Anonymous Referee #1

Received and published: 1 November 2018

4.2K BP event is a hot topic issue. However, the cause of 4.2K BP event is remaining unclear. This study made contribution to understand how the 4.2k BP event occurred, using a group simulation consisting of full forcing experiment and multiple single-forcing experiments. Through comparing the results from these experiments with each other, this study draws a conclusion that the 4.2K BP event is induced by internal variability. I recommend to accept this manuscript, but some issues should be addressed.

Reply: Thank you very much for the comments. We have modified the manuscript carefully according to your valuable comments.

1. Line 193-194, warming over the SH could be related to the orbital change, which induces insolation increases over the SH but decreases over the NH. How to approve this result. I recommend to plot the temperature anomaly spatial distribution induced by orbital forcing.

Reply: The temperature difference between the cold and warm period induced by the orbital forcing is calculated by the average of period 4200 BP-3900 BP minus the average of period 4800 BP-4500 BP. The figure has been added in the revised version as Figure S3.

2. Line 202-203, Over East China, the precipitation anomalies show a wet south dry north pattern. The figure 3b could not support this result, since the signal is too weak to be insignificant.

Reply: Yes, it's not so significant. So a statement has been added in the revised version. Lines 218-222.

3. Line 223-224. The subtropical highs and the relative anticyclones in both the SH and NH are strengthened. We only find the strengthened subtropical high over SH while we could not find the strengthened subtropical highs over NH (Figure 5c). Please examine it carefully.

Reply: The strengthened subtropical highs can be represented not only by pressure but also by wind field. But yes, the significant pressure changes are different over NH and SH, with most significant at low level over the NH while at high level over the SH. We added a statement to illustrate this phenomenon more carefully. Lines 245-247.

4. Line 235-236. With higher SLP over land and lower SLP over the adjacent ocean (Fig. 5a). We also could not find this character. Please examine it carefully.

Reply: The SLP gets higher over land significantly while lower over ocean not significantly. Yes, additional statements have added in the revised version. Lines 261-263.

5. Line 244-245. The land over the SH experiences cool but wet conditions, and the mid latitude SH ocean is warmer. Is there proxy-based evidence over SH?

Reply: Unfortunately, we don't have significant evidences right now. But we can tell from the southward shift of the ITCZ position, which tends to locate over the warmer hemisphere.

6. Figure 6. Please clarify the spatial domain of the EOF.

Reply: The region for the EOF is (70W-40E, 25N-80N), which has been added in the figure caption of Fig. 6.

Anonymous Referee #2

Received and published: 2 November 2018

This paper uses a transient model simulation (TraCE-21ka) to explore the possible causes of the 4.2 ka event. While various hypotheses exist regarding the causes of this event, this remains an open and interesting question. The authors find evidence in the transient simulation for climate fluctuations in the middle Holocene that show some of the same temporal and spatial patterns as the 4.2 ka event, and through analysis using several additional single-forcing experiments, argue that the fluctuations likely arose through internal variability of the climate system. The results support some previous hypotheses and work on the causes of this event, and the paper does make a contribution in its use and analysis of the TraCE simulation.

I had several major concerns with the paper, including the overlap between this paper and another paper by the same authors that is under review in Climate of the Past, as well as how well some of the conclusions are supported by the results. These concerns are described in more detail below.

Major comments

1. The authors have another paper under review in Climate of the Past ("Comparing the spatial patterns of climate change in the 9th and 5th millennia B.P. from TRACE-21 model simulations" by Ning, Liu, Bradley and Yan) that has significant overlap with this manuscript. The Ning et al. paper uses the same model simulation (TraCE-21ka) to analyze the 8.2 ka and 4.2 ka events. Both papers present analysis using the same techniques (anomaly maps, principal component analysis). The Yan et al. paper (this review) provides a more in-depth analysis of the 4.2 ka event, but it is unclear why two papers are necessary. Perhaps even more important, the two papers come to conflicting conclusions about the cause of the 4.2 ka event. In Ning et al., it is stated "We speculate that long term changes in insolation related to precessional forcing led to cooling, which passed a threshold around 4500 years B.P., leading to a reduction in the AMOC and associated teleconnections across the globe. Based on widespread paleoclimatic evidence for the onset of neoglaciation (Solomina et al., 2015), it seems clear that there was a fundamental shift in climate around this time." Whereas, Yan et al. argue that stochastic variability internal to the climate system caused the 4.2 ka event independent of any external climate forcing.

Reply: Thank you very much for your valuable comments. We agree with you that we need to clarify the difference between the two papers. This is a very important issue that we should address carefully.

First, the two papers focus on different aspects about the 4.2 ka BP event. Ning et al. paper focuses on the spatial patterns, comparing the differences between the 9th and the 5th millennial BP using TraCE simulations on a long-term perspective, and concludes that there might be a phase transition of AMOC from stronger state in the beginning of the 5th millennial BP to weaker state through most of the late Holocene due to the reduction of orbital-insolation, but with fluctuations. Yan et al. also uses TraCE simulations but mainly focuses on the physical mechanisms and possible causes of the 4.2 ka BP event, and concludes that the fluctuations relating to the 4.2 ka BP event might be related to the internal variabilities. It is possible that the internal variability related fluctuations be superposed on the orbital related long-term trend found in Ning et al. paper. Therefore, the results of the two papers are not incompatible. Actually, we also mentioned the role of external forcings in Yan et al. paper, in the revised version, we make this point more clearly.

Second, unlike the reconstruction work, different aspects can be investigated based on the same set of climate experiments from different perspectives, e.g. from the atmospheric point of view, from the oceanic point of view, and from the time scales point of view etc, because the climate model is physical-based and spatiotemporally continuous. Especially from the time scales point of view, we may get different results, since the mechanisms and the causes may differ on different time scales. The results from Ning et al. paper is on a longer time scale than Yan et al. paper. So the two papers are actually complementary.

Third, the EOF is an efficient method to illustrate the leading modes of climate changes. Ning et al. paper uses it to show the main patterns and the evolution of the SST during the two periods. While Yan et al. paper uses EOF to show the leading circulation change during the period of around 4.2 ka BP event. Before we analyze the physical mechanisms of the event, we need to make sure that the model performance is reasonable comparing to the records, which might be the concern of overlap between the two papers, but this is necessary.

Therefore, to address your concerns, we have modified the manuscript to show the different aspects that our manuscript focuses on from Ning et al. paper. Lines 117-122, 351-358.

2. It would useful to show on Figure 3 the locations of proxy records discussed in the text that document anomalies at 4.2 ka (perhaps circles color coded according to whether proxy anomalies were cold/warm or wet/dry during the event). This would help to make the point that the model event has the appropriate spatial pattern.

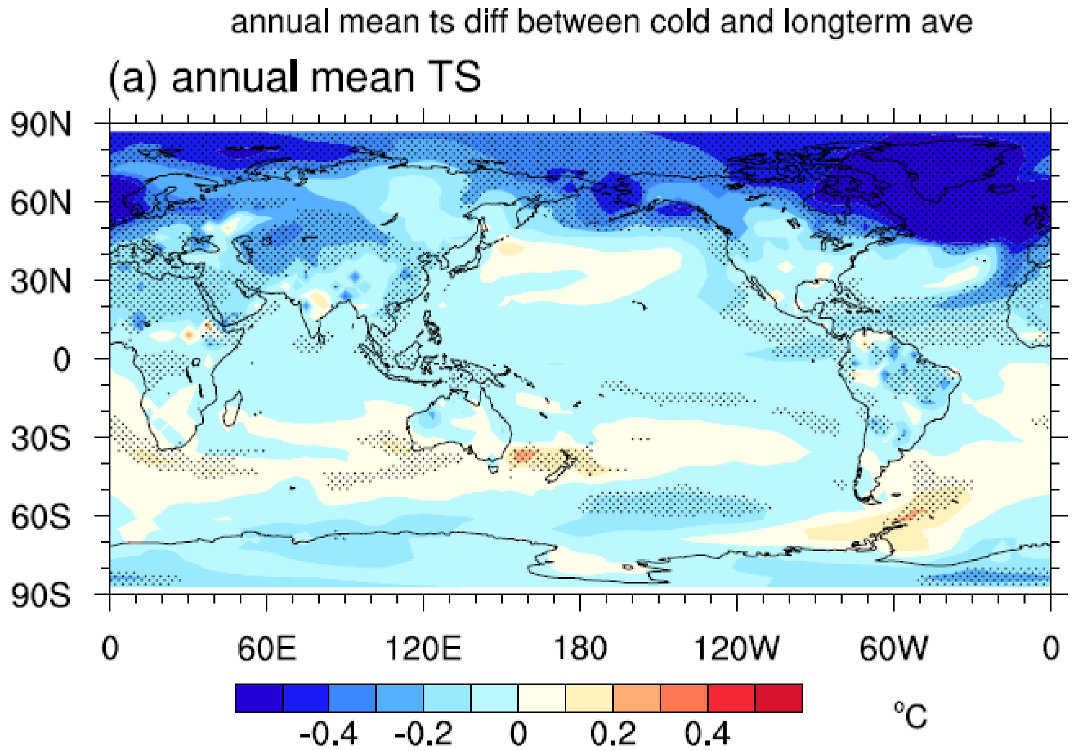
Reply: Yes, thank you for pointing out this issue. Some sites denoting the wet/dry anomalies during the event are added in the revised Fig. 3b, and the relative model-data comparison has been added in the revised version. Lines 209-212.

3. The authors need to discuss the implications that their maps show the difference between warm event and cold event – namely, that this approach amplifies the model anomaly as compared to taking the difference between cold event and long-term average, which is probably what most of the proxy records are showing. Specifically, the authors should also discuss whether differences between cold event and long-term average (say averaged 500-1000 years before the event) are statistically significant. More generally, the authors need to make a point of discussing that the size of the modeled anomalies ARE VERY SMALL. I think it is fine to use the simulations to put forth a hypothesis about processes causing the 4.2 ka event, but given the small size of the modeled changes, it is also very important to be clear that we still might not be modeling events comparable to the 4.2 ka event (e.g., make this point clearer on lines 253-254).

Reply: Yes, the model responses to the external forcings are small even giving a strong forcing, especially in the Holocene because of the absence of a significant change of the AMOC and the meltwater forcing after 6 ka (Liu et al., 2014). So we use the amplified anomaly between the cold and warm periods to investigate the possible mechanisms.

It is still significantly cool and dry over Europe and Central America, given the temperature and precipitation differences between the cold event and the long-term average (averaged over 5000-3000 BP) (Fig. A). And the North Atlantic region is still the active center. But yes, we need to clarify the smaller signal in the modeled changes. The statement of "but with smaller magnitude" has been added in the revised version, Line 279.

The required statement has been added in the last section, Lines 441-448.



