Reply to the reviewer #1 (pp.1-4)

Minor comments:

Throughout the manuscript different the present and past tense are often mixed. Please read the manuscript carefully to be consistent in the usage of the different tenses.

The tense in the text has been adjusted. The past tense indicates phenomena in earlier time (the early Holocene in most cases), otherwise the present tense is used.

Throughout the manuscript the word 'the' is often used when it should not, or missing where it should have been used. For example line 4 on page 9 'of FIS' should be 'of the FIS' and use 'ORBGHG' or 'the ORBGHG simulation'.

It has been done.

Throughout the manuscript 'N' is used to indicate 'North' or 'Northern', perhaps a personal preference, but consider writing out the whole word.

The whole word (and northwestern as well) has been used in the revised version.

Throughout the manuscript be consistent and clear in the use of PI or preindustrial or present or 0ka.

The term of preindustrial (era) and 0ky are now used as synonyms in the manuscript, as declared in Section 2.2, while the term PI (defined in table 1) now only indicates our control simulation for preindustrial climate condition (i.e. modern conditions without anthropogenic effects).

Throughout the manuscript I find the usage of 'ka' as 'ka BP' a little confusing because then, strictly speaking, you also use for instance °C (ka BP)-1. Consider using 'ky' instead of 'ka', for instance °C ky-1.

We have changed °C ka^{-1} into °C ky^{-1}. The note ka BP (ka) has also been changed to ky BP (ky) for consistency.

Lines 12-17 page 1: Consider mentioning in the first paragraph what has previously been found in proxy-based studies, as to introduce the importance of your results presented in the remainder of the abstract. For instance something like 'Proxy-based temperature reconstructions suggest a Northern Hemisphere warming, but also indicate important regional differences. Here we show what forcings and feedbacks can underlie these regional differences…'. If for instance Alaska and Northern Canada are mentioned, then the focus on these two specific regions in the remainder of the abstract doesn't seem so arbitrary anymore.

Thanks for such a nice point. The paragraph has been revised following this suggestion.

Lines 29-31 page 5: So the ice sheet reconstruction that is used is solely based on geological constraints, not on ice-sheet modelling?

Yes, the ice-sheet extent is indeed based on geological data and this has now been indicated in text. But the ice-sheet topography is based on the modelling study of Ganopolski et al. (2010).

Lines 11-12 page 6: How can an equilibrium meltwater forcing match estimates for the early Holocene?

We mean that the total freshwater forcing used in our transient experiment (11.5 ky-6.8 ky) matches the estimated sea level change that occurred during the same period.

Section 2.3: It is still not clear to me how the two freshwater forcing scenarios are different. Is their initial value the same or different? Is the rate of change the same or different. Please clarify in the text.

These two freshwater scenarios started from the same point. The differences between them are a faster rate of change for the FIS and a larger fwf for the GIS (shown in Fig. 2b). This has been explained in the revised version.

The results sections could become a little more clear if you write them all following the same structure. Such a structure could be to first present the summer results, then winter and finally annual mean. Then the reader knows what to expect and where to look for a certain result.

We are trying to follow the above overall pattern: summer, winter and annual. However, there are some interruptions with explanations at some points when further clarification is required.

Lines 24 page 12: Shortly introduce the stacks of Shakun et al. (2012) and Marcott et al. (2013).

The sentence "Shakun et al. (2012) and Marcott et al. (2013) stacked multiple proxies to construct a record of temperatures since the LGM" has been added as an introduction.

Line 32 page 12: Is this bias found for specific regions and how does this compare to the 30-90N model-data comparison that is performed here?

Lohmann et al. (2012) found a large bias at high latitudes (where the production may be limited by light), and this specification has been added in the text. This potential high-latitude bias is generally consistent with our assumption, however, a quantitative comparison with the proxy-based reconstructions of Lohmann et al. (2012) is not straightforward since they did not stack the records together.

Line 34 page 12: CP does not have a page limit, as far as I know, as long as the content is relevant.

We have rephrased the sentence as: "Further region-by-region comparisons of these warming rates with proxy records are beyond the focus of this work and will be dealt with in a future publication".

Line 12 page 13: And how did they interpret this result and how does it connect to the work presented here? Shortly elaborate.

We followed the suggestion. The text now reads: "A potentially different early Holocene atmospheric circulation near the North Atlantic has also been found in a proxy record of Steffensen et al. (in 2008), who reported an abrupt transition of deuterium excess that indicates a temperature change of precipitation moisture sources, and is thus indirectly connected to atmospheric circulation changes."

Line 30 page 13: Explain what causes a southward migration of the tundra under a warming climate.

In spite of higher summer temperatures, the early Holocene was still cooler than the preindustrial era (as suggested by slightly lower annual mean temperatures). This overall cooler climate caused more extended tundra.

Lines 31-33 page 13: They counterbalanced, but still led to a substantially cooler climate? Please explain.

The word 'counterbalance' caused the confusion. We have rephrased as follows: "The albedo-related feedbacks and the smaller annual insolation anomalies jointly resulted in a 0.5–2°C cooler climate at 11.5 ky".

Lines 1-3 page 15: Does this part discuss the results of FWF-v1 or FWF-v2? Or both? If the latter, perhaps move to earlier part of the manuscript.

Yes, this concerns both scenarios, but it is used as a general induction to freshwater flux efficiency discussion and has been modified in the text with removal of the first part.

Line 15 page 15: Perhaps shortly repeat the differences between the two freshwater scenario and how they can explain the AMOC differences.

It now reads: “Since the second freshwater scenario (OGIS_FWF-v2) includes a slightly larger fwf from the GIS (compared to that in OGIS_FWF-v1) and the fwf was released in a sensitive area, the location-dependent sensitivity could also partially explain further AMOC weakening in the OGIS_FWF_v2 simulation compared to OGIS_FWF-v1.”

Line 27 page 15: Perhaps shortly mention future plans: comparison with previously performed transient deglacial/early Holocene experiments etc.

The following sentence has been added: “The further comparison with proxy data and with other model transient simulations will be conducted in a future paper”.

Technical comments:

All corrections pointed out by the reviewer have been done. Only rephrased parts and places needing further explanation are included below.

Line 1-3 page 2: This is a little hard to read, consider rewording. Moreover, it would be good to say that this kind of work has the potential to constrain the uncertainties in ice sheet reconstructions.

We have revised the sentence as follows: “Comparison of simulated temperatures with proxy records illustrated uncertainties related to the ice sheet melting, and such kind of comparison has the potential to constrain the uncertainties in ice sheet reconstruction”.

Line 2 page 2: configuration instead of deglaciation?

If we considered it at some specific point of time (e.g. 10 ky BP), it would mean configuration. However, if we are interested in some period (early Holocene in our case), it would refer to the deglaciation. Hence, it actually indicated both the configuration and deglaciation of ice sheet. It has been changed to ‘ice sheet melting’ which is more related to freshwater flux.

Lines 2-6 page 3: Difficult to read, please rewrite.

We have rephrase to: “For instance, a large-scale ice sheet could generate a glacial anticyclone that locally could have reduced further the temperature (Felzer et al., 1996), but it may also have caused a 2–3°C warming over the North Atlantic in the Last Glacial Maximum (LGM) (Pausata et al., 2011; Hofer et al., 2012)”.

Line 34 page 3: Not sure if ‘in preparation’ is allowed in CP, I’ll leave it to the editor.

CP seems to allow work submitted to, in preparation, in review in the reference list.

Line 2 page 5: Younger Dryas strictly speaking not an example of a Holocene study.

The phrase 'in the Holocene' has been removed for consistency.

Line 26 page 5: PMIP3 protocol up to 11.5ka?

Yes, the PMIP3 protocol has extended to the early Holocene.

Line 1 page 6: The average thickness?

We meant maximum thickness and this has been clarified in manuscript.

Line 28 page 6: Why mention experiments that are not presented in the manuscript?

We conducted a couple of test experiments (for example having only ORB or GHG) to get a general understanding. However, we've modified and removed this mention in new version.

Line 30 page 7: ‘southern regions’, where is that?

We meant regions located South of the Arctic, and now ‘southern regions’ has been replaced by 'lower latitudes'.

Lines 27-29 page 9: Isn’t this part of the equilibrium response?

It's the end of the equilibrium response, but also the transient starting point (in Fig 5)

Section 4.3: Perhaps the description of AMOC changes in section 3.2 could be moved to section 4.3?

We indeed intensively and specifically discuss AMOC changes in section 4.3. However, we are not sure about this comment, since AMOC changes were not described in section 3.2

Line 27 page 14: around 10 degrees?

We meant that the strongest cooling happened at 10 ky. It has been rephrased to: “with the strongest temperature reduction at around 10 ky”.

Line 32 page 14: 1-2Sv compared to?

We meant by 1-2 Sv compared to FWF_v1, and this has been added to the text.

Table 2: What is FWF? FWF_v1 or FWF_v2 or are those also the same for 11.5ka?

FWF_1 and FWF_2 started at the same point– the ending of OGIS11.5 forced by FWF which has been clarified in the text and in the notation of table 2.

Figure 2: present? PI, 0ka?

It has been changed to 0ky for consistency.

Figure 4: why is the shaded bar only shown for the top panel?

Because the Holocene Thermal Maximum usually refers to summer conditions, and it is easier to compare this summer warm period with palaeoecological proxy data.

Figure 4: On basis of which scenario are these slopes calculated?

Based on the FWF_2 scenario. This has been clarified in the caption.

Figure 9: Perhaps the proxy data for the modern period can be removed since no human induced warming is included in the simulations.

We agree that it would be more consistent with the manuscript if the human-induced warming was excluded. However, the original publication did not separately discuss the anthropogenic impacts and we are not sure how much warming should be removed from this stacked temperature reconstruction.

Figure 10: Wind vectors could perhaps give a clearer picture of the changes in atmospheric circulation.

We have tried wind vectors as well, but geopotential height gives a clearer indication of atmospheric circulation changes.

Figure 12: Consider giving the maximum AMOC strength for the different panels for illustration.

The maximum AMOC strength value reached at about 1200 m depth was 17 Sv in both PI and OGIS, while it was only about 11 Sv in the OGIS11.5 simulation. This information has been added to the caption of Figure 12.

Figure S4: why 10ka?

Since the largest AMOC weakening and temperature reduction (in OGIS_FWF_v2 compared to OGIS_FWF_v1) happened at around 10 ky, and in Figure S4 we intend to analyze this temperature change.

Reply to the reviewer #2 (pp. 5-6)

Claimed edits

We apologize for these missed corrections in the last version. Each point has been addressed carefully in the new version.

Old numbering 5353.22-23: The authors say they rephrased a sentence to […]. But it appears to have been deleted entirely.

We were trying to limit the number of pages and decided to leave this out in the last version. However, the sentence "While the global annual-mean insolation stayed at almost the same level (not shown), both changes in obliquity and precession are resulting in insolation variations on the multi-millennial time-scale of the Holocene." has been included in this version.

Figure numbering

Numbering has been carefully checked in revised version.

Minor points

6.1: What do you mean by relative thickness?

We were referring to an ice sheet thickness relative to the present. The word 'relative' has been removed to avoid this confusion.

6.28: Why do you mention that you did more simulations than you present?

We conducted a couple of test experiments (e.g. the experiment with ORB and GHG forcing) to get a general understanding. However, we have modified this part of the text and removed this mention.

7.3+4: Why do you refer to Fig 2b and Fig 2c for the two FWF's, respectively? Both figures show both FWF's, don't they?

We apologize for this mistake caused by different figure versions we have. A correction has been done in the legend and text.

7.6 Default what?

Default modern climate condition and this clarification has been included in the new version.

7.10: "Surface temperatures" or "near-surface air temperatures"? Is it actually the surface temperature?

Yes it is the near surface temperature and the correction has been done.

7.12-13: What does this sentence about the 0.5 C cooler bias mean? I don't really understand it.

The temperature would be 0.5°C cooler if the lapse rate were applied to correct the simulated temperature (based on the average thickness of ice sheet).

9.10: It is interesting that the annual mean warming is about twice that of both summer and winter. This indicates that something drastic is taking place in the two other seasons. What? And why isn't this shown/discussed?

The Arctic (here we refer to the region located north of 70 ° N) has a large area covered by ocean where a few months delay in the maximum response has been reported by Renssen et al. (2005). This study found the largest response in the winter half year (especially in fall) due to this delayed response that was ultimately caused by the thermal inertia of the oceans (Renssen et al 2005). Indeed, this explanation was further supported by the simulated larger warming rate in fall (up to 0.78 °C ky^{-1}). Hence, the simulated large annual warming could be attributed to this largest response in the winter half year. This illustration has been added to the text.

13.23-24 Again, I don't understand this sentence about the cooling bias.

Like we explained above, this cold bias would occur when compared with site-specific proxy records.

Language

Please note that only the comments that need further explanation are listed below. Otherwise, they have been directly done in revised version.

8.10 "fell below" Do you mean "well below"?

Yes and we have accordingly adjusted the sentence.

14.27-28: "with a stronger temperature reduction of around 10 ka". Do you mean "with a stronger temperature reduction around 10 ka"? Or do you mean "with a stronger temperature reduction of around XX deg C"? Either way, the sentence sounds strange.

We meant the strongest temperature reduction at around 10 ky. This section has been modified accordingly.

Fig 2a: Title: Ice sheet area…

It has been corrected.

Fig 2c: What do the symbols show? They aren't mentioned in the caption and aren't shown in the legend

Solid lines with symbols indicate the FWF_v2 and this has been added in figure's legend in the new version.

Fig 5a: Does the linear slope really make any sense to show in this case where things are behaving so obviously non-linearly?

The linear fitting line here is just for comparison with the temperature evolution over other regions.

Fig 9, caption: Please add reference for the reconstruction.

The reference has been added.

List of relevant changes

1. Language problems, such as tenses, articles and other related issues, have been corrected throughout the manuscript.
2. The terms that have caused potential confusion (e.g. PI, preindustrial, present and 0ka) have been clarified.
3. Detailed explanations have been given when they are needed or asked of by the reviewer (s).
4. Problems that have arisen during modification have also been addressed accordingly.
5. Corresponding corrections and modifications have been done within the figures and tables as well.

Effects of melting ice sheets and orbital forcing on the early Holocene warming in the extratropical Northern Hemisphere

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Abstract

The early Holocene is marked by the final transition from the last deglaciation to the relatively warm Holocene. Proxy-based temperature reconstructions suggest a Northern Hemisphere warming, but also indicate important regional differences. ~~S~~Model studies have analyzed the influence of diminishing ice sheets and other forcings on the climate system during the Holocene. The climate response to forcings before 9 ky~~a~~ (refers to ky B.P), however, remains not fully comprehended. We therefore, by employing the LOVECLIM climate model, studied how orbital and ice-sheet forcings contributed to climate change and to these regional differences during the earliest part of the Holocene (11.5–7 ky~~a~~) ~~by employing the LOVECLIM climate model~~.

Our equilibrium experiment~~s~~ for 11.5 ky~~a~~ suggests~~ed a~~ lower annual mean temperatures at the onset of the Holocene than in the preindustrial era ~~in the Northern extratropics~~ with the exception of Alaska. The magnitude of this cool anomaly varied~~s~~ regionally and these spatial patterns are broadly consistent with proxy-based reconstructions. Temperatures throughout the whole year in ~~N~~northern Canada and ~~NW~~ northwestern Europe for 11.5 ky~~a~~ were 2–5°C lower than those of the preindustrial era as the climate was strongly influenced by the cooling effect of the ice sheets, which was caused by enhanced surface albedo and ice-sheet orography. In contrast, temperatures in Alaska for all seasons for the same period were 0.5–3°C higher than the control run, which were caused by a combination of orbital forcing and stronger southerly winds that advected warm air from the South in response to prevailing high air pressure over the Laurentide Ice Sheet (LIS).

