked to the summer insolation anomaly associated with the MIS-5e orbit (Otto-Bliesner et al., 2006). The exceptional summer warmth of MIS-5e compared to other interglacials was previously thought to have caused a substantial reduction in the GIS, however, more recent work suggests the GIS contributed only ~1.4 to 4.3 m of equivalent eustatic sea level rise during the LIG (Colville et al., 2011; Quiquet et al., 2013; Robinson et al., 2011; Stocker et al., 2013; Stone et al., 2013), and remained mostly intact (Dahl-Jensen and NEEM community members, 2013). This suggests that our simulations of MIS-5e with a modern GIS are a good approximation for this period. Colder and fresher sea surface conditions in the North Atlantic, Labrador and Norwegian Seas have been found in marine sediments records possibly indicating freshwater input (perhaps from parts of Greenland) which may have led to early LIG warming attributed to stronger ocean overturning

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(Govin et al., 2012). In the model, Arctic warming during MIS-5e allows almost a full replacement of shrub tundra with deciduous forest in and around the Lake E region. Pollen analysis during this period shows tree species of birch, alder, pine and spruce (Melles et al., 2012). However, multiproxy studies of MIS-5e show a change in MTWM of only +2 °C compared to modern temperatures (Melles et al., 2012) (Table 2). It can be concluded that the warm boreal summer orbit at MIS-5e can account for much of the warmth in Beringia and the cirum-Arctic, but the particularly muted response in the Lake E proxy record to summer insolation forcing cannot be fully explained.

Simulations of MIS-11c exhibit another very warm interglacial at Lake E, with MTWM maxima approaching +2.2 °C warmer than pre-industrial temperatures (Table 2). Similarly to MIS-5e and 1, peak warmth coincides with perihelion during boreal summer, however low eccentricity and obliquity attenuates the effects of precession relative to 5e and 1, making summer insolation less intense. A combination of eccentricity, obliquity and precession elevates summer insolation for ~45k years, a much longer (but less intense) interval of elevated summer insolation than during the other interglacials studied here. The overall warmth of MIS-11 is, in part, an outcome of reduced snow and ice cover.

Another possible mechanism contributing to Lake E warmth at MIS-11 might be related to elevated sea level at this time (Raymo and Mitrovica, 2012), possibly contributing to increased Bering Strait throughflow. Today, the Bering Strait is limited to ~50 m in depth with a net northward transport of ~0.8 Sv (Woodgate et al., 2010). Oceanic heat transport into the Arctic basin might have been elevated during high sea level, providing a source of warm water intrusion into the Arctic Ocean basin from the North Pacific. As a simple test of the potential for a warmer Arctic Ocean with less sea ice to affect temperatures over terrestrial Beringia, heat flux convergence under sea ice in the Arctic Ocean was increased from 2 to 10 W m^{-2}. Summer sea ice fraction was reduced by 25 – 50 % and summer ocean temperatures warmed by 0.2 – 1.0 °C (Fig. 4A,B). The warmer Arctic Ocean warmed the Lake E region, but only slightly (+0.7 °C), and does not account for the exceptional warmth observed during MIS-11c relative to MIS-5e.

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The influence of MIS-11c temperatures on terrestrial biome distributions is supported by a poleward advance of evergreen needle-leaf forest around the lake, which is in good agreement with palynological analysis (Melles et al., 2012) showing forest-tundra and northern larch-taiga dominated by spruce, pine, birch, alder and larch (Melles et al., 2012). Surface warming as a result of albedo feedbacks associated with needle-leaf forests during snow-covered months accounts for some of the warming during this period, however increased evergreen, terrestrial forest and enhanced evapotranspiration provides a slight net cooling during the summers.