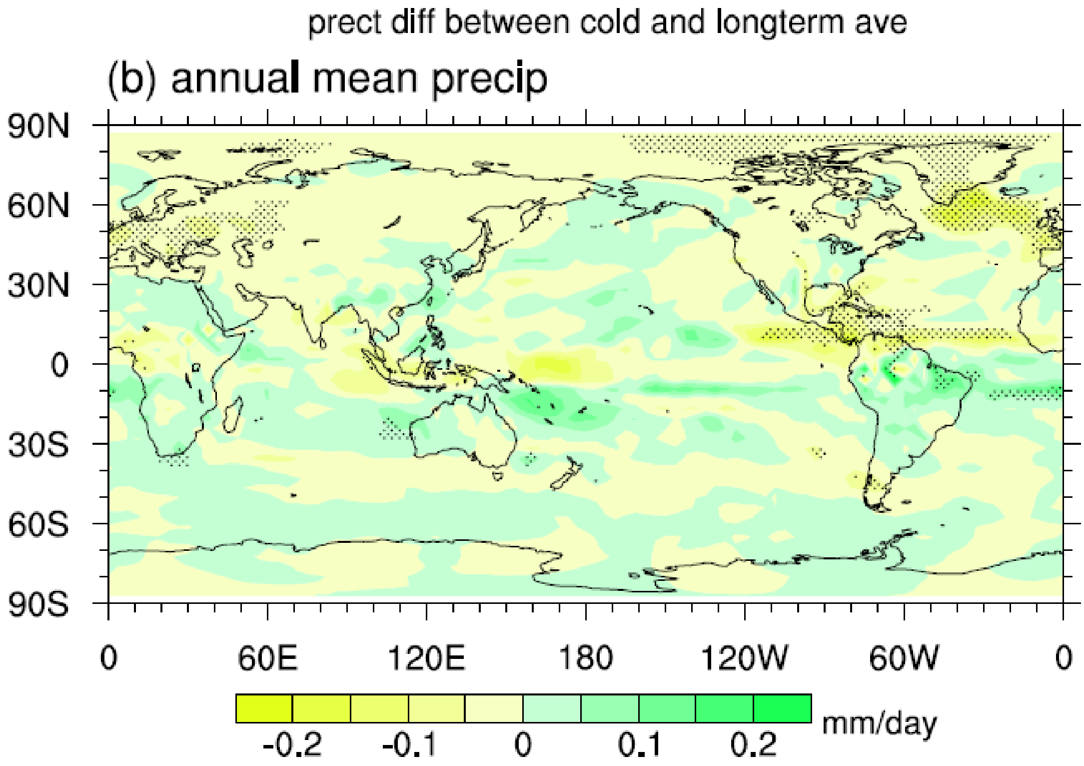


Figure A Spatial distribution of the annual mean (a) surface temperature and (b) precipitation anomalies of the cold periods against the long-term average of 5000-3000 BP derived from the TraCE-ALL run. Those regions where significant above 95% confidence level are dotted.

4. Analysis of AMOC: The authors mention several times that simulated patterns are similar to those caused by AMOC, but AMOC is not analyzed. Further, the Ning et al. paper specifically attributes the event to AMOC changes. It is not difficult to generate an AMOC time series from TraCE (e.g., maximum of the meridional overturning streamfunction – the variable 'MOC' – over the North Atlantic avoiding the surface wind-mixed layer) and this would greatly help to clarify what the role of AMOC is.

Reply: Thank you for pointing out this issue. Yes, we can easily provide the time series of the simulated AMOC (Fig. B). It is clear that the 8.2 ka BP event-related AMOC is dominated by the meltwater forcing, as has been revealed by Ning et al. paper. However, for the 4.2 ka BP event-related AMOC, it might be forced by both the orbital variation on longer time scale (orange line in Fig. B) and internal variation on centennial time scale. From this point of view, this paper and Ning et al. paper are actually not incompatible. We just put forward these two possibilities.

Figure B has been added in the revised version as Fig. S4, along with the spatial pattern of the temperature and precipitation differences between the weak and strong AMOC states. We have added statements about the AMOC in the discussion part, Lines 401-407.

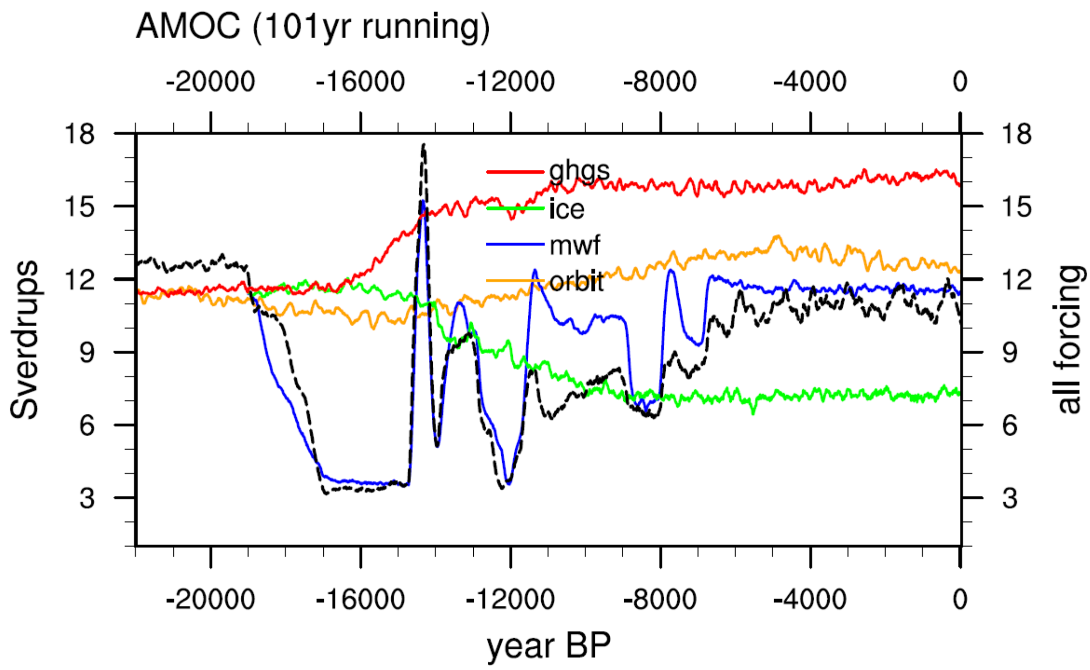


Figure B Time series of simulated AMOC over the past 22 ka derived from the all forcing run (black dashed line) and each single forcing run (colored lines). A 101-year running mean is applied to the time series.

5. Lines 289-292: The difference between the sum of the single-forcing experiments and the ALL simulation is not strictly internal variability. The difference will also include any interactions between the single forcings. This should be more clearly stated on these lines.

Also on Line 295: add "in isolation" to the end of the phrase "the 4.2 ka event might not be triggered by those external forcings" because it is possible that interactions between forcings could be important.

Reply: Yes, you are right that the forcings and internal variability can be interacted between each other. We need to consider the linearity of climate responses to the external forcings at different spatial scales. Additional statements have been added in the revised version. Lines 323-328.

Yes, "in isolation" has been added in the revised version. Line 332.

6. Line 202-204, 234-239: Precipitation changes in China are largely insignificant. Recommend deleting these sentences.

Reply: Although not so significant, we can still draw a general view on how the climate changes over China. But yes, we need further investigations with higher resolutions of modeling works and reconstruction works.

The statements have been changed in the revised version. Lines 218-222, 261-263.

Minor comments

Line 20: Change "many" to "several"

Reply: Changed, Lines 20-21.

Line 46: "there were warming periods in Holocene induced by natural forcing comparable to current warming." Current warming, being driven by increased atmospheric greenhouse gas concentrations cannot by definition be comparable to any warming periods in the Holocene. Do you mean comparable in size? Even then, this is debatable.

Reply: There are some reconstructed records reported that there are some historical warming periods comparable to the current warming period in magnitude. But yes, this is debatable. We deleted this statement in the revised version. Lines 47-48.

Line 57-58: "that inaugurated the "modern" El Nino Southern Oscillation (Fisher et al. 2008)." The record cited is not a direct record of ENSO (it is an ice core in the Yukon) and there are lots of more direct records of ENSO from the tropical Pacific that suggest complexity in how ENSO changed through the middle to late Holocene. Delete this phrase.

Reply: Yes, deleted. Lines 59-60.

Line 70: "Moreover, according to the hydrologic cycle: : :" I'm not sure what this means. Is the point that hydroclimate changes are often regionally specific, and other regions could have had different hydroclimate changes?

Reply: Yes, from the perspective of hydrology balance, the hydroclimate changes are often regionally specific. This has been added in the revised version. Lines 72-73.

Lines 76-80: "For the causes of the event, some reconstruction studies have suggested that orbital forcing played an important role in the early Holocene: : :" Does this refer to abrupt changes in the early Holocene, or longer-scale changes? Please provide references. ": : :; however, no strong evidence has shown that the solar forcing affected glacier fluctuations (cooling events) in the late Holocene: : :" Does "solar forcing" here refer to solar irradiance changes or to orbital forcing? Also, glacier fluctuations are only one indication of cooling, other temperature proxies do seem to be sensitive to solar irradiance changes.

Reply: "For the causes of the event, some reconstruction studies have suggested that orbital forcing played an important role in the early Holocene: : :", we mean the abrupt changes in the early Holocene.

The "solar forcing" refers to the solar irradiance change.

But yes, I understand what you mean. We should use the same forcing here. So we have changed the statement and clarified the forcing to be "solar irradiance".

The references (Wang et al., 2005; Rupper et al., 2009; Owen and Dortch, 2014) are provided in the revised version. Lines 79-85.

Lines 90-91: For clarity, change "Additionally, there are discrepancies in the circulation pattern during the late Holocene (Finkenbinder et al., 2016)" to something like "However, studies come to differing conclusions on the likely phase of the NAO-like pattern during the late Holocene."

Reply: Yes, changed. Lines 95-97.

Line 94: Change "might could be" to "could be"

Reply: Changed. Line 100.

Line 159: It is important to be very careful about calling a particular event in the model simulations the 4.2 ka event, especially since the variability being described in the model is internally driven. It is likely coincidental that these events described in the TraCE experiment happen around 4.2 ka – particularly if they are the result of internal variability. It is more appropriate to say "which indicates that simulated climate events potentially comparable to the 4.2 ka event" instead of "which indicates that the 4.2 ka BP event has multidecadal to centennial variabilities." Similarly, on the following lines, use "Moreover, the centennial warming periods right before and after the simulated cooling event indicate that this event might be included in a quasi-millennium variation" instead of "Moreover, the centennial warming periods right before and after the 4.2 ka BP event indicate that this event might be included in a quasi-millennium variation."

Reply: Yes, you are right. Thank you for pointing out this. It would be coincidental that the cooling events in the TraCE run happen around 4.2 ka if they ARE induced by the internal variability. The statements are changed in the revised version. Lines 170-172.

Figure captions: Specify which of the model simulations (i.e., "ALL") is plotted.

Reply: Yes, the statements of "derived from the TraCE-ALL run" have been added into the figure captions of Figures 3-9.

Figure 1: flip x axis so that time matches the sense of the x axis in Figure 2. Also, it seems that June insolation is not the most informative since the climate fluctuation in question is mostly a wintertime response and plots are all showing mean annual.

Reply: Fig. 1 has been modified and limited to the period of 5000-3000 BP.

Yes, the orbital-induced insolation changes are seasonal dependent. Here we use summer insolation as an example, since the long-term variations in Northern Hemisphere summer insolation are generally thought to control glaciation (Huybers, 2006). Also, according to the Milankovitch theory, the ice age cycles are paced by the Earth's orbital variations, with Northern Hemisphere summer insolation intensity playing a dominant role in the growth and decay of Northern Hemisphere ice sheets (TraCE-21ka Description, http://www.cgd.ucar.edu/ccr/TraCE/).

Figures 3, 4, 5, 7: Plot full globe, 90 degrees south to 90 degrees north.
Reply: The figures have been re-plotted with a full global map.

Line 197: change “most regions” to “many land regions”
Reply: Changed. Line 207.

Line 198: change “central and southern North America (Intra America)” to “interior North America and central America”
Reply: Changed. Lines 208-209.

