

In the following text we go point by point through the technical corrections and comments of the two reviewers, additionally considering short comments received by other members of the scientific community, detailing how we dealt with these concerns reported in **Bolt**, and, when necessary, specifying the modifications applied within the revised manuscript in *italic*

Reply to
1st Reviewer

*Mid-to-late Holocene Temperature Evolution and Atmospheric
Dynamics over Europe in Regional Model Simulations by Russo,
Emmanuele; Cubasch, Ulrich cp-2016-10*

- **General Comments**

The paper can be broadly divided into three parts: i) validation of the simulation, ii) comparison with reconstructions iii) search for explanations of the disagreements. In all these three elements, I can identify caveats that in my opinion should be improved with different/complementary analyses. I have tried to review them in a comprehensive, yet constructive way, as detailed below. Besides the technical aspects, I think there is room in the manuscript for improvement regarding writing style. It was challenging for me to read and understand many parts of the paper. This is in part due to incomplete information in the captions and the main text, wrong labelling in the figures, and the misleading use of some concepts as observation or validation. The internal structure in the paragraphs is confusing: paragraphs loosely connected, overly short, or in a misleading order respect to the panels in the figures. These issues add complexity that makes the lecture of the paper uncomfortable. Despite this rather negative view, I try to be constructive giving a list of points that develop the aspects that in my opinion can be improved in the manuscript. Note however that this list is not comprehensive.

We agree with the referee.

We developed a clearer structure of the manuscript as suggested by the reviewer. We divided the discussion of the manuscript in three main parts: the first based on the validation of the model configuration for present-days, the second one based on the comparison against proxy-data, additionally providing analyses and discussion on the advantages of the use of highly resolved simulations for the comparison against reconstructions, and the third one in which we will provide explanations for possible mismatches. We also provide improved/complementary analyses accordingly to the referee's comments. In addition, we corrected the manuscript, keeping in mind that, as mentioned by the referee, the comparison against proxy data is by no means a validation. We provide such comparison in a clearer way, cautious on the use of proper terminology. Additionally, as detailed in the comments below, we tried to improve the grammar of the manuscript and its presentation, in order to better tie together the entire discussion.

1. Abstract/Introduction:

L1-3: In the first line, is always been mentioned is grammatically wrong. Despite that, it sounds a bit loose, almost sceptical. Is it an important factor or not? This ambiguous tone of the first sentence of the abstract is manifest through the whole manuscript. By the way, the authors do not make an attempt to demonstrate that this is indeed the case for these simulations. More on this below.

We agree with referee. Further details on additional analysis we conducted with respect to the previous comment are presented in the comments to the second referee.

We reformulated the sentence according to additional analysis we provided within the text. In the revised version of the manuscript we present a section in which we conduct a detailed comparison between the models at different resolutions and proxy-data, elucidating possible advantages of Dynamical downscaling. We implemented our discussion and the manuscript consequently, following a common suggestion of both the authors.

L5-6: The paper is somewhat optimistic regarding the use of for the first time. It is true that, as far as I know, there are no other set of time slide simulations. However there are various high-resolution simulations for the last millennium for Europe. Actually there exists at least one transient simulations for the last two millennia, in fact driven by the same

ECHO-G run used by the authors of the manuscript. The authors should not ignore such previous, yet scarce efforts in this topic in the intro, but also the discussion of the results.

We agree with the referee.

As the the referee mentioned, there are other paleo-simulations for Europe for mid-to-late Holocene. Nevertheless, such simulations often investigate only a time slice or do not cover the entire mid-to-late Holocene. Even if they do so, as the case of the ECHO-G simulation used for this study, their low resolution is often mentioned as one of the possible reasons for the disagreement between model results and reconstructions ([Fischer & Jungclaus 2011];[Bonfils et al. (2004)]). With the previous sentence, we wanted to highlight the fact that no previous simulation exists for Europe, at such high resolution, covering different time-slices of mid-to-late Holocene. Our optimism, in this sense, regards the fact that these simulations could contribute in clarifying the debate on models and proxy disagreement.

We modified the previous sentence accordingly to the referee's comment. Additional discussion and more references (e.g. [Strandberg et al. (2014)],[Schimanke et al. (2012)],[Braconnot et al. (2007a)],[Braconnot

L6: In line 6, validation is used in a wrong context. The model is validated normally against observations. But you can not validate the model looking at a reconstruction. Neither you validate a reconstruction looking at a simulation. You can only compare them, and try to gain insight through the disagreements. The use of validation in this wrong context is spread through the manuscript and should be avoided.

Accordingly to the referee's comment, we think that the terminology previously employed was incorrect.

We corrected the term "validation" with "comparison" here and throughout the manuscript, when referring to the comparison with proxy data.

I think at least the first four paragraphs can be safely merged.

We agree with the reviewer.

We merged such paragraphs reformulating them in a more concise and clearer way.

L39-41: it is argued that then changes in solar irradiation were negligible, and latter than we expect that such changes would imply relevant variations.... It sound contradictory.

In this sentence our goal was to highlight the fact that during mid-to-late Holocene yearly variations in insolation, over northern latitudes in general, were negligible when compared to the seasonal variations. The latest are expected to imply "relevant changes in the seasonal values of surface variables".

We re-formulated this period in a more comprehensive way.

L42-45: The paragraph in lines 42 to 45 is made out of a single sentence, which is too long. Still, the paragraph itself is short and can be merged with the former. Further, such sentence demands references.

We agree.

We reformulate the paragraph and join it with the former. We also added further references (i.e. [Cheddadi et al. (1997)], [Bonfils et al. (2004)], [Braconnot et al. (2007a)], [Braconnot et al. (2007b)]).

In the paragraph starting in line 89, some examples of RCM simulations in palaeoclimate applications are outlined. It's strange to see that no simulation for Europe is referred. Examples of such simulations are: Gmez-Navarro et al. (2011, 2012, 2013, 2015a, 2015b) and Schimanke et al. (2012).

We agree.

Apart from the ones suggested by the referee, we also take into consideration, in the revised version of the manuscript, other works in which high resolved paleo-simulations for Europe were performed (i.e. [Strandberg et al. (2014)]; [Renssen et al. (2001)]).

2. Model Validation:

It is not clear how long is the control period used in section 3.1. The only hint is the label in Figure 2, 1990-2000. Is that the case? It should be clearly stated, not only in the main text, but also in the caption of the figure. Actually, the length of this period is CRITICAL for the model evaluation, a fact

that is not acknowledged in the discussion of the results. A 10-year period of a GCM simulation is strongly populated with internal variability. Under this scenario, a comparison with observations is tricky. The model could be by chance going through a cold or warm phase, which would have a strong impact in the validation, at least in the way it has been established in the paper, focused on mean values. In this sense, the validation does not look at important aspects such as the variability. How is the variance reproduced by the model? I'm not sure due to the short length of the simulation, but it could make sense to look at the variability modes of temperature and precipitation.

As indicated by the referee, the control run is 10 years long and covers the period 1991-2000. We are aware that the length of this simulation is "CRITICAL" for models' evaluation. Unfortunately, due to computational reasons, we were not able to cover a longer period. Additionally, realizing that we have not been properly explicit in the description of our experiment, we want to clarify that the regional simulation was driven by the ERA-Interim reanalysis dataset and not by the GCM, as mentioned by the referee. We will implement our text accordingly, with the main goal of better specifying such technical details. Since the main goal of the present-day experiment is to test whether the changes applied to the model routine, for this particular case of study, allow to obtain reliable results in comparison to the outcomes of other studies, we think that the validation focusing on mean values is a useful tool in this context. Nevertheless, we also conduct now an analysis of model and observations variability that we aim to provide as supplementary material in the revised manuscript. Additionally, we now also consider the E-OBS dataset ([Haylock et al. (2008)]) as a benchmark for the validation of our results, and present the mean climatology of temperature and precipitation, for both winter and summer, as reproduced in the three datasets.

In addition to previous conclusions based on the bias of seasonal mean, the new analyses show that, the model is able to reproduce, with a certain degree of accuracy, the climatology of the observations. Additionally, the analysis of the standard deviation (Fig.S1 and Fig.S2) shows that the area with the larger bias are the ones where the model is not able to correctly reproduce the variability of the observations, in particular for precipitation.

In the revised version of the manuscript we added more informations on the length of the simulation throughout the text. We also added such specification in the caption of Fig.3, Fig.4 and Fig.5. We additionally acknowledge now the choice of performing a 10-years run within the text. We replaced the previous analyses of precipitation and temperature with the one presented in Fig.3 and Fig.4 of the new manuscript, and developed our discussion accordingly. A more detailed description is provided in the captions of such figures.

I do not think the choice of target for the validation is the best one. Using ERA Interim for the validation of precipitation in particular is a bad idea, since it is not constrained by precipitation observations, so there is no warranty that this dataset is bias free. I think it would be wiser to use the E-OBS dataset, which was developed specifically for the validation of RCMs in Europe (Haylock et al. 2008).

We agree with the author that the ERAInterim Reanalysis is not the best choice for model's validation, in particular for precipitation. For this reason, as mentioned above, we now compared the model's results against the CRU observational dataset and the E-OBS dataset.

The way the similarity between the model and the observations is presented is a bit confusing to me. When the difference between two normally distributed variables is shown, the standard and intuitive approach, which steams from the application of the Central Limit Theorem, is to apply a t-test. The KS test is more suited for testing the shape of PDFs when the mean is know to be the same. For example if two dataset have the same mean, but different variance, the figure would show null bias (yellow colour here), but still the test would produce significant differences, which is misleading for the reader.

For the comparison of mean values we agree with the referee that a T-test is better suitable for our purposes.

We now perform the Student's T-test for the validation of the considered variables (Fig.3; Fig.4 and Fig.5).

I think the maps showing precipitation difference are not very useful. A difference of 5 mm/day might be huge or tiny depending on the mean precipitation. I think changes in precipitation are more meaningful when shown as perceptual

deviations with respect to the mean.

We agree with the referee on the fact that changes in precipitation are more meaningful when shown as percentual deviations with respect to the mean.

In the new maps (Fig.3 and Fig.4), we now present precipitation biases as the percentual deviations from the observations values.

It is mentioned that the dots indicate grid where differences are significantly not different. That's not exactly true. They indicate areas where the null hypothesis of the data being sampled from the same underlying distribution could not be ruled out, i.e. where they are not significantly different.

We agree. The previous sentence was not totally correct.

We now reformulate the sentence as follows: "the dots show the points where the null hypothesis of a Student T-test, at a significance level of 5%, assuming that the data being sampled could be drawn from the same underlying distribution, is not rejected".

I agree with the hypothesis used to explain the model deficiencies in Souther Europe regarding soil- atmosphere feed-backs. The particular role of these processes in RCM simulations in areas with strong water deficit was investigated in detail by Jerez et al. (2010, 2012).

We proposed additional references within the new manuscript as the ones indicated by the reviewer and listed at the end of this text.

L206: reads These findings CONFIRM that... are MOST PROBABLY.... This is an example of doubtful and confusing sentence that should be avoided.

We agree. The previous sentence was doubtful as indicated by the reviewer.

We corrected our sentence accordingly. Our analysis in fact confirms that model performances are influenced by its scarce capacity to reproduce soil-atmosphere exchanges correctly. This has consequences on both temperature and precipitation (particularly in summer when the biases are more pronounced) presenting a similar pattern of anomalies.

Maybe is worth to mention that generally the model skill resembles that identified in similar simulations for Europe (Schimanke et al. 2012, Gmez-Navarro et a. 2011, 2013).

We agree. Although a few works that generally propose similar model skills have been already considered within the discussion paper, it is reasonable to include additional bibliography, that would help in strengthening our conclusions.

3. Comparison with Pollen Reconstructions:

As pointed out above, this comparison is by no means a model validation. This should be made clear in the wording. As such, all sentences like CCLM performs well should be modified. The maps in Figure 5 are calculated as means with respect to which period?

We are aware of the incorrect terminology employed, as already highlighted before.

We corrected this period substituting the term "validation" with "comparison", being the pollen reconstructions not an observational dataset. We also aim at using better expressions in order to indicate the good or the bad agreement of the two datasets. We now modified Figure 5 of the discussion paper (also accordingly to the comments of the 2nd reviewer). In the revised manuscript, we present the maps of the anomalies as represented in the two datasets, calculated for every investigated period with respect to the pre-industrial times. We also propose to accompany them with the corresponding maps of the pollen-based reconstructions uncertainties. Please refer to the 2nd reviewer response for further details.

In Figure 6, error bars are provided for the pollen data, but not for the simulation. I'm aware it is not easy to establish them. However, such errors/uncertainties should not be neglected in the discussion of the results. The model has deficiencies that introduce systemic biases. But on top of then, there are non systematic biases introduced by unpredictable internal variability. This factor might lower or rise mean temperature in the simulation quite significantly, as pointed out by Gmez-Navarro et al. (2012) in a very similar scenario. Thus, this should be discussed at least qualitatively in this part of the text.

It has been a choice of the authors not to include the model's uncertainty interval to the plots of Figure 6 of the discussion paper.

Since the uncertainties of the 25 years CCLM simulations are considerably smaller than the ones of the proxy-reconstructions, we think that neglecting them, in this figure, was an appropriate choice.

Nevertheless, following the suggestion of the reviewer, we added such considerations within the manuscript. Additionally, we proposed a new analysis of the trends of temperature in which the uncertainties are taken into consideration by means of a weighted least squares method.

Many conclusions are drawn from Figure 6 regarding matchings of trends. I'm not sure at what extent such conclusions have any statistical significance, since in almost all cases the simulation lies within the uncertainty of the reconstruction. Having an almost perfect match between the reconstruction and the simulation is still perfectly possible within the range of uncertainty of the reconstructions.

Following the referee's comment, we realized that the computation of the mean and of the relative uncertainties presented in Fig.6 of the discussion paper should be re-performed. In particular, the plots we previously proposed and the conclusions we have drawn from them had no statistical significance. In fact, in a first place, we simply calculated the error as a mean of the provided uncertainty for every point. Realizing that this procedure is not correct, we tried to be more cautious with our analyses.

We present now new maps in Fig.9, representing the trends of seasonal means of 2 meters temperature calculated, for every grid box, by means of the weighted least squares method. The points where the trends are not significant, according to a F-test at a significance level of 10%, are additionally masked out. We provide again more details in the caption of the figure. We think that these maps are better suitable for our discussion. In fact, they are statistically more robust, allowing to consider trends and relative uncertainties for every grid box and time slice, resulting in a better suitable benchmark for the comparison against the pollen-based reconstructions or other proxy datasets. In the revised version of the paper we replaced Fig.6 and Fig.11 of the former manuscript with Fig.9.

