Response letter

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1 Comments from Reviewer 3

This paper documents in detail the calendar effects on analyses of paleoclimate simulations for the mid-Holocene (MH), the Last Interglacial (LIG) and pre-industrial periods as well as for transient simulations. Indeed, due to the slow variations of the Earth's orbital parameters, the position of seasons is modified within the ellipse, affecting the length of the seasons. This effect has been documented in Joussaume and Braconnot (1997) and more recently in Bartlein and Shafer (2019) but is usually not accounted for. This paper uses the most recent simulations of PMIP4 with coupled models and allows to revisit this question. Indeed, at the time of PMIP1, in Joussaume and Braconnot (1997), sea surface temperatures were prescribed to today, thus including a hidden present-day calendar in past climate simulations. Moreover, the paper presents results from transient simulations. These results deserve to be published although some improvements of the text would help its readability.

Dear Reviewer,

Thank you very much for your positive and constructive comments. In the following, we present our point-to-point responses. Our answers to your comments are written in bold.

Thanks again for your time and efforts.

Best,

Xiaoxu

There is a need to better explain how the 90° angular seasons are positioned relative to the vernal equinox which provides the reference for dates (March 21st), the way the seasons are computed is not fully clear in the paper.

To answer this question, we first add an equation which relates the time elapsed since Earth passes the perihelion to true anomaly θ (the angle between the axis of the perihelion and the actual position of the earth):

$$t_p(\theta) = \frac{MT}{2\pi} = \frac{(E-\epsilon\cdot\sin(E))T}{2\pi} \text{ with } E = 2\cdot\arctan(\sqrt{\frac{1-\epsilon}{1+\epsilon}}\cdot\tan(\frac{\theta}{2}))$$

Then we clarify in our revised paper:

The relation between the true anomaly θ and the time elapsed since Earth passes perihelion t_p allows to define seasons with respect to Earth's position on the orbit rather than relying on a fixed number of days. Based on the "fixed-angular" approach, there are two ways to define the seasons: 1) The orbit is distinguished into four segments: A true anomaly of $\theta = 0°$) corresponds to March 21st and therefore marks the first day of spring. The length of the summer is gained by calculating t_p ($\theta = 90°$). Similarly, the terms t_p ($\theta = 180°$) and t_p ($\theta = 270°$) mark the beginning of fall and winter, respectively. 2) The other method is based on the "meteorological" definition, in which the spring is defined as March-April-May, as typically done in paleoclimate modelling, although the VE is set to March 21st. The second approach is adopted in our study, and in this case, we firstly compute the starting and end time for each month, then average over the respective months in order to compare the angular seasonal means with the classical seasonal means.

We also add texts on how we define months:

Months can be defined as 30° increments of the true anomaly. Just one additional step has to be executed before calculating angular months: As no months starts at the VE, the starting day has to be shifted from March 21st to April 1st. Since the time between nowadays March 21st and April 1st may not be true for past calendars, we defined April 1st by the angle. Therefore, we first calculate the angle between nowadays March 21st, noon (the VE) and the point of time occurring 10.5 days later, denoting April 1st. Finally, starting from the angle corresponding to April 1st, we are able to calculate the starting time of the next month by 30° increments of the true anomaly.

Concerning the simulations used, it would be good to summarize the PMIP4 boundary conditions in section 2.2 and explicit whether the three transient simulations use the same boundary conditions and whether they differ or not with PMIP4 for the mid-Holocene.

According to the comment, we add a table describing the PMIP4 boundary conditions for pre-industrial, mid-Holocene and Last interglacial (see table 1 of this letter), and we also illustrated in the paper:

Table 1. PMIP4 boundary conditions for pre-industrial, mid-Holocene and Last interglacial.