Line 212-213: There are many more citations of relevance here, going back to Vellinga and Wood (2002) Climatic Change 54: 251-267 and Zhang and Delworth (2005) Journal of Climate 18: 1853.
Reply: Yes, thank you for providing the references. The references have been added in the revised version, and Figure S4 is added to illustrate the spatial pattern of the temperature and precipitation differences between the weak and strong AMOC states. Lines 231-232.

Line 252: Change “The solar irradiance is not included: : :” To “Changes in solar irradiance are not included: : :” Solar irradiance is included in this model, it is just not changing.
Reply: Yes, you’re right. Changed in the revised version. Lines 276-277.

Lines 273-276: Clarify here that there was no meltwater flux applied in the model for the years analyzed (5000-3000 years BP). Why might these correlation coefficients be significant given that there is no meltwater flux? Is this likely due to chance? Please discuss this more in the paper.
Reply: Yes, thank you for pointing out this issue. A short discussion has been added in the revised version. Lines 301-307.

Lines 368-369: “We attributed the internal variabilities to be an essential forcing of the 4.2 ka BP event; however, why it occurs at approximately 4400 BP to 4000 BP remains unknown.” If the event is stochastic (as argued), there is nothing more to know about why it occurred when it did.
Reply: Yes, it would be stochastic if it IS forced by the internal variability. However, we still need more evidences and modeling works to make sure that this event IS forced by the internal variability. We have changed the statement in the revised version. Lines 430-434.

Acknowledgements: The TraCE-21ka team and funding should be acknowledged. See instructions at: https://www.earthsystemgrid.org/project/trace.html.

Reply: Thank you for pointing out this, the acknowledgement has been added in the revised version. Lines 461-463.

References: There are other papers that have hypothesized links between the North Atlantic and the 4.2 ka event and that should be cited. They include: Cullen, H. M., Kaplan, A., Arkin, P. A., and deMenocal, P. B.: Impact of the North Atlantic Oscillation on Middle Eastern climate and streamflow, Climatic Change, 55, 315–338, 2002. Kushnir, Y. and Stein, M.: North Atlantic influence on 19th–20th century rainfall in the Dead Sea watershed, teleconnections with the Sahel, and implication for the Holocene climate fluctuations, Quaternary Sci. Rev., 29, 3843–3860, 2010.

Reply: Thank you for providing the references. The mentioned and additional references have been added in the revised version. Lines 363-365, 395-400.

References:

Booth, R. K., Jackson, S. T., Forman, S. L., Kutzbach, J. E., Bettis, I. E. A., Kreig, J., and Wright, D. K.: A severe centennial-scale drought in mid-continental North America 4200 years ago and apparent global linkages, The Holocene, 15, 321-328, 10.1191/0959683605hl825ft, 2005.

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Editor Decision: Publish subject to minor revisions (review by editor) (14 Jan 2019) by Monica Bini

Comments to the Author:

Basically, the authors have replied to all the changes requested. However, it is fundamental that the authors explicitly indicate the differences between Ning's work and their work in the text, as requested by referee 2. The work can then be accepted once it has been possible to verify that all the changes in the text have been made.

Reply: Thank you very much for your decision.

We have added the statements of the difference between the two papers and the related discussion in the revised version according to referee 2 and your comments.

Introduction section, Lines 117-122, "Recently, Ning et al. (2019) briefly compared the spatial patterns of climate change in the 9th and 5th millennia BP using a set of transient modeling results on a long-term perspective. In the present study, we will use the same set of simulation results to provide an in-depth characteristics of the 4.2 ka BP event and will focus on the possible causes and mechanisms behind this event."

Discussion section, Lines 351-358, "Ning et al. (2019) compared the 5th millennium BP cooling with the 9th millennium cooling and concluded that the 9th millennium BP cooling was resulted from the freshwater forcing while the orbital forcing is the most likely explanation of cooling in the North Atlantic starting from the early 5th Millennium BP through most of the later Holocene, but with fluctuations. In the present work, we attribute this fluctuation to the internal variability, which is superposed on the orbital induced long-term trend. This work and Ning et al.'s work (2019) focus on different aspects and different time scales, and are complementary to better understand the 4.2 ka BP event."

Physical processes of cooling and megadrought in 4.2 ka BP event: results from TraCE-21ka simulations

Mi Yan[1,2], Jian Liu[1,2*], ~~Liang Ning[1,2,3]~~

[1]Key Laboratory of Virtual Geographic Environment, Ministry of Education; State key Laboratory of Geographical Environment Evolution, Jiangsu Provincial Cultivation Base; School of Geographical Science, Nanjing Normal University, Nanjing, 210023, China

[2]Jiangsu Center for Collaborative Innovation in Geographical Information Resource Development and Application, Nanjing, 210023, China

~~[3]Climate System Research Center, Department of Geosciences, University of Massachusetts, Amherst, 01003, United States~~

*jliu@njnu.edu.cn

Abstract

It is widely believed that multidecadal to centennial cooling and drought occurred from 4500 BP to 3900 BP, known as the 4.2 ka BP event that triggered the collapse of ~~many~~ several cultures. However, whether this event was a global event or a regional event and what caused this event remain unclear. In this study, we investigated the spatiotemporal characteristics, the possible causes and the related physical processes of the event using a set of long-term climate simulations, including one all-forcing experiment and four single-forcing experiments. The results derived from the all-forcing experiment show that this event ~~occurred~~ occurs over most parts of the Northern Hemisphere (NH), indicating that this event could have been a hemispheric event. The cooler NH and warmer Southern Hemisphere (SH) illustrate that this event could be related to the slowdown of the Atlantic Meridional Overturning Circulation (AMOC). The comparison between the all-forcing experiment and the single-forcing experiments indicates that this event ~~was~~ might be ~~likely~~ caused by internal variability, while external forcings such as orbital and greenhouse gases might have modulation effects. A positive North Atlantic Oscillation (NAO)-like pattern in the atmosphere (low troposphere) triggered a negative Atlantic Multidecadal Oscillation (AMO)-like pattern in the ocean, which then triggered a Circumglobal Teleconnection (CGT)-like wave train pattern in the atmosphere (high troposphere). The positive NAO-like pattern and the CGT-like pattern are the direct physical processes that lead to the NH cooling and megadrought. The AMO-like pattern plays a "bridge" role in maintaining this barotropic structure in the atmosphere at a multidecadal-centennial time scale. Our work provides a global image and dynamic background to help better understand the 4.2 ka BP event.

1 Introduction

Understanding the characteristics and mechanisms of climate changes during the Holocene can help predicting future changes~~, because there were warming periods in Holocene induced by natural forcing comparable to current warming~~. The multidecadal-to-centennial abrupt climate change, or the rapid climatic change during ca. 4.5-3.9 ka BP (before 1950 CE), the so called "4.2 ka BP event", was one of the major climate events during the Holocene (Wang, 2009; Staubwasser and Weiss, 2006; Mayewski et al., 2004; Wang, 2010). This event is considered to be closely linked to the cultural evolutions of different regions of Eurasia such as the collapse of the Akkadian empire, the termination of the urban Harappan civilization in the Indus valley and the collapse of Neolithic Cultures around the Central Plain of China (Weiss et al., 1993; Weiss and Bradley, 2001; Wu and Liu, 2001; Staubwasser et al., 2003; Wu and Liu, 2004; An et al., 2005; Staubwasser and Weiss, 2006; Liu et al., 2013; Weiss, 2015, 2016). Moreover, this event is also thought to be the transition of the Middle to Late Holocene (Walker et al., 2012; Finkenbinder et al., 2016)~~ that inaugurated the "modern" El Niño Southern Oscillation (ENSO) (Fisher et al., 2008)~~. However, the characteristics, causes and corresponding mechanisms behind this event remain unclear.

The 4.2 ka BP event is mostly characterized by rapid events at various latitudes (Jansen et al., 2007), e.g., cooling in Europe (Lauritzen, 2003), centennial megadroughts in North America (Booth et al., 2005), decreased precipitation in both southern and northern China (Tan et al., 2008), and the weakened summer monsoon in India (Nakamura et al., 2016); however, the manifestation of this event is far from convincing and needs more evidence and simulation investigations (Roland et al., 2014). Many reconstructions have shown that the 4.2 ka BP event is dominated by megadroughts at centennial-scale over mid-low latitudes (Tan et al., 2008; Yang et al., 2015; Weiss, 2016). However, Roland et al. (2014) found no compelling evidence, at least in peatland records, to support that there was a 4.2 ka BP event in Great Britain and Ireland. Moreover, according to the hydrologic cycle (i.e. the hydroclimate changes are often regionally specific), it cannot be ruled out that there were no flooding events somewhere else during this period. For example, Huang et al. (2011) and Tan et al.

(2018) found that successive floods occurred over the middle reaches of the Yellow River in China in association with the abrupt climatic event of 4.2 ka BP.

Understanding the causes and mechanisms of the 4.2 ka BP event can provide explanations for the reconstructed discrepancies over different regions. For the causes of the event, some reconstruction and modeling studies have suggested that the ~~orbital~~ solar irradiance ~~forcing~~ could have played an important role in the early Holocene climate changes (Wang et al., 2005; Rupper et al., 2009; Owen and Dortch, 2014); however, no strong evidence has shown that the solar ~~forcing~~ irradiance affected glacier fluctuations (cooling events) in the late Holocene since there is yet no good mechanistic explanations of how small changes in solar irradiance could significantly affect large scale climate changes (Solomina et al., 2015). Tan et al. (2008) thought that the 4.2 ka BP event could have been induced by the southward shift of the Intertropical Convergence Zone (ITCZ) and oceanic sea surface temperature (SST) changes, as well as the vegetation feedback caused by the solar activity. Liu et al. (2013) and Deininger et al. (2017) argued that the atmospheric circulation, such as the North Atlantic Oscillation (NAO)-like pattern but on a centennial time scale, could have played a more important role than the ocean circulation in this event, although the mechanisms that forced the circulation change remained unclear. A new reconstruction study has also shown that the dry phases over the western Mediterranean in the period of 4.5 ka BP-2.8 ka BP generally agreed with positive NAO conditions (Ramos-Román et al., 2018). ~~Additionally, there are discrepancies in the circulation pattern during the late Holocene~~ However, studies come to different conclusions on the likely phase of the NAO-like patter during the late Holocene (Finkenbinder et al., 2016). Some studies show positive NAO-type patterns during the late Holocene (Tremblay et al., 1997; Sachs, 2007; Ramos-Román et al., 2018), whereas others show negative NAO-like patterns (Rimbu et al., 2004). Since the mechanisms ~~might~~ could be a complex set of air-sea interactions (Roland et al., 2014), it is hard for reconstruction to provide a general record due to its limitations such as interpretation and spatially incompleteness. The mechanisms behind the 4.2 ka BP event need to be clarified.

Therefore, to improve understanding of the 4.2 ka BP event, new high-resolution reconstruction studies that focus on the 4.2 ka BP event are required. On the other hand, physical-based modeling research can provide general concepts of the characteristics of the event along with the causes and the mechanisms. Climate simulations have been conducted to investigate another abrupt cooling event in the early Holocene, the so-called 8.2 ka BP event. The simulations were used to test the hypothesis raised by the reconstruction studies that the 8.2 ka BP event was most likely caused by freshwater forcing and was associated with weakening of the Atlantic Meridional Overturning Circulation (AMOC) (Morrill et al., 2013; Wagner et al., 2013; Morrill et al., 2014; Matero et al., 2017; Ljung et al., 2008; Alley and Agustsdottir, 2005). For example, the simulations argued that the meltwater from the collapse of the ice dome over Hudson Bay was an essential forcing of the 8.2 ka BP event (Wagner et al., 2013; Matero et al., 2017). However, little modeling work has been applied to the 4.2 ka BP event.