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A deglaciated Greenland has been shown to have regional effects on SSTs and sea-ice conditions, however warming of the circum-Arctic has been shown to be minimal (Koenig et al., 2012; Otto-Bliesner et al., 2006). This is also demonstrated in our simulations, whereby the loss of the GIS warms summer annual temperatures around Lake E by only 0.3 °C (Table 2). An analysis of 500 hPa geopotential height anomalies show ridging (positive height anomalies of > 10 m) to the east and troughing (negative height anomalies) to the west of Lake E, indicating a slight change in the large-scale planetary wave patterns over Beringia. Over Lake E, positive height anomalies are also present, indicating slightly warmer conditions and a slight eastward shift of an atmospheric ridge that may have been set up further west of Lake E. The ridging in these simulations may also be related to a decrease in precipitation at Lake E when the GIS is removed in GCM. Extended high pressure over Beringia associated with ridging would create somewhat drier conditions for the region. If the exceptional warmth of MIS-11c is indeed related to the melting of the GIS, freshwater input may have been a mechanism to strengthen North Atlantic overturning creating the warmth missing in our simulations (Govin et al., 2012). Furthermore, it is not clear why the GIS would have survived MIS-5e warmth, and not MIS-11c. In sum, the exceptional Arctic warmth of MIS-11c remains difficult to explain and is not a straightforward result of greenhouse gases, orbital forcing, vegetation feedbacks, or Arctic Ocean warming.

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Elevated GHG concentrations and a very warm summer orbit can explain much of the warmth during MIS-31, assuming atmospheric CO_2 was higher than MIS-5e and MIS-11 (Hönisch et al., 2009). In the model, the combination of elevated greenhouse gases and strong summer insolation forcing at 1072 ka allow dense needle-leaf and

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deciduous forests to grow around the Lake. Simulated summer temperatures are about 12 °C (Table 2), +2 °C warmer than modern summer temperatures around Lake E. Biome simulations derived from pollen analysis of the Lake E core show a maxima of trees and shrubs during peak northern hemisphere insolation of MIS-31 at 1072 ka. Our model simulations show similar results around Lake E, with increased boreal forest and less tundra and small dwarf shrubs. The snow-albedo effect combined with low-albedo forest cover allows temperatures to increase in the Arctic during MIS-31. Peak precipitation rates derived from proxy analysis indicate about 600 mm year^{-1}, or about 125 mm year^{-1} more precipitation than in our modern model simulation (Melles et al., 2012). GCM results at MIS-31 indicate annual precipitation of ~490 mm year^{-1} (Table 2), the most annual precipitation among the four interglacials simulated here. While the GCM does not fully capture the enhanced precipitation indicated in the proxy record, a relative increase in precipitation is evident. Extraordinary warmth during MIS-31 correlates well with a diminished WAIS (Pollard and DeConto, 2009) implying strong inter-hemispheric coupling that has been related to possible reductions in Antarctic Bottom Water (AABW) formation during times of ice-shelf retreat and increased fresh water input into the Southern Ocean (Foldvik, 2004). WAIS collapse could also be linked with the Beringian and Lake E warmth during MIS-11c and MIS-5e, but definitive evidence of WAIS retreat during these later Pleistocene interglacials is currently lacking (McKay et al., 2012).

5. Conclusions

Lake E provides a high-resolution terrestrial proxy record of climate variability in the Arctic. A linked climate modeling study described here shows that Arctic summers were significantly warmer during several Pleistocene interglacials by as much as + 2 °C during MIS-1 and 11c, and by as much as + 4 °C during MIS-5e and 31 relative to pre-industrial. It can be inferred that most of the warming in the interglacial simulations can be attributed to a combination of elevated GHGs and astronomical forcing, although, astronomical forcing (at times producing high-intensity summer insolation >50 Wm^{-2} higher than today) was the dominant warming mechanism. Greenhouse gas levels during

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MIS-31 remain poorly known, and the extreme warmth of this particular interglacial could have been substantially augmented by GHG forcing. MIS-1 had relatively low CO$_2$ around the time of peak Holocene warmth, producing 0.44 Wm^{-2} less radiative forcing relative to pre-industrial levels (Melles et al., 2012), but the combination of orbital forcing and perhaps other factors such as changes in Antarctic Bottom Water (AABW) production and reduced Arctic sea-ice may have contributed to exceptional Arctic warmth at this time. Thorough testing of these ideas will require additional simulations with coupled atmosphere-ocean models, changes in circum-arctic ice sheets, eustatic sea-levels, continentality, changes in sea-ice distributions and the addition of melt-water inputs into northern and southern hemisphere oceans.