Something I miss in this analysis here is the GCM simulations used to drive COSMO. I wonder how the ECHO-G and later ECHAM5 compares also with reconstructions. Is the RCM adding anything relevant to these simulations? If the

answer is certainly yes, then the use of the RCM is fully justified and the paper would gain interest. If the answer is mostly no, it would be still interesting, since it would imply that the many GCM simulations available for the last millennia are still relevant at rather regional scales. I'm sure the PMIP community would be very interested in answering this question.

A similar comment has also been addressed by the 2nd reviewer. We refer to the answer to his comment as an exhaustive response to this point. As suggested by the referee, we think that answering this question would definitely strengthen the paper.

In the revised manuscript we added a section in which the possible advantages of highly resolved simulations for the comparison of change in 2 meters temperature against proxy reconstructions is investigated.

4. Interpretation of Paleo Records:

Generally it was difficult to follow the arguments in this section. It would significantly help to label the maps as Fig 6b, Fig 6c, etc. and use such labels extensively through the manuscript. In this regard, the discussion of the results starts with summer, whereas the first row shows winter. Small inconsistencies like this, although non critical for the scientific message, have a dramatic impact in the reading pace.

We agree.

In order to make the manuscript more easibly readable we labeled the maps accordingly to the referee's suggestion. We also corrected the order of the seasonal analyses within the text.

The EOFs for MSLP are shown and used in the discussion. They are used to argue regarding NAO and SNAO, for instance. I'm not totally comfortable with that, since the NAO is defined as the leading pattern for a spatial window that is not that of the RCM. This explains in my opinion why the NAO pattern does not stand out as the leading mode in winter, and second mode in summer just resembles the SNAO pattern. I think a more orthodox approach would be to calculate the EOFs within the GCM, in a window that properly encompasses the North Atlantic. This is justified since the

large scale circulation is fixed by the GCM, and thus the NAO simulated should be consistent with the climate variability within the RCM domain. Hence, such patterns could still be used to discuss about regional variability within the RCM domain.

We agree with the referee's comment.

We now conduct the analysis of MSLP anomalies of the ECHAM5 simulations in order to properly consider a spatial window that encompasses the entire North Atlantic region. We select the region in between 90W and 40E and in between 20N and 80N, as defined in [Hurrell et al. (2003)]. This would allow us to infer about changes in the NAO and other atmospheric circulation patterns characteristic of this region. The results are shown in Fig.10 and Fig.11 of the new manuscript. Since the RCM large scale circulation is "dictated" by the GCM, we reasonably think that such results can be used to argue about regional variability within the RCM. We modified the discussion within the revised manuscript accordingly to the new analysis.

Line 255 reads In summer the first EOF shows that the model reproduces similar conditions in atmospheric circulation between the mid-Holocene and pre-industrial times. I do not understand how that conclusion is drawn from the map in Figure 8.

We propose to modify the previous sentence accordingly to the new analysis presented above. Since the investigation area is different now, the results of the EOF analysis changed. Additionally, as will be elucidated in the next points, we conduct in the new version of the manuscript, in substitution of the EOF analysis, a canonical correlation analysis (CCA) of MSLP and T2M.

We modified the discussion within the revised version of the paper accordingly to the new analysis, being more cautious about arising risky conclusions as the one spotted out by the referee.

In page 8 the wording observed is used in various sentences, and it's not fully clear what is meant (most likely respect to the simulation, but it could also be the reconstruction). I think simulated is more appropriate and precise.

As highlighted in previous points we agree with the referee.

We corrected the sentence accordingly in the revised manuscript.

Some inferences about the clearness of the sky are made which are based in indirect evidence such as EOF analysis. I think it is not necessary to make such risky affirmations. We have direct information that can tell us exactly how cloudy the simulated climate was. After all, in the simulation we can check directly variables such as cloud cover, which give a direct measure of what is being argued. I would go for a direct measure whenever possible, as it is the case. Similarly, in the paragraph between lines 277 and 279 (and Fig. 11) the more pronounced positive phase of the NAO can be directly tested within the GCMs, rather than indirectly inferred through a map of temperatures.

We modified the previous sentence within the revised manuscript, accordingly to the fact that, even if the SNAO shows a trend that in this case is positive throughout the mid-to-late Holocene, such trend is not significant and presents high variability. We propose to review our previous discussion and to avoid any conclusion on the trend of cloud cover due to the high variability of the emerged pattern throughout the investigation time . As already mentioned, we also preferred to merge Fig.11 together with fig 6 of the discussion paper, considering also summer analysis.

Finally, I think there are more powerful statistical tools than the one used here to study the co- variability between temperature and MSLP. Canonical Correlation Analysis could be used to derive relations between the variability of MSLP and temperature, and it would produce a picture of such co-variability more robust than the one provided by maps in Figure 10, for instance. An example of the application of such a tool in a very similar context is Gomez-Navarro et al. (2015b)

We agree.

We now investigated the covariability of MSLP and temperature by means of Canonical Correlation Analysis and present the results of such analysis in Fig. 10 and Fig.11 of the revised manuscript. We referred to the study of [Gomez-Navarro et al. (2015b)] as a good example of application of such method for the investigation of the relations between atmospheric variability and temperature. For our analysis we employed the method of Barnett and Preisendorfer 1987, for

which the data are pre-filtered by a EOF analysis before applying the CCA, retrieving only the principle components that explain most of the variability. We have to acknowledge the fact that, realizing that the computations relative to the CCA we provided in the public response to the referee presented some errors, we proceeded to new analyses, the results of which are shown in Fig.10 and Fig.11 of the revised manuscript. Such figures result different from the former ones. Aware of the mistake we apologize for such inconvenient.

5. Comments regarding Figures

Figure 1: The colour scale shows everything below 1000 meters as green. I think a palette with stronger contrast could be chosen.

We improved the previous plot accordingly to the referee's suggestion.

We moved the modified figure to Fig.2 of the revised manuscript.

Figure 2: The reference period should be stated in the caption. I think the limits of the palette can be adjusted to better span the range of temperatures.

We agree.

We added the reference period within the caption and further details. We also provided, in the same figure, the results of additional analysis and improved the palette in order to better span the range of temperature. For better developing the discussion within the paper, we preferred to present together, in the revised manuscript, the plots of the analyses of temperature and precipitation, for winter, in Fig.3 and, for summer, in Fig.4.

Figure 3: The colour palette provides barely any contrast all. Everything is yellow in the maps.

We modified the plot accordingly to the previous point.

Figures 4 and 5: Same comments as in former figures

Figure 4 has been adjusted accordingly to the referee's comment. Figure 5 of the discussion paper has now been modified accordingly to the comments of the 2nd referee. The new plots are presented in Fig.7 and Fig.8 of the revised manuscript.

Figure 6: Please label panels as 6a, 6b, etc. I do not think using colour in the caption is an orthodox approach. Note that the caption does not agree with the order of panels.

First row does not show North, but it is the first column which does, etc.

We agree.

We now label the panels of the new map presented in Fig.10 of the revised version of the manuscript as 10a,10b, etc., as suggested by the referee. We also avoid using colours in the caption. We also modified the order of the captions, accordingly to the figure.

Figure 7: I can barely see the numbers and labels in the figures in the right.

We modified this figure in order to make it clearer and more easily readable. Accordingly to a comment of the second referee, we propose to move this picture to section two of the revised paper (now Fig.1).

Figure 8: I think the label with the loading can be moved to inside the maps. This would allow to put the maps closer together, which would allow to make maps larger and more readable. The latter comment can be applied to almost all figures.

We agree.

We moved the loadings inside the maps (Fig.11 and Fig.12 of the revised manuscript). We also applied similar modifications to all the pictures in order to make them larger.

Figure 9: Please label panels to indicate which represent EOF1 etc. Where are the units? Either the EOF or the PC carries the units, in this case pressure. I guess they are included in the EOF patterns in Figure 8. If so, please label the palette accordingly.

Realizing, following the referee's comment, that we were not precise in our previous discussion, we propose to add further details in the caption of this figure, with more specification regarding the units and the analysis we conducted.

Reply to

2nd Reviewer

Mid-to-late Holocene Temperature Evolution and Atmospheric Dynamics over Europe in Regional Model Simulations by Russo, Emmanuele; Cubasch, Ulrich cp-2016-10

1. Main Comments

The grammar and spelling can be much improved. There are many long sentences that are hard to read. I have indicated a few below. I strongly suggest to have the text thoroughly checked by a native English speaker.

We agree.

We improved the structure and the grammar of the paper in order to make it more easily readable. We also shortened long sentences and expressed complex periods in a more concise and robust way.

I propose to compare the results of COSMO-CLM to the results of ECHAM5. The latter results have already a relatively high spatial resolution (T106 or 1.125x1.25 degr) compared to previous GCM studies. This resolution is actually close the resolution of the reconstructions (1x1 degr). In the manuscript, the authors have regridded (up scaled) their regional climate model results from 0.44x0.44 degree resolution to 1x1 degree to make the comparison in Fig 5. It would be interesting to see to what extent the COSMO-CLM produces a better match. Is it, from a paleoclimate perspective, worthwhile to make the considerable effort to nest the regional model in the high-resolution GCM results? Or do both models produces very similar results? In my view, addressing these questions would strengthen the paper. To make room for such a comparison, Figures 2, 3 and 4 could be moved to the supplementary information, as these figures do not directly concern the core topic of this study (mid-to-late Holocene temperatures and atmospheric dynamics).

According to the [IPCC(2007)] report: "Paleoclimate data are key to evaluating the ability of climate models to simulate realistic climate change". In particular, since the details added by high resolution models can help in the interpretation of proxy data that are often influenced by processes taking place on smaller scales than the ones

resolved in coarser models, they are considered a particularly suitable tool for paleoclimate studies.

Within this context, in our discussion we try to highlight the importance of using high resolution models, and in particular Regional Climate Models, for the simulation of past climate change. Aiming at investigating the value added by highly resolved simulations for the comparison of near surface temperatures against proxy-reconstructions, we follow a two steps approach:

- (a) Firstly, we conduct a qualitative analysis of the simulations performed with three models at different resolutions in order to detect visible differences in the reproduced signals.
- (b) Secondly, we employ a quantitative approach in order to estimate the skills of the RCM, in comparison to the driving GCM, in reproducing the same changes in temperature during mid-to-late Holocene as derived from proxy-reconstructions.

As a benchmark for such comparison we use the pollen-based temperature reconstructions of [Mauri et al. 2014]. In this way we aim at establishing whether the representation of smaller scale processes and improved orographic features of the region of study, could lead to results that are in better agreement with the mentioned proxy-reconstructions.

In Fig. 6 of the revised manuscript we present the anomalies of summer and winter seasonal mean temperatures between 6000BP and the Pre-industrial period, as reproduced by the different models. From these maps we first notice as, in both the seasons, a similar signal of climate change is present for all the simulations. This is expected, being, in every case, the data constrained by the coarser resolved models. Nevertheless, while the higher resolved simulations allow to catch a warmer bias over Northern Europe in winter, also present in the proxy data, the ECHO-G does not show such behaviour. Additionally, the land-sea area in the ECHO-G is considerably different than the ones of the other models. Regions such as Southern Spain and the Black sea area, Italy and Scandinavia are partly or completely masked-out in this case.

Consequently, we reasonably suggest to focus further analyses on the comparison between the ECHAM5 and the CCLM results. In both seasons additional details are easily detectable in the CCLM pattern. The

coastline is also better reproduced in this case, resulting in more suitable informations for possible comparison with proxy-data. Nonetheless, the CCLM shows better defined patterns as a consequence of higher resolution, being able to discriminate higher spatial variability.

In the successive step, we try to quantify how better the CCLM reproduces the reconstructed temperatures in comparison to the ECHAM5. Under the mentioned considerations, we use a similar approach to the one employed by [Zhang et al. (2010)] and based on the work of [Goosse et al. (2006)]. After upscaling the RCMs results and interpolating the ECHAM5 ones on the reconstructions grid, we introduce a Cost Function defined as:

$$CF_{mod}^k = \sqrt{\frac{1}{n} \sum_{i=1}^n \omega_i^k (T_{rec,i}^k - T_{mod,i}^k)^2} \quad (1)$$

where CF_{mod}^k is the value of the cost function for each considered time slice k of mid-to-late Holocene, and each model mod . The parameter n is the number of the reconstructions grid boxes, $T_{rec,i}^k$ the reconstructions temperature at every location i , while $T_{mod,i}^k$ is the correspondent temperature of the model simulation. The parameter w_i^k is instead introduced for considering the uncertainties of the reconstructions at every location and time period. Its value is given by:

$$\omega_i^k = \frac{1}{(SE_i^k)^2 + 1} \quad (2)$$

where SE_i^k represents the standard error of the pollen-based reconstructions at every grid point and every timestep k . In this way reconstructions with higher uncertainties will contribute less in the calculation of the Cost Function. We neglected models uncertainties since they are considerably small ($\sim 0.01^\circ C$) in comparison to the reconstructions ones, similarly to [Goosse et al. (2006)].

The values of the CF for the two models are provided in Tab.1 and in Tab.2.

As we can notice, even if not particularly large differences are present, the Cost Function computed for the CCLM is in almost all the cases lower than the ECHAM5 one. In particular the CCLM results are, in

some cases, closer by almost 10% to the reconstructions. It is important to mention that the scale considered in our analysis is closer to the resolution of the ECHAM5 than the one of the CCLM. As suggested by [Di Luca et al. (2015)], given that the main difference between the GCM and the RCM is related with their horizontal resolution, it seems natural that the results depend on spatial scale of the analysis.

Additionally, is key to state that the evinced results are relative to this case of study and other comparisons should be performed, considering different couples of RCM-GCM, in order to derive more robust conclusions on the suitability of higher resolved models for the comparison against proxy-reconstructions.

Nonetheless, the motivation behind producing higher resolution climate simulations is not only related to scientific arguments of the type described above. From a different perspective, such results, due to the greater level of detail, could be preferable for applications in studies in which human adaptation or environmental response to past climatic changes would be investigated. The need for climate information at very fine scales, for application such as archaeology or vegetation reconstructions, hence constitutes a strong incentive to perform higher-resolution climate simulations ([Di Luca et al. (2015)], [Rummukainen (2016)]).