Recently, Ning et al. (2019) briefly compared the spatial patterns of climate change in the 9^{th} and 5^{th} millennia BP using a set of transient modeling results on a long-term perspective. In the present study, we will use the same set of simulation results to provide an in-depth characteristics of the 4.2 ka BP event and will focus on employed a set of transient climate simulation results to investigate the characteristics of the 4.2 ka BP event and the possible causes and mechanisms behind this event. The model and experiments are introduced in Sect. 2. The results are shown in Sect. 3. The possible causes and mechanisms are discussed in Sect. 4, and conclusions are drawn in Sect. 5.

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2 Model and experiments

A set of transient simulations (TraCE-21ka, Simulation of Transient Climate Evolution over the past 21,000 years, He, 2011) conducted with the Community Climate System model version 3 (CCSM3) was used to investigate the spatial and temporal characteristics of the 4.2 ka BP event and to determine the possible causes and mechanisms behind this event. The experiments are listed in Table 1, including one transient experiment with all-forcings (TraCE-ALL), one single-forcing experiment forced only by transient orbital variation (TraCE-ORB), one single-forcing experiment forced only by transient melt-water flux (TraCE-MWF), one single-forcing experiment forced only by quasi-transient ice-sheet (TraCE-ICE), and one single-forcing experiment forced only by transient greenhouse gases concentrations changes (TraCE-GHG). The simulations were conducted from 22000 BP to 1990 CE for the TraCE-ALL, the TraCE-ORB and the TraCE-GHG experiments, and from 19000 BP to 1990 CE for the TraCE-MWF and the TraCE-ICE experiments.

The transient June insolation changes at 60°N and 60°S that resulted from the orbital variation and the transient CO_2 change used in the simulations are shown in Fig. 1. The continental ice-sheet and topography changes are based on the ICE-5G (VM2) reconstruction (He et al., 2013; Peltier, 2004). For the geography changes, the Barents Sea opens at 13.1 ka BP, the Bering Strait opens at 12.9 ka BP, Hudson Bay opens at 7.6 ka BP, and the Indonesian Throughflow opens at 6.2 ka BP. The freshwater injected into Northern Hemisphere (NH) and Southern Hemisphere (SH) oceans are based on specific time slices (e.g., 19 ka BP into North Atlantic, 17 ka BP into North Atlantic, 11.5 ka BP into Arctic, St. Lawrence River, Hudson Strait, Barents Sea, North Sea, Ross Sea and Weddell Sea). Note that no freshwater was delivered to the ocean after 5000 BP in the TraCE-ALL and TraCE-MWF experiments. The detailed information about the experiments design can be referred to He (2011) and He et al. (2013).

The TraCE-21ka simulation was evaluated with reconstructions and was found that it could reproduce major deglacial temperature evolutions (Clark et al., 2012; Shakun et al., 2012). It has been used to depict the causes and mechanisms of Holocene climate changes, such as the Bølling-Allerød warming (Liu et al., 2009), cooling into the Younger Dryas and recovery to warm conditions (Liu et al., 2012) and the ENSO evolution over the past 21 ka (Liu et al., 2014a). In the present work, we adopted the period of 5000 BP-3000 BP to focus on the 4.2 ka BP event.

3 Results

3.1 Identification of 4.2 ka BP event in the model simulation

The 101-year running mean annual NH surface temperature and precipitation during 5 ka BP-3 ka BP shows double peak centennial cooling and drought from 4.4 ka BP to 4.0 ka BP (Fig. 2, dashed black line). However, the variabilities are smaller over the SH than those over the NH. There is no significant cooling and drought event during that period (Fig. S1, dashed black line) over the SH. The SH precipitation even shows a double-peak wet condition during the period of 4.4 ka BP-4.0 ka BP.

The double peak centennial cooling and drought are still obvious when the 31-year running mean is applied to the time series (not shown), which indicates that the simulated climate events potentially comparable to the 4.2 ka event~~4.2 ka BP event has multidecadal to centennial variabilities~~. Moreover, the centennial warming periods right before and after the ~~4.2 ka BP~~cooling event indicate that this event might be included in a quasi-millennium variation. Therefore, the 4.2 ka BP event could be a multiscale event, i.e. from multi-decadal to millennium.

The seasonal mean NH surface temperature changes show that the annual mean variability is dominated by the boreal winter (December-January-February, DJF) surface temperature change (~~Figure~~ Fig. S2). The correlation coefficient between the annual mean NH surface temperature (NHT) and the DJF mean NHT is 0.96 (after the 101-year running mean), which is significant above the 99% confidence level, much higher than the correlation coefficient between the annual mean and the boreal summer (June-July-August, JJA) mean of only 0.30 (after the 101-year running mean), which is not significant. However, this is different for the precipitation change, for which both the JJA mean and the DJF mean contribute to the annual mean precipitation change (not shown).

To identify the characteristics of the 4.2 ka BP event, two centennial cool periods and two centennial warm periods that exceeded ±0.5 standard deviations are selected. The two centennial cool periods span from 4320 BP to 4220 BP and from 4150 BP to 4050 BP, and the two centennial warm periods span from 4710 BP to 4610 BP and from 3980 BP to 3880 BP.

3.2 Spatial characteristics of surface temperature and precipitation

To help draw a coherent global view of the 4.2 ka BP event, the spatial characteristics of temperature and precipitation changes during the 4.2 ka BP event are shown in Fig. 3.

Figure 3a gives the spatial distribution of the annual mean surface temperature difference between the cold periods and the warm periods. The cooling significantly occurred over most regions of the NH, especially over the middle to high latitudes of the NH and most land regions of the SH. Most parts of India, northern Mexico and the middle latitudes of the SH ocean experienced warm conditions. Such asymmetric change between the hemispheres (cool NH and warm SH) favors the southward shift of the ITCZ. The spatial distribution of the surface temperature change is still dominated by the boreal winter pattern (not shown). The large cooling over the NH and small warming over the SH could be related to the orbital change (Fig. S3), which induces insolation increas~~es~~ing over the SH but ~~decreases~~ decreasing over the NH.

The spatial distribution of annual mean precipitation differences between the cold periods and the warm periods is shown in Fig. 3b. During the cold periods, significant drought is mainly located over ~~most~~ many land regions of the NH, especially over Europe, western Asia, and interior North America and Central America~~central and southern North America (or Intra America)~~. The significant dry conditions over the Dead Sea, the Gulf of Omen, interior North America and western North Africa and the wet condition over South America are consistent with the reconstructions (Yechieli et al., 1993; Cullen et al., 2000; Forman et al., 1995; Marchant and Hooghiemstra, 2004). For the SH, the land precipitation increased, which indicates a southward shift of the ITCZ, as suggested by the aforementioned asymmetric temperature change and by the previous studies based on both reconstructions (Fleitmann et al., 2007; Cai et al., 2012) and simulations (Broccoli et al., 2006). Over East China, the precipitation anomalies show a wet south-dry north pattern, which indicates a weakened East Asian monsoon ~~consistent with~~revealed by the reconstruction record (Tan et al., 2018). However, the simulated anomaly pattern is not very significant over East China. This might be related to the model resolution, the model performance, or the actual climate change. Therefore, simulations with higher resolution, inter-model and model-data comparisons are required to draw a clearer view about the climate change over East China.

The sea surface temperature (SST) shows that the largest change occurs over the northern Atlantic Ocean and then the northern Pacific Ocean (Fig. 4). The warmer south and cooler north over the Atlantic Ocean indicates an Atlantic Multi-Decadal Oscillation (AMO)-like pattern with its cold phase. The cold phase of the AMO has been confirmed to induce summer rainfall decreases over India and Sahel in both simulations and proxy data (Zhang and Delworth, 2006; Shanahan et al., 2009).

The simulated characteristics of the temperature change, the precipitation change, and the SST change are similar to those responses to the weakened AMOC state (Vellinga and Wood, 2002; Zhang and Delworth, 2005; Delworth and Zeng, 2012; Brown and Galbraith, 2016) (Fig. S4).

3.3 Circulations associate with the 4.2 ka BP event

The sea level pressure (SLP) differences between the cooler periods and the warmer periods show that the largest change occurs over the mid-high latitudes of the NH and SH (~~Figure~~ Fig. 5a). The negative SLP anomalies over the high North Atlantic and positive SLP anomalies over the middle North Atlantic during the cool periods resemble a positive North Atlantic Oscillation (NAO)-like pattern but on a centennial-millennial time scale. The positive NAO-like pattern is accompanied by cyclonic circulation over Iceland and anticyclonic circulation over the Azores Islands and thus strengthened westerlies over the downstream regions (Fig. 5a). The subtropical highs and the relative anticyclones in both the SH and NH are strengthened during the cold periods from low troposphere (850 hPa) to high troposphere (200 hPa), which illustrates a barotropic structure (Fig. 5). Note that the strengthened subtropical highs over the NH are most significant at low level (sea level and 850 hPa), while the subtropical highs over the SH are most significant at high level (200 hPa). The centers with positive geopotential height anomalies during the 4.2 ka BP event over Western Europe, Central Asia, East Asia, the east north Pacific and Eastern North America, as well as the anti-cyclonic circulation anomalies at 200 hPa (Fig. 5d), resemble a Circumglobal Teleconnection (CGT)-like wave pattern (Ding and Wang, 2005; Lin et al., 2016) but on a centennial-millennial time scale.

The strengthened subtropical highs with mid-latitudes anticyclones from lower to upper levels are the direct physical processes that cause the precipitation decreases and thus the following megadrought over mid-latitudes of NH regions, particularly over Eurasia. The cooler land-warmer ocean over East Asia and the West Pacific (Fig. 3a) indicate weakened land-ocean thermal contrast associated with significantly higher SLP over land and lower SLP over the adjacent ocean (insignificant) (Fig. 5a). The weakened land-ocean contrast can lead to a weaker East Asian monsoon, accompanied by precipitation increases over the southern China pattern and precipitation decreases over the northern China pattern (Fig. 3b). Such conclusion is very rough, since the simulated anomaly patterns are not very significant. More investigations with higher resolutions of modeling and reconstruction works are required to get satisfactory results.

4 Discussions

The simulations show that the cool and dry conditions of the 4.2 ka BP event is more like a hemispheric phenomenon, mainly located over the NH, rather than a global phenomenon. The land over the SH experiences cool but wet conditions, and the mid-latitude SH ocean is warmer. The potential causes and mechanisms of this event will be discussed in this section.

4.1 The possible causes of the 4.2 ka BP event

Some records suggested that solar irradiance was one of the essential mechanisms that drove the Holocene climate variation at centennial to millennial time scales (Bond et al., 2001), whereas others suggested that the linkage between solar irradiance and multicentury scale cooling events during the Holocene was weak, particularly in the mid- to late-Holocene (Turney et al., 2005; Wanner et al., 2008). ~~The~~ Changes in solar irradiance are~~is~~ not included in the experiments used in the present work. Nonetheless, we still obtain multicentury cooling events (such as the 4.2 ka BP event) in the TraCE-ALL experiment, but with smaller magnitude. This side-fact indicates that the solar irradiance might not be the driving factor for the Holocene cooling events.