Experiment	CO_2 (ppm)	CH_4 (ppb)	N_2O (ppb)	Eccentricity	Obliquity	perihelion - 180°
PI	284.3	808.2	273	0.016764	23.459°	100.33°
MH	264.4	597	262	0.018682	24.105°	0.87°
LIG	275	685	255	0.039378	24.040°	275.41°

According to Otto-Bliesner et al. (2017), the CO_2 concentration applied in the PMIP4 protocol for mid-Holocene is derived from ice-core measurements from Dome C (Monnin et al., 2001, 2004). CH_4 has been derived from multiple Antarctic ice cores including EPICA Dome C (Flückiger et al., 2002), EPICA Dronning Maud Land (Barbante et al., 2006) and Talos Dome (Buiron et al., 2011).The N_2O data around 6 ka are compiled from EPICA Dome C (Flückiger et al., 2002; Spahni et al., 2005) and Greenland ice cores. The concentrations of CO_2 during the LIG are derived from Antarctic ice cores (Bereiter et al., 2015; Schneider et al., 2013), CH_4 has been derived from EPICA Dome C and EPICA Dronning Maud Land (Loulergue et al., 2008; Schilt et al., 2010b), and N_2O from EPICA Dome C and Talos Dome (Schilt et al., 2010b, a). Table 2 provides a summary of PMIP4 boundary conditions for pre-industrial, mid-Holocene and Last interglacial.

Then we add another sentence in our paper:

Therefore, in the transient simulations, the orbital forcings used at 6 ka and 0 ka are the same as the PMIP4 equilibrium simulations. However, there are differences between the greenhouse gas concentrations applied in the transient and PMIP4 equilibrium simulations, as the values have been taken from different reconstructions.

The use of angular seasons is indeed more appropriate when comparing seasons from different periods in paleoclimate simulations, however, it would be good to add some elements in the discussion on possible implications for the model-proxy data comparisons.

It is a good idea to discuss about the implication of calendar on model-proxy comparison, based on the comment, we added in the discussion section:

Proxy-based reconstructions provide us another ability to examine the temperature evolution of the past and can help assess the model's performance in simulating the past climates. Since paleoclimate data often records the seasonal signal (e.g. local summer temperature), an appropriate choice of calendar is therefore important for temperature comparisons between model results and proxy data. For the mid-Holocene, Bartlein et al. (2011) is an often-cited study that compiled pollen-based continental temperature reconstructions. The question arises whether the consideration of calendar effects could lead to an improved model-data agreement. Here we show in Fig. S11 the simulated classical mean temperature anomalies (MH minus PI) versus continental reconstructions. The expected increased seasonality occurs only over Northwest Europe as indicated by the proxy records. The opposite sign is shown over northern America, with winter warming and summer cooling, and is therefore not consistent with the ensemble model result. Bartlein et al. (2011) attributes such a model-data mismatch to changes in local atmospheric circulation that tend to overwhelm the insolation effect. The calendar impacts, as illustrated in Fig. 4, result in warming of less than 0.2 K over the Northern Hemisphere in both DJF and JJA, implying that model-data consistency is improved for Northwest Europe in summer, and Northern America in winter, while for most other regions using the adjusted calendar results in a poorer match between model and proxy temperatures. These results reveal that for the mid-Holocene the calendar adjustment does not guarantee a better model-data agreement, and the underlying reason might be that, in addition to the solar insolation, the proxy could be strongly influenced by the local environment, such as flow of humid air and increased cloud cover (Harrison et al., 2003) or warm-air advection (Bonfils et al., 2004).

Since there are very few high-resolution reconstructed temperature records for the LIG, we use here the compilation from Turney and Jones (2010) for the annual mean temperature anomalies between LIG and PI, and compare them with modeled classical mean values for boreal summer (Fig. S12). We keep in mind that the summer mean LIG temperatures are usually higher than the annual mean values documented by the proxy records. At high latitudes of Northern Hemisphere continents (e.g. Greenland, Russia and Alaska), as well as over subpolar oceans (e.g. the Nordic Sea and the Labrador Sea), we find that the models underestimate the recorded LIG warming. Part of the bias can be corrected by calendar adjustment which leads to a warming of up to 1 K over Northern Hemisphere continents in JJA (Fig. 3k).