In conclusion, the evinced results and the proposed discussion, give us concrete motivations for the choice of conducting RCM simulations for this particular case of study. Nevertheless, we keep Fig.2, Fig.3 and Fig.4 of the discussion paper within the revised version of the manuscript, as representing a satisfactory test for the reliability of the chosen model setup, they could be suitable for other studies conducting paleoclimate simulations for the region.

In the new version of the manuscript we added a section based on the presented analyses accompanied by detailed and pertinent discussion.

The left column of Fig 5 presents maps of the winter and summer temperature anomalies (model minus reconstructions), "averaged over all the mid-to-late Holocene time slices". It is not clear to me what the authors have actually done here. Have they first averaged the maps of the different time-slices for the model and the data, and then calculated the model-data anomaly? Or have they calculated the trend between 6000 and 200 BP in both model and data, and then made a

map of the difference between the two methods? The caption suggests that they have applied the first method, but in my view this would only be meaningful if the anomalies are more less constant through time, which is clearly not the case (see Figure 6). Since the trends from 6000 to 200 BP seem approximately linear in both model and data, it would make more sense to compare maps of these trends or to show maps for different time slices. Figure 11 actually shows linear trend maps for both the model and the reconstructions, but only for DJF. It is unclear to me how to relate Figure 11 to Figure 6. Figure 11 seems to indicate a pollen-based linear warming in Southern Europe of mostly less than 0.4 C, while Figure 6 shows a warming trend for the pollen-based reconstructions of 1 C for Southern Europe. In addition, the pollen-based cooling trend in Figure 6 of more than 2 C does not match Figure 11 which shows a much smaller cooling trend. Is there an inconsistency between Figure 6 and 11, or have I missed something? Please clarify.

In the previous analysis, Fig.5 was obtained by simply averaging the anomalies over all the time-slices. The same procedure was also applied in order to obtain a map of the average uncertainties. Following the considerations of the referee, we realized that such approach was not totally correct and we re-performed our analysis consequently.

In Fig.7 and Fig.8 of the revised manuscript, we computed the seasonal anomalies of 2 meters temperature between the CCLM and the pollen-based reconstructions for every single period of time. We additionally provided, together with the anomalies, the respective pollen-based reconstructions uncertainties. This choice is reasonable since the uncertainties maps could result useful in the interpretation of the mismatches arising between the two datasets. Additionally, we are now considering a new approach for the investigation of seasonal trends. We recomputed figure 6 of the old version of the manuscript taking into consideration, this time, the uncertainties in both the datasets (for more specifications please refer to the first referee response). Here the new plots (Fig.9) are similar to Fig. 11 of the discussion paper, showing this time both winter and summer trends. Only the area where the trends are significant, according to a F-test at a significance level of 10%, are shown. Additionally, such trends are calculated by mean of

a weighted least squares method, allowing to take into consideration, as said, the uncertainties of the two datasets. Since the changes in both the datasets are not homogeneous over the region, we think that these maps should be more appropriate than the previous ones based on regional means. We want to highlight, relatively to the referee's comment, that the new maps do not show values of changes in temperature. Rather they show the slope of the trend associated to every grid box.

The right column of Fig. 5 shows the uncertainties in the pollen-based temperature reconstruction. How were these maps constructed? According to Fig. 6, these uncertainties are not constant through time, so simply averaging the errors for the different time slices is not informative here either. Please clarify.

Please refer to the previous point.

For the summer in Southern Europe, the model and the reconstructions show opposite trends: cooling in the model and warming in the reconstructions. The authors provide an explanation for this model-data mismatch that is based on the warm bias of the model in S Europe due to the underestimation of evaporation in summer. However, the mismatch may also be explained by uncertainty in the pollen-based reconstructions in S Europe. Paleoclimate reconstructions based on pollen rely on the assumption that changes in the vegetation were driven by the parameter to be reconstructed (i.e. summer temperature). In the Mediterranean region, vegetation distribution is mainly limited by effective precipitation, rather than by summer temperature (e.g. Osborne et al. 2000). It would therefore be good to discuss the associated uncertainties in the methodology of the pollen-based reconstructions and to mention Holocene temperature reconstructions that are based on other proxies. For instance, summer temperature reconstructions from the S Europe domain based on Chironomids, show a clear Holocene cooling (Heiri et al. 2015; Toth et al. 2015) that actually support the presented modelling results. In addition, Holocene SST reconstructions from the Mediterranean Sea show a similar cooling trend (e.g. Marchal et al. 2002). The discussion section should be extended accordingly.

The choice of the dataset of [Mauri et al. 2014] has been done for several reasons. First of all, it allows to perform a comparison against model results over most of the simulations domain, considering different variables (even if we only focus on temperature in our discussion). Then, it covers exactly the same time-slices of our model simulations. No other dataset has this temporal and spatial coverage at such high spatial resolution. Additionally, the robustness of the data has been thoroughly tested, in [Mauri et al. 2014], against other proxies (including chironomids, $\delta^{18}\text{O}$ from speleothems and lake ostracods, bog-oaks, glacio-lacustrine sediments, wood anatomy and other pollen reconstructions based on different reconstruction methods) leading to satisfactory results. Nonetheless, similar pollen-based climatic reconstructions have been extensively employed in other data-model comparisons, and, most recently, for the evaluation of the PMIP3/CMIP5 climate models included in the last IPCC report (Stocker et al. 2013, Harrison et al. 2015).

As the referee mentioned, different studies already criticized the use of pollen-based data for reconstruction of temperature over the Mediterranean region, claiming that the vegetation distribution is mainly limited by effective precipitation, rather than by summer temperature (e.g. [Osborn et al. 2000]; [Renssen et al. 2009]). In response to such critiques we want to refer to a detailed comment provided by Basil Davis, and attached to the discussion paper.

According to the aforementioned reasons, and additionally supported by the explanations given by B. Davis in his comments, we think that the employed pollen-based reconstructions can be considered a very reliable source for the main goals of our paper.

Nevertheless, in accordance to the referee's comments, in the new version of the manuscript we will provide further discussion on the uncertainties in the methodology of the pollen-based reconstructions and specify more details on the reliability tests conducted by [Mauri et al. 2014]. Since the comparison against independent and different proxies has already been performed by [Mauri et al. 2014], we feel that such analysis could be omitted from our manuscript. Additionally, the previous analyses of mid-to-late Holocene temperature evolution were misleading. In fact, simply considering regional means, they did not allow to have a proper overview of the trends at different locations, possi-

bly resulting in a mismatch in the comparison against other proxies. The new maps presented in Fig. 4 show now a more heterogeneous behaviour, and are in better agreement with other independent reconstructions such as the one of [Heiri et al. 2015], mentioned by the referee, for which summer temperatures over the Alpine region were characterized by a decreasing trend during mid-to-late Holocene.

In the discussion, the results should also be compared to other modelling studies that focus on the mid-to-late Holocene climate. Do the new results presented here confirm earlier findings? How do the seasonal trends and 6k-0k anomalies compare to that of other models (e.g., PMIP3)? What do other Holocene modelling studies say about changes in atmospheric circulation over Europe and the North Atlantic basin?

We agree.

We present, in the revised version of the manuscript, a section in which our results are compared against other studies. In particular, we focus our analysis on the anomalies between 6000BP and the pre-industrial period, performing a direct comparison against the outcomes of 12 models from the PMIP3 experiment. We compute the regional means for two regions over Northern and Southern Europe for all the datasets. We include such values in two tables, provided as supplementary material in the revised manuscript. The main features arising from such analysis are, a common positive bias over Southern Europe in summer, and the failure to properly represent winter anomalies in both the regions. We aim to implement and develop our discussion accordingly.

Conclusions: The conclusions should be made less descriptive / more quantitative. The paragraph starting on line 296 does not contain conclusions and can be removed. Please explain on Line 310 what atmospheric circulation configuration is meant here.

We agree.

We make our conclusions more quantitative. According to the new analysis presented here and as a response to the 1st referee, we aim at extending our discussion and develop our conclusions in a more

concise and robust way.

2. Minor Comments:

Line 26: I suggest providing a more accurate definition of climate models

We agree.

We tried to develop a more detailed description of the climate models.

Line 34: "orbital parameters". I propose to use astronomical parameters instead, since obliquity is not a parameter of the Earth's orbit.

We agree.

We changed the term "Orbital" in "Astronomical".

Line 37: Please rephrase this sentence, as it is not easy to read

We agree.

We rephrased the highlighted sentence accordingly to the referee's comment

Line 43: "solar forcing". Usually, "solar forcing" is used to describe changes in solar activity as opposed to astronomical forcing that reflects changes in insolation due to changes in astronomical parameters. To avoid confusion, I suggest using astronomical forcing here.

We agree.

Aware of the mistake, we corrected the term "solar forcing" with "astronomical forcing".

Line 46: In my view, this sentence does not introduce the reader to the paragraph, so I propose using a different topic sentence.

We agree.

We modified this part in order to better connect it with the following text.

Line 57: It is not clear to me what is meant by "hampered climate anomalies"

We agree.

We reformulated this sentence. With "hampered anomalies" we wanted to indicate that, the improvement in the reproduction of soil water storage and heat fluxes by climate models, as suggested by [Starz et al. 2013], could lead to a reduction of the biases arising from the comparison with observations. We agree with the referee that the former expression was somehow misleading and we reformulated it in a clearer way.

Line 60: typo, atmopshere

Corrected in atmosphere.

Line 60: "not being able to reproduce correctly the reconstructed data over the entire region". Please clarify. Was the model too cold or too warm? What was the bias?

We agree.

We extended the previous period with further details, referring to the results of [Fischer & Jungclaus 2011]. In particular, their results presented only a weak shift to a positive phase of the NAO at mid-Holocene in Winter, resulting in colder conditions over Northern Europe and warmer over Southern Europe with respect to the values of reconstructions. In summer, again, the signal seemed to be mainly driven by changes in insolation, resulting in homogenously warmer conditions at 6000 BP.

Line 63: Please rephrase the sentence starting at this line.

We agree.

We reformulated the sentence accordingly to the referee's comment.

Line 72: " In many cases" What cases, please elaborate. The objectives of the paper should be explained more clearly. On page 3, two objectives are provided. The first objective is to "obtain a better interpretation of the new pollen database..."

Why better? What problems have been encountered in the interpretation?

We agree. The objectives of the paper should be better explained. We try to do so also based on the referee comments and the additional analyses provided in the revision.

[Mauri et al. 2014] presented a possible interpretation of the anomalies evinced from their reconstructions between 6000BP and the pre-industrial period, mainly based on changes in atmospheric circulations. Supported by previous findings, we use our results and the entire mid-to-late Holocene time slices reconstructions of [Mauri et al. 2014], in order to arise plausible interpretations. In particular, while for winter we agree with their interpretation of a more pronounced positive phase of the NAO at mid-Holocene, our findings support different interpretations for summer temperature behaviour.

We tried to improve our discussion accordingly.

Line 105. This first sentence of Section 2 does not provide information on the applied methods. I suggest moving this sentence to Section 1 and to replace it with a topic sentence that introduces the methodology used.

We agree.

We moved this sentence to section 1 and modified it in order to better introduce the reader to the employed methodology.

Line 128: Berger and Loutre (2002) do not calculate astronomical parameters and is not the appropriate reference here. In their figure they show the values of such parameters, but these are based on Berger (1978), so I suggest to use this reference here.

We agree.

We changed the reference accordingly to the referee's comment.

Line 133: "only the latest ones". I am not sure what is referred to here. The latter effects?

In the previous sentence we referred to the changes in insolation due to astronomical forcings.

We tried to express the period in a clearer way within the revised manuscript.

Line 175: "while coloured are the anomalies". Please rephrase and clarify.

We agree. We wanted to indicate that biases between the two datasets are represented by a chromographic gradient, from blue (when negative), to red (when positive).

We reformulate the sentence accordingly.

Line 194: I propose to use "anomalously warm conditions" here.

We agree.

We corrected the sentence accordingly to the referee's suggestion.

Line 195: " as a consequence of a wrong conversion of energy towards latent heat." This suggests to me that there is an error in the model code that described this conversion. Is that the case, or is the conversion in principle correct and does the model have a bias in S Europe?

Being our results consistent with the ones of previous studies investigating present-day conditions (Kotlarski et al. 2014; Jacob et al. 2014; Hollweg et al. 2008), we suggest that the model code describing soil-atmosphere interactions should be reliable. Some biases are present, particularly over Southern Europe, most presumably due to difficulties in properly reproducing soil water storage capacity for this complex orographic area.

Line 205: typo "teperature"

Corrected in Temperature

Line 213: I suggest replacing "Pollen" by "pollen-based temperatures"

We agree.

We replaced "Pollen" with "pollen-based temperatures" accordingly to the referee's comment, here and throughout the text.

Line 214: Please rephrase, as this sentence is confusing. The sentence suggests that Section 3.2 will discuss the results after the validation against Mauri et al's data has taken place, while in fact the next paragraph deals with this validation. Besides, I would prefer using evaluation instead of validation here.

We agree.

We used "Comparison" as a better suitable word in this case.

Line 216: I suggest referring to Figure 1, as this figure shows the boundaries of the two domains.

We agree.

We modified Figure 1 accordingly to the new analysis we presented.

Line 220: I assume that the model results are up-scaled and regridded on a 1x1 degree grid before the anomalies are calculated. Please clarify this here

The model results are up-scaled to the observations' grid as hypothesized by the referee.

We provided further details within the revised manuscript when necessary.

Line 231: I propose replacing "Paleo-Results" by Paleoclimate results.

We agree.

We modified the sentence accordingly to the referee's suggestion.

Line 237: Figure 7 shows the insolation changes over the mid-to-late Holocene. This is the main radiative forcing for the model experiments, so I suggest to show it already in Section 2 where the experimental design is discussed.

We agree.

We moved the mentioned picture to the second chapter accordingly to the editor's suggestion.

Line 250: what other cases?

We realized that the previous sentence was misleading.

We replaced it with "other regions".

Caption Figures 8 and 9: The captions are not consistent with the figures. Are summer results plotted at the upper or the lower row?

As the referee noticed, in Figures 8 and 9 of the discussion paper the upper row represented winter while the lower summer. The captions, instead, were previously inverted.

We changed the caption accordingly.

Figure 8: How is Figure 8 constructed? On what timeslice is it based, or is it based on results from several time slices?

Figure 8 of the discussion paper represented the first two EOFs of winter and summer seasonal mean of mean sea level pressure, standardized to the preindustrial period. We now used a different analysis in the revised version of the manuscript, accordingly to the suggestions of the 1st referee.