If the results derived from the TraCE-ALL experiment are consistent with those derived from a particular single-forcing sensitivity experiment, we assume the variation to be forced by that forcing. Otherwise, if the results derived from the TraCE-ALL experiment differ from those from the single-forcing sensitivity experiments, we assume the variation to be forced by the internal variability. In this section, we use the series after applications of 101-year running means as an example and compare the results derived from the all-forcing experiment to those derived from the single-forcing experiment to determine the possible forcings that triggered the 4.2 ka BP event.

The correlation coefficients between the annual mean NHT derived from the TraCE-ALL run and the NHT derived from each single-forcing run are listed in Table 2. A two-sided Students t-test is used for the statistical significant test, assuming 20 degrees of freedom, which is estimated simply from a 2000-year time series subjected to a 100-year running mean (Delworth and Zeng, 2012). There is no significant clue that the annual mean NHT variation is forced by the orbital variation or the other forcings due to the non-significant correlations. During the period of 5000 BP - 3000 BP, the variation of simulated JJA mean NHT is likely forced by the solar radiation due to the orbital variation (Table 2; the correlation coefficient between the two series is 0.79 at $p<0.05$), whereas the greenhouse gas change has a comparable negative impact on the JJA mean NHT (the correlation coefficient is -0.73 at $p<0.05$). The melt-water flux also has a moderate contribution to the JJA mean NHT change (the correlation coefficient is 0.48 at $p<0.05$). For the DJF mean NHT, ~~however,~~ only melt-water flux has a notable negative effect (the correlation coefficient is -0.43 at $p<0.05$). However, there is no meltwater forcing during this period, so the NHT change can be taken as internal variability. Therefore, the significant correlation coefficient between the all forcing run result and the meltwater forcing run result might be a coincidence, due to the autocorrelation of internal variability. This is another side-fact indicating the cold events during the late Holocene might be related to the internal variability. ~~A two-sided Students t-test is used for the statistical significant test, assuming 20 degrees of freedom, which is estimated simply from a 2000-year time series subjected to a 100-year running mean (Delworth and Zeng, 2012).~~ Note that if the effective degree of freedom is used, none of the ~~aforementioned~~ abovementioned correlation coefficients are significant. The effective degree of freedom is calculated by the following equation:

$$N_{dof} = N \times \frac{1 - r1 \times r2}{1 + r1 \times r2}$$

where N_{dof} is the effective degree of freedom regarding to the two correlation samples, N is the total sample size, r_1 and r_2 are autocorrelation lag-1 values for sample 1 and sample 2, respectively (Bretherton et al., 1999).

On the other hand, the annual mean NHT difference between the TraCE-ALL run and the sum of the 4 single-forcing sensitivity experiments shows variation similar to the NHT derived from the TraCE-ALL run from 5000 BP to 3000 BP (Fig. ~~S3~~S5). The correlation coefficient between these two time-series is 0.66, which is significant above the 95% confidence level (assuming 20 degrees of freedom). We ~~define~~ assume the difference between the TraCE-ALL run and the sum of the 4 single forcing runs to be the internal variation, taking that the climate responses to the external forcings are linear at global and hemispheric scales. Therefore, the internal variation might play a dominant role in the climatic variation during the period of 5000 BP-3000 BP. However, the linearity of the climate responding to the external forcings need further clarification, since there would be interactions between each forcing and between forcings and internal variability.

Moreover, there is no double-peak cooling event during the period of 4400 BP-4000 BP in any single forcing run (Fig. 1, colored lines), which indicates that the 4.2 ka BP event might not be triggered by those external forcings, including the orbital, the melt-water flux, the ice-sheets and the greenhouse gases in isolation. Volcanic eruptions have been identified as one of the important drivers of climate variation, whereas there were few eruptions during 4400 BP-4000 BP (Sigl et al., 2018). Therefore, we conclude that the variability relating to the 4.2 ka BP event ~~is~~ might be driven by the internal variability. Klus et al. (2017) also suggested that the internal climate variability could trigger abrupt cold events in the North Atlantic without external forcings (e.g., solar irradiance or volcanic).

However, why such large variation due to the internal variability occurs at approximately 4.2 ka BP remains unknown. There is little ice-sheet change and no melt water discharge after 5.0 ka BP in the TraCE-ICE run and TraCE-MWF run, and the variations of climate derived from these two runs can thus be considered as internal variabilities. The multicentennial cooling events can also be found in the standardized

NHT during the last 5000 years of the two experiments (Fig. ~~S4~~S6), and there are drought events in the standardized NH precipitation time series (not shown). However, the timing of those cooling and drought events occurs stochastically. This indicates a general concept of the random variation of the internal mode of the climate system. There is a reduction of NH temperature and precipitation at around 4600 BP in the TraCE-ORB (Fig. 2, orange lines), which might be related to the timing of the event as speculated by Ning et al. (2019).

Ning et al. (2019) compared the 5^{th} millennium BP cooling with the 9^{th} millennium cooling and concluded that the 9^{th} millennium BP cooling was resulted from the freshwater forcing while the orbital forcing is the most likely explanation of cooling in the North Atlantic starting from the early 5^{th} Millennium BP through most of the later Holocene, but with fluctuations. In the present work, we attribute this fluctuation to the internal variability, which is superposed on the orbital induced long-term trend. This work and Ning et al.'s work (2019) focus on different aspects and different time scales, and are complementary to better understand the 4.2 ka BP event.

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4.2 The mechanisms of the centennial-millennial cooling and drought

As has mentioned in Sec. 3.3, the low level NAO-like pattern and upper level CGT-like pattern are the direct mechanisms that cause cooling and megadroughts over most part of the NH. Previous studies also proposed that the temperature and precipitation changes over Eurasia and Africa were directly linked to the NAO (Cullen et al., 2002; Kushnir and Stein, 2010).~~Moreover, t~~The first leading mode of the Empirical Orthogonal Function (EOF) of the annual mean SLP during 5 ka BP-3 ka BP shows a double-peak positive NAO-like pattern but on a centennial scale during the period of 4400 BP-4000 BP (Fig. 6). The first leading EOF of geopotential height at 200 hPa after application of a 31-year running mean shows a CGT-like pattern and similar double-peak variation during the period of 4400 BP-4000 BP, which is more obvious after applying the 101-year running mean (Fig. 7). This means that the double-peak cooling and drought of the 4.2 ka BP event could be strongly related to the double peak positive NAO-like pattern (at low level) and CGT-like pattern (at high level) at a centennial time scale.

Li et al. (2013) suggested that the NAO is a predictor of NHT multidecadal variability during the 20th century. In this study, significant correlation is also found between the annual mean NAO index and the annual mean NHT during the period of 4400 BP-4000 BP, with the NAO leading by approximately 40 years (Fig. 8). The NAO index is defined by the first leading mode of the EOF of the SLP. The regressed annual mean surface temperature against the NAO index 40 years earlier during 4400 BP and 4000 BP shows cooler NH high latitudes and a warmer SH (Fig. S5S7), especially the cooling over the northern North Atlantic Ocean, Europe, East Asia and North America.

The geopotential height at 200 hPa regressed against the SST over the two North Atlantic outstanding regions (Fig. 4) shows a CGT-like pattern after application of a 31-year running mean (Fig. 9), which is similar to the conclusion from Lin et al. (2016) that the CGT could be excited by the AMO-related SST anomaly. The regressed 200 hPa geopotential height shows a similar pattern after application of a 101-year running mean (not shown). The anticyclones associated with CGT-like pattern over the West Europe, Central Asia and North America can suppress the precipitation and thus lead to megadrought over these regions.

Considering the NAO-like pattern, the CGT-like pattern and the AMO-like pattern together, we suggest that the AMO could be playing a “bridge” role to keep the barotropic structure at the centennial scale, which is similar to the synthesis proposed by Li et al. (2013) that the AMO is a “bridge” that links the NAO and NHT at a multidecadal timescale. Delworth and Zeng (2016) suggested that the NAO variation had significant impact on the AMOC and the subsequent influence on the atmosphere and large-scale climate at multidecadal-centennial time scales. Other studies also focused on the role of SST anomalies over the North Pacific and North Atlantic oceans when investigating the possible mechanisms of the 4.2 ka BP event (Kim et al., 2004; Marchant and Hooghiemstra, 2004; Booth et al., 2005).

We notice the centennial-millennial variation of the AMOC after the mid-Holocene in the all forcing run (Fig. S4a). There also exits a double peak variation during the period of 4400-4000, accompanied by the similar spatial patterns of temperature and precipitation anomalies as the simulated 4.2 ka BP event (Fig. S4b, c). However, whether this AMOC variation is related to the external forcing, such as the orbital forcing, or just the internal variability remains unknown, and needs further investigations.

5 Conclusion

The characteristics of the 4.2 ka BP event along with the potential drivers and the mechanisms are investigated using a set of transient climate simulations. The simulated event is characterized by hemispheric cooling and megadrought over the NH, whereas the SH experiences warming (over mid-latitude ocean) and wet conditions during this event. The annual mean temperature change is dominated by the boreal winter change. The cool and dry NH and warm and wet SH pattern indicates a southward shift of the ITCZ, as suggested by the reconstructions. These characteristics could also be related to a weakening of the AMOC, which needs further investigation.

By comparison between the all-forcing experiment and the single-forcing sensitivity experiments, the 4.2 ka BP event can largely be attributed to the internal variability, although the orbital forcing and the greenhouse gases could impact the boreal summer NHT variation. The origin could be in polar regions and the North Atlantic and may influence the NH climate through teleconnections such as the NAO-like pattern and the CGT-like pattern. The positive NAO-like pattern in the atmosphere triggers cooling over the NH and the negative AMO-like pattern in the ocean, which may last for decades or even centuries. The negative AMO-like pattern triggers CGT-like wave patterns at a multidecadal-centennial time scale accompanied by anticyclones over West Europe, Central Asia and North America, which induce megadrought over those regions. The simplified diagram of the mechanism is shown in Fig. 10.

Our findings provide a global pattern and mechanical background of the 4.2 ka BP event that can help better understanding this event. We attribute~~d~~ the internal variabilities to be an essential forcing of the 4.2 ka BP event~~;~~. H~~h~~owever, ~~W~~whether or not the external forcings have modulation effects need to be clarified. For example, ~~,~~is the timing of the event stochastic due to the internal variability or modulated by the external forcings such as the orbital changes?~~why it occurs at approximately 4400 BP to 4000 BP remains unknown.~~ Why the SST forcing in the North Atlantic can be maintained at a multidecadal-centennial time scale requires more study. ~~Whether or not the external forcings have modulation effects need to be clarified.~~ Current results are mainly based on annual mean precipitation and temperature, whereas the impacts of external forcings may have seasonal dependence; further investigations are required to evaluate these impacts.

The model responses to the external forcings are small, especially in the Holocene because of the absence of a significant change of the AMOC and the meltwater forcing after 6 ka (Liu et al., 2014b). So we use the amplified anomalies between the cold and warm periods, rather than simply the cold anomalies against the long-term average, to illustrate the mechanisms of the event. We need to keep in mind that we still might not be modeling the events comparable to the 4.2 ka BP event, particularly during the late Holocene. More model-data, inter-model and inter-events comparisons are required to better understand the cold events during the Holocene.