The transient experiments indicate~~d~~ a highly inhomogeneous early Holocene temperature warming

over different regions. The climate in Alaska was constantly cooling over the whole Holocene, whereas there was an overall fast early Holocene warming in ~~N~~northern Canada by more than 1°C ky~~a~~$^{-1}$ as a consequence of progressive LIS decay. Comparisons of ~~S~~simulated temperatures ~~compared~~ with proxy records illustrate~~d~~ uncertainties related to the reconstruction of ice-sheet melting~~deglaciation~~, and such kind of comparison has the potential to constrain the uncertainties in ice sheet reconstruction.~~which can be constrained by applying different freshwater scenarios~~. Overall, our results demonstrate~~d~~ the variability of the climate during the early Holocene, both in terms of spatial patterns and temporal evolution.

1 Introduction

The early Holocene from 11.5 to 7 ky~~a~~ B.P (hereafter noted as ky~~a~~) is palaeoclimatologically interesting as it represents the last transition phase from full glacial to interglacial conditions. This period is characterized by a warming trend in the Northern Hemisphere (NH) that has been registered in numerous proxy records and indicated by stacked temperature reconstructions (Shakun et al., 2012). Oxygen isotope measurements from ice cores in Greenland (Dansgaard et al., 1993; Grootes et al., 1993; Rasmussen et al., 2006; Vinther et al., 2006; 2008) and the Canadian high-Arctic (Koerner & Fisher, 1990) consistently show an increase in δ^{18}O by up to 3–5 ‰, which indicates an approximate ~~couple of degrees~~ warming in the climate system (Vinther et al., 2009). Moreover, this early-Holocene warming is also registered in biological proxies. For example, a 4–5°C warming in western and northern Europe is indicated by chironomids and macrofossils data obtained from lake sediments (Brooks & Birks, 2000; Brooks et al., 2012; Birks, 2015). In addition, this transition is recorded in other high-resolution records from further East in Eurasia, such as in the speleothems from China (Yuan et al., 2004; Wang et al., 2005). Comparable trends have been identified in marine sediment core data, such as ~~a~~ sea surface temperatures (SSTs) rise in the North Atlantic reflected by the variation in δ^{18}O and in planktonic foraminifera (Bond et al., 1993; Kandiano et al., 2004; Hald et al., 2007). Although these proxy records provide a general view of early Holocene warming, their detailed expression in different regions and the reasons for this spatial variation are poorly known.

The orbitally induced increase in NH June insolation was one of the main external drivers of ~~the~~ climate change during the last deglaciation (Berger, 1988; Denton et al., 2010; Abe-Ouchi et al., 2013; Buizert et al., 2014). This increase peaked in the earliest Holocene (Berger, 1978) and resulted in warming over large areas. However, the early Holocene was also characterized by ~~critical~~ adjustments in components of the climate system that further affected the temperature through various feedback mechanisms. In the cryosphere, the Laurentide ice Sheet (LIS) and Fennoscandian Ice Sheet (FIS) were melting at a fast rate and eventually demised around 6.8 kya and 10 kya, respectively (Dyke et al., 2003; Occhietti et al., 2011), which exerted multiple influences on the climate system (Renssen et al., 2009). First, the surface albedo was much higher over the ice sheets compared to ice-free surfaces, which resulted in relatively low temperatures. Second, the ice-sheet topography could~~an~~ also influence the climate through the mechanism of adjustment to the atmospheric circulation (Felzer et al., 1996; Justino & Peltier, 2005; Langen & Vinther, 2009). For instance, ~~the orography of~~ a large-scale ice sheet could generated a glacial anticyclone that locally ~~tended to~~could have reduced further the temperature (Felzer et al., 1996), but it may also have caused a 2–3°C warming over the North Atlantic ~~under~~ in the Last Glacial Maximum (LGM) (Pausata et al., 2011; Hofer et al., 2012). Third, both modelling and proxy studies have found that the Atlantic Meridional Overturning Circulation (AMOC) was relatively weak during the early Holocene due to the ice-sheet melting, which led to reduced northward heat transport and extended sea-ice cover (Renssen et al., 2010; Roche et al., 2010; Thornalley et al., 2011; 2013). Overall, the net effect of ice sheets on the early Holocene climate can be expected to have tempered the orbitally induced warming at the mid and high latitudes. Important adjustments in the carbon cycle occurred in the early Holocene, as evidenced by the rise in atmospheric CO_2 levels by 20–30 ppm that contributed to the warming (Schilt et al., 2010). Changes also happened in the biosphere during the early Holocene. Vegetation reconstructions revealed a northward expansion of boreal forest in the circum-Arctic region after the retreat of the ice sheets (MacDonald et al., 2000; Bigelow et al., 2003; CAPE project 2001; Fang et al., 2013). This expansion of boreal forest into regions that were not previously vegetated or were covered by tundra caused a reduction of the surface albedo and induced a positive feedback to the warming trend (Claussen et al., 2001).

The impact of ~~all~~ these forcings on the Holocene climate has been examined in modelling studies. The~~ particular~~ focus in these studies has been on the influence of the decay of the LIS and Greenland ice sheet (GIS)~~ decays had~~ on the climate after 9 kya relative to other climate forcings (Renssen et al., 2009; Blaschek & Renssen, 2013). Renssen et al. (2009) used transient simulations performed with the ECBilt-CLIO-VECODE model and found that the Holocene climate was sensitive to the ice sheets and that the LIS cooling effects delayed the Holocene Thermal Maximum (HTM) by up to thousands of years. Blaschek and Renssen (2013) applied a more recent version of the same model (renamed ~~as~~ to LOVECLIM) and revealed that the GIS melting had an identifiable impact on the climate over the Nordic Sea. However, these Holocene modelling studies only started at 9 kya~~, implying that the climate of the early Holocene between 11.5 and 9 ka was not included in these studies~~. The most important challenges in simulating climate during ~~this~~ the initial phase of the early Holocene are the inherent uncertainties in the ice-sheet forcings in terms of the ice-sheet dynamics and the related meltwater release. Recent deglaciation studies based on cosmogenic exposure dating indicate slightly older ages of deglaciation in some regions than suggested by radiocarbon dating data (Carlson et al., 2014; Clark in preparation), primarily because of a large uncertainty in bulk organic sample ages and the possibility of old carbon contamination (Carlson et al., 2014; Stokes et al., 2015). Furthermore, the Younger Dryas stadial ended at 11.7 kya and may still have influenced the early Holocene climate due to the long response time of the deep ocean (Renssen et al., 2012). Therefore, the climate system's response to forcings before 9 kya, especially those of the ice sheets is poorly comprehended.

We have extended the study of Blaschek and Renssen (2013) back to 11.5 kya in the present study to explore the early Holocene climate response to these key forcings. By employing the same climate model of intermediate complexity LOVECLIM, we first analyzed the impact of forcings on the climate at 11.5 kya and subsequently investigated the influence of two ice-sheet deglaciation scenarios in transient simulations. The comparison of these different simulations enables us to disentangle how the ice sheets influenced the early-Holocene climate. More specifically, we have addressed the following research questions: 1) What were the spatial patterns of simulated temperature at the onset of the Holocene (11.5 kya)? 2) What were the roles of the forcings, especially ice-sheet decay, in shaping these features? 3) What was the spatiotemporal variability in the simulated early Holocene temperature evolution?

2 Model and experimental design

2.1 The LOVECLIM model

We conducted our simulations with version 1.2 of the three-dimensional Earth system model of intermediate complexity LOVECLIM (Goosse et al., 2010), in which the components of the atmosphere, ocean including sea ice, vegetation, ice sheets and carbon cycle are dynamically included. However, in our version, the components for the ice sheets and the carbon cycle were not activated. Therefore, the ice-sheet configuration evolution and greenhouse gases werewas prescribed in our present study. The atmospheric component is the quasi-geostrophic model ECBilt that consists of three vertical layers and has T_{21} horizontal resolution (Opsteegh et al., 1998). CLIO is the ocean component which consists of a free-surface, primitive-equation oceanic general circulation model (GCM) coupled to a three-layer dynamic-thermodynamic sea-ice model (Fichefet & Maqueda, 1997). The ocean model includes 20 vertical levels and a 3°x3° latitude-longitude horizontal resolution (Goosse & Fichefet, 1999). These two core components were further coupled to the biosphere model VECODE, which simulates the dynamics of two main terrestrial plant functional types, trees and grasses, in addition to desert (Brovkin et al., 1997). More details on LOVECLIM can be found in Goosse et al. (2010).

The LOVECLIM model is a useful tool to explore the mechanisms behind climate change and it has made critical contributions to our understanding of the long-term climate change ~~in the Holocene~~ observed in proxy records (Renssen et al., 2005; 2006; 2010). For example, it has helped the investigations of the potential forcings behind the Younger Dryas (Renssen et al., 2002; Wiersma et al., 2006, Renssen et al., 2015), and the role of the decaying LIS and GIS in ~~the~~ temperature evolution over the last 9 ky~~a~~ (Renssen et al., 2009; Blaschek & Renssen, 2013). Moreover, the LOVECLIM model simulates a reasonable modern climate (Goosse et al., 2010). It also simulates ~~a reasonably well~~ the meridional overturning streamfunction reasonably well and reproduces a large-scale structure of atmosphere circulation~~, which~~ that agrees with observations and with other models (Goosse et al., 2010). In addition, the model's sensitivity to freshwater perturbation is reasonable compared to that of other models (Roche et al., 2007), and its sensitivity to a doubling of atmospheric CO_2 concentration is 2 K, which is in the lower end of ~~estimation in of~~ coupled general circulation model~~s~~ (GCM~~s~~) estimates (Flato et al. 2013).

2.2 Prescribed forcings

We included the major climatic forcings in terms of greenhouse gases (GHG) in the atmosphere, astronomical parameters (orbital forcing or ORB) and decaying ice sheets. In all simulations, the solar constant, aerosol levels, the continental configuration and bathymetry were kept fixed at preindustrial values. We based the concentrations of CO_2, CH_4 and N_2O on ice core measurements for GHG forcing (Loulergue et al., 2008; Schilt et al., 2010). The radiative GHG forcing anomaly (relative to 0~~-~~ky~~a~~) in W m^{-2} (Ramaswamy et al. 2001), representing the overall GHG contribution, at first showed a rapid rise with a peak of -0.3 W m^{-2} at 10 ky~~a~~, which was followed by a slight decrease towards a minimum at 7 ky~~a~~, and gradually increased towards 0~~–~~ky~~a~~ (Fig. 1). The astronomical parameters (eccentricity, obliquity and longitude of perihelion) determine the incoming solar radiation at the top of atmosphere, and were derived from Berger (1978). An example of the resulting change in insolation is shown as the anomaly for June at 65° N in Figure 1, which shows the gradual decrease over the course of the Holocene. While the global annual-mean insolation stayed at almost the same level (not shown), both changes in obliquity and precession are resulting in insolation variations on the multi-millennial time-scale of the Holocene. At the beginning of the Holocene (11.5 ky~~a~~), the orbitally-induced insolation anomaly in the NH was positive in summer and negative in winter (Fig. SI1). Overall, this setup of GHG and ORB forcing is in line with the PMIP3 protocol (http://pmip3.lsce.lsce.ipsl.fr), except that our simulation excluded the increase in GHG levels during the industrial era (Ruddiman, 2007). Accordingly, the terms pre-industrial (era) and 0ky are considered equivalent in the present text and indicate modern conditions without anthropogenic impacts.

We took three aspects into account concerning the ice-sheet forcing, namely: their spatial extent, their thickness and their meltwater discharge. The reconstructions of ice-sheet spatial extent wereare based on the dating of geological features and on the correlation of these geological datasets between different regions (Dyke et al., 2003; Svendsen et al., 2004; Putkinen & Lunkka, 2008). According to these reconstructions, tThe FIS at 11.5 kya covered most of Fennoscandia except for southern Scandinavia and eastern Finland (Svendsen et al., 2004; Putkinen & Lunkka, 2008; Clark in preparation). The LIS occupied most of the lowland area north of the Great Lakes region and filled the whole Hudson Strait (Licciardi et al., 1999; Dyke et al., 2003; Occhietti et al., 2011). The relative thickness of LIS was up to 2000 m, and for the FIS this thickness was only about 100 m (Ganopolski et al. 2010), which is comparable with the ICE-5G reconstruction (Peltier 2004). Both the spatial extent of the ice sheets and their thickness were updated every 250 yrs in our transient experiments, and they decreased rapidly during the earliest Holocene, followed by a more gradual deglaciation rate from 8 kya onward (Fig. 2a).

We applied the meltwater release for 1200 yrs in our equilibrium experiments for 11.5 kya by adding 0.11 Sv (1 Sverdrup is 10^6 m^3/s) of freshwater at the St. Lawrence River and 0.05 Sv at Hudson Strait and Hudson River, 0.055 Sv from FIS and 0.002 Sv from GIS (Licciardi et al., 1999; Jennings et al., 2015). The total freshwater volume added to the oceans in our transient experiments was about 1.46×10^{16} m^3 in the first 4700 yrs (Fig. 2b), which roughly matches the estimated ice-sheet melting volume during the early Holocene (Dyke et al., 2003; Ganopolski et al., 2010; Clark in preparation). The volume of meltwater was slightly lower than the volume of the estimated 60 m sea level rise that took place during the early Holocene (Fig. 2c) (Lambeck et al., 2014), which suggests a coeval Antarctic melting contribution that is not considered here. Given the lack of a direct imprint left by meltwater on terrestrial records and hence the relatively large uncertainty, we used two versions of the freshwater flux (thick dashed lines and solid lines with symbols in Fig. 2b) that represent two possible deglaciation scenarios of the GIS and FIS, named FWF-v1 and FWF-v2. The GIS FWF_v1 scenario is derived from the ICE_5G reconstruction, and FWF_v2 is based on the reconstruction of Vinther et al. (in 2009) that suggests a faster GIS thinning. The two FIS fwf scenarios are based on two estimations of the FIS melting, since the recent cosmogenic dating (FWF_v2) supports a faster melting (Clark in preparation) than previously thought (FWF_v1). However, we kept the freshwater discharge from LIS the same as in version-1, since the LIS deglaciation has been relatively well studied and we are more certain about its contribution.

2.3 Setup of experiments

We performed two types of experiments: equilibrium and transient simulations. First, ~~a series of~~the equilibrium experiments of OG11.5 and OGIS11.5 with boundary conditions for 11.5 ky~~a~~ (Table 1) were designed~~, of which only two simulations are presented here: OG11.5 and OGIS11.5~~. The OGIS11.5 experiment included ice-sheet forcing whereas no ice sheets were included in OG11.5 (Table 2). Each of these experiments was initiated from the model's default modern condition, and was run for 1200 yrs, of which the last 200 yrs of data were used for the analysis. Renssen et al. (2006) have demonstrated that a 1200-yr~~ear~~ spin-up is sufficient to reach a quasi-equilibrium in all components of the model.

The end of the 1200-yr~~s~~ equilibrium run data were then taken to initialize the transient experiments that covered the last 11.5 ky~~a~~. In the first transient simulation named ORBGHG, both GHG and ORB varied~~y~~ on an annual basis. In the second simulation OGIS_FWF-v1, the ice-sheet topography (Fig. 2a) and FWF_v1 (thick dashed lines in Fig. 2b) were additionally included. A third experiment (named OGIS_FWF-v2) was performed with the freshwater version-2 (solid lines with symbols in Fig. 2b~~c~~) and with the same ice-sheet topography as in ~~the~~ OGIS_FWF-v1 to further investigate the climate response to the relatively uncertain freshwater forcing. Both OGIS_FWF-v1 and OGIS_FWF-v2 were initialized from the OGIS11.5 experiment. A pre-industrial simulation (PI) was run for 1200 yrs from the model's default (representing modern conditions) with the boundary conditions that are shown in Table 1 and, similarly as for the other equilibrium experiments, the results of the last 200 yrs were used as a reference. These simulations and their forcings are summarized in Table 2. All temperature values in this study are shown as deviations from the PI simulation (indicates the climate at 0ky). ~~The~~ T~~t~~emperatures presented here are simulated near surface temperature values without the environmental lapse rate corrections to the sea level temperature, which imply approximately a 0.5°C ~~cooler~~ cold bias over ice-sheet covered regions when compared with site specific proxy records.