We replaced the maps of the EOFs of MSLP with the ones of a Canonical Correlation Analysis conducted on MSLP and T2M and presented in Fig10 and Fig.11. Nevertheless we added more details in the caption of these figures, being the previous ones not very precise.

Line 268: "scarce ability" Replace by poor ability?

We agree.

We modified "scarce ability" with "poor ability" following the referee's suggestion.

Line 276: "showing instead low correlation over the South". This is a confusing statement. Figure 10 shows that over most of the Mediterranean, the correlation in winter is strongly negative for the 1st EOF and strongly positive for summer.

We realized that the previous period was not really clear. In fact, with the term SNAO we wanted to refer here to the Summer NAO.

The conclusions we were proposing, were definitely the same as the ones suggested by the referee.

For this reason we better expressed this period in order make it more easily readable.

Line 284: "the model simulates a lower weight of the NAO ($\sim 40\%$) for mid-to-late Holocene in comparison to present-days conditions ($\sim 55\%$)". How can we reconcile this with the notion of a "more pronounced positive phase of the NAO during the mid- Holocene" as stated on line 277?

We agree. Nevertheless, we want to highlight the fact that, according to different comments of both the authors, we deeply modified the previous analysis of atmospheric circulation.

Based on the new analyses, we corrected the previous sentence on line 284.

Reply to

A. Strandberg

Mid-to-late Holocene Temperature Evolution and Atmospheric Dynamics over Europe in Regional Model Simulations by Russo, Emmanuele; Cubasch, Ulrich cp-2016-10

1. **I would like to draw the authors attention to a study (Strandberg et al., 2014) that simulates 6k BP and 0.2k BP climate in Europe with a RCM. Although it only consists of two time slices I think it qualifies as high resolution simulations for different time slices of mid-to-late Holocene performed over Europe using a Regional Climate Model (perhaps the first such simulations). Furthermore, since Strandberg et al. (2014) use boundary data from ECHO-G and compare the results with the reconstructions from Mauri et al. (2014) it should be of interest for Russo and Cubash.**

Thanks for suggesting the work of Strandberg et al. 2014. It is interesting and gave us the opportunity to consider new proxy-reconstructions

for our discussion. Additionally, the paper structure, and in particular the paragraph on the comparison against other PMIP results, makes it a good reference to consider in order to further improve the first draft of our manuscript.

2. **I know that it is a characteristic of modellers to exaggerate the uncertainties in the models and downplay the uncertainties in the reconstructions, but I would be careful to validate the model against one set of reconstructions alone since they may be of equally good/poor quality as the model simulations. When considering astronomical forcing alone (see Fig. 2 in Wagner et al., 2007), we would expect 6k to be warmer than 0.2k and the temperature difference to be largest in summer in northern Europe. This is the signature we see in the model simulations of Strandberg et al. (2014). The non-pollen proxy based palaeoclimatic data presented in Strandberg et al. (2014) and the pollen based reconstruction of Peyron et al. (2013) rather support the differences in summer temperatures simulated by Strandberg et al. (2014) than the reconstruction of Mauri et al. (2014), in particular for southern and eastern Europe.**

The choice of the dataset of Mauri et al. 2014 has been done for many reasons. First of all it allows to perform a comparison with model results over most of the simulations domain, considering different variables (even if we only focus on temperature in our discussion). Then, it covers exactly the same time-slices of the model simulations. No other dataset has this temporal and spatial coverage. Additionally, the robustness of the data has been already tested, in Mauri et al. 2014, against other proxies (including chironomids, $\delta^{18}O$ from speleothems and lake ostracods, bog-oaks, glacio-lacustrine sediments, wood anatomy and other pollen reconstructions based on different reconstruction methods). For such reasons we think that the reconstructions of Mauri et al. 2014 are a reliable source for the comparison of model results. Nevertheless, considering other proxies for our analyses could be an important point. Preliminary qualitative analysis against other reconstructions, such as the ones of Hairi et al. 2014 and Peyron et al. 2013, confirm that the data used in our discussion present a similar behaviour. In our former analysis this was not evident since we considered regional means for the investigation of mid-to-late Holocene temperature evolution. For this reason, we now performed additional

analysis accordingly to this point.

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Mid-to-late Holocene Temperature Evolution and Atmospheric Dynamics over Europe in Regional Model Simulations

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Abstract. The improvement in resolution of climate models ~~is~~ has always been mentioned as one of the most important factors when investigating past climatic conditions, especially in order to evaluate and compare the results against proxy data. Despite this, only few studies have tried to directly estimate the possible advantages of highly resolved simulations for the study of past climate change.

In Motivated by such considerations, in this paper we present ~~for the first time~~ a set of high resolution simulations for different time slices of mid-to-late Holocene performed over Europe using ~~a the~~ state-of-the-art Regional Climate Model ~~Through a validation~~ COSMO-CLM.

After proposing and testing a model configuration suitable for paleoclimate applications, we
compare the mentioned mid-to-late Holocene simulations against a new pollen-based climate re-constructions dataset, covering almost all of Europe, ~~we test the model performances with two main objectives: testing the advantages of high resolution simulation for paleoclimatic applications and investigate, and investigating~~ the response of temperature to variations in the seasonal cycle of insolation during mid-to-late Holocene, with the aim of ~~clarifying earlier debated uncertainties,~~ giving physically plausible interpretations of ~~both the pollen data and the model results mismatches between model and reconstructions. Focusing our analysis on near surface temperature, we demonstrate that concrete advantages arise in the use of highly resolved data for the comparison against proxy-reconstructions and the investigation of past climate change.~~

~~The~~ Additionally, our results reinforce previous findings showing that summertime temperatures during mid-to-late Holocene were driven mainly by changes in insolation and that the model is too sensitive to such changes over Southern Europe, resulting in drier and warmer conditions. In winter, instead, the model does not reproduce correctly the same amplitude of changes, even if it captures the main pattern of the pollen dataset over most of the domain for the time periods under investigation. Through the analysis of variations in atmospheric circulation we suggest that, even though in some areas the wintertime discrepancies between the two datasets are most likely due to high pollen uncertainties, in general the model seems to underestimate the changes in the amplitude of the North Atlantic Oscillation, overestimating the contribution of secondary modes of variability.

1 Introduction

Climate has a direct effect on all living organisms and so has always, and always will have an influence on human affairs (Wigley et al., 1981). From antiquity to present days human life and civilization have been affected by the availability of natural resources such as water, food, construction materials, etc.

Under the current threat of global warming, understanding how climate will change in the next century has become of fundamental importance for the impacts it could have on the life of our planet.

Useful instruments for the study of ~~human impact on the climate system~~ climate change and its possible consequences are climate models. ~~Climate models are not reality itself but the best possible physical representation of it.~~ In general terms, a climate model can be defined as a mathematical representation of the climate system based on well-established physical principles (Randall et al., 2007).

Many uncertainties still affect climate models, in particular regarding their sensitivity to changes in the external forcings (Collins and Allen, 2002; Yip et al., 2011). To improve our predictions of the future climate it is necessary to better understand such response: this can be accomplished through the application of climate models for the study of changes in past climatic conditions.

An important case of study is represented by the evolution of European climate during mid-to-late Holocene (from 6000 years ago to present days). ~~For this period a~~ The large number of proxy data ~~are~~ available and the particular configuration of the Earth ~~orbital parameters~~ astronomical parameters, make it a useful period for the evaluation of models' response to changes in insolation (De Noblet et al., 1996; Kutzbach et al., 1996; Masson et al., 1999; Vettoretti et al., 2000; Bonfils et al., 2004; Braconnot et al., 2007a, b; Mauri et al., 2014).

During mid-to-late Holocene (~~in this study the period between 6000 years Before Present (BP) and the pre-industrial time~~), over northern latitudes in general, ~~the~~ changes in the total amount of insolation during the year (with respect to present days conditions) were negligible ($\leq 4.5 \text{ W/m}^2$) when compared to the seasonal variations (up to more than 30 W/m^2 for summer insolation at high latitudes) (Fischer and Jungclauss, 2011). ~~We expect that such changes would imply~~ Indeed, relevant variations in the seasonal values of surface variables :

would be expected. However, evidences show that reconstructed climatic parameters, such as surface temperature, over Europe, did not always follow directly the ~~solar forcing: in fact their~~ astronomical forcings (Cheddadi et al., 1997; Davis et al., 2003; Bonfils et al., 2004; Braconnot et al., 2007a, b; Mauri et al., 2014). Their signals seem to have been also influenced by other complex processes (~~such as~~ atmospheric circulation, geography, or land-surface interactions with the atmosphere).

Different studies have been conducted in order to understand the mechanisms driving the seasonal behaviour of European surface variables during mid-to-late Holocene. Cheddadi et al. (1997) showed as a result of a ~~pollen~~ pollen-based reconstruction dataset constrained by lake-level data, that sum-

mer and winter temperatures were different over Northern and Southern Europe at mid-Holocene in comparison to ~~present day values: in particular winters~~ present-day values: winters, in particular, were warmer over Northern Europe even if the insolation was reduced, ~~and while~~ summers were colder over Southern Europe, despite the higher insolation. Similar results were obtained by Davis et al. (2003) who proposed an updated database of European pollen reconstructions for the entire Holocene. Bonfils et al. (2004), within the PMIP (Paleoclimate Model Intercomparison Project (Joussaume and Taylor, 1995)) collaboration, hypothesized that winter atmospheric patterns and summer soil conditions had an important influence on ~~seasonality~~ seasonal changes of temperature and precipitation. This has also been highlighted by a study from Starz et al. (2013) who performed a simulation for the mid-Holocene with a coupled soil-ocean-atmosphere circulation model ~~with and~~ dynamic vegetation to better reproduce soil water storage and heat fluxes. They found that changes in soil physical properties of the model led to ~~hampered climate anomalies and~~ improved model results and hampered anomalies, with respect to proxy-data, of surface variables. Fischer and Jungclaus (2011) studied the evolution of the European seasonal temperature cycle in a transient mid-to-late Holocene simulation with an ~~ocean-atmosphere~~ ocean-atmosphere global climate model, however not being able to reproduce correctly the reconstructed data over the entire region of study. ~~Conversely~~ In particular, their results presented only a weak shift to a positive phase of the NAO at mid-Holocene in winter, resulting in colder conditions over Northern Europe and warmer over Southern Europe, with respect to the values of reconstructions. In summer, again, the signal seemed to be mainly driven by changes in insolation, resulting in generally warmer conditions over the entire domain and period of study. ~~Conversely,~~ in their recent work, Mauri et al. (2014) suggested that the different response of surface variables ~~to the solar forcing in at~~ mid-Holocene ~~is caused by~~ was highly related to changes in atmospheric circulation ~~patterns~~ both in winter and in summer. ~~In particular~~ Specifically, they proposed that ~~during mid-Holocene, while~~ in summer a ~~more positive phase of a major incidence of the~~ "Scandinavian ~~pattern~~ High" ~~of pressure anomalies caused a block situation over Northern Europe and the advection of colder air was most probably the reason for colder temperatures~~ over Southern Europe ~~, in winter~~ 6000 years ago. In winter, on the contrary, a more positive phase of the North Atlantic Oscillation would have been responsible for warmer and wetter conditions over Northern Europe and an opposite behaviour in the South.

Although these interpretations are all physically plausible, still general consensus is missing on the correct explanation of the response of the climate system to changes in insolation for this period. ~~All~~

Within the mentioned studies, all the climate model applications have been conducted with transient simulations or considering a single time slice with ~~global-circulation models~~ Global Circulation Models. In many cases the resolution of these simulations was not high enough to allow for an assessment of the climate behaviour on a regional scale. As suggested by Renssen et al. (2001), if we want to evaluate the data against climatic reconstructions based on pollen data or any other record,

an improvement in the resolution is required (Bonfils et al., 2004; Masson et al., 1999). Additionally, higher resolution is expected to lead to an improvement of the results (Fischer and Jungclaus, 2011), allowing the representation of small-scale processes and more detailed informations on surface and soil features (Feser et al., 2011).

~~In this paper we employ for the first time a regional climate model, the COSMO-CLM (CCLM), for the investigation of the main climatic changes that characterized Europe during Mid-to-Late Holocene. A set of highly resolved simulations covering different time slices is performed and the results are compared and validated against a new pollen-based climate reconstruction dataset, which constitutes an update of the previous work of, derived from a wider sample, covering a bigger area and adjusted with isostatic corrections.~~

~~The main goal of this study is to evaluate model's performances for paleoclimate studies from a double perspective: first, to obtain a better interpretation of the new pollen database and, secondly, to give a substantial contribute to the reconstruction of the evolution of temperatures over Europe during mid-to-late Holocene, eventually understanding the dynamics responsible for their changes.~~

~~In general~~ Under these considerations, in recent years the application of regional climate models for ~~studies of paleoclimate is not that~~ paleoclimate studies has become more frequent. For example, Prömmel et al. (2013) used the COSMO-CLM in order to address the effect of changes in orography and insolation on african precipitation during the last interglacial. Fallah et al. (2015) ~~instead~~ investigated precipitations and dry periods during the Little Ice Age and the Middle age Warm Period over central Asia. Wagner et al. (2012) compared mid-Holocene and pre-industrial climate over South America, while Felzer and Thompson (2001) evaluated a regional climate model for paleoclimate applications in the Arctic.

~~No regional climate simulation, to our knowledge, has been ever performed for Europe during mid-to-late Holocene.~~ In several studies, regional simulations of European climate during different times of mid-to-late Holocene have been performed ((Gómez-Navarro et al., 2011), (Gómez-Navarro et al., 2012), (Gómez-Navarro et al., 2013), (Gómez-Navarro et al., 2015), (Schimanke et al., 2012), (Renssen et al., 2001), (Strandberg et al., 2014)). Nevertheless, they either focused on a singular time-slice, or covered a more recent period of time, for which changes in insolation due to astronomical forcings were negligible.

In this paper we employ for the first time a regional climate model, the COSMO-CLM (CCLM), for the investigation of the main climatic changes that characterized Europe during multiple time-slices of Mid-to-Late Holocene, with three main objectives:

- Propose and test a model configuration suitable for paleoclimate studies
- Investigate the possible added value of highly resolved simulations arising in the comparison against proxy-reconstructions

- Analyze proxy and model mismatches, providing plausible physical interpretations of the dynamical processes responsible for them

Our ~~work~~discussion is structured as ~~follow~~follows: in section 2 the employed methodology, including a brief description of the ~~model~~models and the pollen ~~dataset~~datasets, is presented. Results are illustrated and discussed in section 3: first a validation of the data for ~~present-day~~present-day conditions is conducted in order to test the performances of the model with the changes necessary for paleoclimate applications; then the mid-to-late Holocene simulations are ~~evaluated and finally the interpretation of the paleo-results is presented~~compared against the pollen-based reconstructions, trying, in a first instance, to highlight the advantages related to the performance of highly resolved simulations specifically for this case of study; finally, physically plausible interpretations of the mismatches between the CCLM results and the reconstructions are proposed; the results of other studies are additionally discussed.