Moreover, you have made the choice to define 4 times 90° angular seasons and to compare to pre-industrial, but nothing is said on how you would compare to present-day. In Joussaume and Braconnot (1997), the choice was to use the same angular seasons as used today (even if they are not perfect 90° angles) to ensure consistency with present-day. It could be interesting to add some discussion on the impact of those different choices.

Thanks for the suggestion. Now in our revised manuscript we added the following texts into the discussion part:

In previous studies, the angular calendar was defined using the true anomaly of the Earth corresponding to the present-day seasons, in other words, each month begins and ends at the same celestial longitude as present-day for any period (Joussaume and Braconnot, 1997; Bartlein and Shafer, 2019; Timm et al., 2008; Chen et al., 2011; Pollard and Reusch, 2002). The work of Chen et al. (2011) and Timm et al. (2008) applied a 360-day year which is, originally, divided into 12 months with 30 days. The VE is set to day 81 in a calendar year. Pollard and Reusch (2002), Joussaume and Braconnot (1997) and Bartlein and Shafer (2019), on the other hand, performed the calendar adjustment based on today's classical calendar with 365 days in a non-leap year. In their studies, an assumption was made that the seasonality defined by the classical calendar is in phase with the insolation and solar geometry for modern-day. In our study, by calculating the onset of present-day months/seasons using the approach described in Section 2.1, we find that the classical "fixed-length" calendar is very similar to the angular calendar for today, but they are not completely the same. This is evidenced in the small shift of months between the two calendars as seen in Table 3. In particular the angular October is delayed by 3 days compared to the classical October, resulting in negative anomalies in the adjusted-minus-unadjusted solar insolation. Though different methods are used in our work from the mentioned previous studies, our results are identical: for the LIG, the adjusted-minus-unadjusted surface air temperature over the Northern Hemisphere is up to 5 K during SON (Joussaume and Braconnot, 1997; Bartlein and Shafer, 2019; Chen et al., 2011) or September (Pollard and Reusch, 2002); and the Northern Hemisphere monsoon precipitation in SON is underestimated by the use of the classical calendar (Bartlein and Shafer, 2019; Chen et al., 2011). Similar biases are found for the early-Holocene (Timm et al., 2008) and mid-Holocene (Joussaume and Braconnot, 1997; Bartlein and Shafer, 2019) but less pronounced . These results are consistent with the findings in our study, however, comparing results of our 3 transient simulations with that from the TraCE-21ka transient simulation, as it was investigated in Bartlein and Shafer (2019), distinct differences emerge for the boreal autumn surface air temperature near present-day. In Bartlein and Shafer (2019), the artificial bias in MH-minus-PI temperature and precipitation totally stems from the bias in MH when the classical calendar is applied (as for PI both calendars are identical).

In contrast, our study reveals that such bias is mainly dominated by the deviation between angular and classical calendars for present-day. It should be noted that these discrepancies are not due to the different models used in our studies, but rather to the different approaches adopted for calendar adjustment.

In the discussion, it would also be interesting to know if some of the forcing or boundary conditions of simulations may still keep some memory of the present-day calendar (e.g., prescribed vegetation or aerosols) and may add some bias in the analyses.

Thanks for the interesting comment, we now discussed about this point in the revised version:

Finally, we should bear in mind that the forcing or boundary conditions of simulations may still keep some memory of the present-day calendar (e.g., prescribed ozone, vegetation or aerosols). This is particularly important for paleoclimate simulations with stand-alone atmosphere or ocean models, as they are often forced by fields in classical calendar, and this may introduce further bias in the simulated seasonality even though with the calendar being adjusted.

The text needs some reading to correct some sentences, some are mentioned below.

Specific comments:

L12: The largest difference occurs in autumn is related to the choice of a fixed date for the vernal equinox, this should be made clearer in this sentence

Thanks for the suggestion, we now add in our manuscript:

The largest cooling bias occurs in autumn when the classical calendar is applied for the mid-Holocene and last interglacial, due to the fact that the vernal equinox is fixed at 21th March.