3 Results

3.1 Equilibrium experiments at the onset of the Holocene

3.1.1 Simulation with only ORB & GHG forcings at 11.5 ky~~a~~ (OG11.5)

In the experiment ~~of~~ OG11.5, summer temperatures were 2–4°C higher over most of the extratropical continents than in the PI simulation~~ of PI~~, with ~~the~~ a maximum deviation of 5°C in the central parts of the Northern Hemisphere continents (Fig. 3~~4~~a). The warming over the oceans was about 1.5°C, and less conspicuous than that ~~of~~ over the continents. These warmer conditions were caused by the orbitally induced positive summer insolation anomaly, as all atmospheric greenhouse gas levels were lower at 11.5 ky~~a~~ than in the preindustrial era (Fig. 1). The most obvious feature of ~~the~~ simulated winter temperatures ~~anomaly~~ was the marked contrast between high latitudes and areas more to the South (Fig. 3b). For instance, ~~the~~ mid-latitudes were 1.5–3°C cooler with the strongest cooling in the central continents, whereas the high-latitude Arctic was clearly warmer with a maximum up to +3°C than in ~~the~~ PI. This latitudinal gradient can be seen in ~~the~~ annual mean temperatures as well (Fig. 3c). Annual mean temperatures over the Arctic were about 1–4°C higher than in ~~the~~ PI. The warming was ~~with~~ slightly larger~~stronger warm climate~~ in winter than in summer, and this seasonal difference mirrors~~which indicates~~ the Arctic Ocean damping effect on a seasonal signal due to a large heat capacity. ~~The t~~Temperatures at lower latitudes were annually~~roughly~~ unchanged (mostly within ±0.5°C) ~~over the southern regions~~ with a stronger seasonality (with warmer summers and cooler winters), which is consistent with the insolation change at 11.5 ky~~a~~ (Fig. SI1~~2~~).

3.1.2 Climate response to melting ice sheets at 11.5 ky~~a~~ (OGIS11.5)

Our simulation OGIS11.5 (including the impact of ice sheets) suggests a much cooler climate than that of ~~the~~ OG11.5~~ (Fig. 4d)~~. Most notably, ice sheets induced a strong summer cooling over ice-covered areas, and reduced temperatures up to 5°C compared to the PI simulation, with the strongest cooling at the center of the LIS (Fig. 3d). Additionally, ~~the~~ SSTs ~~was~~ were also more than 1.5°C lower over the North Atlantic Ocean. In contrast, temperatures over the ice-free continents were mostly above the preindustrial level, but still lower than those found in ~~the~~ OG11.5, except for the Alaska region. ~~The OGIS11.5 simulation in winter indicated warmer central Arctic than that of in the PI, a~~Although the area with colder conditions clearly expanded more in the OGIS11.5 simulation than in ~~the~~ OG11.5, the central Arctic was still warmer in OGIS11.5 relative to PI,~~with anomalies fell below −5°C~~ (Fig. 3~~4~~e). Alaska was the only continental region where ~~the~~ winter temperatures exceeded the preindustrial values by up to +3°C. The strongest cooling effect was present in the regions covered by ice sheets, for instance more than 3°C cooler over the LIS. ~~The s~~Simulated annual mean temperatures in ~~the~~ OGIS11.5 clearly showed ~~an~~ overall lower values than in ~~the~~ PI due to the ice-sheet impacts (Fig. 3~~4~~f). The Eurasian continent was mostly 1.5–3°C cooler, and a maximum temperature reduction~~s~~ of more than 5°C was ~~simulated~~ found over the LIS. Only two areas were still warmer: Alaska, including the adjacent sector of the Arctic Ocean, and the Nordic Seas. The most distinct feature was thus a thermally contrasting pattern over North America, with simulated temperatures being around 2°C higher than those in ~~the~~ PI for Alaska, whereas over most of Canada ~~the~~ temperatures were more than 3°C lower.

3.2 Transient simulation for the Holocene

It is clear in our analysis of section 3.1 that the climate showed different responses in the following areas: the Arctic, ~~NW~~northwestern Europe, ~~N~~northern Canada, Alaska and Siberia (marked in Fig. SI2). Therefore, these areas were selected for special examination and the temperature evolutions of these regions will be shown. Our major focus was on ~~the~~ millennial-scale temperature trends, therefore we applied a 500-yr running mean to our simulated time-series that effectively filtered out high-frequency variability.

3.2.1 Temperature evolution in the Arctic

~~The~~ Arctic summer temperatures in ~~the~~ ORBGHG continuously decreased, which resulted in a total cooling of 2°C during the Holocene (Fig. 4). ~~The w~~Winter temperatures showed an even stronger overall cooling ~~that fell by about~~ of -3°C. ~~Accordingly, the annual mean temperature displayed a cooling that was intermediate between that of the summer and winter seasons.~~

The simulation OGIS_FWF-v1 with full forcings reveals~~ed~~ a more complicated Arctic climate evolution compared to that of ~~the~~ ORBGHG. The effect of ice sheets at the onset of the Holocene caused ~~the~~ temperatures in both summer and winter to be more than 2°C lower than those indicated by ORBGHG. ~~It was no surprise that the simulated effect of the ice sheets was larger at the beginning of the Holocene than afterwards when the deglaciation had progressed further.~~ The final deglaciation of the FIS happened at 10 ky~~a~~ and the corresponding deglaciation for LIS occurred at 6.8 ky~~a~~. Therefore, their cooling effects no longer existed after 6.5 ky~~a~~, and all three runs showed similar temperatures after that time. As a consequence, the temperature evolution curve of OGIS_FWF-v1 first showed a warming, with the peak being reached at around 7 ky~~a~~ when the cooling effects of the ice sheets had been counterbalanced by the insolation anomalies. This was subsequently followed by a gradual cooling that was controlled by demise in the orbital forcing. ~~The~~ Simulated temperatures initially had increased by 6.5 ky~~a~~ at rate of about 0.26, 0.21 and 0.44°C ky~~a~~$^{-1}$ for summer, winter and annual temperatures, respectively. The larger warming rate in annual mean than in summer and in winter was due to a largest response in the winter half year. The Arctic (here we refer to the region located north of 70 ° N) has large part of ocean where a few months delay in the maximum response has reported by Renssen et al. (2005). The study found the largest response in the winter half year (especially in fall) due to above delayed response that was ultimately caused by the thermal inertia over the oceans (Renssen et al 2005). Indeed, this explanation was furtherly supported by the simulated large warming rate in fall (up to 0.78 °C ky-1). The OGIS_FWF-v1 simulation indicates~~d~~ that ~~the~~ Arctic summer climate ~~in the Arctic~~ experienced a slightly faster warming at the beginning, followed by a more gradual warming toward the maximum anomaly of 1°C warmer than PI at about 7.5 kya (Fig. 4a). ~~The s~~Simulated winter temperatures stayed at a ~~lower~~ level ~~that was~~of 2°C lower than that of ORBGHG before 7 kya, which was followed by a rapid increase of about 1.5°C within a 500 yr~~s~~ period~~s~~, and then reached a temperature peak of about 1.5°C warmer than in ~~the~~ PI (Fig. 4b). ~~The s~~Simulated annual mean temperatures showed a relatively stable rise until 6.5 kya, which reached a maximum of about 1.5°C warmer than that of~~the~~ PI (Fig. ~~4a~~4c). The simulation OGIS_FWF-v2 gives~~gave~~ similar results for the Arctic, but had an even cooler climate before 9 kya than in OGIS_FWF-v1 with the maximum cooling of up to 0.3°C for all seasons at 10.5 kya.

3.2.2 Temperature evolution in ~~NW~~northwestern Europe

The ORBGHG simulation indicates smaller climate variability in ~~NW~~ northwestern Europe than in the Arctic. ~~The~~ ~~t~~Temperatures declined by around 1.5°C through the entire period in summer, less than 0.5°C for annual mean and rose by 0.5°C in winter (Fig.~~6~~5), which implied a ~~stronger~~ decreasing seasonality ~~than in~~toward the preindustrial era ~~period~~. This contrasts markedly with the clear cooling of climate in each season in the Arctic.

The OGIS_FWF-v1 simulation show~~sed~~ an overall cooler climate in ~~NW~~ northwestern Europe at the onset of Holocene, with ~~the~~ temperature anomalies of -1.5°C in summer, -3°C in winter and -2.8°C in annual mean compared to the PI simulation. ~~The t~~Temperatures increased from this point (11.5 kya) toward 6 kya at an overall rate of 0.28, 0.48, 0.54 °C kya^{-1} for summer, winter and annual mean, respectively. The most important feature in summer was a sharp temperature rise ~~of temperature~~ from a negative anomaly (-1.5°C) to a positive one (+1°C) by 10 kya, when the first peak was reached. Subsequently, a slight cooling was noted before 8 kya, followed by another temperature increase, which led to a second warming peak at 7.4 kya. The climate in winter showed a relatively stable warming by 6.5 kya with no identifiable warm peak. ~~The a~~Annual temperatures reflected the same phases of warming as in summer, one before 10 kya and another before 7.5 kya, but without a clear early temperature peak. Temperatures in all seasons from around 7 kya followed the ORBGHG simulation. It is worth noting that the OGIS_FWF-v2 simulation indicates ~~produced~~ a further cooling in summer between 11.5 and 9 kya ~~relative~~ compared to ~~the~~ OGIS_FWF-v1, which was also reflected in ~~the~~ annual mean temperatures. As a result, there was only one clear thermal maximum in summer for ~~NW~~ northwestern Europe, which peaked at around 7.4 kya.

3.2.3 Temperature evolution in ~~N~~northern Canada

Simulated temperatures in ORBGHG for ~~N~~northern Canada decreased by 2.2°C in summer, by 0.6°C in winter and by 1.1°C for annual average during the Holocene (Fig.~~7~~6). The stronger cooling in summer than in winter reflected ~~the~~ a strong early-Holocene seasonality, which decreased over the whole period.

The OGIS_FWF-v1 simulation ~~described~~ describes a much cooler climate in ~~N~~northern Canada during the early Holocene than that indicated by ~~the~~ ORBGHG. This cooling was up to 5°C for all seasons at the onset of Holocene. The climate dramatically warmed ~~up~~ with an overall high rate of more than 1°C ky~~a~~$^{-1}$ in both winter and summer during the early Holocene, which was due to the impact of the decaying LIS. The early Holocene warming was however not linear because an initial phase with more rapid warming was followed by a more gradual temperature increase. In summer, this warming resulted in a thermal peak at around 7.4 ky~~a~~, which was about 1.5°C warmer than in ~~the~~ PI. From 7.4 ky~~a~~ onwards, the climate experienced a gradual cooling that ~~is~~ was very similar to that of ~~the~~ ORBGHG. ~~The s~~Simulated temperatures in winter and annual mean did not show such a clear warm peak in comparison to summer. The results of OGIS_FWF-v2 only indicated marginal differences relative to OGIS_FWF-v1 for all seasons. Overall, the most significant feature of ~~the~~ simulated temperatures in Northen Canada was the strong warming that took place in the early Holocene.

3.2.4 Temperature evolution in Alaska

The ORBGHG simulation ~~showed~~ shows an overall cooling ~~climate~~ in Alaska for all seasons. ~~The s~~Simulated summer and annual mean temperatures experienced a decrease of more than 2°C throughout the whole period. ~~The w~~Winter temperatures had slightly increased by 10 ky~~a~~, and then stayed about 2°C higher for a period of 800 yrs, which was followed by a constant decrease toward the preindustrial ~~era~~value.

In contrast to other areas, both summer and winter temperatures in OGIS_FWF-v1 showed an overall cooling trend in Alaska during the entire Holocene (Fig. 7), which was slightly ~~warmer~~ higher than in our ORBGHG simulation. The OGIS_FWF-v1 simulation indicates a 2°C decline in summer temperature over the whole period with a slightly faster rate between 7 ky~~a~~ and 6.5 ky~~a~~. ~~The s~~Simulated winter temperatures decrease~~d~~s by 3.5°C during the early Holocene, with two small declines at 9.5 ky~~a~~ and 6.7 ky~~a~~. ~~The a~~Annual temperatures in the OGIS_FWF-v1 simulation reflected a 2.3°C cooling during the Holocene. The OGIS_FWF-v2 simulation ~~produced~~ represents a rather similar Alaskan temperature trend to that of ~~the~~ OGIS_FWF-v1.

3.2.5 Temperature evolution in Siberia

The ORBGHG simulation ~~described~~ describes an almost 2°C decline of summer temperatures over Siberia during the last 11.5 ky~~a~~ (Fig. 8). Simulated winter temperatures showed a smaller variation, as it decreased by less than 1°C, and annual mean temperatures decreased by around 1°C ~~on~~ over the course of the Holocene. The evolution of simulated temperatures in ~~the~~ ORBGHG ~~simulation~~ over Siberia was on a similar scale to that of ~~NW~~northwestern Europe.

The difference of simulated Siberian temperatures between ORBGHG and OGIS_FWF-v1 varied in summer and winter. On the one hand, ~~the~~ simulated summer temperatures in ~~the~~ OGIS_FWF-v1 ~~was~~ were generally similar to that in ~~the~~ ORBGHG with the exception of a small warming of 0.7°C before 10 ky~~a~~. On the other hand, ~~simulated~~ winter temperatures in the OGIS_FWF-v1 simulation ~~was~~ were around 2°C lower than in ~~the~~ ORBGHG before 7 ky~~a~~, followed by a rapid increase over the next 500 yrs after which it followed the ORBGHG simulation. Consequently, ~~the~~ simulated early Holocene warming lasted much longer in winter than in summer. ~~The s~~Simulated Siberian temperatures evolution in OGIS_FWF-v2 generally followed that of ~~the~~ OGIS_FWF-v1.

4 Discussion

We will evaluate our results by briefly comparing the simulations with proxy-based reconstructions, which will be followed by an analysis of the mechanism behind the simulated temperature patterns. The impact of freshwater forcing will also be discussed based on the two fwf scenarios.

4.1 Comparison of simulations with proxy records

At the onset of the Holocene, the overall cool climate indicated by the reconstructions generally matches that of our OGIS11.5 simulation, which shows~~ed~~ ~~a~~ lower annual temperatures at 11.5 ky~~a~~ than in ~~the~~ PI. Climate reconstructions based on proxy data generally show a cooler early Holocene over Northern Europe than at ~~the present~~0ky both in the summer and winter (Heiri et al., 2104; Mauri et al., 2015). Terrestrial and ocean sediment data also suggest a cooler early Holocene climate over eastern Siberia (Klemm et al., 2013; Tarasov et al., 2013) and ~~a~~ slightly lower SSTs over the North Atlantic Ocean (Came et al., 2007; Berner et al., 2008). Cooler conditions over the Barents Sea and Greenland are also indicated by multiple proxies (Peros et al., 2010; de Vernal et al., 2013; Vinther et al., 2008). Therefore, these proxy data agree with ~~the~~ simulated lower temperatures over these areas.

However, there is less agreement with proxies in places where the reconstructions are sparse. ~~O~~The only available pollen-based reconstruction~~s~~ from the western side of the Ural Mountains suggests ~~a~~ similar early Holocene summer temperatures (within 1°C anomaly) ~~to that~~compared to the preindustrial era~~present~~ (Salonen et al., 2011), whereas OGIS11.5 indicates that ~~the~~ summer temperatures ~~was~~ were slightly higher at 11.5 ky~~a~~ over most areas. At ~~the~~ high latitudes, the sea-ice cover reconstructions serve~~s~~ as an indirect palaeotemperature~~climate~~ proxy due to the scarcity of temperature records, and reveal~~s~~ an inconclusive temperature signal~~s~~ over the Canadian Arctic (de Vernal et al., 2013), whereas our simulation ~~reflected~~ reflects an overall warmer climate in the west and cooler conditions in the east.