Extreme interglacial warmth shifted Lake E vegetation from mostly tundra with small shrubs as we see the Arctic today to thick, lush evergreen and boreal forest. Due to the extreme warmth, wetter conditions prevailed during the super-interglacials, allowing forest biomes to thrive and increase their maximum extent poleward. While simulated warming at Lake E is broadly similar during each interglacial, the vegetation response in each simulation is unique, reflecting differences in seasonal temperatures and hydroclimate. The GIS was significantly reduced during some interglacials (Stone et al., 2013), allowing summer temperatures to increase to almost 16 °C warmer than present over Greenland, but with limited impact on temperatures around Lake E. The observed response of Beringia's climate and terrestrial vegetation to super-interglacial forcing is still not fully understood and creates a challenge for climate modeling and for quantifying the strength of Arctic amplification. Among the interglacials studied here, MIS-11c is the warmest interglacial in the Lake E record, yet MIS-5e is the warmest simulated by the model. The model produces overall drier conditions in the earlier interglacials (11c and 31) than suggested by pollen analysis. If the proxy interpretations were correct, this would suggest that the model is missing some important regional processes. The timing of significant warming in the circum-Arctic can be linked to major deglaciation events in Antarctica, demonstrating possible inter-hemispheric linkages between the Arctic and Antarctic climate on glacial-interglacial timescales, which have yet to be explained.

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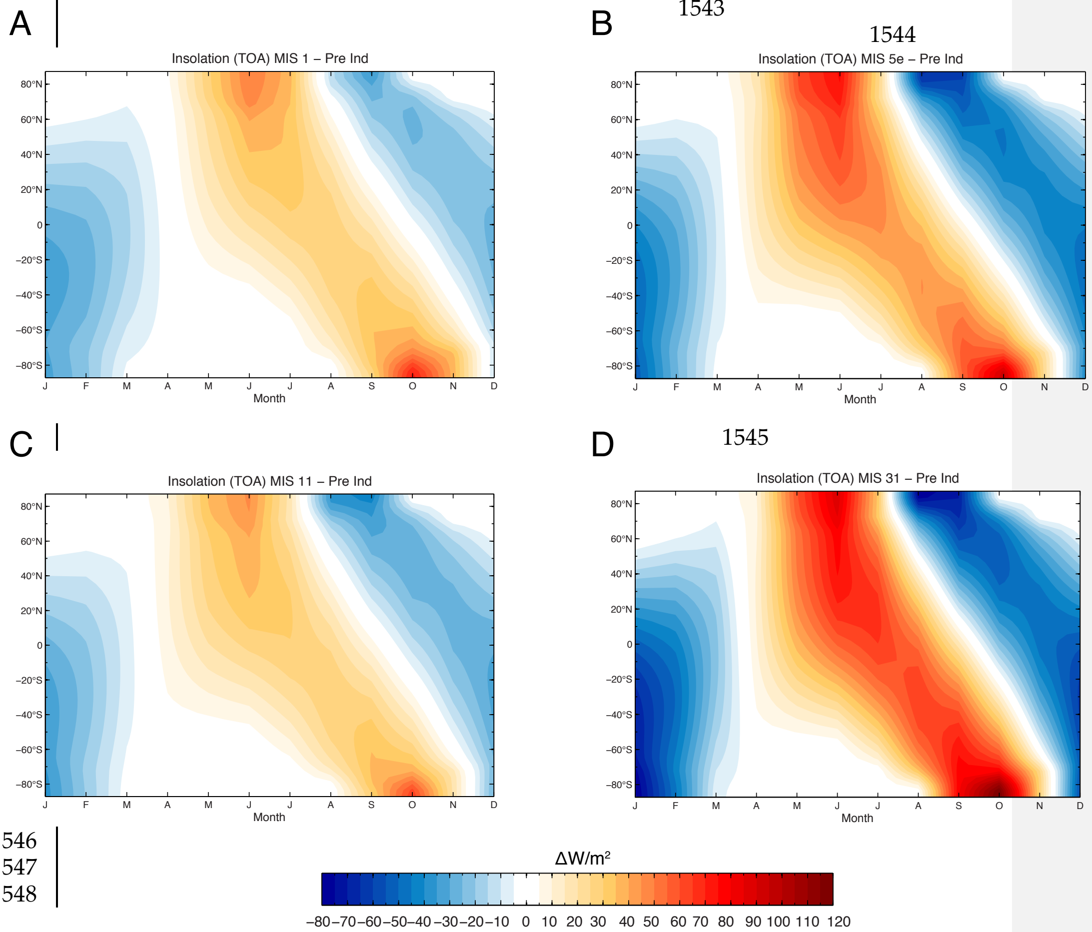