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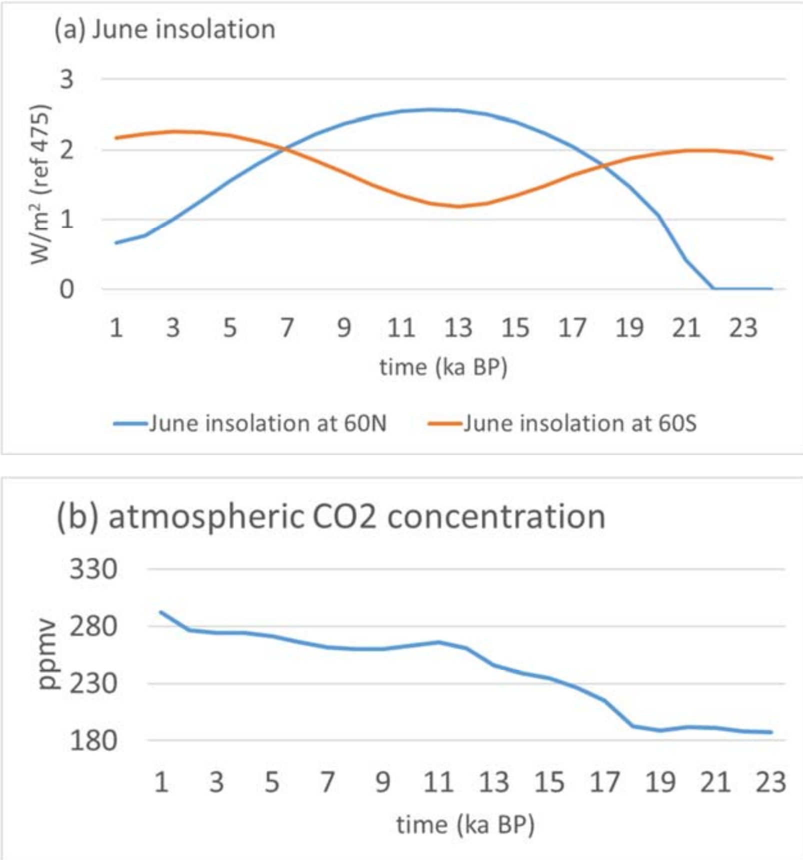


(a) June insolation
W/m² (ref 475)
3
2
1
0
1 3 5 7 9 11 13 15 17 19 21 23
time (ka BP)
June insolation at 60N
June insolation at 60S
(b) atmospheric CO2 concentration
ppmv
330
280
230
180
1 3 5 7 9 11 13 15 17 19 21 23
time (ka BP)

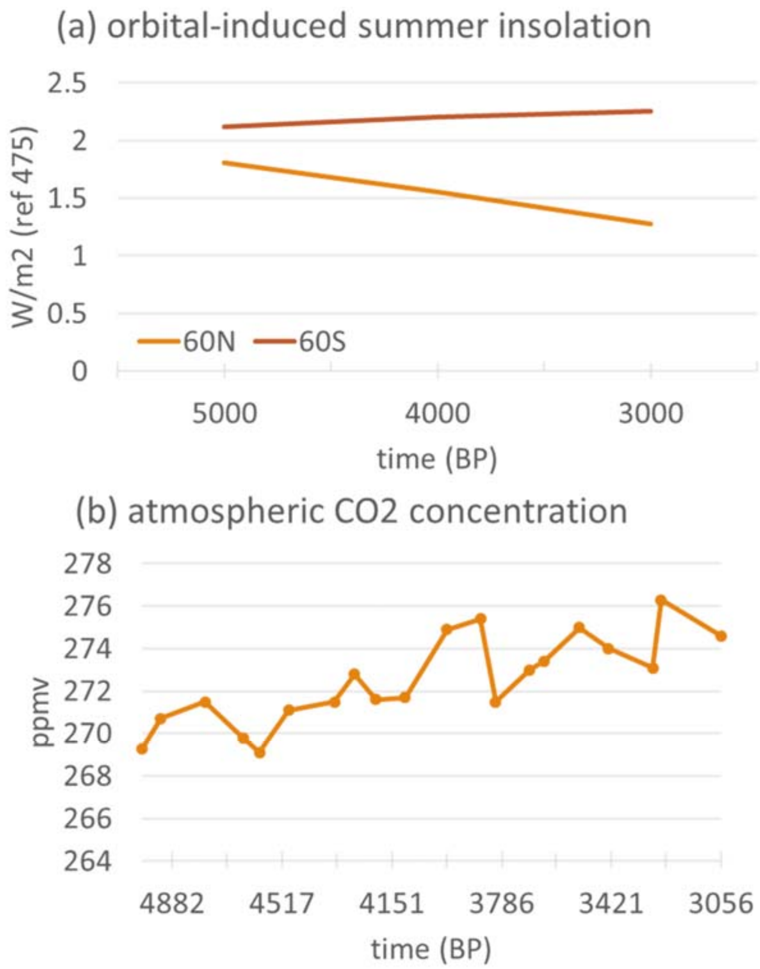


Figure 1 Time series of (a) transient ~~June~~ summer insolation (at 60°N and 60°S) changes resulted from the orbital variation and (b) the transient CO_2 change used in the simulations.

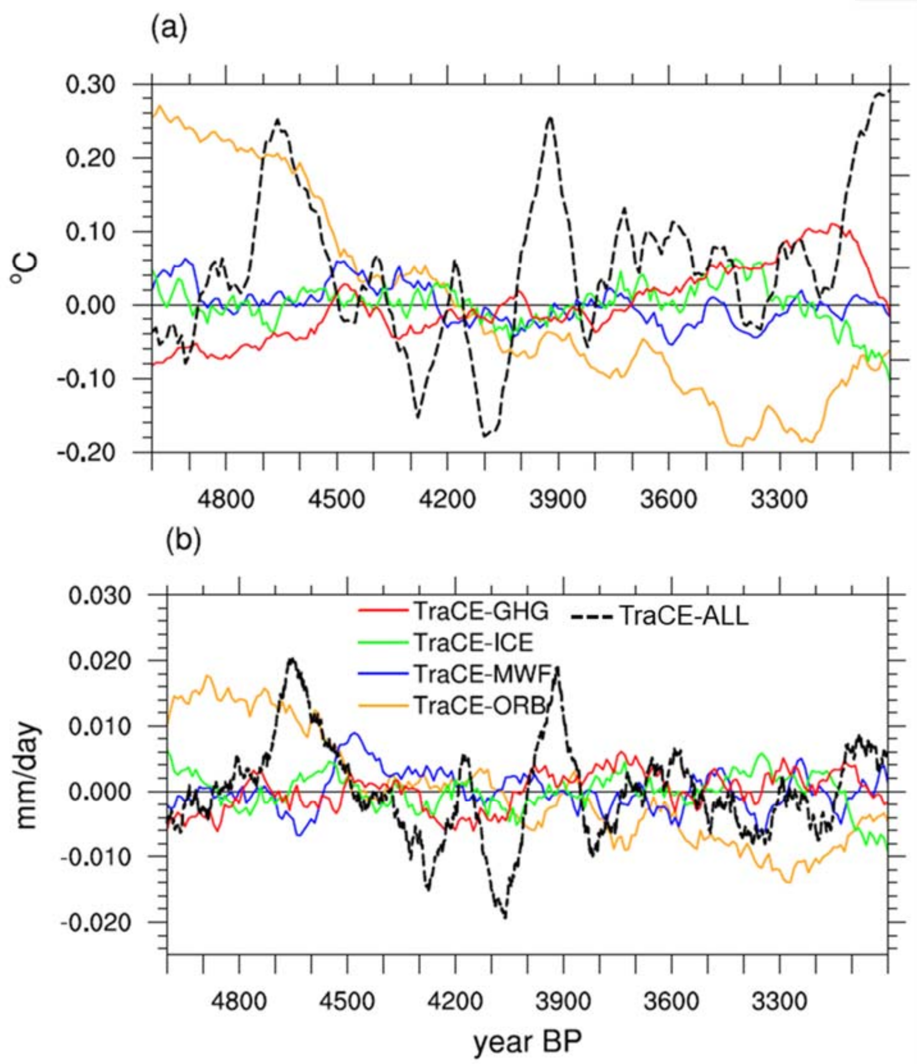
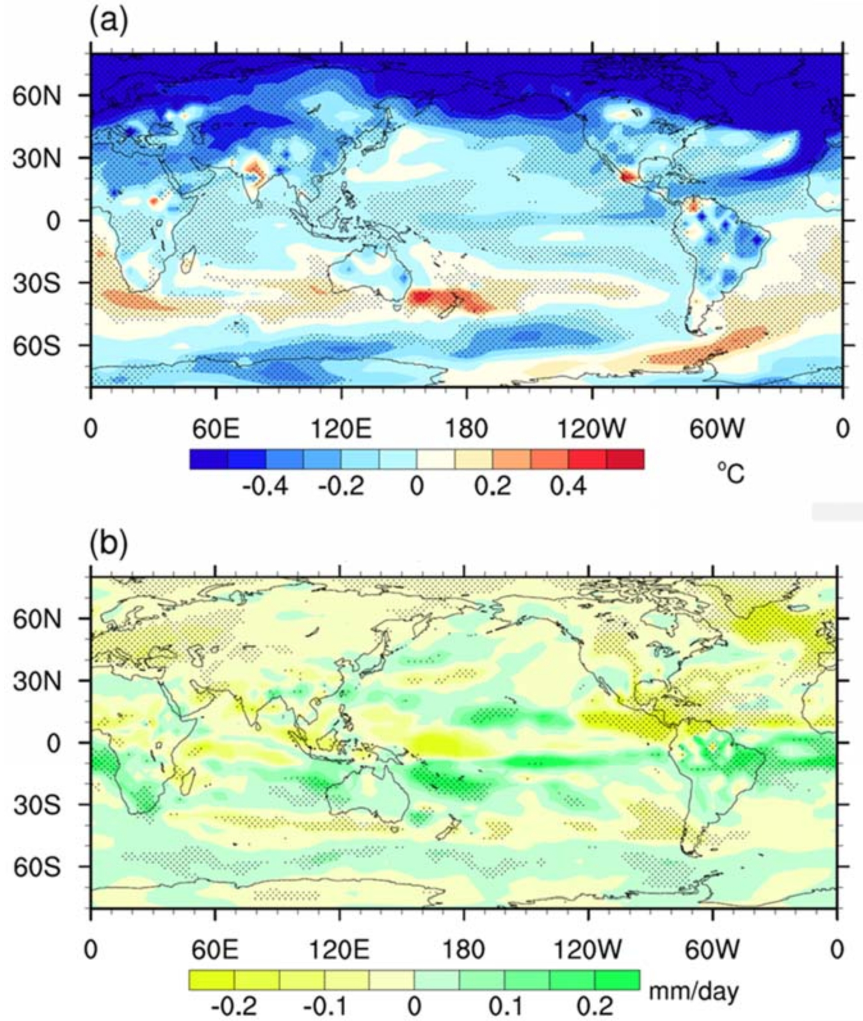


Figure 2 Time series of annual mean NH (a) surface temperature anomalies and (b) precipitation anomalies derived from the TraCE-ALL run (dashed black lines) and each single forcing runs (solid color lines) from 5 ka BP to 3 ka BP. A 101-year running mean has been applied to the time series.