2 Methods

~~, and have suggested that high-resolution simulations of European climate during~~
In this work we perform a set of climate simulations, covering several time-slices of mid-to-late Holocene should help in getting more valuable results, useful for the comparison and evaluation against proxy data. In order to reduce the computational expenses of the simulations we employ the so-called time-slice technique. The "modus operandi", employing models at different resolution.
 The modus operandi consists of three ~~steps~~parts and is based on the so-called *time-slice* technique (Cubasch et al., 1995):

1. First a transient continuous simulation is performed with the coupled atmosphere-ocean circulation model ECHO-G, composed by the ECHAM4 (Roeckner et al., 1996) and the ocean model HOPE (Wolff et al., 1997), at a spectral resolution of T30 ($\sim 3.75^\circ \times 3.75^\circ$). Further information on the simulation realization are provided in Wagner et al. (2007).
2. We then select 7 different time slices, at a temporal distance of approximately 1000 years from each other, from 6000 years ago down to the pre-industrial period, 200 years before present, in accordance to the time slices for which the pollen reconstructions are available. For every time slice, a simulation is conducted, for a 30 years period, with the atmosphere-only global circulation model ECHAM5 (Roeckner et al., 2003) at a spectral resolution of T106 ($\sim 1.125^\circ \times 1.125^\circ$), using prescribed sea ice fraction and sea surface temperatures derived from the ECHO-G continuous run.
3. Finally the ECHAM 5 outputs are further downscaled with the regional climate model COSMO-CLM model version 4.8 clm 19 at an horizontal resolution of 0.44 longitude degrees, using

40 vertical levels. The CCLM model is a non-hydrostatic RCM with rotated geographical coordinates and a terrain following height coordinate (Rockel et al., 2008), developed from the COSMO model by the German weather service (DWD) (Doms and Schättler, 2003).

In a first step we want to test whether the RCM setup and the applied model's code modifications, required for implementing values of GHGs and astronomical forcings, are suitable for paleoclimate studies.

In order to set the orbital parameters corresponding to the mid-to-late Holocene configuration, we applied values of astronomical parameters for the corresponding investigation periods, we apply the routine of Prömmel et al. (2013), that allows the estimation of latitudinal and seasonal insolation at the top of the atmosphere based on Earth's orbital-astronomical parameters calculated by Berger (1978). In Fig.1 the anomalies of zonal mean insolation on top of the atmosphere (TOA) between pre-industrial period PI and 6000 years BP are presented. Additionally, the winter and summer mid-to-late Holocene evolution of TOA insolation for 60 and 30 latitudes North are also shown in the same figure (Right).

Additional changes to the original model code are required in order to set the values of equivalent CO_2 concentration, representing variations in CH_4 , CO_2 and N_2O . These data are deduced from air trapped in ice core (Flückiger et al. (2002)). The contribute of mid-to-late Holocene changes in GHGs concentration to the radiative balance is negligible (less than $2W/m^2$) in comparison to the effects of changes in insolation, and only the latest-ones-latter are considered in our analyses.

The setup of the COSMO-CLM is based upon the work of Hollweg et al. (2008) within the Euro-CORDEX Downscaling experiment (Jacob et al., 2014). A more detailed description of the model configuration used is provided in Table 1.

For this study the model has been used-employed coupled to a Soil Vegetation Atmosphere Transfer scheme, the **TERRA ML**, a multi layer model with a constant temperature lower boundary condition that allows to reproduce the fluxes of heat, water and momentum between the soil-surface and the atmosphere. shows-the-model-configuration-used-in-this-study. Recent data of the Earth's surface physical parameters (e.g., orography, land use, vegetation fraction, and land-sea mask) were used-are employed for the simulations. The model domain, shown in Fig.1-2, is the one used for the Euro-CORDEX simulations (Jacob et al., 2014), extending from Southern Greenland to Western Russia in the North and from the Western Atlantic coast of Morocco to the Red sea in the South. Each simulation includes a 5 years spinup period used to let the model reach a semi-equilibrium state as suggested by Hollweg et al. (2008).

For the model validation for present climate, the ERA-Interim(ERA-IntE-OBS)-reanalysis dataset (Haylock et al., 2008) and the Climate Research Unit (CRU) observations dataset (Harris et al., 2014) observational datasets are used as benchmarks for the comparison with the results of a COSMO-CLM control run covering the period 1991-2000 and driven by the ERA-Int-dataset-, ERA-Interim(ERA-Int) dataset (Dee et al., 2011). The validation is conducted with respect to the total precip-

itation and 2 meter temperature ~~-. Additionally, winter and summer seasonal means.~~ Additionally, CCLM heat fluxes and evapotranspiration values, from the same simulation, are validated against the GLDAS (Global Land Data Assimilation System Version 1 Products) dataset.

210 Subsequently, the results of mid-to-late Holocene simulations are compared ~~and evaluated~~ against the dataset of Mauri et al. (2015). This is the latest updated pollen-based climate reconstruction dataset for Europe and constitutes an ~~improvement~~ upgrade of the results of Davis et al. (2003). It is derived with the same methodology, but with a wider number of fossil and surface-samples, following a more rigorous quality control. The data cover a time slice every millennium for the entire Holocene and are derived through a 4-dimensional ~~interpolation-spline-interpolation~~ in time and space. They are deduced with an analogue transform method and corrected with postglacial isostatic readjustment. Along with the data, a standard error estimate derived from the transform and the interpolation methods is also provided. Reconstructions contain informations on ~~winter, summer and annual~~ seasonal (winter and summer) and annual values of precipitation and temperature, as well as a measure of moisture balance and of growing degree days over 5 degrees, and are provided on a regular grid with a resolution of 1×1 longitude degrees.

~~In our analysis we focus only on the seasonal changes of temperature~~ The choice of the dataset of Mauri et al. (2015) has been done for several reasons. First of all, it allows to perform a comparison against model results over most of the simulation domain, considering different variables (even if we only focus on temperature in our discussion). Then, it covers exactly the same time-slices of our model simulations: no other dataset has this temporal and spatial coverage at such high spatial resolution. Additionally, the robustness of the data has been thoroughly tested, in Mauri et al. (2015), against other proxies (including chironomids, $\delta^{18}O$ from speleothems and lake ostracods, bog-oaks, glacio-lacustrine sediments, wood anatomy and other pollen reconstructions based on different reconstruction methods) leading to satisfactory results. Nonetheless, similar pollen-based climatic reconstructions have been extensively employed in other data-model comparisons, and, most recently, for the evaluation of the PMIP3/CMIP5 climate models included in the last IPCC report ((Stocker et al., 2013; Harrison et al., 2015)).

3 Results and Discussion

235 3.1 Model Validation and Evaluation for Present Days

As a first step a control simulation has been performed with present ~~day~~-values of orbital parameters and greenhouse gases (sec.2), in order to test the ability of the ~~model~~ CCLM, modified accordingly to our purposes, to properly reproduce ~~present-day climate.~~ present-day climate. Additionally, this provides further knowledge about the spatial distribution of the model performances.

240 The simulation covers a 10 years period, between 1991 and 2000. Even if the length of this simulation

can be considered as "critical" for model's validation, we want to acknowledge that, due to computational reasons, it was not possible to cover a longer period.

In Fig.3 and Fig.4, winter and summer seasonal means of temperature (left panel) and precipitation (right panel) from the CCLM simulations are compared against the CRU and the E-Obs observational datasets. In the first column of each panel, the climatology of the different datasets is shown: the model is able to correctly reproduce, within a certain degree of accuracy, the climatology of the observations for both temperature and precipitation in winter and in summer.

In the right column of every panel, instead, Temperature and Precipitation values from the present-days present-day control run are directly validated, through a Kolmogorov-Smirnov (KS)-non-parametric significance test at a significance level of 0.05 Student's T-test, against the CRU and the ERA-Interim E-Obs datasets. The same test is conducted for evaporation and heat fluxes but against the GLDAS dataset. In (Fig. 2; Fig. 3; Fig. 4) in Fig. 5. In these figures the black dots represent the grid cells where the compared datasets are significantly not different, while coloured are the anomalies null hypothesis of the T-test, assuming that the data being sampled could be drawn from the same underlying distribution, is not rejected at a significance level of 5%. The biases between the CCLM results and the observations are instead represented with different colours. The results show that, for temperature, the model performs well over Northern Europe during summer and winter in both winter and summer. Winter-time results are in particularly good agreement with observations and the ERA-Interim re-analysis over Northeastern Europe and Scandinavia (Fig.3II). However, larger deviations are present over Central Europe, Turkey and Northern Africa. In particular the model tends to simulate generally colder conditions over these regions (Fig. 2, upper row). Winter precipitation results seem to be in good agreement over a major part of the domain, with some deviations from the observations over regions with particularly complex orography, in the Northern African coasts of the Mediterranean Sea and in regions that are normally highly affected by westerlies (Fig. 3, upper row 3IV).

In summer, instead, the main discrepancies are found over Southern Europe both for temperature and precipitation (Fig. 2, Fig. 3, lower row 4).

It has been shown in previous works (Hagemann et al., 2004; Christensen et al., 2008; Kotlarski et al., 2014; Jerez et al., 2010, 2012) that, in general, regional climate models poorly simulate Southern European-southern european summer conditions. They suggest that this is This seems to be most likely related to deficiencies in soil-atmosphere coupling (Seneviratne et al., 2006; Fischer et al., 2007; Seneviratne et al., 2010). In soil moisture-controlled evaporative regimes, such as the Mediterranean basin, low soil moisture contents (due probably to an underestimation of precipitations-spring-time precipitation or badly represented soil properties in consequence of complex orography) limit the amount of energy transferred by the latent heat flux. This increases the sensible heat flux, ultimately leading to an increase of air temperature-, on the one-hand, and to a decrease of local precipitation on the other (Zveryeav and Allan, 2010).

Based on these considerations, we suggest that the model reproduces ~~warmer~~ anomalously warm and dry conditions over a wide part of Southern Europe and the Mediterranean basin, during summer, as a consequence of a wrong conversion of energy towards latent heat in these regions. This hypothesis is supported by the heat fluxes and evapotranspiration maps (Fig-45) presenting a spatial distribution of the anomalies resembling the ~~one of temperatures~~ ones of temperatures and precipitation. In particular, the model underestimates latent heat flux and evapotranspiration, while overestimating sensible heat over corresponding area.

~~In summer the role of local and surfaces processes, in particular land surface evaporation, is also important for the variability of regional precipitation, while the role of atmospheric moisture advection is diminished. Indeed wrong estimates of evapotranspiration are expected to have an high influence on local precipitation.~~

~~As already shown, the spatial pattern of the summer precipitation anomalies is similar to the one of temperature, with particularly high biases present over Southern Europe, where the model simulates drier conditions. These findings confirm that the poor performances of the model are most probably influenced by its scarce capacity to correctly reproduce soil-atmosphere exchanges with a consequent effect on both precipitation and temperature.~~

Nevertheless the performances of the model with the applied changes are in good agreement with the results of other works focusing on the same region (Hollweg et al., 2008; Kotlarski et al., 2014; Schimanke et al., 2012; Gómez-Navarro et al., 2011, 2013), having in general the same features and spread of the anomalies. Indeed the applied changes and configuration appear to be exploitable for paleoclimate ~~studies~~ applications.

3.2 ~~Comparison with Pollen for mid-to-late Holocene time slices~~

~~In a second step, after a validation of the model results against the pollen dataset of through a KS-test for winter and summer temperature, we divide Europe in two regions, one North from 55N to 72N and one South from 35N to 50N with the goal of discriminating the effects of possible shifts in the westerlies and changes in their intensity. Analyzing the temporal evolution of temperature and the effect of the forcings, we try to assess to what extent the changes in circulation are the responsible for climatic changes in both seasons.~~

~~The validation maps (Fig. 5) show that, when compared to the pollen dataset, the CCLM performs well during summer over Northern Europe and during winter over Southern Europe with the highest anomalies over Northeastern~~

3.2 Possible added Value of Highly Resolved Simulations for Paleoclimate Studies

In a successive step, we conduct a comparison of the three models at different resolution in order to estimate possible advantages in the use of highly-resolved simulations for paleoclimate studies.

According to Solomon et al. (2007): "Paleoclimate data are key to evaluating the ability of climate models to simulate realistic climate change". In particular, since the details added by high resolution models can help in the interpretation of proxy data that are often influenced by processes taking place on smaller scales than the ones resolved in coarser models, they are supposed to be a particularly suitable tool for paleoclimate studies.

Within this context, in our discussion we try to highlight the importance of using high resolution models, and in particular Regional Climate Models, for the simulation of past climate change.

Aiming at investigating the value added by highly resolved simulations for the comparison of changes in near surface temperatures against proxy-reconstructions, we follow a two steps approach:

1. Firstly, we conduct a qualitative analysis of the simulations performed with three models at different resolution in order to detect visible differences in the reproduced signals.
2. Secondly, we employ a quantitative approach in order to estimate the skills of the RCM, in comparison to the driving GCM, in reproducing the same mid-to-late Holocene changes in temperature as derived from proxy-reconstructions.

As a benchmark for such comparison we use the pollen-based temperature reconstructions of Mauri et al. (2015). In this way, we aim at establishing whether the representation of smaller scale processes and improved orographic features of the region of study, could lead to results that are in better agreement with the mentioned proxy-reconstructions.

In Fig.6 we present the anomalies of temperature summer and winter seasonal means between 6000BP and the Pre-industrial period, as reproduced by the different models. From these maps we first notice as, in both the seasons, a similar signal of climate change is present in all the simulations. This is expected, being, in every case, the data constrained by the coarser resolution models. Nevertheless, while the highly resolved simulations allow to catch a warmer bias over Northern Europe in winter ($\sim 4^{\circ}C$) and over Southern Europe in summer ($\sim 3^{\circ}C$). In accordance with these results the time evolution plots of temperature (Fig. 6) show that the data are in good agreement for winter over Southern Europe and for summer over Northern Europe. In these cases the two datasets show similar trends. The most interesting situations arise in summer over Southern Europe and in winter over Northern Europe. In the first case not only the model simulates always warmer conditions, but the trend of the two datasets are anticorrelated. In the second, instead, the trends are both negative, but the slopes in-, also present in the proxy data (not shown), the ECHO-G does not present such behaviour. Additionally, the land-sea area in the ECHO-G is considerably different than the ones of the other models. Regions such as Southern Spain, the Black sea area, Southern Italy and Scandinavia are partly or completely masked-out in this case.