L16: the conclusion on using monthly data is not clear in the abstract, you should add compared to using daily data

To make it clearer, now we illustrated in the revised version:

Finally, monthly-adjusted values for surface air temperature and precipitation are very similar to the daily-adjusted values, therefore correcting the calendar based on the monthly model results can largely reduce the artificial bias.

L24: “is highly depends” should be “highly depends”

Thanks for the correction. We have corrected the error in the revised version.

L25: March 21st and not 31 !

Thanks for the correction. We have corrected the date for vernal equinox in the revised manuscript.

L30: the classical reference is rather to Berger (1978) than 1977

Thanks for the correction, we now refer to Berger (1978).

L44: modelling groups and not model groups

We changed it into *"a number of modelling groups"*

L48: I do not think we can say that the MH and LIG are chosen due to their great potential to resemble future scenarios. Please reconsider this statement

We now changed the texts in the revised paper:

Two interglacial episodes, i.e., the mid-Holocene (MH, a period roughly from 7 to 5 ka B.P) and the Last Interglacial (LIG, roughly equivalent to 130-115 ka B.P.), are particularly the focus of PMIP (Otto-Bliesner et al., 2017), as they are the two most recent warm periods in geological history.

L50: receive more insolation in summer and less in winter is only true for the Northern Hemisphere

We agree. Based on the comment, we changed in our manuscript:

Due to the Earth's orbital parameter anomalies with respect to the present, the MH and LIG receive more insolation in summer and less in winter over the Northern Hemisphere, leading to larger seasonal contrast in the two time periods, which holds true for both hemispheres in most model simulations (Kukla et al., 2002; Shi and Lohmann, 2016; Shi et al., 2020; Zhang et al., 2021; Kageyama et al., 2021; Herold et al., 2012). Such effect is much more profound in the LIG than in the MH (Lunt et al., 2013; Pfeiffer and Lohmann, 2016). However, in earlier simulations using CCSM3 and LOVECLIM, Nikolova et al. (2013) found smaller seasonality across Lazarev Sea (in CCSM3) and South Atlantic Ocean (in LOVECLIM) during the Last interglacial as compared to PI.

L83 to L86: a drawing to explain M and E is missing. It could be added at least in the supplementary material

Based on the comment, we added a figure in the supplementary describing the relation among he mean anomaly (M), eccentric anomaly (E) and true anomaly (θ), here we refer to Fig. S1 in the revised supplementary.

L102: IPSL is the name of the institution not of the model (IPSL-CM)

Thanks for the correction, we now changed the name of the model into "IPSL-CM" in the revised manuscript.

L132: Sahel and not Sahal

Sorry for the typo. We now corrected this term in the updated manuscript.

Table 2: mentions that the present-day calendar is not an angular one and should be corrected: could that correction be described ? at least in supplementary ?

In previous studies (e.g. Joussaume and Braconnot (1997)), the choice was to use the same angular seasons as used today, though they are not perfect 90° angles. In our study, we would like to calculate the start of each season/month according to an accurate 90° /30° increment of the true anomaly. In the revised version, we described how we performed the calendar correction for present-day in more detail:

The relation between the true anomaly θ and the time elapsed since Earth passes perihelion t_p allows to define seasons with respect to Earth's position on the orbit rather than relying on a fixed number of days. Based on the "fixed-angular" approach, there are two ways to define the seasons: 1) The orbit is distinguished into four segments: A true anomaly of $\theta = 0^\circ$) corresponds to March 21st and therefore marks the first day of spring. The length of the summer is gained by calculating t_p ($\theta = 90^\circ$). Similarly, the terms t_p ($\theta = 180^\circ$) and t_p ($\theta = 270^\circ$) mark the beginning of fall and winter,