Proxies indicate significantly different climate patterns over the east and the west of ~~N~~ northern America. The later initiation and termination of HTM over ~~N~~northern Canada imply lower temperatures during the early Holocene in the east (Kaufman et al., 2004). Whereas, the higher-than-present early Holocene temperatures over Central Beringia and Alaska are reflected by peat accumulation and by northward expansion of animal species (Kaufman et al., 2004; Jones & Yu, 2010). This thermal contrast agrees with those simulated patterns in the OGIS11.5 simulation, which indicates ~~a~~ warmer temperatures for Alaska and a much cooler climate over Canada. However, this interpretation of high temperature was recently ~~changed~~ challenged by Kaufman et al. (2016), who argued that the highest summer temperature in Alaska occurred as late as 8-6 ky~~a~~. Hence our simulation agrees better with the interpretation of Kaufman et al. (2004). In general, our simulation with full forcings was able to capture ~~the~~ main temperature features ~~that are also~~ indicated in proxy-based reconstructions.

Shakun et al. (2012) and Marcott et al. (2013) stacked multiple proxies to construct a record of temperatures since the LGM. Both above stacked reconstructions ~~(Shakun et al., 2012; Marcott et al., 2013)~~ and our simulation OGIS_FWF-v2 show that the Holocene was generally characterized by an initial warming and subsequent Holocene warm period over the NH extratropics, which indicates the broad consistency between simulation and proxy data. However, there are some disagreements related to seasonality (Fig. 9). Marcott et al. (2013) interpreted the stacked temperature reconstruction as representative of the annual mean climate, whereas it shows a better agreement with our simulated summer temperature than with annual mean value (Fig. 9). One potential explanation for this seasonal mismatch is that ~~the~~some proxy records have seasonal bias toward summer conditions, as has been suggested recently for many marine-based SST reconstructions from high latitudes (Lohmann et al. 2013). Further region-by-region comparisons of these warming rates with proxy records ~~are hindered~~ are beyond the focus of this work and will be dealt with in a future publication.~~by limited space.~~

4.2 Mechanism of climate response to forcings

It is clear from our data that the spatial patterns of climate response at the onset of the Holocene can be attributed to the variation in the dominant forcings prevailing in the different areas. Orbital scale insolation variations ~~is~~ are one of the important driving factors for the early Holocene climate. For instance, ~~the~~ higher temperatures in Alaska could be attributed to the orbitally induced positive insolation anomaly in combination with an anomalous atmospheric circulation caused by the remnant LIS. The air descended over the cold LIS surface, which created a high surface pressure anomaly that produced a clockwise flow anomaly at the surface, as indicated by the 800 hPa ~~Geopotential~~ geopotential height (Fig.10~~1c~~). This would induce stronger southerly winds over Alaska, which advected relatively warm air from the South. A potentially different early Holocene atmospheric circulation near the North Atlantic has also been ~~reported~~ found in a proxy record of ~~by~~ Steffensen et al. (in 2008), who ~~found~~reported an abrupt transition of deuterium excess that indicates a temperature change of precipitation moisture sources, and thus indirectly connected to atmospheric circulation changes.~~and a considerable reduction in dust concentration from the GRIP core data.~~

The strong influence of the ice sheets on early Holocene temperatures has been found in previous studies (Renssen et al., 2009; 2012). ~~The s~~Simulated lower summer temperatures over Northern Canada and ~~NW~~northwestern Europe in our OGIS11.5 simulation ~~is~~ were the result of such ice-sheet induced cooling, which would fully overwhelmed the warming effect of the positive summer insolation anomaly. The ice-sheet cooling effect ~~can~~ could ~~be~~ partly be explained on a local scale by the enhanced albedo over the ice sheets and by the climate's high sensitivity to albedo change (Romanova et al., 2006). Indeed, the summer surface albedo over the ice sheets ~~is~~ was much higher (up to 0.8) than over ice-free surfaces where the values varied~~y~~ from only 0.1 to 0.5, depending on the vegetation type and the fractional snow cover (Fig. 11~~0~~). ~~The t~~Temperatures ~~can~~ could be further reduced by the ice-sheet orography impact. The elevation of ice sheets introduced descending air ~~over~~over the ice-sheet surface, which caused ~~the~~ locally cooler condition~~ on the local scale~~. There ~~is~~ was also an approximate 0.5 °C cold ~~cooling~~ bias induced by the lapse rate effect when compared with the site-based records.

Changes in vegetation and land cover during the early Holocene contributed to climate change as well, especially over ecotonal regions. Modelling studies suggest that deforestation in boreal regions could decrease ~~the~~ regional temperatures by up to 1°C due to an increase in surface albedo and related positive feedbacks (Levis et al., 1999; Claussen et al., 2001; Liu et al., 2006). Taking Siberia as an example, the insolation-induced warming was partially offset by the overall higher summer albedo (Fig. 11~~0~~) induced by the southward expansion of the tundra or/and bare ground and related feedbacks at 11.5ky~~a~~, resulting in a minor warming in summer~~ which led to only a minor warmer summer climate than PI~~. The albedo-related feedbacks and the smaller annual insolation anomalies ~~annually counterbalanced~~ jointly result in a 0.5–2°C cooler in annual climate at 11.5 ky~~each other at 11.5 ka, and resulted in a 0.5–2°C cooler climate~~. We are aware of the potential role of permafrost at high latitudes, however, the discussion of the impact of permafrost thaw is hindered by the fact that our model version did not include a dynamic permafrost module. A version of LOVECLIM that is coupled to a permafrost module (VAMPERS) is currently in development (Kitover et al. 2015), and should enable us to quantify the role of permafrost in a future study.

Meltwater release and sea-ice related changes also had a footprint in the early Holocene climate. The OGIS11.5 simulation produce~~d~~s a sluggish AMOC in the North Atlantic with the largest decrease being more than 3 Sv. It was also reflected in a shallower overturning circulation at 11.5 ky~~a~~ compared to the PI simulation ~~period~~ as a response to meltwater release (Fig. 12). This slowdown also coincides with the foraminifera data from the Arctic Ocean and the Fram Strait that suggest a reduced northward oceanic heat transport (Thornalley et al., 2009). The slowdown and reduced heat transport led to ~~a~~ slightly lower temperatures at high latitudes (western Arctic Ocean) at 11.5 ky~~a~~ than that at 0ky~~found in the PI~~. Likewise, after the meltwater fluxes of the LIS diminished around 7 ky~~a~~ strong intensification of the AMOC followed. This sudden intensification of AMOC would explain the rapid Arctic temperature increase that occurred at this time (Fig. 4). However, it is important to notice ~~worth noting~~ that the temperature decrease was not simply inversely linear with the amount of northward transport of heat since the sea-ice feedbacks further reinforce this change (Roche et al., 2007). Actually, sea-ice coverage in the OGIS11.5 simulation was much more extensive over the Davis Strait (~~N~~northern Labrador Sea) than the corresponding value in ~~the~~ OG11.5 (Fig. 13). This extended sea-ice cover in this region was stronger than the direct cooling effect of the reduced oceanic heat transport. Such an anomaly might be explained by positive feedbacks involving sea-ice being active (Renssen et al., 2005). The Greenland Sea warming ~~can~~ could be attributed to enhanced convective activity that releases more oceanic heat into the atmosphere. This enhanced convective activity was caused by the shift of deep water formation from the eastern Greenland Sea to the west, which was initially induced by the freshwater discharge from ice-sheet melting. The net ~~overall~~ response of the climate reflects the impact of a combination of forcings and feedbacks, which showed a high temporal-spatial variability.

4.3 Early Holocene warming and climate-ocean system response to freshwater

The simulation of OGIS_FWF-v2 ~~produced~~ indicates a stronger cooling (before 9 ky) in the Arctic and ~~NW~~northwestern Europe than those found in the OGIS_FWF-v1 ~~before 9 ka~~ with ~~a~~ the stronge~~r~~st temperatures reduction ~~of~~ at around 10 ky~~a~~. The enhanced freshwater influx from the GIS and the redistributed meltwater from the FIS caused an alteration in the surface ocean freshening in the Nordic Seas, which reduced convective activity (Renssen et al., 2010; Blaschek & Renssen, 2013). Indeed, this reduction led to a further slight reduction of the northward heat transport by the Atlantic Ocean, which was associated with a further ~~weakened~~ AMOC weakening (by 1-2 Sv than in FWF_v1): this in turn produced a slightly stronger cooling at 10 ky~~a~~ (Fig. SI3) and a sea-ice expansion over the Denmark Strait (Fig. 14 & SI4).

~~The meltwater flux freshened the surface ocean in the deep-water formation area, which led to a slowdown in the ocean circulation.~~ However, the efficiency of above meltwater flux freshening ~~this~~ effect is determined by multiple aspects. The most important factor is the maximum flux of meltwater that was added to the ocean, while the total freshwater amount had only a second-order effect (Roche et al., 2007). Numerous investigations on the behavior of the coupled atmosphere-ocean system suggest that the ~~applying~~ application of freshwater will not lead to a disruption of the North Atlantic Deep Water production (NADW) as long as a certain threshold is not crossed (Ganopolski et al., 1998; Rahmstorf et al., 2005). Apart from the intensity and duration, the ocean circulation response to freshwater also depends on the location where this freshwater is released. For instance, it is more sensitive to the release of freshwater in the eastern Norwegian Sea than at the St. Lawrence River outlet since the former is closer to the main site with NADW formation (Roche et al., 2010). This is consistent with a previous study by Blaschek & Renssen in (2103), who found that freshwater from the GIS did have a tangible impact on Nordic seas, even though the total amount was minor. Since the second freshwater scenario (OGIS_FWF-v2) includes a slightly larger fwf from the GIS (compared to that in OGIS_FWF-v1) and the fwf was released in a sensitive area, ~~This~~ the location-depende nt~~d~~ sensitivity could also partially explain further ~~why the~~ AMOC weakening ~~was weaker~~ in the OGIS_FWF_v2 simulation ~~than in~~compared to OGIS_FWF-v1.

The OGIS_FWF-v1 simulation indicates~~d~~ two peaks in the temperature evolution over ~~NW~~northwestern Europe, at around 10 and 7 ky~~a~~. High temperatures at 7 ky~~a~~ are recorded in proxy-based reconstructions as well. However, no warm peak at 10 ky~~a~~ was observed in pollen-based reconstructions, which actually suggests a cooler climate prevailed at 10 ky~~a~~ than in the preindustrial ~~present-day~~ Europe (Mauri et al., 2015). In contrast to the climate simulated in ~~the~~ OGIS_FWF-v1~~ simulation~~, the simulation with updated freshwater (OGIS_FWF-v2) produced a warming trend that is consistent with a highest temperature around 7 ky~~a~~. Moreover, the OGIS_FWF-v1 produced a temperature decrease between two peaks whereas the proxies indicated a rapid temperature increase at the beginning followed by a more gradual warming (Brooks et al., 2012). Therefore, from the viewpoint of ~~the~~ temperature evolution in ~~NW~~northwestern Europe, the OGIS_FWF-v2 represented a more realistic climate than OGIS_FWF-v1 did, which implies~~d~~ that the existing uncertainties in the reconstructions of ice-sheet dynamics can be evaluated by applying different freshwater scenarios. The further comparison with proxy data and with other model transient simulations will be conducted in a future paper.

5 Conclusions

We performed both equilibrium and transient simulations by employing the LOVECLIM climate model to explore the spatial patterns of the climate response to forcings at the onset of the Holocene and ~~the~~ temperature evolution over the last 11.5 ky~~a~~. We focused on three research questions in our analysis, which are outlined below with the main finding:

1) What were the spatial patterns of simulated temperature at the onset of the Holocene?

The temperature~~s~~ anomalies relative to PI at 11.5 ky~~a~~ were regionally heterogeneous ~~compared with those of PI~~, which are shown as a range of annually negative anomalies over many areas but which were ~~higher~~ positive in Alaska. The climate in eastern ~~N~~northern Canada and ~~NW~~northwestern Europe ~~was~~ were much cooler than those in other regions with temperature anomalies of -2 to -5°C relative to 0ky~~a~~ throughout the year. The climate over the ~~N~~northern Labrador Sea and the North Atlantic was also 0.5–3°C cooler. ~~The t~~Temperatures in Siberia were 0.5–3°C and 1.5–3°C lower in winter and annually, and ~~the~~ summer temperatures showed only a small deviation (between +0.5 to -1.5°C) compared to 0 ky~~a~~. ~~The~~ Simulated summer temperature anomaly in the eastern Arctic Ocean was also small (between ±~~-~~0.5°C), and annual temperatures were 0.5–2°C lower. In contrast to cooler conditions in other areas, ~~the t~~Temperatures in Alaska were 1.5–3°C higher than the pre-industrial period for all seasons.

2) What were the roles of forcings, especially ice-sheet decay, in shaping these features?

The ice-sheet cooling effect in ~~N~~northern Canada and ~~NW~~northwestern Europe overwhelmed the warming impact of the positive insolation anomaly, which caused the relatively cold climate at 11.5 ky~~a~~. In particular, the enhanced surface albedo over the ice sheets and the orographic effect were important ~~for~~ in promoting these~~is ice-sheet related~~ cold conditions. The cooler climate over the ~~N~~northern Labrador Sea and the North Atlantic was related to both reduced northward heat transport and ~~activated~~enhanced sea-ice feedbacks ~~which were initiated by weakened ocean circulation~~. A small summer temperature anomaly was found in Siberia, where the positive insolation anomaly was partially offset by the cooling effect of the higher albedo associated with the relatively extensive tundra cover in the early Holocene. ~~The o~~Overall lower winter and annual temperatures at 11.5 ky~~a~~ over central Siberia can be attributed to both vegetation-related albedo feedbacks and to the relatively small negative insolation deviation compared to the preindustrial level ~~over central Siberia~~.

The dominant factors driving the climate in~~for~~ eastern Arctic Ocean climate were the amount of northward heat transport associated with the strength of ocean circulation and the orbitally forced insolation variation. ~~The a~~Annual mean temperatures at 11.5 ky~~a~~ ~~was~~ were lower than at 0ky~~a~~

because the cooling effect of a reduced northward oceanic heat transport (induced by weakened ocean circulation) was larger than the insolation-induced warming. During summer, these two factors were of similar magnitude and temperatures were similar to those of the preindustrial era. Temperatures in Alaska were higher for all seasons in response to the dominant positive insolation anomaly and the enhanced southerly winds induced by the LIS, which advected relatively warm air from the South. Therefore, this regional heterogeneity is the result of the climate response to a range of dominant forcings and feedbacks.

3) What was the spatiotemporal variability in the simulated early Holocene evolution?

Above geographical variability is also reflected in the ~~The~~ Holocene temperature evolution, especially in the ~~and~~ early Holocene warming ~~were also geographically varying~~. In Alaska, the climate was constantly cooling throughout the Holocene due to the decreasing insolation and atmospheric circulation variability. In contrast, ~~N~~northern Canada experienced a strong warming with an overall warming rate over 1°C ky~~a~~$^{-1}$ and this warming lasted until 7 ky~~a~~. Although in ~~NW~~northwestern Europe, the Arctic and Siberia different forcings and mechanisms played different roles, the overall warming effect was similar for these regions, with a rate of around 0.5°C ky~~a~~$^{-1}$. In addition, the comparison of early Holocene temperatures over ~~NW~~northwestern Europe with proxy records suggest that the OGIS_FWF-v2 represented a more realistic climate condition than the OGIS_FWF-v1 does, and impliesy~~y~~ that the uncertainties with regard to the ice-sheet decay can potentially be constrained by applying different deglaciation scenarios and comparing then with networks of proxy-records. Overall, our results demonstrated a large spatial variability in the climate response to diverse forcings and feedbacks, both for the early Holocene temperature distribution and for the early Holocene warming, and it also helps in understanding the difference between proxy-records.