Consequently, we focus further analyses on the comparison between the ECHAM5 and the CCLM results. In both seasons additional details are easily detectable in the CCLM pattern. The coastline is

also better reproduced in this case, resulting in more suitable informations for possible comparison against proxy-data. Nonetheless, the CCLM shows better defined patterns as a consequence of higher resolution, being able to discriminate higher spatial variability.

On the base of such analysis, in the successive step, we try to quantify how better the CCLM reproduces the reconstructed temperatures in comparison to the ECHAM5. Under the mentioned considerations, we use an approach similar to the one employed by Zhang et al. (2010) and based on the work of Goosse et al. (2006). After regridding, by bilinear interpolation, the CCLM and the ECHAM5 results on the reconstructions grid, we introduce a Cost Function defined as:

$$CF_{mod}^k = \sqrt{\frac{1}{n} \sum_{i=1}^n \omega_i^k (T_{rec,i}^k - T_{mod,i}^k)^2} \quad (1)$$

where CF_{mod}^k is the value of the cost function for each considered time slice of mid-to-late Holocene k and each model mod . The parameter n represents the number of the reconstructions' grid boxes. $T_{rec,i}^k$ is the temperature of the proxy-data at every location i , while $T_{mod,i}^k$ is the corresponding temperature of the model simulation. Additionally, the parameter w_i^k takes into account the uncertainties of the reconstructions at every location and time period. Its value is given by:

$$\omega_i^k = \frac{1}{(SE_i^k)^2 + 1} \quad (2)$$

where SE_i represents the standard error of the reconstructions at every grid box i . The corresponding uncertainties of model results are considerably small ($\sim 0.01^\circ C$) in comparison to the ones of the reconstructions, similarly to Goosse et al. (2006), and are indeed neglected. In this way reconstructions with higher uncertainties will contribute less in the calculation of the Cost Function. The values of the Cost Function for the two models are provided in Tab.2 and in Tab.3. Values closer to 0 indicate a better agreement with proxy reconstructions.

As we can notice, even if not particularly large differences are present, the two cases are significantly different, suggesting the fact that the driving process could be the same but probably the model is underestimating its effects or variability. Cost Function computed for the CCLM is in almost all the cases smaller than the ECHAM5's one. In particular the CCLM results are, in some cases, closer by more than 10% to the reconstructions. It is important to mention that the scale considered in our analysis is closer to the resolution of the ECHAM5 than the one of the CCLM. As suggested by Di Luca et al. (2015), given that the main difference between the GCM and the RCM is related with their horizontal resolution, it seems natural that the results depend on spatial scale of the analysis.

Additionally, it is key to state that the evinced results are relative to this case of study and other comparisons should be performed, considering different couples of RCM-GCM, in order to derive

more robust conclusions on the suitability of higher-resolution models for the comparison against proxy-reconstructions.

Nonetheless, the motivation behind producing higher resolution climate simulations is not only related to scientific arguments of the type described above. From a different perspective, such results, due to the greater level of detail, could be preferable for applications in studies in which human adaptation or environmental response to past climatic changes would be investigated. The need for climate information at very fine scales, for application such as archaeology or vegetation reconstructions, hence constitutes a strong incentive to perform higher-resolution climate simulations (Di Luca et al., 2015; Rummukainen, 2016).

The evinced results and the proposed discussion, give us concrete motivations for the choice of conducting RCM simulations for this particular case of study.

3.3 Interpretation of the Paleo-Results

~~In this section possible interpretations of the differences arising between the pollen dataset and the CCLM outputs are proposed.~~

3.3 The CCLM results and their Anomalies in the Comparison with Reconstructions

Finally we focus on the comparison between the CCLM results and the pollen-based reconstructions. After analyzing the differences between the two datasets and their temporal evolution, we propose, by means of correlations with ~~trend~~-trends of insolation and changes in atmospherical circulation patterns, physically plausible interpretations of the evinced mismatches.

~~The trends of northern european summer temperature present both for the pollen and Fig.7 and Fig.8 present the CCLM data a negative trend~~ temperature biases between the two datasets for winter and summer seasonal means, respectively. These are calculated, after upscaling the CCLM results on the grid of the pollen-based reconstructions by bilinear interpolation, for every time slice of mid-to-late Holocene. Additionally, they are accompanied by the maps of the corresponding pollen uncertainties.

In winter generally colder conditions over northern regions are reproduced by the model with slightly warm biases over most of the South (Fig. 6). ~~This suggests that their response in this case could be highly related to the changes in insolation (Fig. 7). Over Southern Europe instead, while the CCLM data seem to be driven by the insolation changes, the pollen data present an opposite trend-7).~~ The largest anomalies (in some cases up to $\sim 4^{\circ}C$) are present over Northeastern Europe (likely related to high pollen-data uncertainty partly due to the fact that seasonal values derived from pollen in this area are biased towards the winter season) and Turkey.

In Summer, instead, CCLM results present a positive bias over most of the domain, with particularly pronounced anomalies ($\sim 3^{\circ}C$) over different parts of Southern Europe and the Mediterranean basin (Fig.8).

~~According to and, the presence of more moisture in~~ In addition to the previous analyses, the maps
415 of temperature temporal evolution are presented in Fig. 9. They show the slope of the mid-to-late
Holocene linear trends of temperature anomalies with respect to ~~the soil during mid-Holocene, due~~
~~to more precipitation, is responsible, as a direct effect of higher insolation, for cooler conditions~~
~~due to stronger latent heat transfer. According to the previous analyses of model's heat fluxes we~~
420 ~~due to a wrong reproduction by the model of soil-atmosphere heat exchanges~~ pre-industrial period,
calculated, at every grid box, by means of a weighted least squares method, taking into account
the contribution of the different uncertainties. The points for which the trends are not significant,
according to a F-test at a significance level of 10%, are masked out in gray.

~~In winter, instead, the situation is inverted. While~~ From these maps we see that, in winter, even
425 if over part of Southern Europe the two datasets present similar trends, in the North ~~the trend of~~
their behaviour is different: CCLM results show no significant trend (Fig.9a), while the pollen-based
reconstructions present significantly decreasing temperatures over a considerable part of the domain
(Fig.9b).

~~Conversely, in summer, the simulated temperature, even if slightly negative, does not correctly~~
430 ~~agree with the highly negative trend exhibited by the~~ model results are characterized by a negative
trend over most of the domain (Fig.9c), highly correlated to changes in insolation. The pollen data,
~~in the South, the results are particularly close and show a much more similar behaviour. While~~
~~over northeastern Europe the wide bias is likely related to high pollen data uncertainty instead, show~~
a significant negative trend similar to the CCLM results only over part of Northern Europe, and
435 ~~an opposite positive trend over most of the South (Fig. 5), partly due to the fact that seasonal~~
~~values derived from pollen in this area are biased towards the winter season, in the other cases~~
~~the anomalies are likely to be connected to a wrong representation by the model of the variability of~~
~~atmospheric circulation patterns.~~

~~In order to investigate changes in atmospheric circulation during mid-to-late Holocene, in Fig9d).~~

440 ~~8 we present the Empirical Orthogonal Function (~~

~~Since changes in atmospheric circulation have often been suggested as possible drivers of temperature~~
~~evolution during mid-to-late Holocene winters and summers (Bonfils et al., 2004; Braconnot et al.,~~
~~2007a; Fischer and Jungclaus, 2011; Mauri et al., 2014), with the aim of gaining further insights~~
~~on the causes of the evinced biases, we conduct a Canonical Correlation Analysis (analysis of the~~
445 ~~anomalies of mean sea level pressure standardized to the CCA) of model's mean sea level pressure~~
~~and temperature anomalies, with respect to the pre-industrial period and in Fig. 9 the trends of the~~
~~time expansion of their principal components. In summer the first EOF shows that period, for winter~~
~~and summer seasons.~~

~~The Canonical Correlation Analysis is particularly suitable for our purposes since it helps to~~
450 ~~identify spatial patterns of maximum correlation between climate variables, indicating potential~~

underlying physical mechanisms (Wilks, 1995; von Storch and Zwiers, 1995). In CCA, according to Gómez-Navarro et al. (2015), "from a physical point of view, the leading patterns should show similar characteristics when the mechanisms leading to the relationships between the climate fields are controlled by the same processes".

In our analysis we adopt the method of Barnett and Preisendorfer (1987) in which a EOF analysis is conducted prior to the CCA, retaining only a few leading EOFs, in order to remove part of the random noise from the data. More specifically, after conducting the EOF analysis on the anomalies, with respect to the ~~model reproduces similar conditions in atmospheric circulation between mid-Holocene and pre-industrial times. Nevertheless, the second pattern arising from the EOFs period, of MSLP~~ and T2M, we select the first eight principal components of both the variables in winter, and the first eight and twelve principal components of, respectively, MSLP and T2M in summer. In this way, in both the cases, the selected PCs will explain approximately 80% of the total variance in the original datasets. We then apply the CCA analysis on the retrieved PCs.

Fig.10 and Fig.11 show the first two canonical pairs of patterns with the largest canonical correlation for both winter and summer.

The MSLP pattern explaining most of the variance, in winter, resembles the NAO (Fig.10c). The model seems to reproduce well the spatial pattern of the NAO when compared to other studies (Gómez-Navarro et al., 2015). Nevertheless, the trend of the temporal evolution of its expansion coefficients (Fig.12c), seems not to be pronounced enough in order to reproduce a response in temperatures comparable with the respective results of pollen data. Additionally, the value of the canonical correlation, even if high, is slightly smaller than the one of a secondary mode of atmospheric variability, in this case represented by a blocking system centered over the Baltic sea. The trend of the expansion coefficients of this pattern is slightly positive but again not particularly pronounced. As a result of the combined effects of the evinced patterns of atmospheric variability, the CCLM temperature trends will be significant only over part of Southern Europe.

In summer, instead, the first CCA pair (Fig.11 a,b) seems to be highly related to changes in insolation (Fig.13 a,b). It is key to note that, the first canonical pattern of summer MSLP anomalies and its structure, seems to be a proper product of this particular case of study. Even if it implies changes in circulation, we do not see any particularly prominent dipole structure characteristic of other well-known circulation patterns for the region. Its effects on temperature are particularly high on the Atlantic coast of continental Europe, resulting in a smoothing of the trend of summer temperature over this region.

In the second CCA pair, the pattern of the mean sea level pressure (Fig.11 c) resembles the positive phase of the Summer North Atlantic Oscillation (SNAO) (Folland et al., 2009). ~~The negative trend of the time expansion of the principle component of this pattern suggests that clearer skies were present over Northern Europe at mid-Holocene that, together with higher insolation, would justify not only the observed warmer conditions over this area but also the good agreement between pollen data~~

~~and model results. For southern Europe instead~~ The trend (Fig. 13 c) of its expansion coefficients is again not particularly pronounced. As a consequence, the changes in the corresponding temperature pattern (Fig. 13 d), are also not particularly remarkable.

Consequently, we suggest that in summer, during mid-to-late Holocene, the changes in the circulation alone would not ~~be enough have been enough in order~~ to justify the ~~observed changes variations~~ in surface temperature ~~in comparison to the changes in the radiation budget ($\sim 30 W/m^2$) and~~, as reconstructed from the proxies. While over Northern Europe the relatively good agreement between the temperature of the two datasets over part of the domain suggests that for this region the insolation is probably the main driver of changes, for southern Europe, instead, the role of land-atmosphere coupling needs to be considered (Seneviratne et al., 2006).

~~Our hypothesis differs from that of in that enhanced soil moisture at~~

According to Bonfils et al. (2004) and Starz et al. (2013), over Southern Europe, the presence of more moisture in the soil during mid-Holocene, ~~resulting from the excessive summer precipitation linked to the SNAO presence, together with increased summer insolation, strongly augmented latent cooling, amplifying the surface temperature anomalies summer, due probably to more winter and early spring precipitation, is responsible, as a direct effect of higher insolation, for cooler conditions~~ due to stronger latent heat transfer. According to the mentioned studies and to the previously presented analyses of model's heat-fluxes, we support this interpretation and suggest that the reason why the model does not manage to capture this trend could be most probably related to a wrong reproduction of soil-atmosphere heat exchanges.

As previously discussed, the scarce ability of the model to correctly reproduce the soil-atmosphere fluxes for this area, leads to an underestimation of evaporation and ~~consequently~~, consequently, to drier and warmer conditions.

Further experiments, with improved soil properties, are indeed necessary in order to better reproduce soil moisture content, and to obtain more robust results for the comparison with reconstructions.

~~From the correlation maps (Fig. 10) of the principal components of MSLP anomalies time expansion and the time evolution of 2 meter temperature it is possible to notice how the model reproduces a high contribution of the SNAO over Northern Europe allowing a greater influence of direct insolation, showing instead low correlation over the South.~~

3.3.1 Other Modelling Studies

~~In winter,~~ An important benchmark for the comparison of our results against other modeling studies is represented by the outcomes of the hypotheses of ~~of a more pronounced positive phase of the North Atlantic Oscillation during mid-Holocene, are supported by the maps of the mid-to-late Holocene linear trends of temperature~~ PMIP3 experiment (Braconnot et al., 2011), for which several simulations have been performed, with different coupled circulation models, for the mid-Holocene and the pre-industrial time. Here we focus on the results of twelve of the PMIP3 simulations.

Specifically, we perform a direct comparison of the regional mean of winter and summer near surface temperature calculated, for each of ours and PMIP3 simulations, for Northern and Southern Europe. The results are presented in two tables, provided as supplementary material, in which the corresponding values derived from the pollen-dataset(Fig.11).