(a)
60N
30N
0
30S
60S
0
60E
120E
180
120W
60W
0
-0.4
-0.2
0
0.2
0.4
°C
(b)
60N
30N
0
30S
60S
0
60E
120E
180
120W
60W
0
-0.2
-0.1
0
0.1
0.2
mm/day

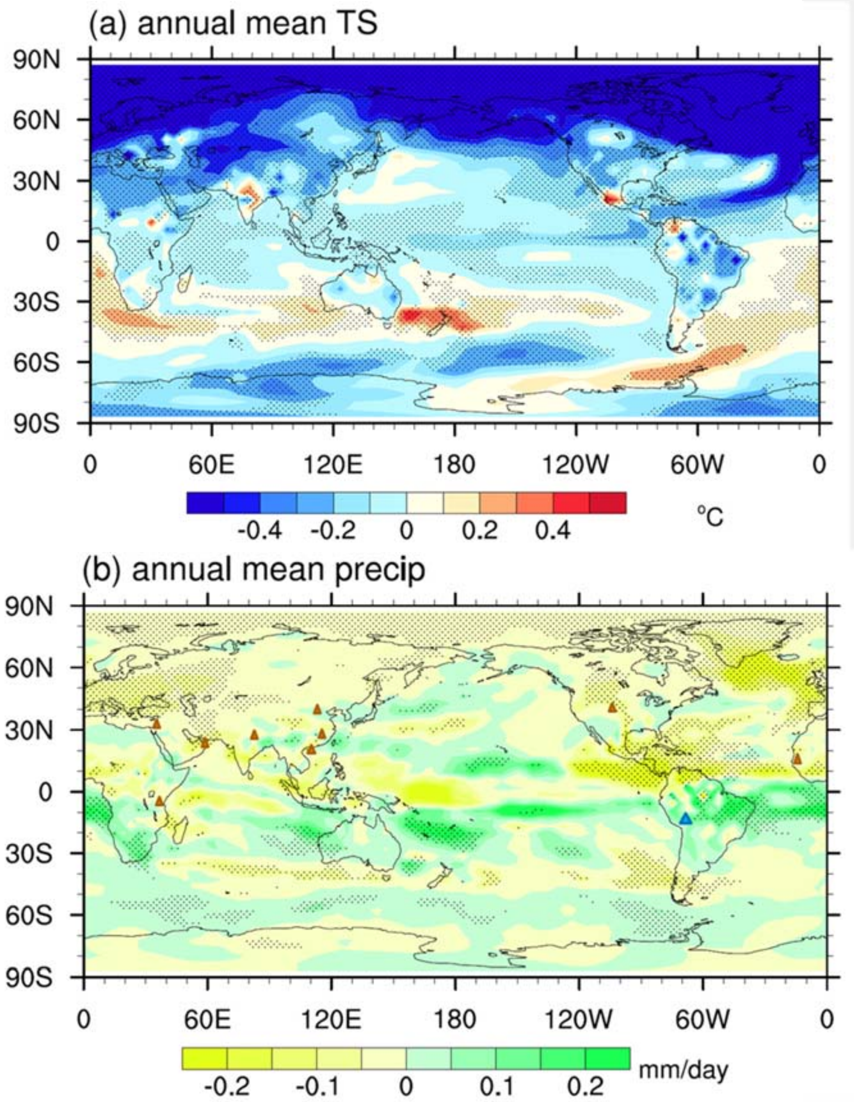
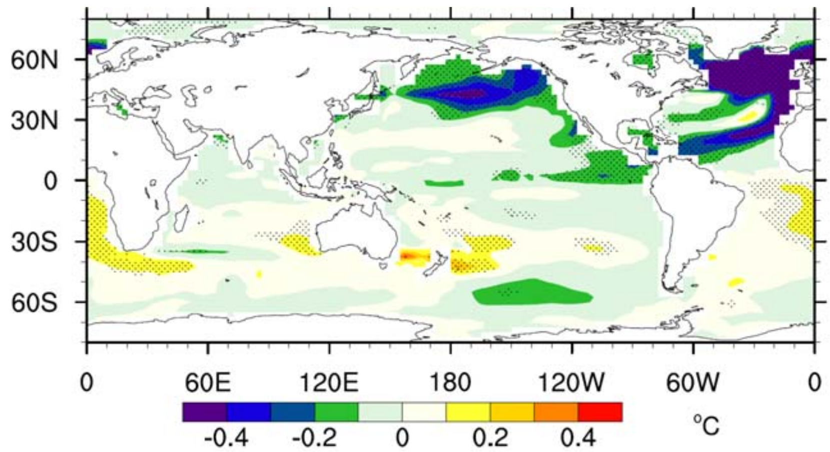


Figure 3 Spatial distribution of the annual mean (a) surface temperature and (b) precipitation differences between the cold periods and warm periods derived from the TraCE-ALL run. Those regions where significant above 95% confidence level are dotted. Triangles in (b) denote the dry (orange) and wet (blue) conditions documented in the records, including the following sites: Kilimanjaro (3°04.6’S, 37°21.2’E) (Thompson et al., 2002), Dead Sea (Yechieli et al., 1993), Gulf of Omen (24°23.4’N,

59°2.5’E) (Cullen et al., 2000), Lake Rara (29°32’N, 82°05’E) (Nakamura et al., 2016), Maar lake in Huguangyan (21.15°N, 110.29°E) (Liu et al., 2000), Daihai Lake (40.58°N, 112.7°E) (Peng et al., 2005), Poyang Lake (29.15°N, 116.27°E) (Ma et al., 2004), Eastern Colorado Dunes (40°20’N, 104°16’E) (Forman et al., 1995), Lake Titicaca (12.08°S, 69.85°W) and Lake Guiers (16.3°N, 16.5°W) (Marchant and Hooghiemstra, 2004).



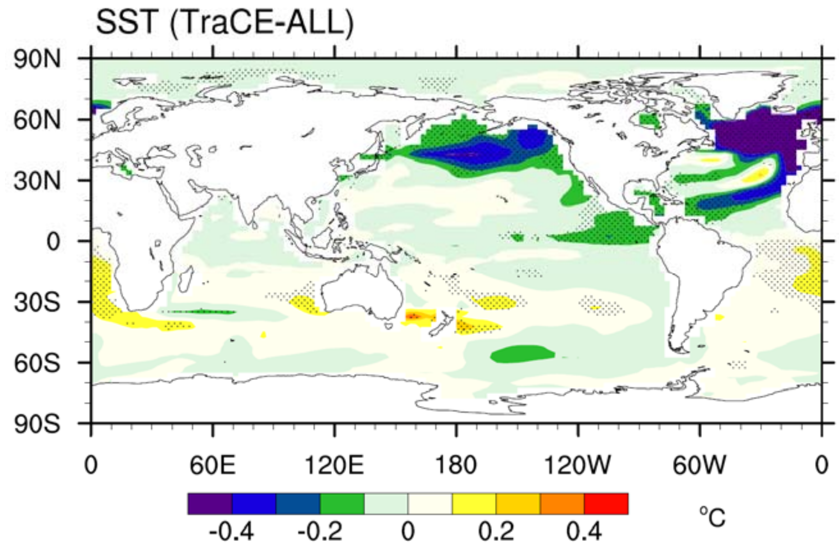
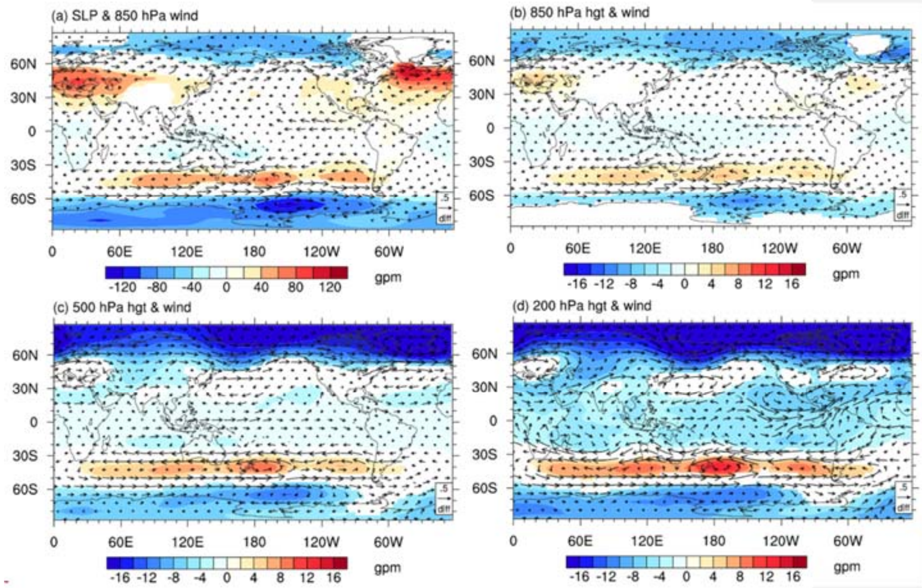


Figure 4 Spatial distribution of annual mean SST difference between the cold and warm periods derived from the TraCE-ALL run. Those regions where significant above 95% confidence level are dotted.



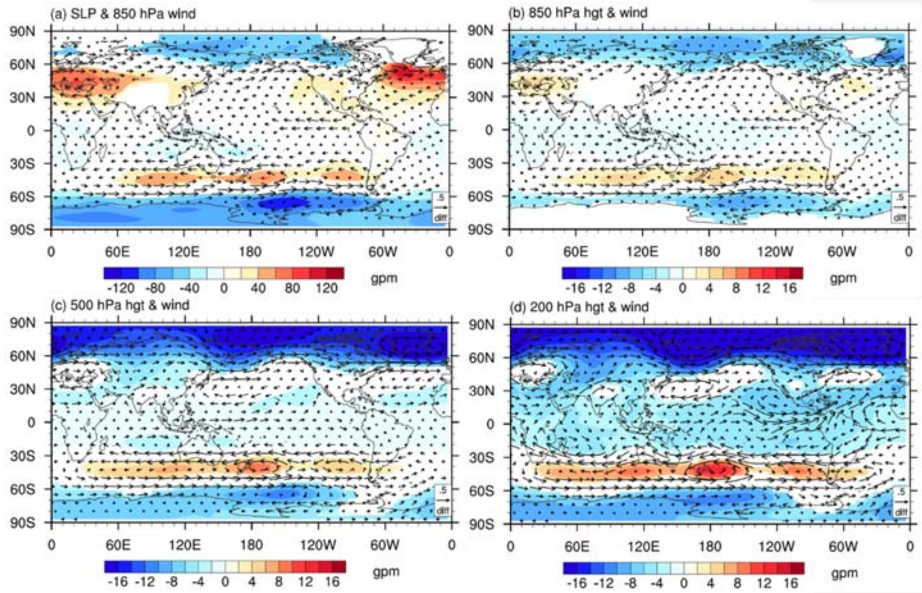


Figure 5 Differences of annual mean (a) sea level pressure and 850 hPa wind, (b) geopotential height and wind on 850 hPa, (c) geopotential height and wind on 500 hPa and (d) geopotential height and wind on 200 hPa between cold and warm periods derived from the TraCE-ALL run. Those regions where significant above 95%

confidence level are plotted.