Figure 1: Monthly insolation anomalies at the top of the atmosphere for the interglacial intervals modeled here [W/m^2]. A MIS-1 anomalies with respect to modern orbit, **B** MIS-5e anomalies with respect to modern orbit, **C** MIS-11c anomalies with respect to modern orbit and **D** MIS-31 anomalies with respect to modern orbit.

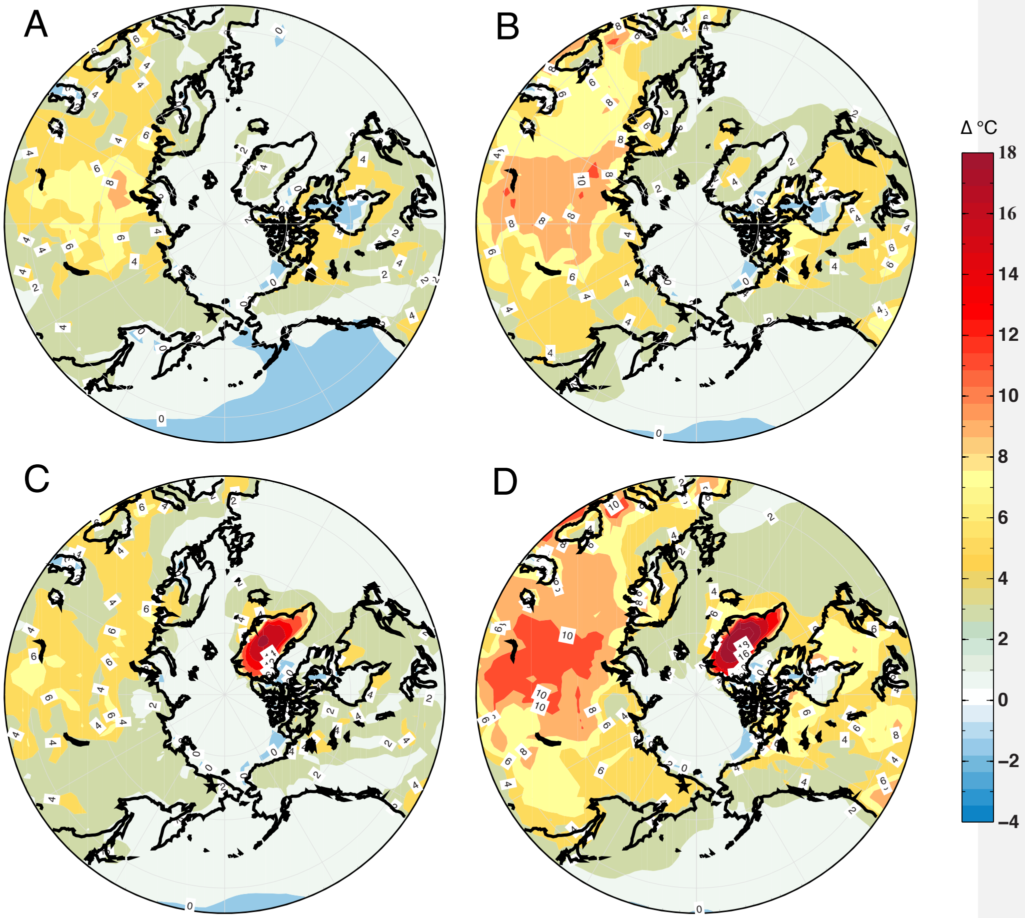

Figure 2: Simulated interglacial anomalies (2-meter annual air temperature in °C) relative to pre-industrial temperatures. **A** MIS-1 (9 ka orbit and GHGs), **B** MIS-5e (127 ka orbit and GHGs), **C** MIS-11c (409 ka orbit and GHGs, and no Greenland Ice Sheet), **D** MIS-31 (1072 ka orbit and GHGs, and no Greenland Ice Sheet). The location of Lake El'gygytgyn (black star) is shown near the bottom of each panel. Areas of no shading (white) roughly correspond to no change that is statistically significant at the 95% confidence interval.

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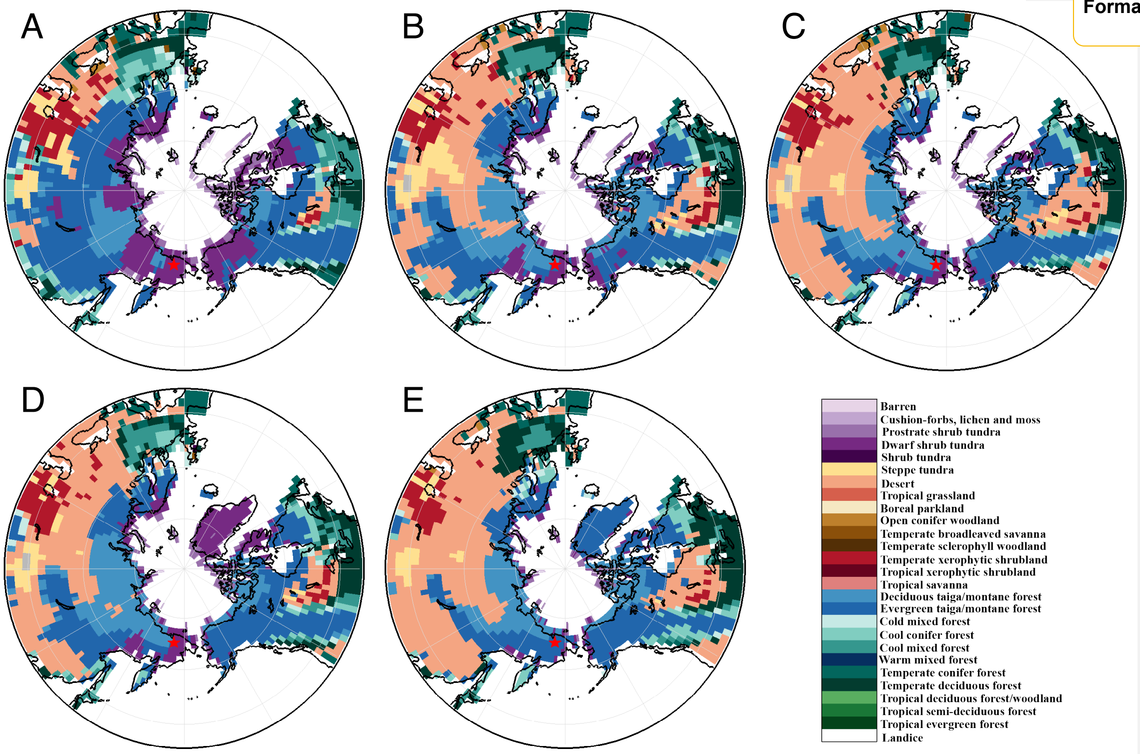