From the EOF analysis of MSLP anomalies we can affirm that the model seems to reproduce well the spatial pattern of the NAO when compared to present day configuration calculated from ERAInterim reanalysis for the period 1979-2013 (not shown) and, according to the correlation maps, even its effects. Nevertheless, the model simulates a lower weight of the NAO ($\sim 40\%$) for mid-to-late Holocene in comparison to present-days conditions ($\sim 55\%$), with a minor influence of westerly winds. pollen-based reconstructions are also included. Two main features arise from such analysis: first of all a common positive bias over Southern Europe in summer for all the models is evident. It indicates that the temperature differences are positive in the model simulations as a result of the higher summer insolation at mid-Holocene than at the preindustrial period. Additionally, the trend of the temporal evolution of the principal components of the first EOF, even if negative, seems not to be pronounced enough in order to reproduce a response in temperature comparable with the respective results of pollen data. At the same time a high impact of the second circulation pattern, consisting in this case in a blocking system centered over the Baltic area would justify the pattern of the anomalies between the two datasets in winter, with colder conditions over central Europe and a warmer climate over part of Southern Europe, Scandinavia and British Isles. another feature that seems to be common to all the models is represented by the failure in representing winter anomalies in both the regions and attributable to a wrong reproduction of changes in the amplitude of NAO (Fischer and Jungclaus, 2011; Strandberg et al., 2014).

4 Summary and Conclusions

This work represents the first application of a regional climate model for study. In this work we performed for the first time a set of highly resolved climate simulations over Europe for different time-slices of mid-to-late Holocene. climatic conditions over Europe: a set of simulations are performed with, by means of the state-of-the-art regional climate model COSMO-CLM for different time-slices from 6000 to 200 years before present.

The performances of the model are tested for present day conditions. Then the temperature values from In a first step, using the CRU and the E-OBS observational datasets as benchmarks, a model setup suitable for paleoclimate investigations has been tested for the reference period 1991-2000. The results show that the RCM is able to reproduce realistic climatology with respect to the observations. The largest biases arise in summer over Southern Europe where the model reproduces warmer and drier conditions ($\sim +4^{\circ}C$ for temperature and $\sim -50\%$ for precipitation), likely related to a wrong conversion of energy towards latent heat over this area. Nevertheless, the results are in good

agreement with the ones of other studies for the same region, and the employed configuration can be considered a valid reference for future applications.

Successively, the results of mid-to-late Holocene ~~"time-slice" simulations are simulations~~ have been compared against a new pollen-based climate ~~reconstructions dataset, covering almost all of Europe. Along with the test of model performances reconstruction dataset.~~ Winter and summer seasonal means of near surface temperature have been considered for our analysis. In a first instance, the possible advantages of higher resolution models for paleoclimate applications ~~, the have been~~ investigated. The RCM seems to better reproduce the signal of the climate-reconstruction when compared to the driving GCMs, with a more detailed reproduction of the coast-line and better defined patterns. Additionally, using a quantitative approach, we have demonstrated that the results of the RCM are closer to the values of the reconstructions in comparison to the driving GCM, in some cases by more than 10 %. Considering also the final user perspective, the evinced results gave us concrete motivations for the choice of conducting highly resolved simulations for this particular case of study.

Finally, the CCLM results are used in order to investigate the response of the climate system to changes in the ~~seasonal-cycle-of-insolation-is also investigated, in order to give a new interpretation of the proxy data and to confirm or deny previously affirmed theories.~~ seasonal cycle of insolation, with the aim of proposing plausible physical interpretations of the mismatches arising in the comparison against the reconstructions.

The results show that while the model produces warmer summer conditions in Southern Europe at mid-Holocene, in comparison to pre-industrial times, as a direct response to insolation changes, the pollen data exhibit instead an opposite trend. According to the results of previous works and to the analyses of simulated heat fluxes and atmospheric dynamics, we suggest that this behaviour is mainly due to a higher partition of radiation towards latent heat, resulting in a cooling effect of the surface, that the model is not able to reproduce due to deficiencies in the representation of soil-atmosphere heat fluxes. The simulated northern summer conditions are instead in good agreement with proxy data and are the consequence of a combined effect of insolation changes and clearer sky conditions due to a particular atmospheric circulation configuration.

~~Over Southern Europe wintertime~~ The results show that, in winter, over Southern Europe temporal behaviour and spatial distribution of temperature in the two datasets are comparable. ~~A significant cold bias, instead, is present~~ Conversely, the model tends to reproduce generally colder conditions over central and northern continental Europe. Through the analysis of atmospheric circulation patterns we argue that this bias is due to a different representation by the model of the expected changes in circulation, as a result of reduced influence of westerly winds and an increased importance of secondary modes of atmospheric variability. Additionally, larger differences are present in Northeastern Europe, likely related to high uncertainties of pollen data over this area.

595 In summer, the simulated northern conditions are in good agreement with the proxy data over
part of the domain. Their behaviour seems to be a direct response to insolation changes. Conversely,
while the model produces warmer summer conditions over Southern Europe at mid-Holocene, in
comparison to pre-industrial times, again mainly due to insolation changes, the pollen data exhibit
an opposite trend. According to the results of previous works and to the analysis of atmospheric
600 dynamics, we suggest that this behaviour is mainly due to a higher partition of radiation towards
latent heat, resulting in a cooling effect of the surface that the model is not able to reproduce due to
deficiencies in the representation of soil-atmosphere heat fluxes over this area.

This paper sets the basis for further investigations: in particular a set of new simulations with
improved radiation schemes, soil properties and land use, could lead to important contributions to cli-
605 mate modelling and, consequently, to the improvement of future climate change ~~prediction~~projections.

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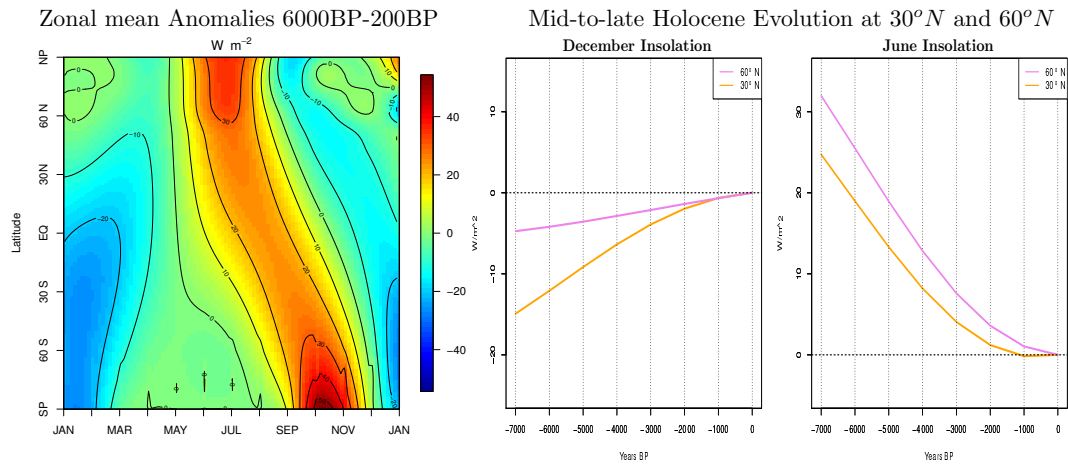


Figure 1. *Orography Map of the COSMO-CLM simulation domain in rotated coordinates. Highlighted are, in orange, the area comprised between*

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Table 1. COSMO-CLM Main model configuration parameters

Convection	Tiedke
Time Integration	Runge-Kutta, $\Delta T=240s$
Robert-Aselin time filter (alphaas)	0.53
Lateral Relaxation Layer	500Km
Radiation	Ritter and Geleyn
Turbulence	Implicit treatment of vertical diffusion using Neumann boundary conditions
Rayleigh Damping Layer (rdheight)	11Km
Soil Active Layers	9
Active Soil Depth	5.74m

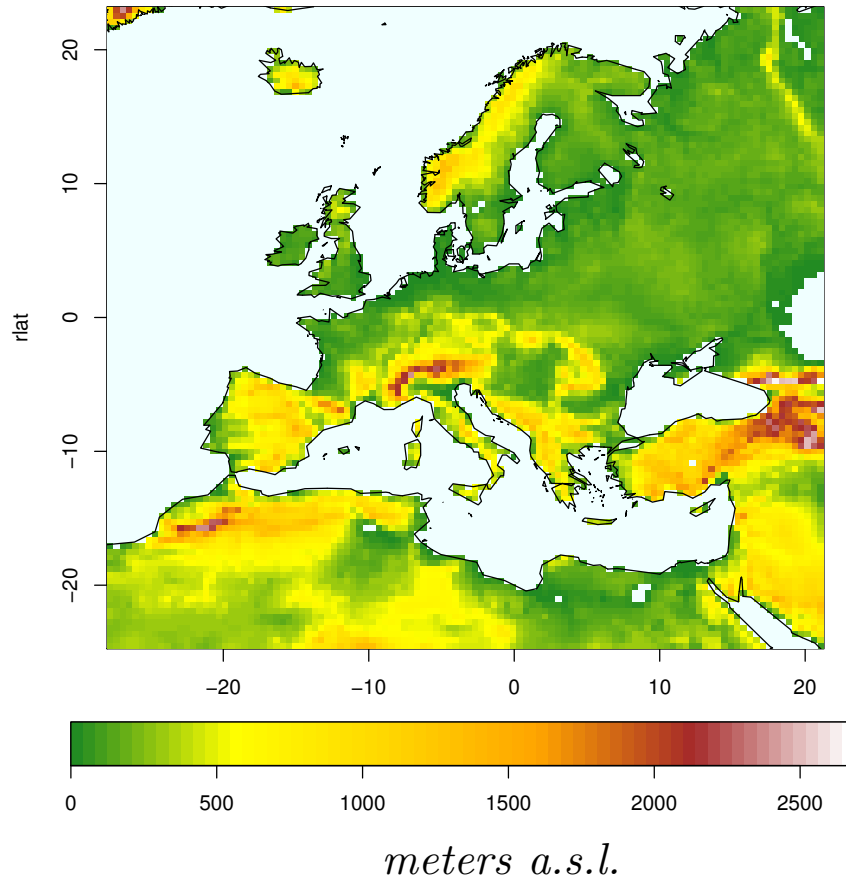


Figure 2. *2-meter temperature anomalies between model results, CRU (left) and ERA-Interim dataset (right). The area with a point represent the g*

Table 2. *Winter Temperature Cost Function estimates for the CCLM and the ECHAM5 models compared to the Proxy reconstructions for each tim*

<u>Time Slice</u>	<u>CCLM</u>	<u>ECHAM5</u>
<u>6000BP</u>	<u>0.87</u>	<u>0.92</u>
<u>5000BP</u>	<u>0.88</u>	<u>0.92</u>
<u>4000BP</u>	<u>0.77</u>	<u>0.84</u>
<u>3000BP</u>	<u>0.78</u>	<u>0.82</u>
<u>2000BP</u>	<u>0.77</u>	<u>0.79</u>
<u>1000BP</u>	<u>0.61</u>	<u>0.61</u>

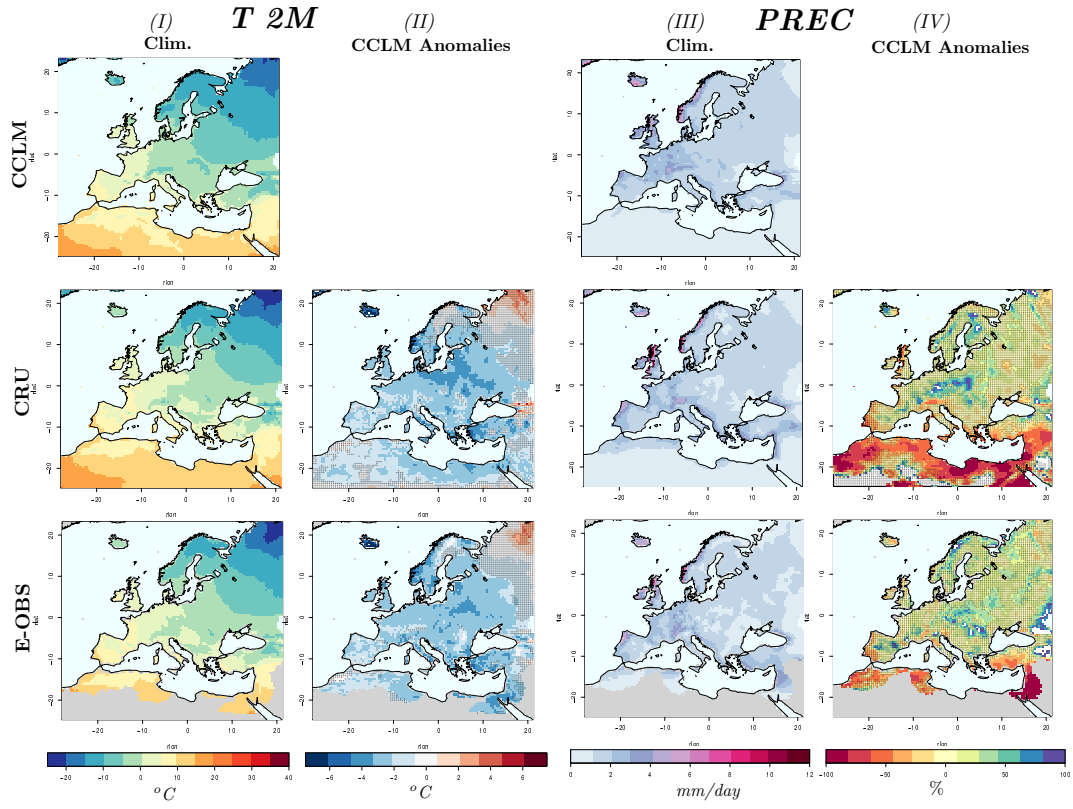


Figure 3. *As Figure 3 but for Total Precipitations anomalies.* Analysis of Winter seasonal means of 2 meter temperature (left panel) and Precipitation anomalies (right panel).