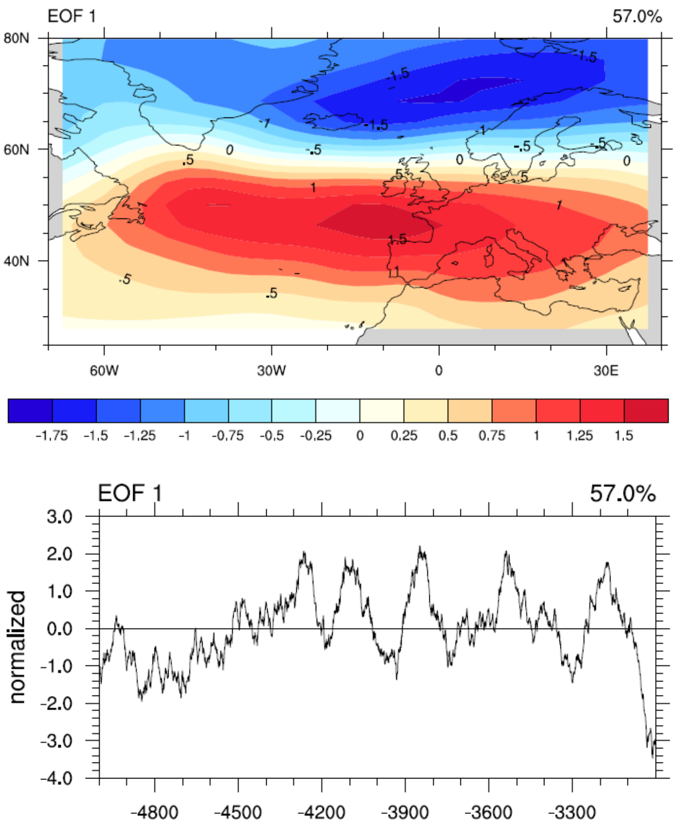
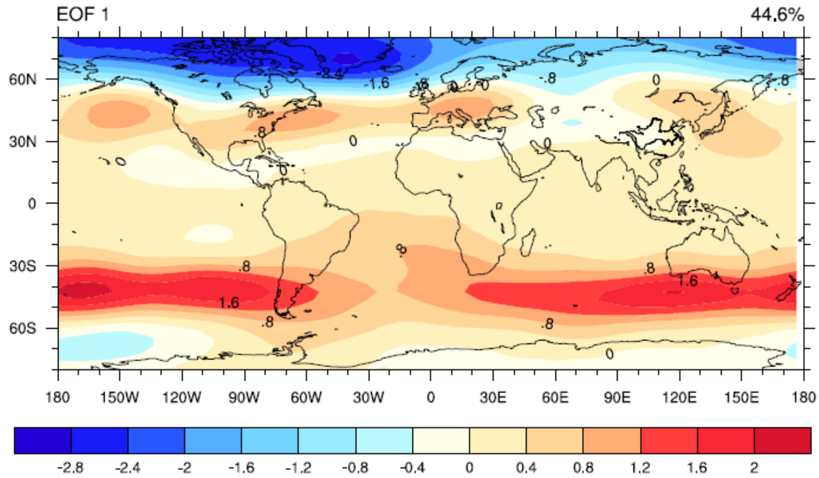
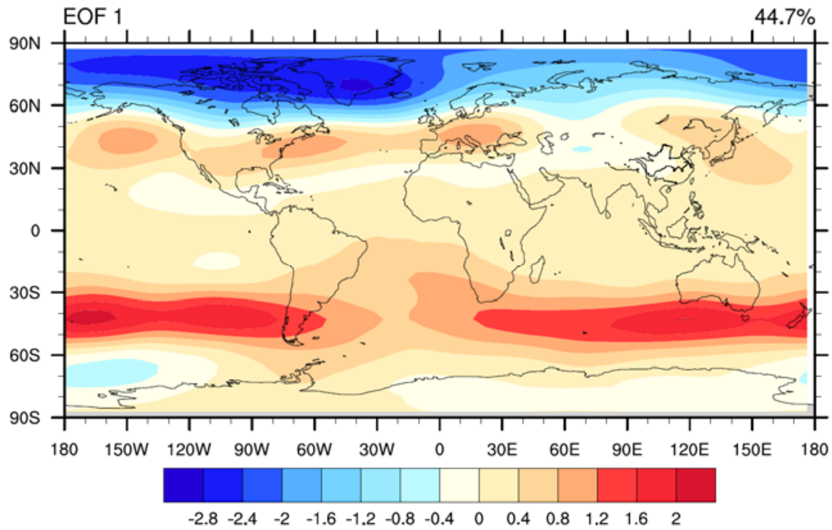


Figure 6 Standardized first leading mode of the EOF of annual mean SLP over the North Atlantic region (70W-40E, 25N-80N) during the period of 5.0 ka BP to 3.0 ka BP derived from the TraCE-ALL run, after application of a 101-year running mean. The spatial distribution is shown in the top panel, and the time series is shown in the bottom panel. Only this mode passed the North test for EOF.


EOF 1
44.6%
60N
30N
0
30S
60S
180 150W 120W 90W 60W 30W 0 30E 60E 90E 120E 150E 180
-2.8 -2.4 -2 -1.6 -1.2 -0.8 -0.4 0 0.4 0.8 1.2 1.6 2


EOF 1
44.7%
90N
60N
30N
0
30S
60S
90S
180 150W 120W 90W 60W 30W 0 30E 60E 90E 120E 150E 180
-2.8 -2.4 -2 -1.6 -1.2 -0.8 -0.4 0 0.4 0.8 1.2 1.6 2

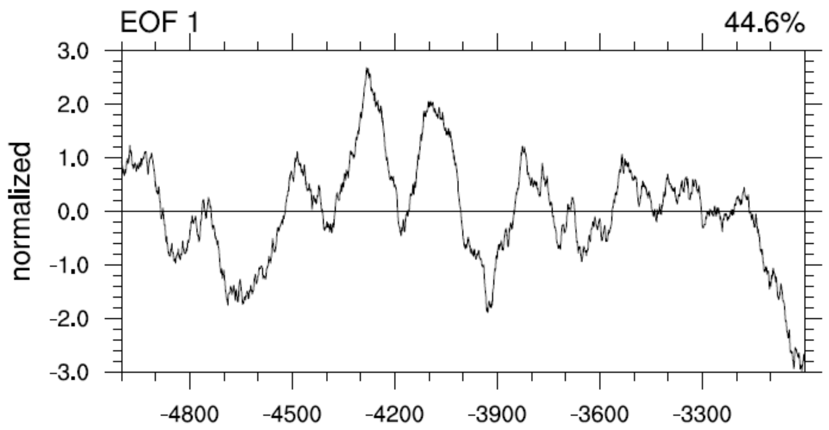


Figure 7 Standardized first leading mode of the EOF of annual mean geopotential height at 200 hPa during the period of 5.0 ka BP to 3.0 ka BP derived from the TraCE-ALL run, after application of a 101-year running mean. The spatial distribution is shown in the top panel, and the time series is shown in the bottom panel. Only this mode passed the North test for EOF.

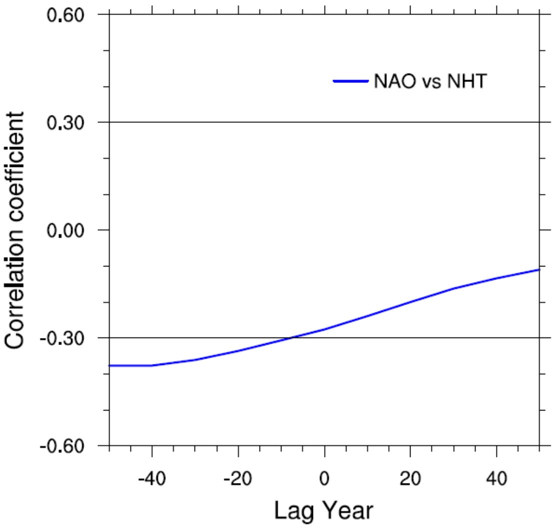


Figure 8 Lead-lag correlation between the annual mean North Atlantic Oscillation (NAO) and the North Hemisphere Surface Temperature (NHT) during 4.4 ka BP-4.0 ka BP derived from the TraCE-ALL run. The black lines (±0.3) show the significance levels ($p<0.05$).

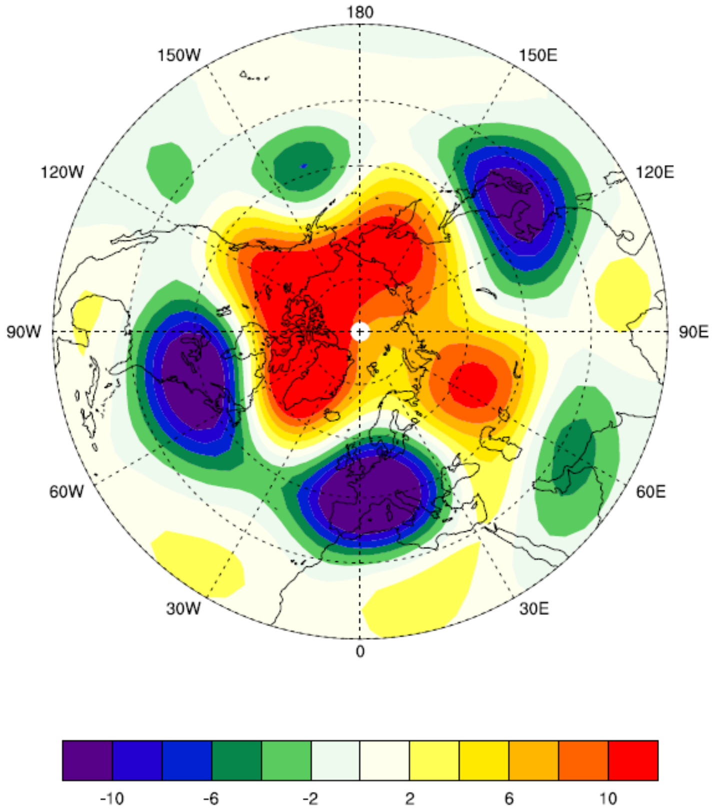


Figure 9 Annual mean geopotential height regressed against the SST over the North Atlantic during 5.0 ka BP - 3.0 ka BP derived from the TraCE-ALL run, after 31-year running mean application.

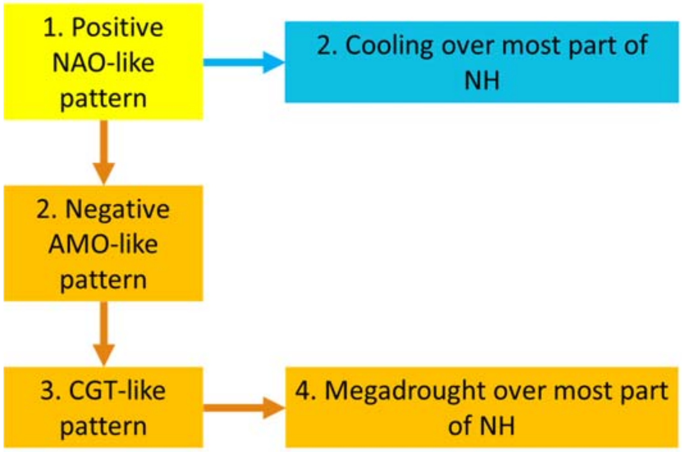


Figure 10 Schematic diagram shown the mechanisms behind the 4.2 ka BP event.

Table 1 The information of the experiments used in this study.

Experiments	**Forcings**	**Time spanning**	**Temporal resolution**
TraCE-ALL	Orbital, melt-water flux, continental ice-sheet, and Greenhouse gases	22000 BP to 1990 CE	Monthly mean
TraCE-ORB	Orbital only	22000 BP to 1990 CE	Decadal mean
TraCE-MWF	Melt-water flux only	19000 BP to 1990 CE	Decadal mean
TraCE-ICE	Continental ice-sheets only	19000 BP to 1990 CE	Decadal mean
TraCE-GHG	Greenhouse gases only	22000 BP to 1990 CE	Decadal mean

Table 2 Correlation coefficients between the annual mean and seasonal mean NHTs derived from the TraCE-ALL run and those from each single-forcing run from 5.0 ka BP to 3.0 ka BP.

Single forcing run	Annual mean	JJA mean	DJF mean
TraCE-ORB	-0.05	0.79	-0.12
TraCE-MWF	-0.18	0.48	-0.43
TraCE-ICE	-0.30	-0.20	-0.18
TraCE-GHG	0.14	-0.73	0.40