respectively. 2) The other method is based on the "meteorological" definition, in which the spring is defined as March-April-May, as typically done in paleoclimate modelling, although the VE is set to March 21st. The second approach is adopted in our study, and in this case, we firstly compute the starting and end time for each month, then average over the respective months in order to compare the angular seasonal means with the classical seasonal means. Months can be defined as 30° increments of the true anomaly. Just one additional step has to be executed before calculating angular months: As no months starts at the VE, the starting day has to be shifted from March 21st to April 1st. Since the time between today's March 21st and April 1st may not be true for past calendars, we defined April 1st by the angle. Therefore, we first calculate the angle between today's March 21st, noon (the VE) and the point of time occurring 10.5 days later, denoting April 1st. Finally, starting from the angle corresponding to April 1st, we are able to calculate the starting time of the next month by 30° increments of the true anomaly.

L155-156: you compare in the following angular (adjusted) versus calendar (non adjusted), as is chosen on the figures as well, whereas in this sentence you reverse the comparison. Please take care to avoid changing the reference to help the reader.

According to the reviewer's comment, we changed in our manuscript:

Fig. 1 depicts the differences in seasonal surface air temperature between angular and classical means. Positive/negative values indicate warming/cooling in angular mean temperatures as compared to classical mean temperatures. We observe spatially-variable changes of surface air temperature in adjusted values as compared to unadjusted values.

L180: It is expected to have continents reacting faster than oceans to solar forcing due to the differences in heat capacity.

We totally agree and in the updated paper we wrote:

the calendar effect on surface air temperature over the ocean is delayed due to the large heat capacity of sea water.

L312: Use of daily data "can completely erase the bias" is strange, isn't it the definition of what is called the bias in the paper ? I guess you mean that compared to daily data, using monthly data do not completely erase the bias ?

Sorry for the confusion, we mean that in order to remove the artificial bias, daily data is necessary for the calendar correction. Now in order to avoid confusion, we directly say in our manuscript:

Daily data is needed for calendar adjustment, however, due to the large volume of daily outputs, they are not preserved by most modelling groups.

L332: indeed, in Joussaume and Braconnot (1997) the choice is made to use the same seasons as defined today to be compatible with the present-day reference. It would be useful to discuss more the implication of your choice if you want to compare to today.

Today's "fixed-length" calendar, strictly speaking, is not an angular calendar, though it is very similar to the angular calendar for modern-day. If we perform calendar correction based on present-day reference, as done in previous studies, slight bias could be introduced for the angular calendar for past time periods, especially for boreal autumn.

In the revised paper, we illustrated that the angular calendar for PI has a shift of -1 to 3 days as compared to the classical calendar, therefore we also need to adjust the calendar for PI. The texts are like the following:

In our study, by calculating the onset of present-day months/seasons using the approach described in Section 2.1, we find that the classical "fixed-length" calendar is very similar to the angular calendar for today, but they are not completely the same. This is evidenced in the small shift of months between the two calendars as seen in Table 3. In particular the angular October is delayed by 3 days compared to the classical October, resulting in negative anomalies in the adjusted-minus-unadjusted solar insolation.

L352: when considering proxy-data we may have to rather consider bioclimatic indicators which are less dependent on the artificial definition of seasons, eg when considering the growing degree-days

We agree and discuss this point in the second last paragraph of the revised paper. In addition, we add another plot about the calendar effect on leaf area index, which shows that the leaf area index is not affected by the calendar definition. In the discussion section, we add the following:

Not all types of archives are sensitive to calendar definition, for instance bioclimatic indicators might be less dependent on the artificial definition of seasons, a typical example here is the the growing degree-days (GDD). In addition, we examined the influence of the calendar effect on the simulated vegetation. For this we analyzed the simulated leaf area index. As revealed by Fig. S13, even during boreal autumn, the deviation in leaf area index between classical and angular calendars is below 0.06% for PI and MH, and below 0.2% for LIG. Therefore, the calendar effect plays no significant role for this vegetation-related variable.

Fig 3: legend of third column is angular minus classical and not classical minus angular

Thanks for the correction, we updated the caption of Fig. 3 in the revised manuscript.

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