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Table 1. Boundary conditions for 11.5 ky~~a~~ and pre-industrial (PI)

	11.5 ky~~a~~			PI [a]		
Greenhouse gases (GHG)	CO_2 253 ppm	CH_4 511 ppb	N_2O 245 ppb	CO_2 280 ppm	CH_4 760 ppb	N_2O 270 ppb
Orbital parameters (ORB)	ecc 0.019572	obl 24.179 °	lon of perih 270.209 °	ecc 0.016724	obl 23.446 °	lon of perih 102.040 °
Ice sheets (relative to 0ky ~~present~~)	Size $69.2*10^5$ km^2	Max thickness 2331 m	Meltwater flux 220 mSv	–	–	–

PI[a]: GHG for 1750 AD; ORB for 1950 AD.

Table 2. Experiments and corresponding setup

Equilibrium		Transient	
Name	Forcing	Name	Forcing
OG11.5	ORB+GHG	ORBGHG	ORB+GHG
OGIS11.5	ORB+GHG+IS+FWF[a]	OGIS_FWF_v1	ORB+GHG+IS+FWF_v1
		OGIS_FWF_v2	ORB+GHG+IS+FWF_v2

FWF[a]: only one freshwater scenario is considered in the OGIS11.5 equilibrium experiment.

Figure captions

Fig. 1. Evolution of greenhouse gas concentrations (GHG) shown as the radiative forcing's deviation from the pre-industrial level (with solid lines corresponding to the left axis), and June insolation at 65 °N derived from orbital configuration (with red line and the axis on the right).

Fig. 2. The prescribed ice-sheet forcing during the early Holocene. (a) Variation in ice-sheet extent (km^2) displayed as the black lines with the axis on the left and their maximum thickness (m) indicated by the green lines with the axis on the right. A relatively minor change in GIS is not shown due to its small scale. (b) Two freshwater flux scenarios (in mSv), FWF-v1 (thick dashed lines) and FWF-v2 (solid lines). (c) Total meltwater discharge in equivalent sea level (m).

Fig. 3. Simulated temperatures for 11.5 ky~~a~~, shown as deviation from the PI. Left column shows the simulation with only GHG and ORB forcings (OG11.5). For the right column, the ice-sheet forcing is included (OGIS11.5). Upper, middle and lower panels present summer (JJA), winter (DJF) and annual mean temperatures, respectively.

Fig. 4. Simulated temperature evolution, shown as the anomalies compared to the PI, since the early Holocene at high latitudes (North of 70°). ~~The red line indicates the simulation with only ORB and GHG forcings (ORBGHG), while the black and green lines represent the simulations OGIS_FWF-v1 and OGIS_FWF-v2, in which the ice-sheet forcing are included.~~ (a), (b) and (c) panels represent the summer, winter and annual values respectively. The slope indicates the overall warming rate and is based on the least squares regression over the period from the 11.5 to 6 ky~~a~~, as from 6 ky~~a~~ the temperature start to decrease. It is only a general estimation, thus uncertainty ranges are not provided. The warmest peak is marked by shaded bar and represents the simulated peak during which the temperature was over 1°C higher than in PI. Both slope calculation and warm peak are based on the OGIS_FWF-2 simulation.

Fig. 5. Simulated temperatures, shown as the anomalies compared to the PI, during the Holocene in Northwestern Europe (5 °W–34 °E, 58 °N–69 °N). The caption is the same as in fig. 4.

Fig. 6. Simulated temperatures, shown as the anomalies compared to the PI, during the Holocene in Northern Canada (120 °W–55 °W, 50 °N–69 °N). The caption is the same as in fig. 4.

Fig. 7. Simulated temperatures, shown as the anomalies compared to the PI, during the Holocene in Alaska (170 °W–120°W, 58 °N–74 °N). The caption is the same as in fig. 4.

Fig. 8. Simulated temperatures, shown as the anomalies compared to the PI, since the early Holocene in Siberia (62–145° E, 58–74 °N). The caption is the same as in fig. 4, except that the

warming rate slope is indicated for a shorter period (11.5–9.8 ky).

Fig. 9. Model-data comparison over the latitudinal band of 30-90 °N, shown as a deviation from the PI. ~~Black lines represent t~~The stacked temperature reconstruction with 1δ uncertainty (grey band) is based on Marcott et al (2013). ~~Red and green lines indicate the simulated summer and annual temperatures.~~

Fig. 10. Summer surface albedo in the extratropical Northern Hemisphere. (a), (b) and (c) represent the control run (PI), the simulations without ice sheets (OG11.5) and with ice sheets (OGIS11.5) respectively.

Fig. 11. Geopotential height (m) at 800 hPa in the extratropical Northern Hemisphere. (a) shows the control condition PI, (b) and (c) are the simulations OG11.5 and OGIS11.5.

Fig. 12. Meridional overturning streamfunction (Sv) in the Atlantic Ocean Basin. (a), (b) and (c) indicate the control run (PI), the simulation OG11.5 and OGIS11.5 respectively. On the left hand side, depth is indicated in meters. Positive values indicate a clockwise circulation. Maximum AMOC strength value was 17 Sv in the PI and OGIS simulation, while it was only about 11 Sv in OGIS11.5. All these values were reached at about 1200 m depth.

Fig. 13. Minimum sea-ice thickness (m) in September for PI (a), OG11.5 (b) and OGIS11.5 (c).

Fig. 14. Response of the ocean variables (shown as a 100-~~-~~yr~~s~~ average) to forcings during the Holocene. (a) Maximum meridional overturning streamfunction (Sv) in the North Atlantic. (b) Sea-ice area (10^{12} m^2) in the Northern Hemisphere. ~~The red line indicates the ORBGHG simulation. The black and green lines reflect results of the simulation OGIS_FWF-v1 and OGIS_FWF-v2.~~

Figure 1

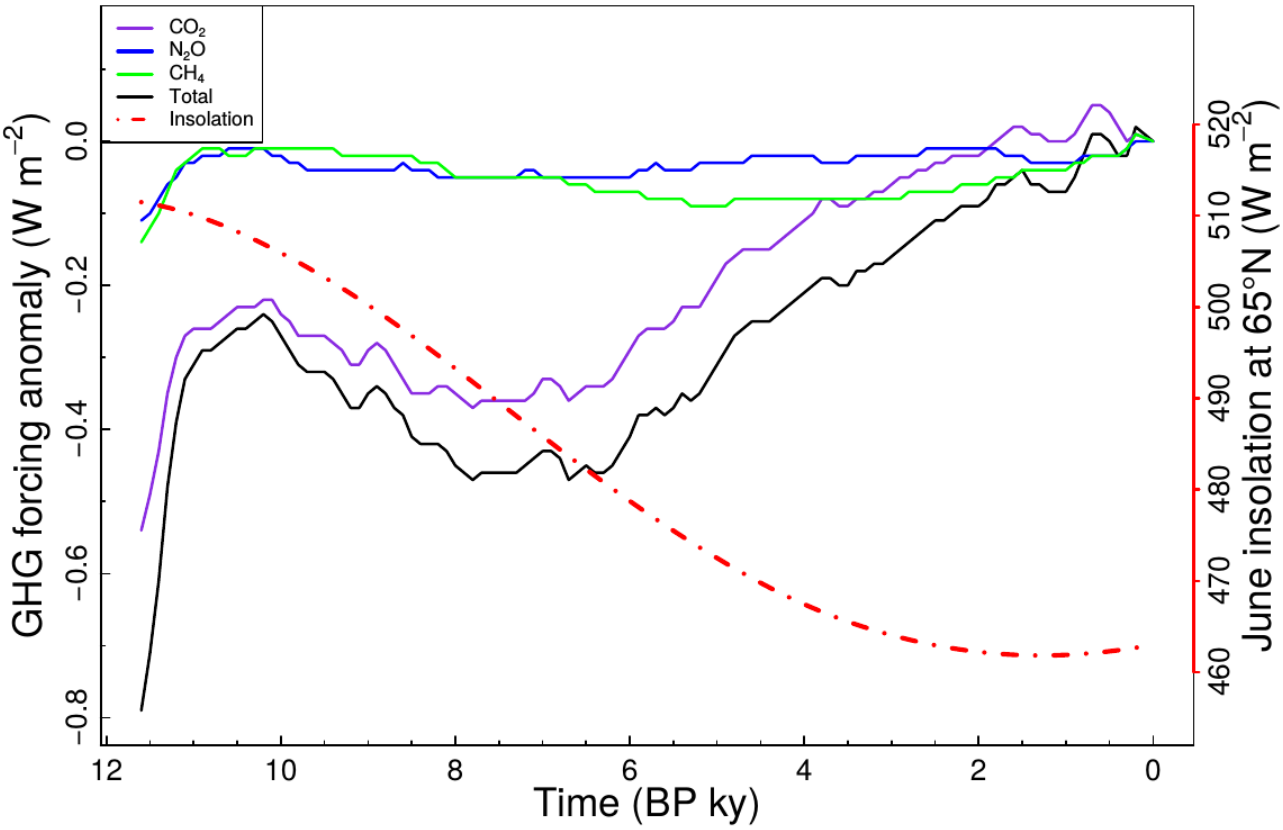
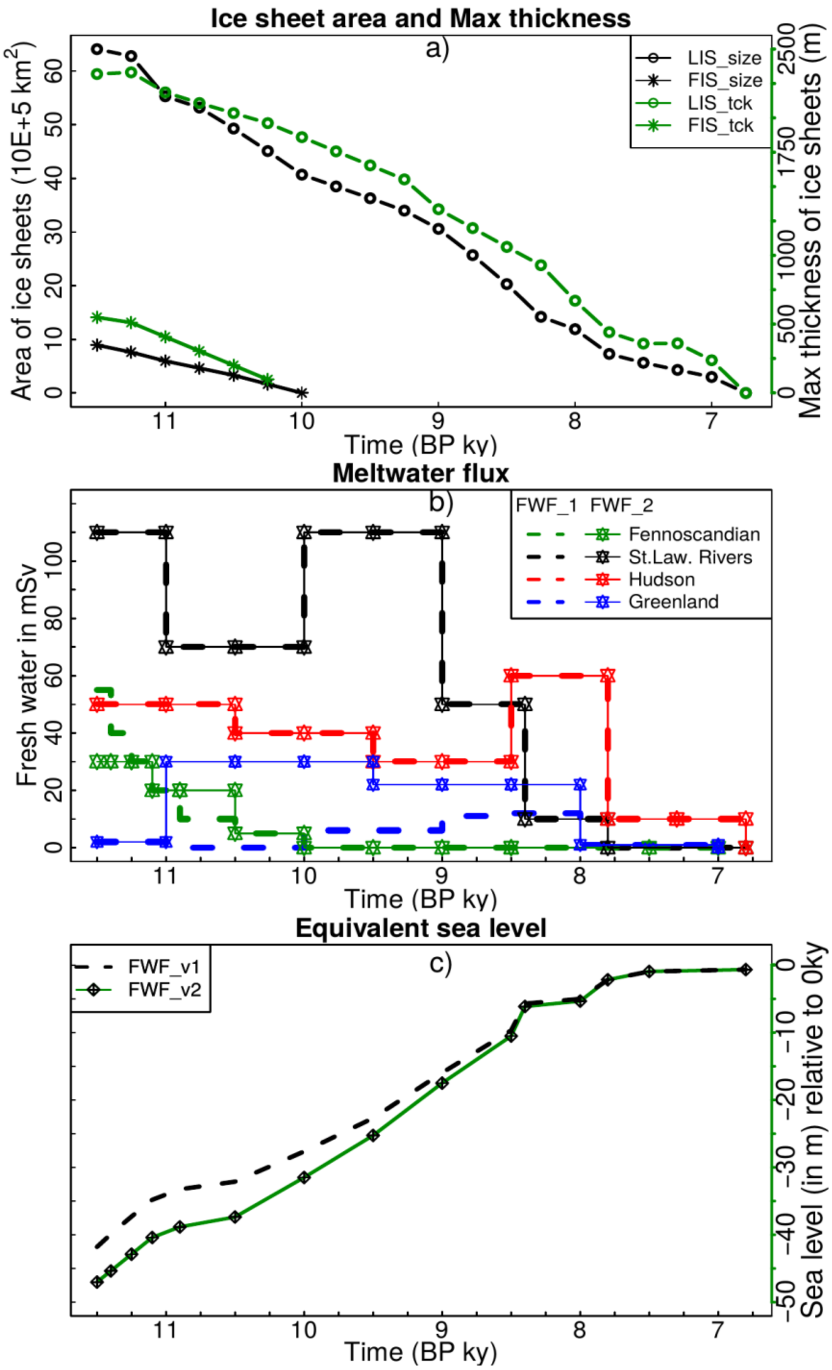

CO2
N2O
CH4
Total
Insolation
GHG forcing anomaly (W m−2)
0.0
−0.2
−0.4
−0.6
−0.8
June insolation at 65°N (W m−2)
520
510
500
490
480
470
460
12
10
8
6
4
2
0
Time (BP ky)

Figure 2


Ice sheet area and Max thickness
a)
LIS_size
FIS_size
LIS_tck
FIS_tck
Area of ice sheets (10E+5 km2)
Max thickness of ice sheets (m)
Time (BP ky)
Meltwater flux
b)
FWF_1 FWF_2
Fennoscandian
St.Law. Rivers
Hudson
Greenland
Fresh water in mSv
Time (BP ky)
Equivalent sea level
c)
FWF_v1
FWF_v2
Sea level (in m) relative to 0ky
Time (BP ky)