Figure 3: Distribution of interglacial vegetation simulated by the BIOME4 interactive vegetation model coupled to the GCM. A Pre-Industrial vegetation corresponding to modern summer anomalies, **B** MIS-1 (9 ka), **C** MIS-5e vegetation, **D** MIS11NG vegetation and **E** MIS-31 (no GIS) vegetation. The location of Lake E is shown near the bottom of each figure with a red star. Note the poleward advancement of evergreen and needle-leaf trees around the lake during each interglacial and the replacement of shrub tundra to taiga forest.

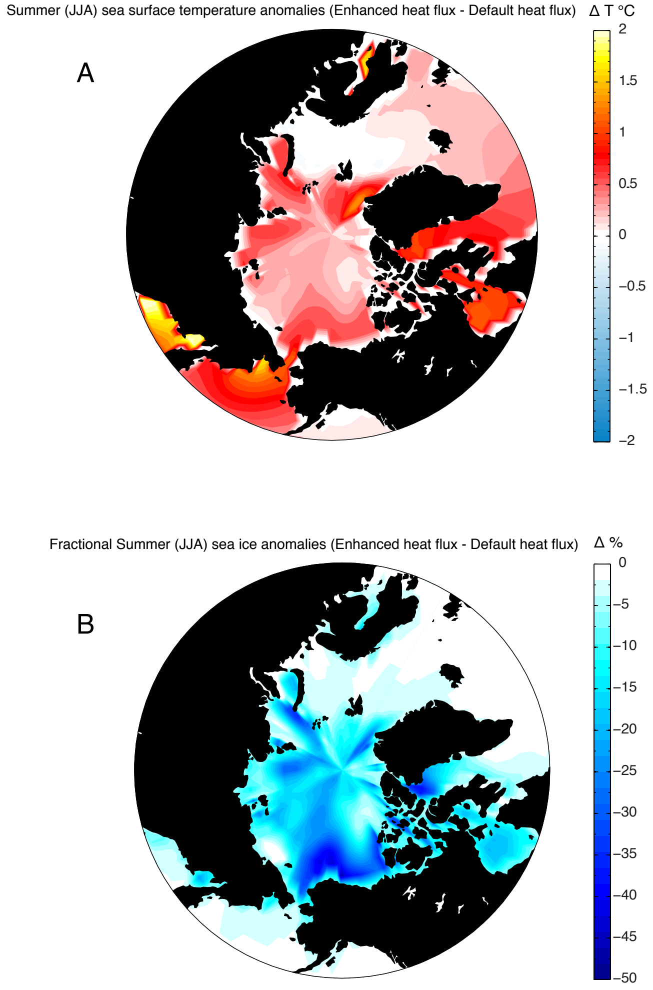

Figure 4: Model simulated (MIS11NG) Summer sea surface temperature and sea ice anomalies caused by enhanced oceanic heat flux (+8 W/m^2) at 409 ka. A Summer (JJA) sea surface temperature change with respect to default heat flux simulation (T °C) and **B** Summer (JJA) sea ice fraction anomalies (%) with respect to default heat flux simulation. With +8 W/m^2 of sub-sea ice heat flux convergence, Arctic Ocean SSTs rise > 0.5 °C and sea ice fraction decreases 25-50% in most areas.