5

Figure 3

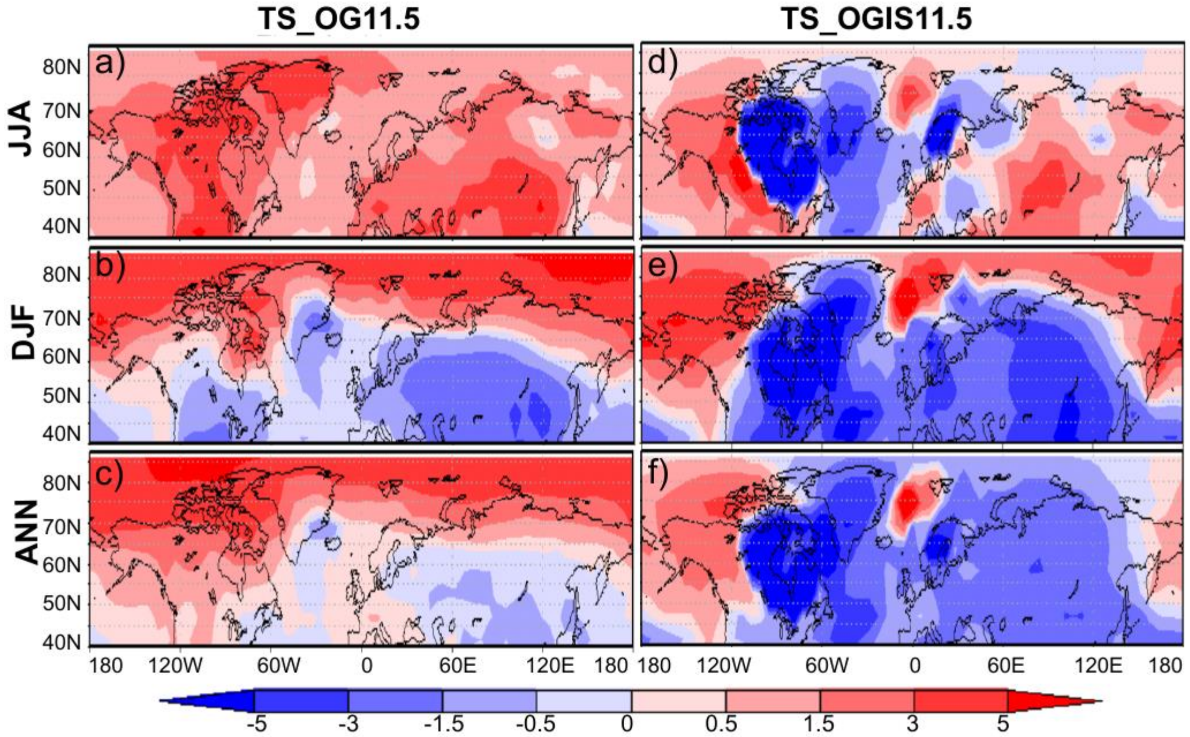
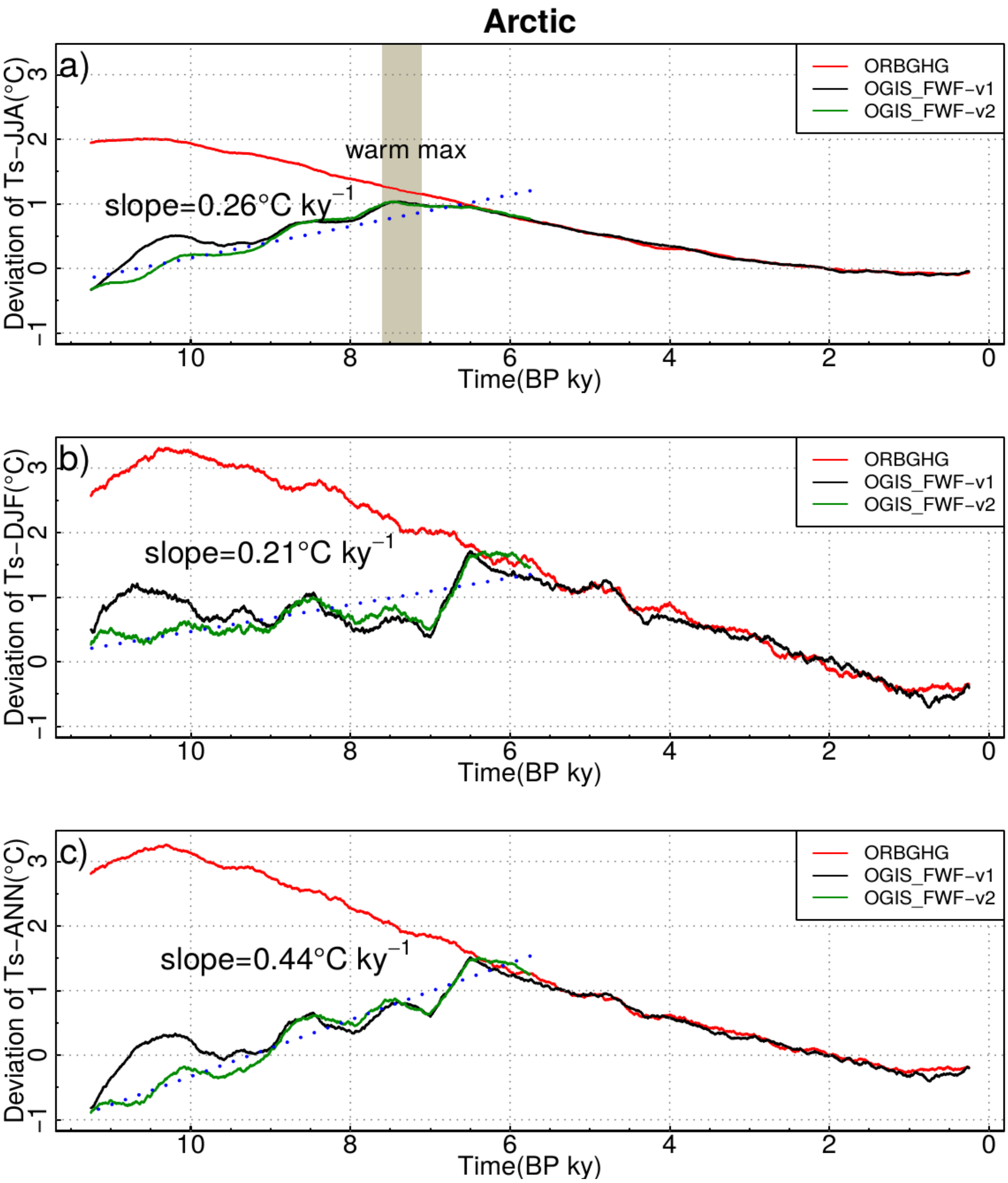

TS_OG11.5
TS_OGIS11.5
JJA
DJF
ANN
a)
b)
c)
d)
e)
f)
80N
70N
60N
50N
40N
180
120W
60W
0
60E
120E
180
-5
-3
-1.5
-0.5
0
0.5
1.5
3
5

Figure 4


Arctic
a)
warm max
slope=0.26°C ky⁻¹
ORBGHG
OGIS_FWF-v1
OGIS_FWF-v2
Deviation of Ts−JJA(°C)
Time(BP ky)
b)
slope=0.21°C ky⁻¹
Deviation of Ts−DJF(°C)
c)
slope=0.44°C ky⁻¹
Deviation of Ts−ANN(°C)

5

Figure 5

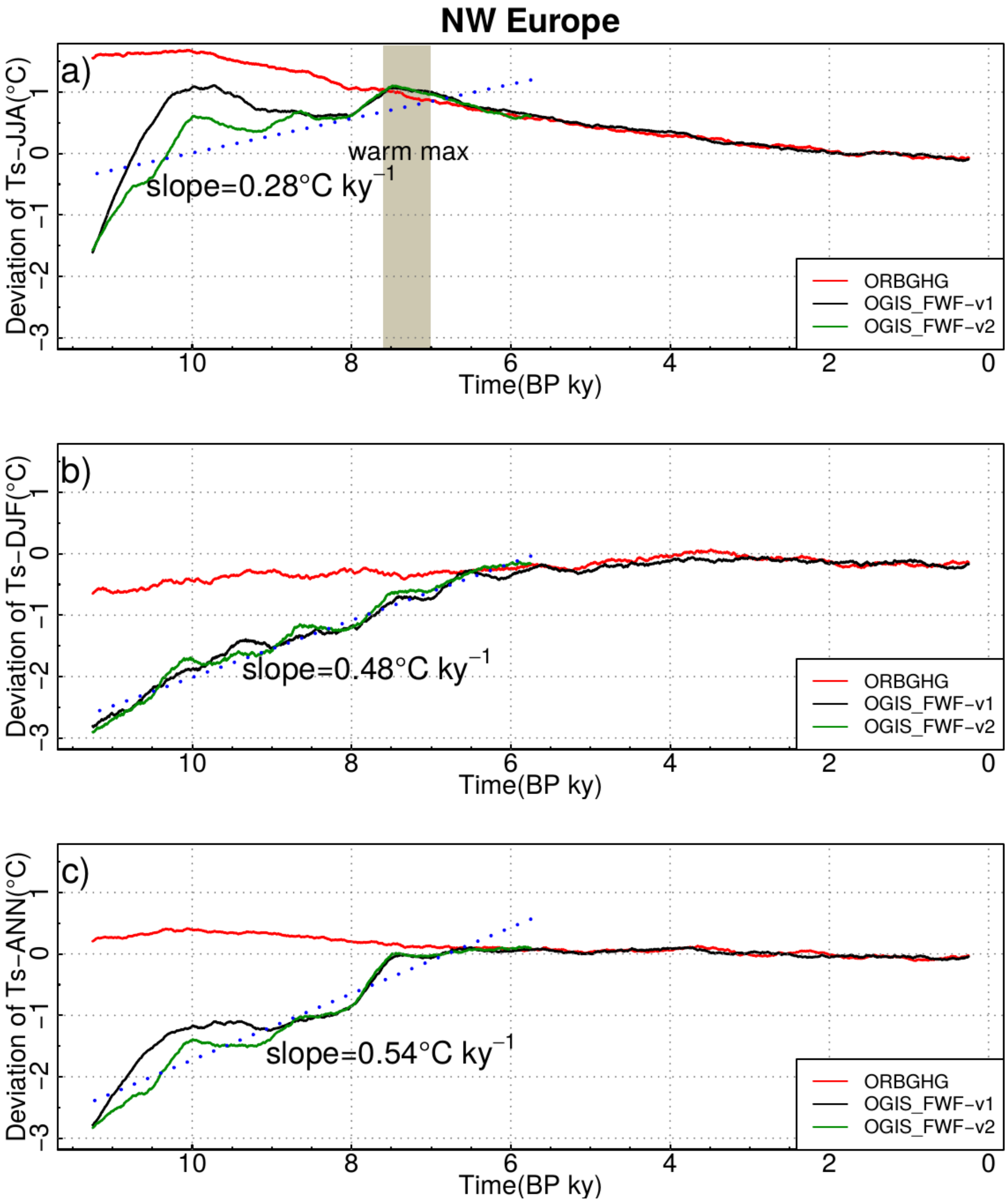

NW Europe
a)
Deviation of Ts−JJA(°C)
warm max
slope=0.28°C ky−1
ORBGHG
OGIS_FWF−v1
OGIS_FWF−v2
Time(BP ky)
b)
Deviation of Ts−DJF(°C)
slope=0.48°C ky−1
ORBGHG
OGIS_FWF−v1
OGIS_FWF−v2
Time(BP ky)
c)
Deviation of Ts−ANN(°C)
slope=0.54°C ky−1
ORBGHG
OGIS_FWF−v1
OGIS_FWF−v2
Time(BP ky)

Figure 6

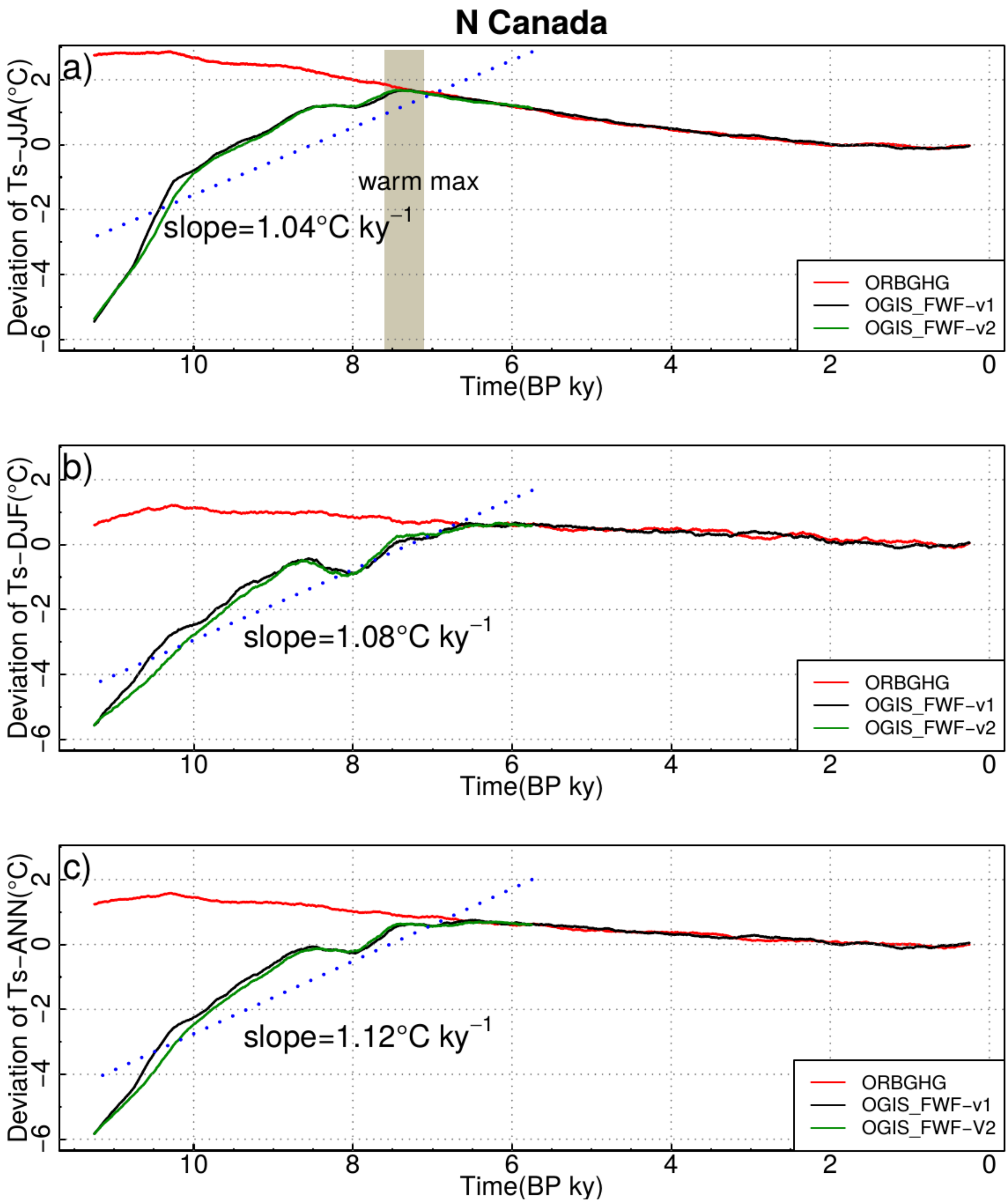

N Canada
a)
Deviation of Ts−JJA(°C)
warm max
slope=1.04°C ky−1
ORBGHG
OGIS_FWF−v1
OGIS_FWF−v2
Time(BP ky)
b)
Deviation of Ts−DJF(°C)
slope=1.08°C ky−1
ORBGHG
OGIS_FWF−v1
OGIS_FWF−v2
Time(BP ky)
c)
Deviation of Ts−ANN(°C)
slope=1.12°C ky−1
ORBGHG
OGIS_FWF−v1
OGIS_FWF−V2
Time(BP ky)

Figure 7

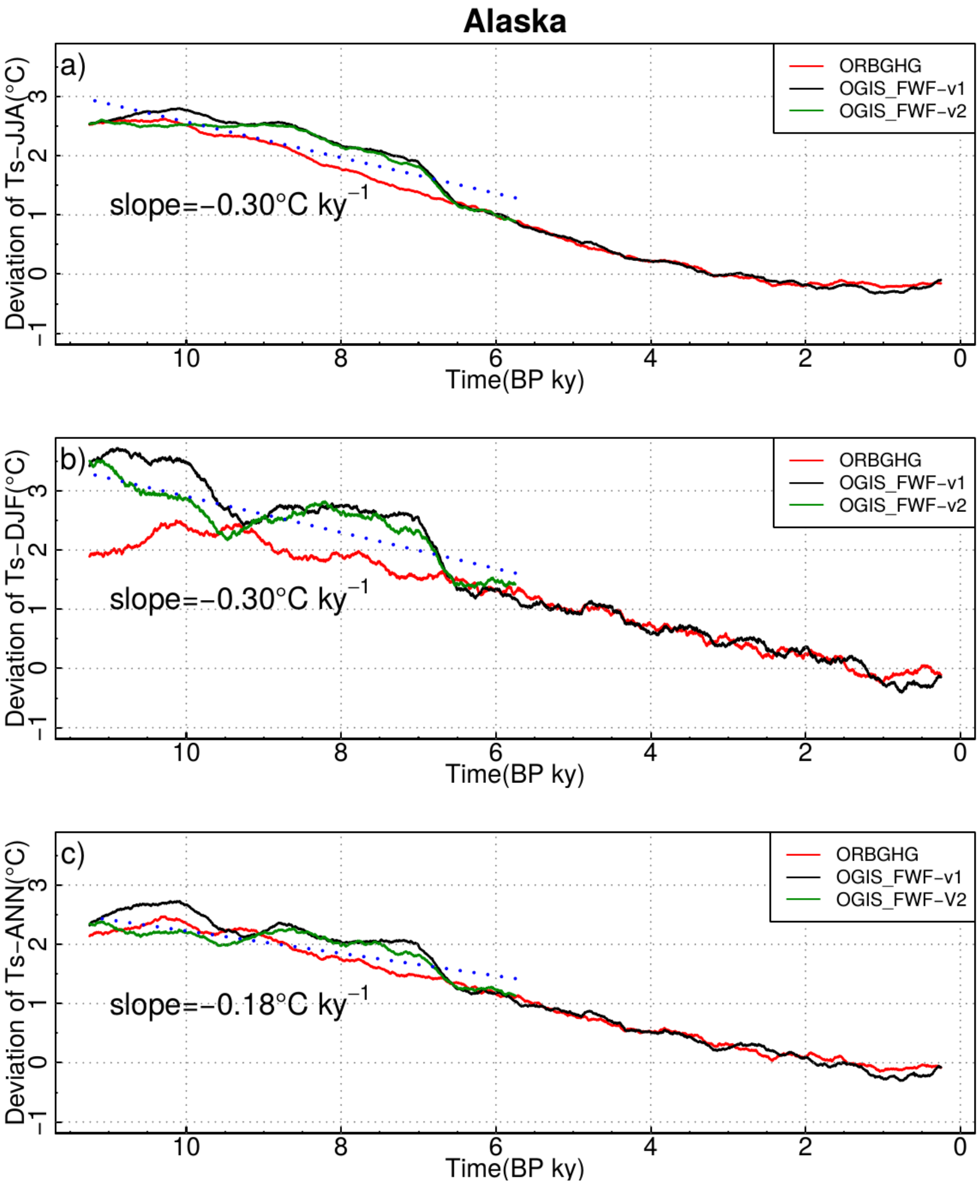
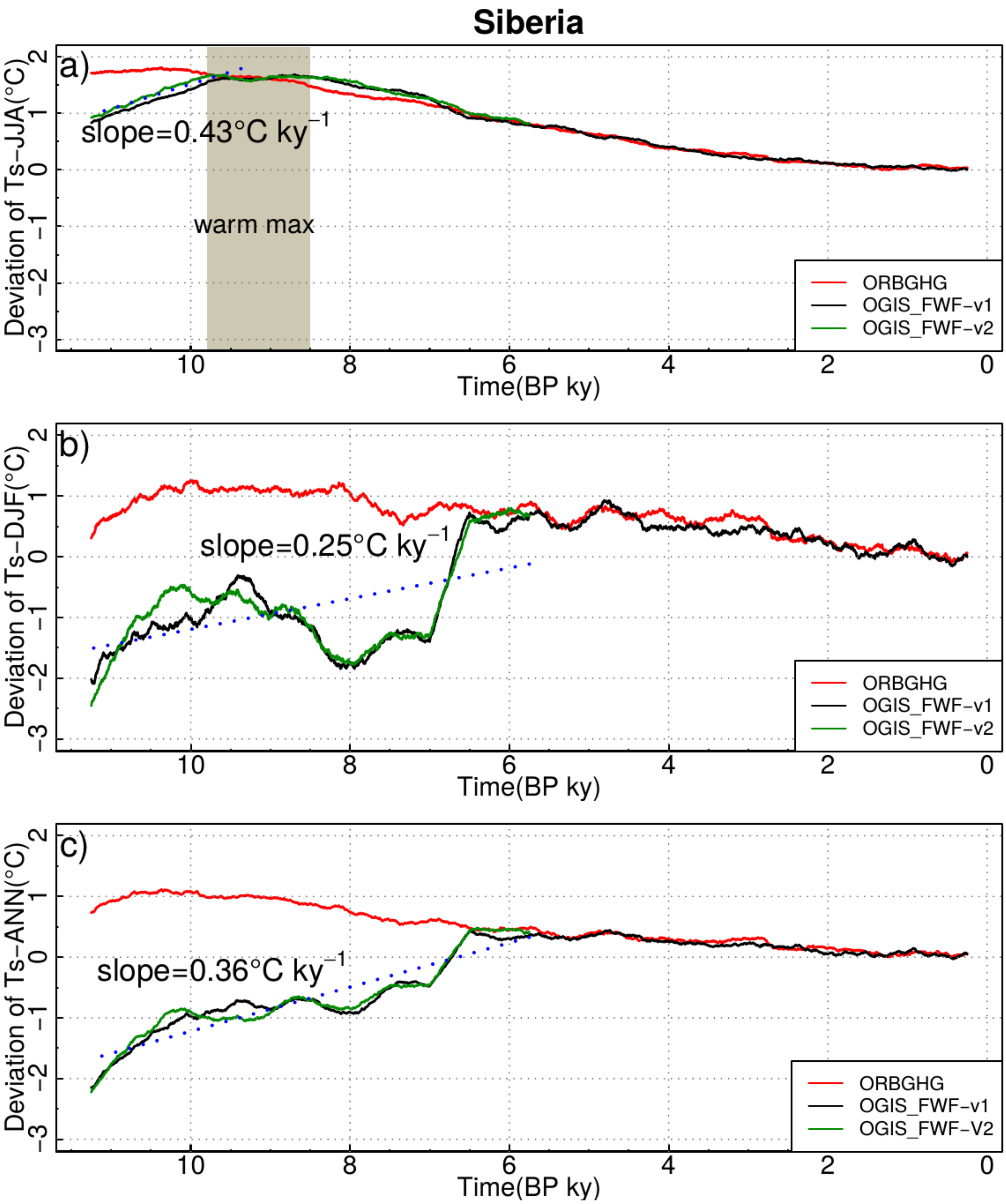

Alaska
a)
ORBGHG
OGIS_FWF-v1
OGIS_FWF-v2
slope=-0.30°C ky^{-1}
Deviation of Ts-JJA(°C)
Time(BP ky)
b)
ORBGHG
OGIS_FWF-v1
OGIS_FWF-v2
slope=-0.30°C ky^{-1}
Deviation of Ts-DJF(°C)
Time(BP ky)
c)
ORBGHG
OGIS_FWF-v1
OGIS_FWF-V2
slope=-0.18°C ky^{-1}
Deviation of Ts-ANN(°C)
Time(BP ky)

Figure 8


Siberia
a)
Deviation of Ts−JJA(°C)
slope=0.43°C ky−1
warm max
ORBGHG
OGIS_FWF−v1
OGIS_FWF−v2
Time(BP ky)
b)
Deviation of Ts−DJF(°C)
slope=0.25°C ky−1
ORBGHG
OGIS_FWF−v1
OGIS_FWF−v2
Time(BP ky)
c)
Deviation of Ts−ANN(°C)
slope=0.36°C ky−1
ORBGHG
OGIS_FWF−v1
OGIS_FWF−V2
Time(BP ky)

5

Figure 9

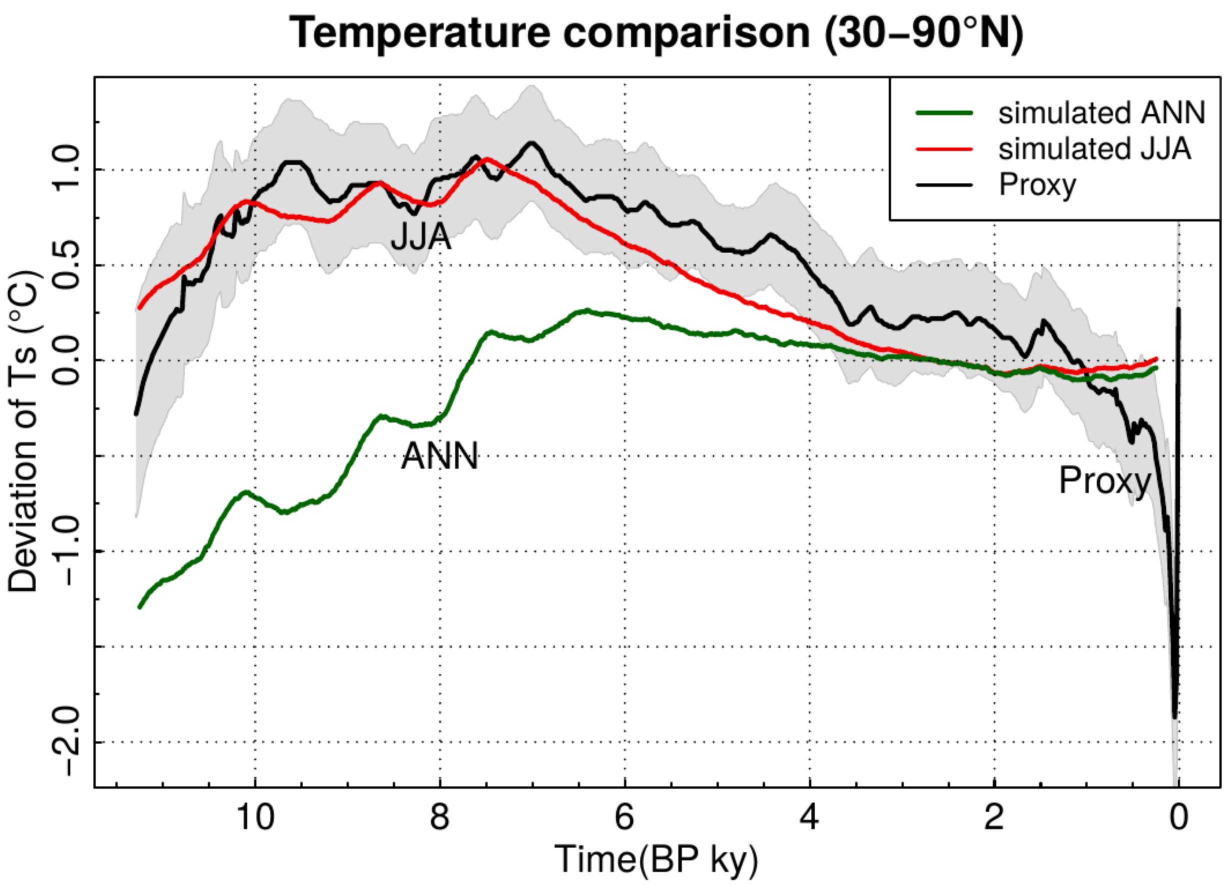

Temperature comparison (30−90°N)
simulated ANN
simulated JJA
Proxy
JJA
ANN
Proxy
Deviation of Ts (°C)
Time(BP ky)
1.0
0.5
0.0
−1.0
−2.0
10
8
6
4
2
0

Figure 10

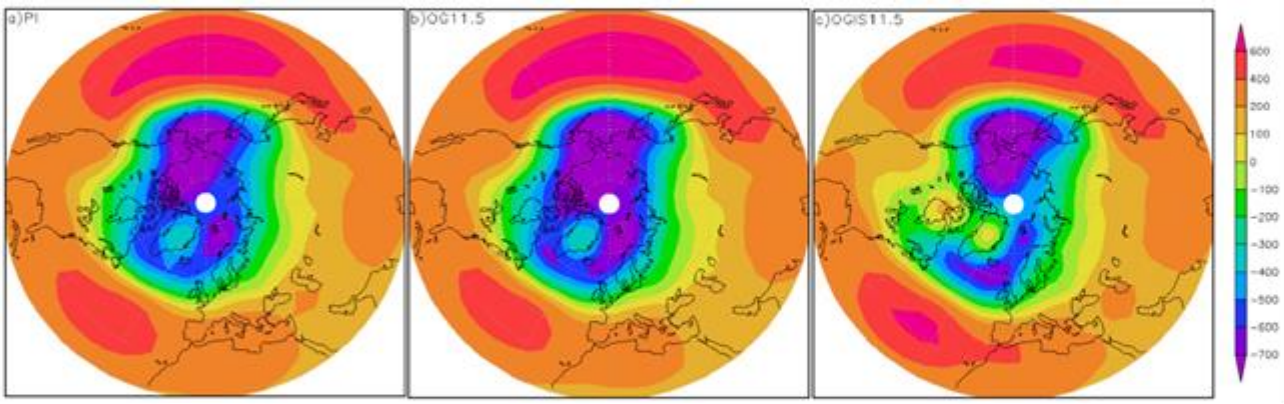

a)PI
b)OG11.5
c)OGIS11.5
600
400
200
100
0
-100
-200
-300
-400
-500
-600
-700

Figure 11

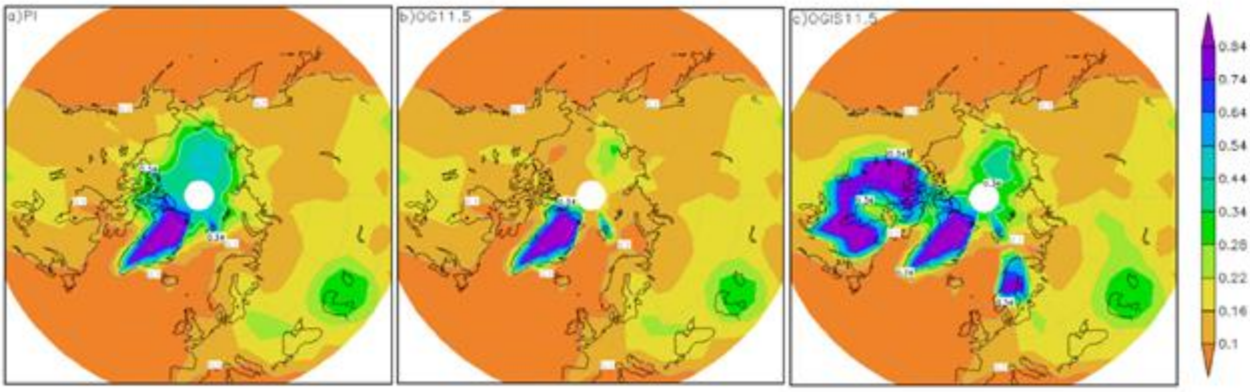


Figure 12

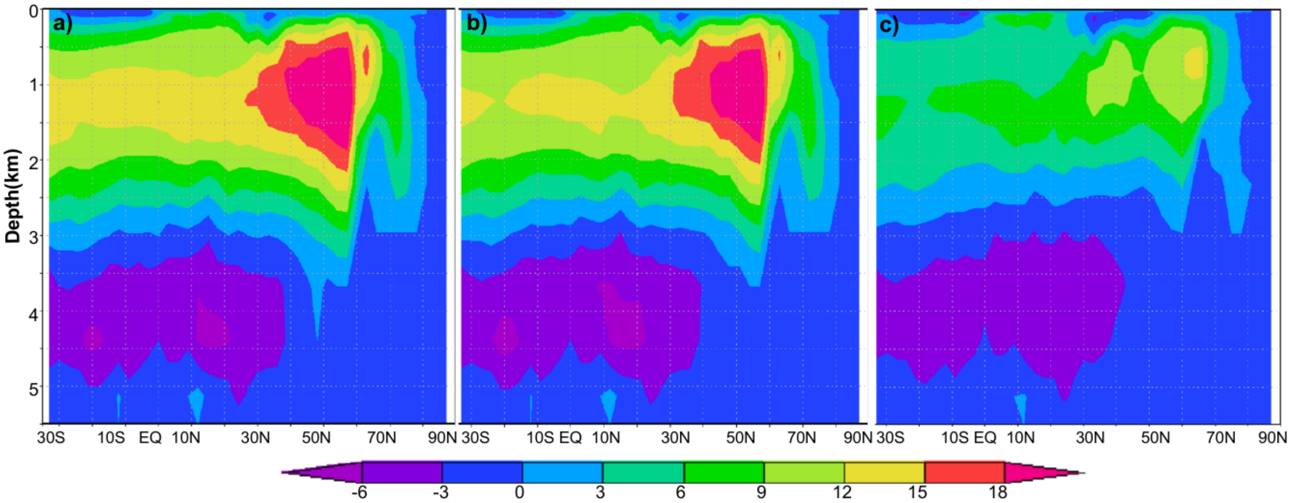

a)
b)
c)
Depth(km)
0
1
2
3
4
5
30S
10S
EQ
10N
30N
50N
70N
90N
-6
-3
0
3
6
9
12
15
18