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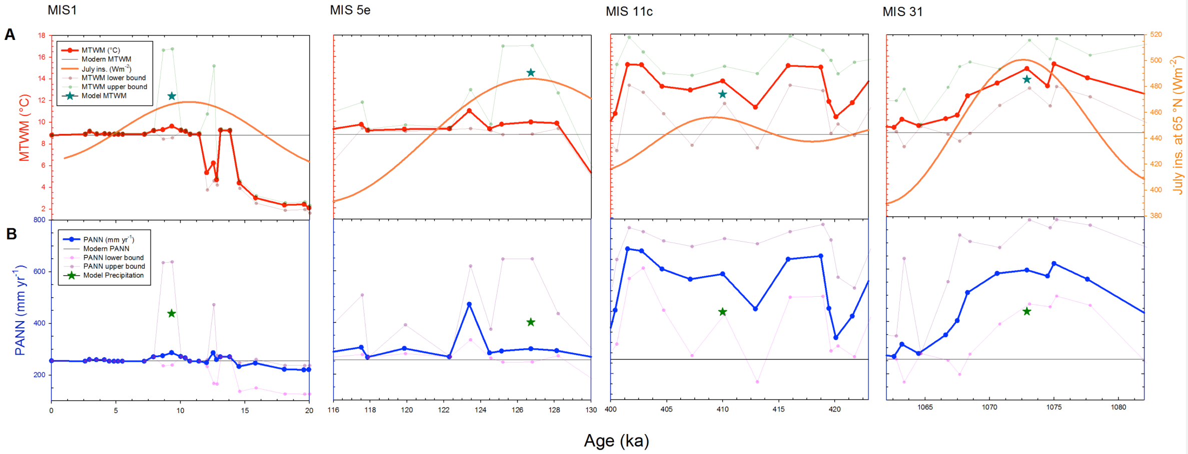

Figure 5: (**A** and **B**) **A** Reconstructed MTWM and **B** PANN from *Melles et al., 2012*. Transparent data above and below the **bolded** lines are upper and lower limits of each data point calculated from a best modern analogue technique (MAT) function. The dark cyan (**A**) and dark green (**B**) stars denote results from the GCM simulations with respect to MTWM and PANN.

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Table 1: Overview of interglacial simulations performed during this study. Orbital configurations
1978) and greenhouse gas (GHG) concentrations **(Honisch et al., 2009; Loulergue et al., 2008; Lüt**
2008; Schilt et al., 2010). Modern GHG concentrations are taken from 1950 AD; obliquity is given in degrees and precession is Ω in degrees.

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Age	Run description	CO_2 (ppmv)	CH_4 (ppbv)	N_2O (ppbv)	Eccentricity	Obliquity (°)	Precession (Ω, °)
1850 AD	pre-industrial simulation with pre-industrial GHG concentrations	280	801	289	0.01671	23.438	101.37
9 ka	MIS 1 - with (modern) GIS	~260	~611	~263	0.01920	24.229	310.32
127 ka	MIS 5e - with (modern) GIS	287	724	262	0.03938	24.040	272.92
409 ka	MIS 11c - with (modern) GIS	285	713	285	0.01932	23.781	265.34
409 ka	MIS 11c - no GIS	285	713	285	0.01932	23.781	265.34
409 ka	MIS 11c - no GIS + 10 Wm^{-2} increase of heat flux under sea ice	285	713	285	0.01932	23.781	265.34
1072 ka	MIS 31 - with no GIS	325	800	288	0.05597	23.898	289.79

Table 2: List of GCM simulations with corresponding variables at the grid cell location of Lake E.

Run	Pre-industrial	MIS 1-with GIS	MIS 5e-with GIS	MIS 11c-with GIS	MIS 11c-no GIS	MIS 11c-noGIS-10Wm^{-2}	MIS 31-without GIS
Lake-E							
MAAT (°C)	-12	-12	-12.4	-11.5	-12.5	-10.5	-10.4
Summer Temp (JJA; °C)	8	9.6	10.5	10	10.2	10.5	11.8
MTWM (July,°C)	10.3	12.4	14.5	12.2	12.5	13.2	13.8
PANN (mm yr^{-1})	438	438	401	475	438	475	438

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