Figure 13

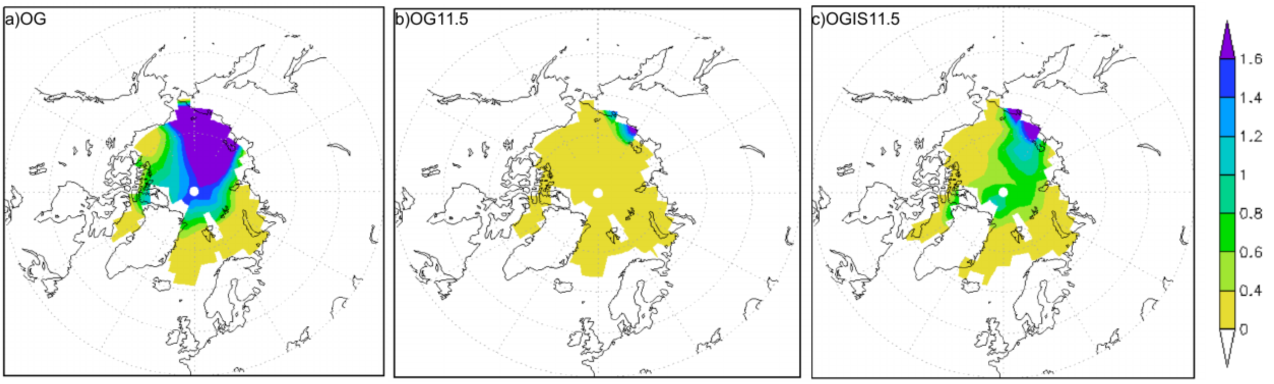
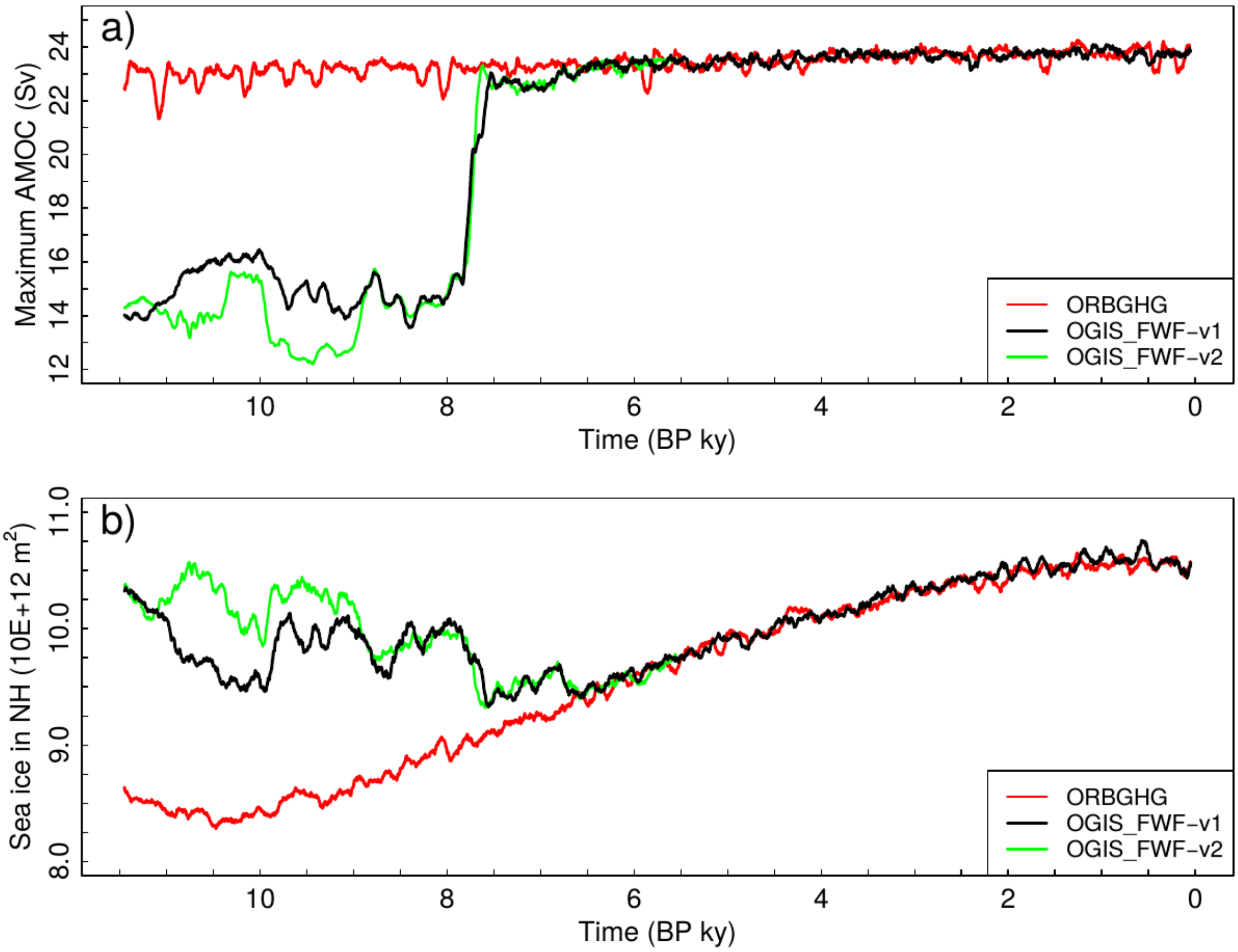


Figure 14


a)
Maximum AMOC (Sv)
12
14
16
18
20
22
24
ORBGHG
OGIS_FWF−v1
OGIS_FWF−v2
10
8
6
4
2
0
Time (BP ky)
b)
Sea ice in NH (10E+12 m^2)
8.0
9.0
10.0
11.0
ORBGHG
OGIS_FWF−v1
OGIS_FWF−v2
10
8
6
4
2
0
Time (BP ky)

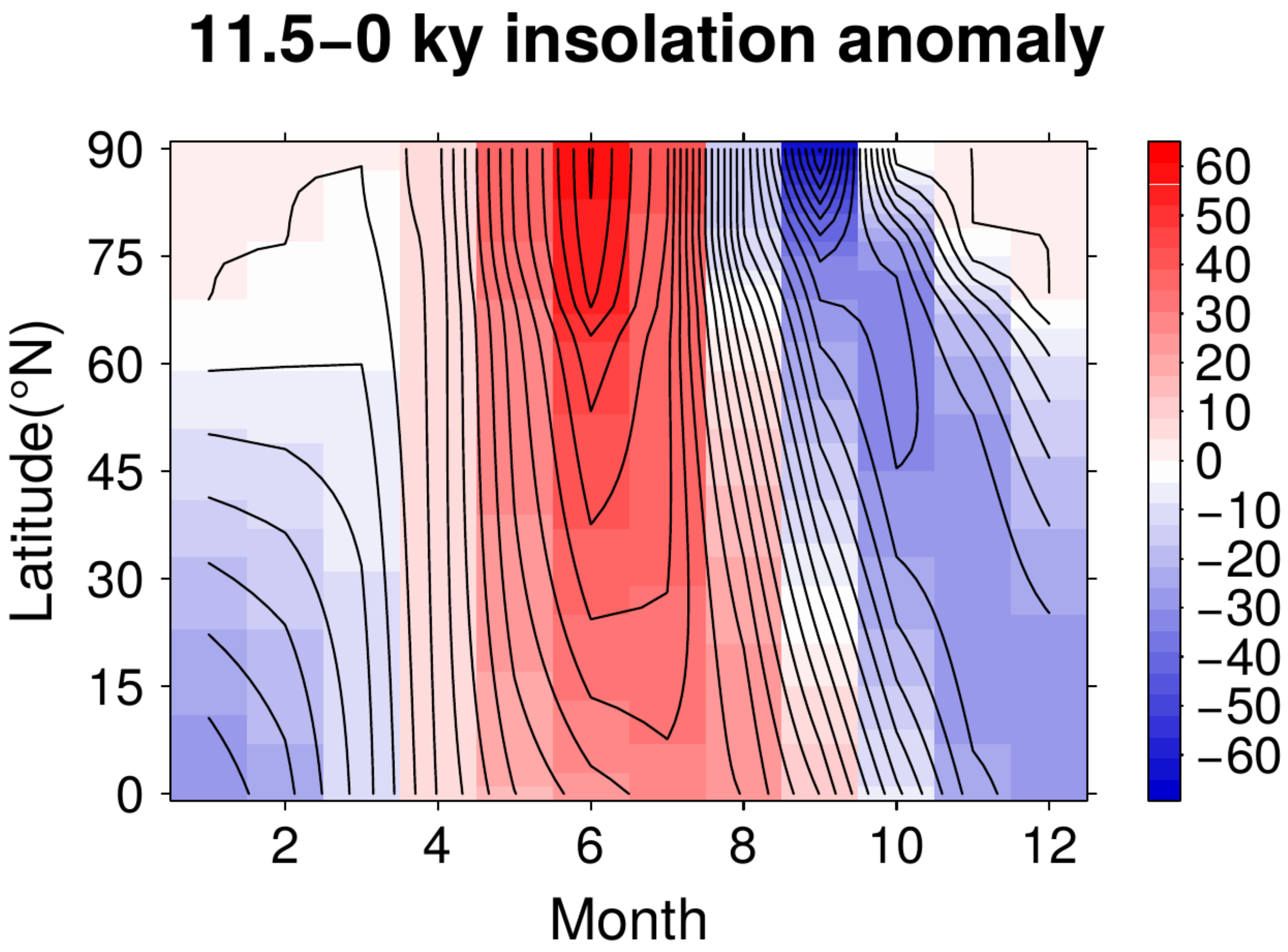


Fig. SI1. Monthly insolation anomaly (W m^{-2}) at 11.5 kya compared to 0kythe present day derived from Berger 1978

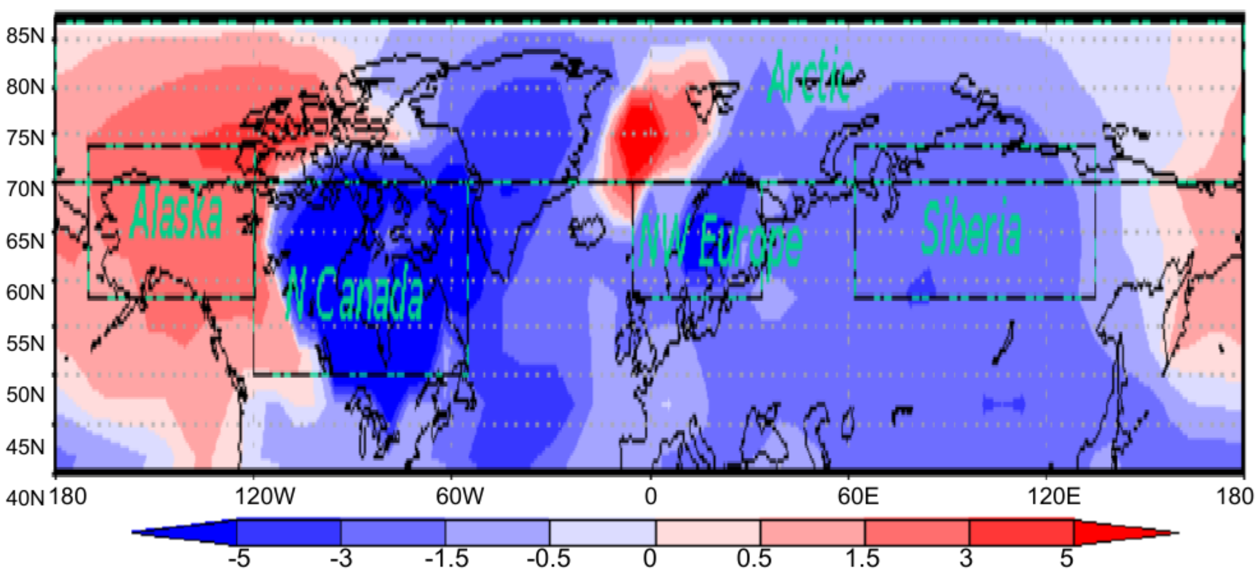


Fig. SI2. Selected region denoted by the box over where the temperature evolution is shown. Shown in the background is the simulated annual mean temperature at the onset of the Holocene.

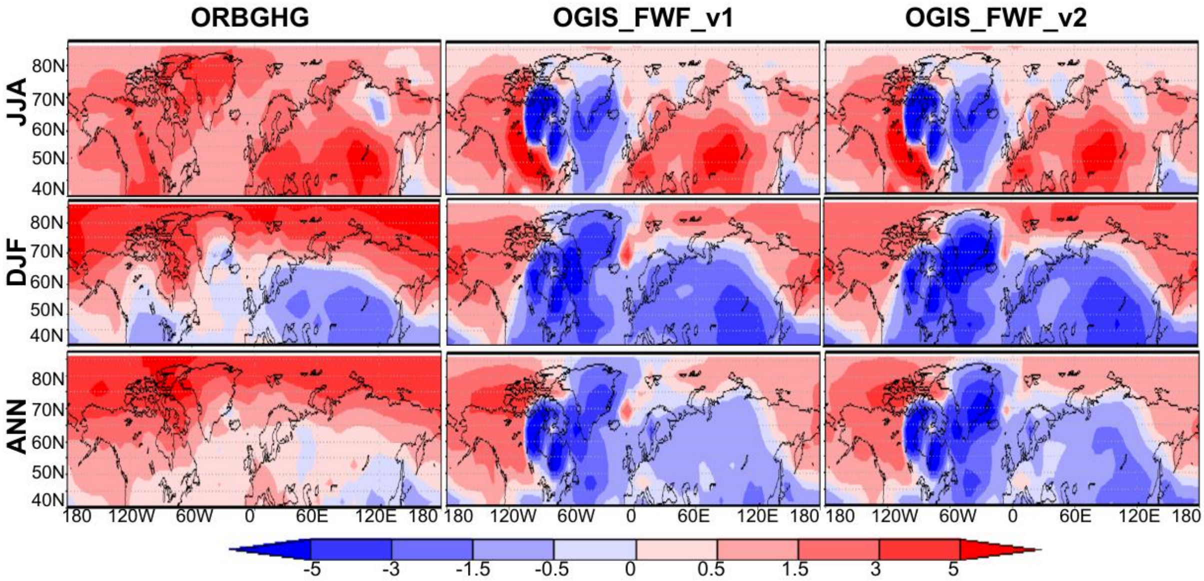


Fig. SI3. Simulated temperatures for 10 kya (shown as the deviation of 100--yrs average from PI). Left, middle and right columns show the simulations ORBGHG, OGIS_FWF-v1 and OGIS_FWF-v2, respectively. Upper, middle and lower panel indicate summer, winter and annual temperatures, respectively

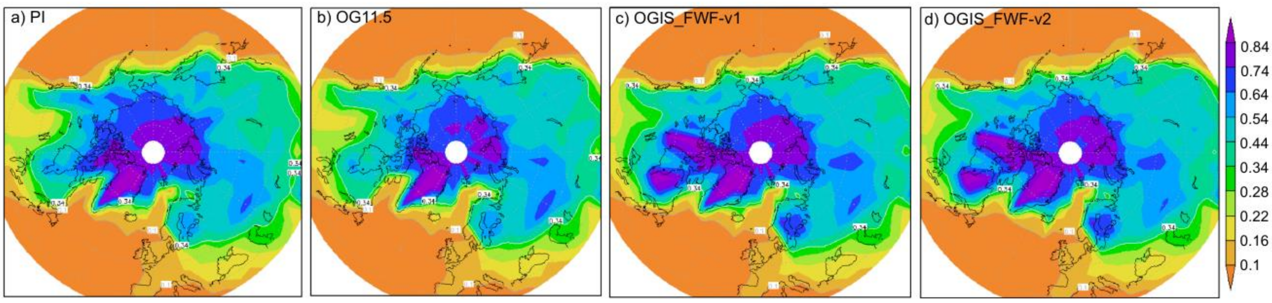


Fig. SI4. Simulated winter surface albedo shown as a 100--yrs average in the extratropical Northern Hemisphere. (a) is for the PI, while. (b), (c) and (d) represent the simulations ORBGHG, OGIS_FWF-v1 and OGIS_FWF-v2 at 10 kya, respectively.