Table 3. *As Table 1 but for Summer Temperature*

Time Slice	CCLM	ECHAM5
6000BP	0.93	0.96
5000BP	0.72	0.72
4000BP	0.65	0.67
3000BP	0.63	0.71
2000BP	0.48	0.54
1000BP	0.43	0.48

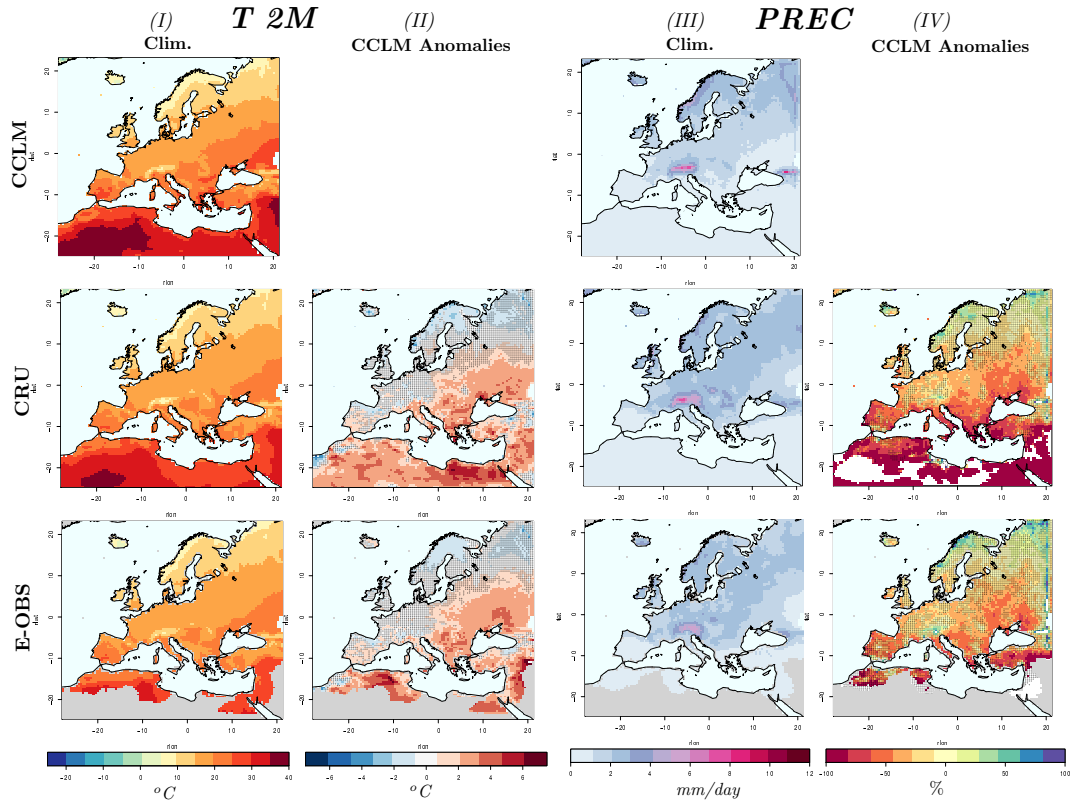


Figure 4. As Figure 3 but for surface evapotranspiration and heat fluxes anomalies between CCLM results and the GLDAS dataset. The sign of the anomalies is as in Figure 3 but for Summer.

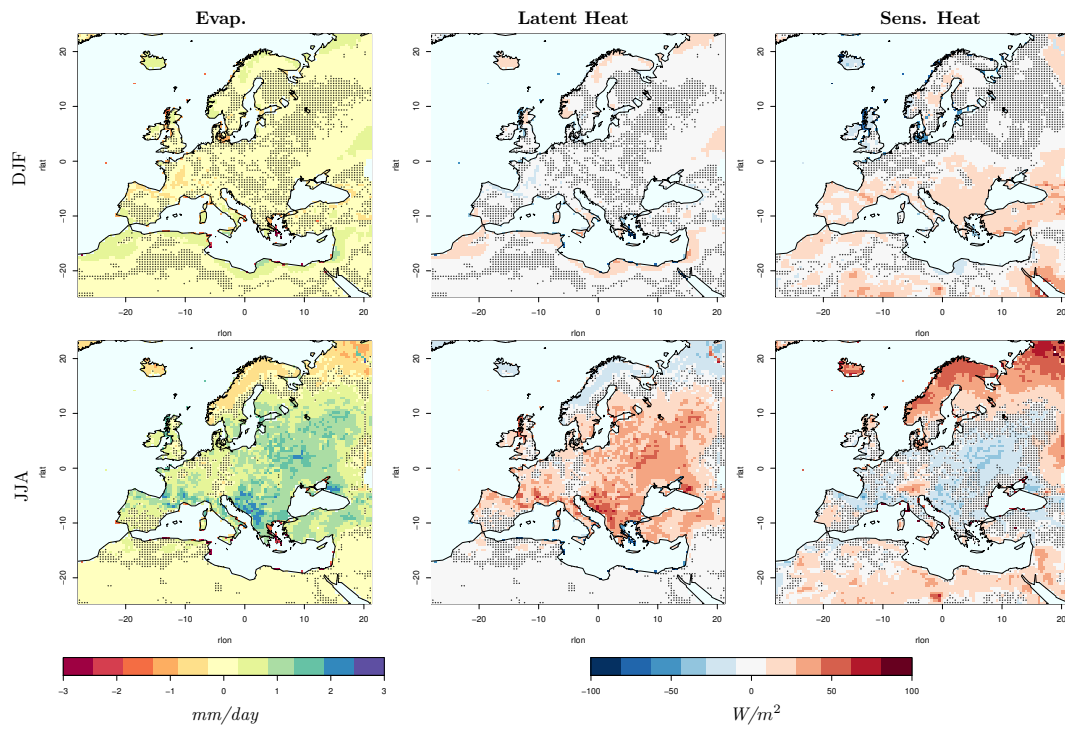


Figure 5. *Left: Map of the differences between the seasonal values of winter and summer 2 meter temperature averaged over all the mid-to-late H*

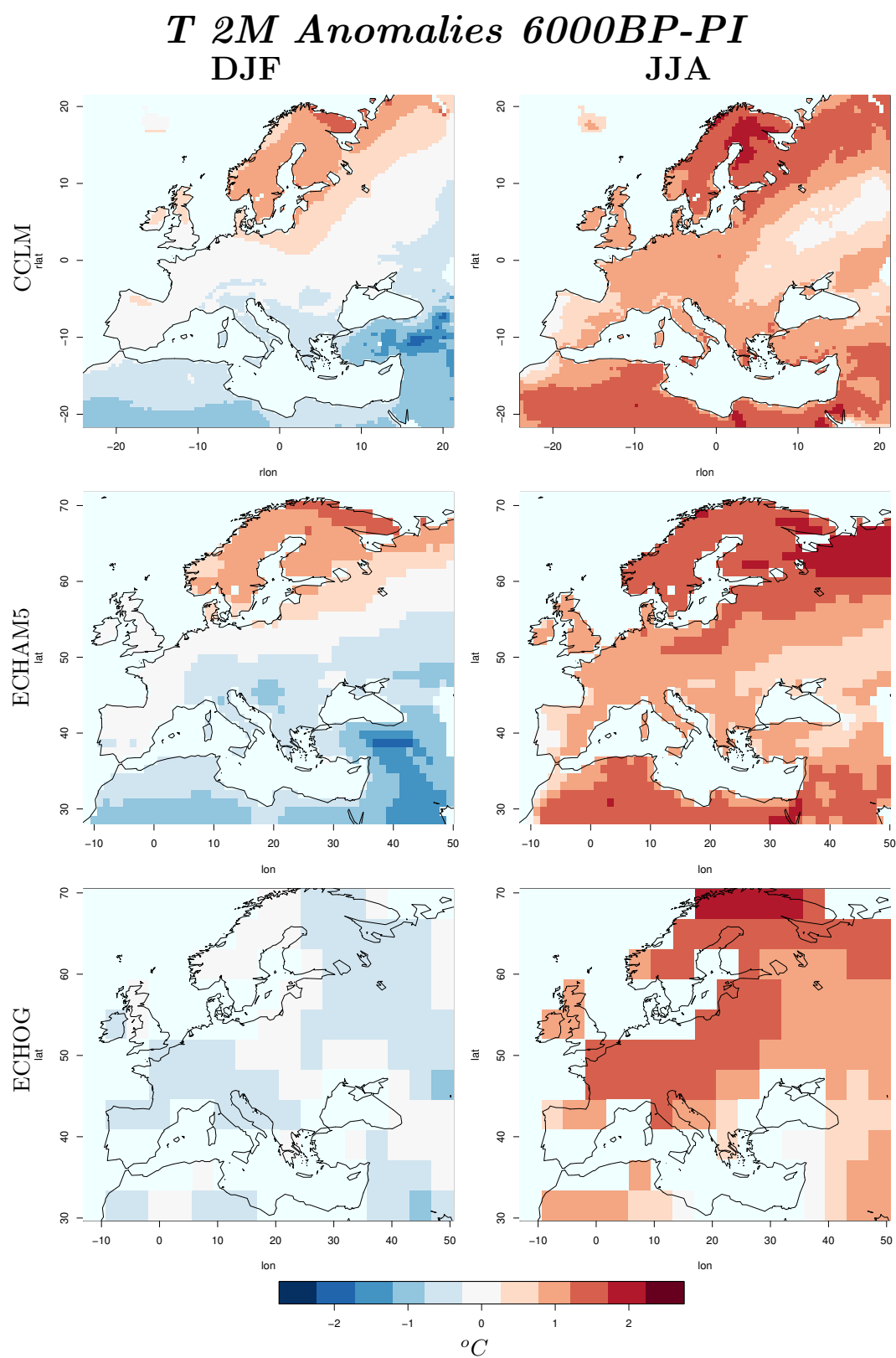


Figure 6. *Mid-to-late Holocene seasonal trends of 2-meter Temperature for Pollen and CCLM results; in the upper row is represented the regional*

Winter

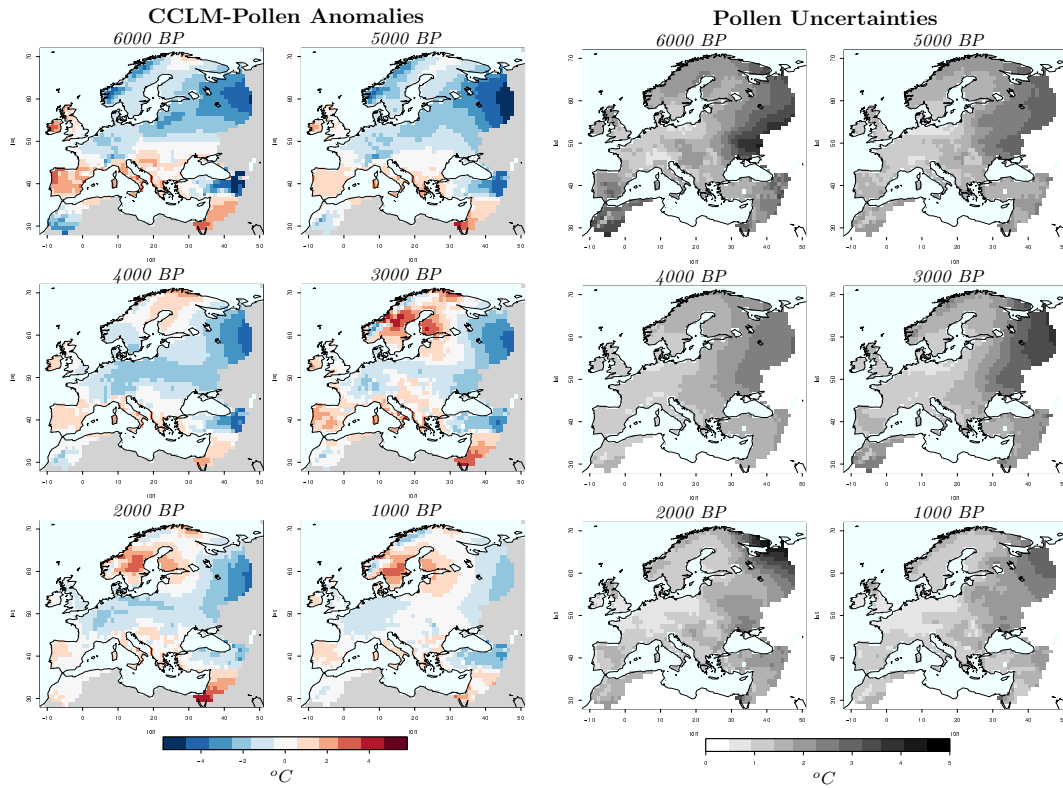


Figure 7. (left) Anomalies of zonal mean insolation on top of the atmosphere between pre-industrial period PI and 6000-years BP. (Right) Trends of

Summer

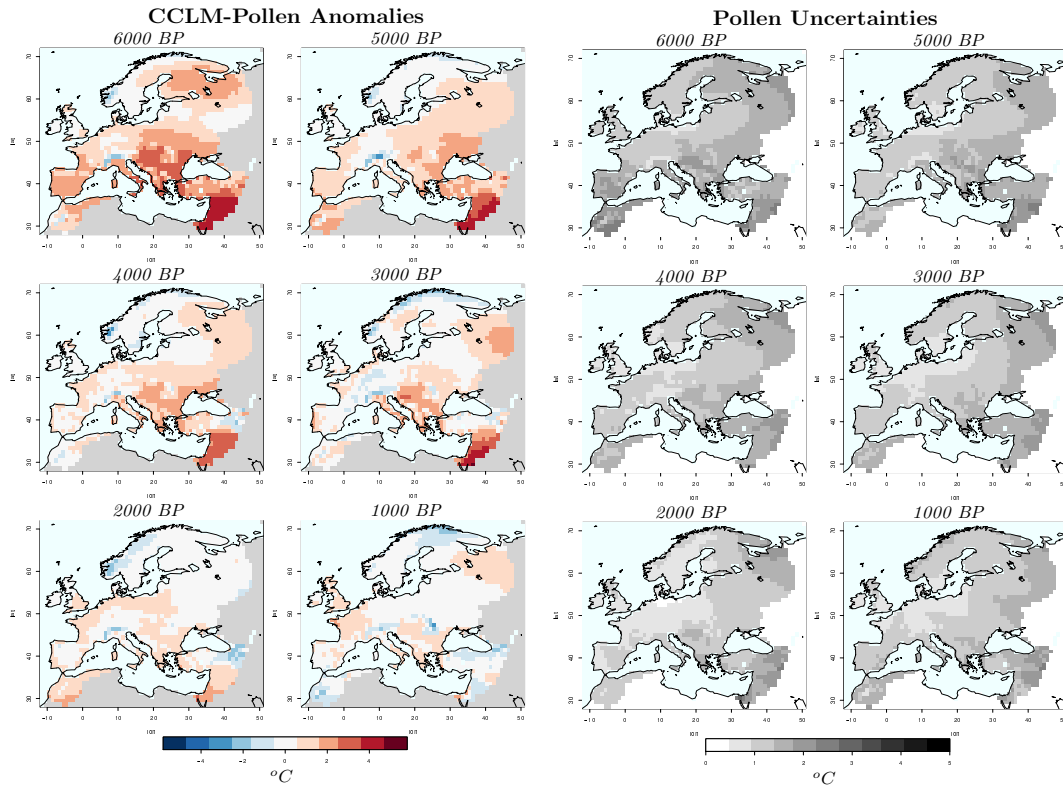


Figure 8. *First two EOFs of Mean Sea Level Pressure anomalies, derived from the CCLM simulations, standardized to the pre-industrial time, for*

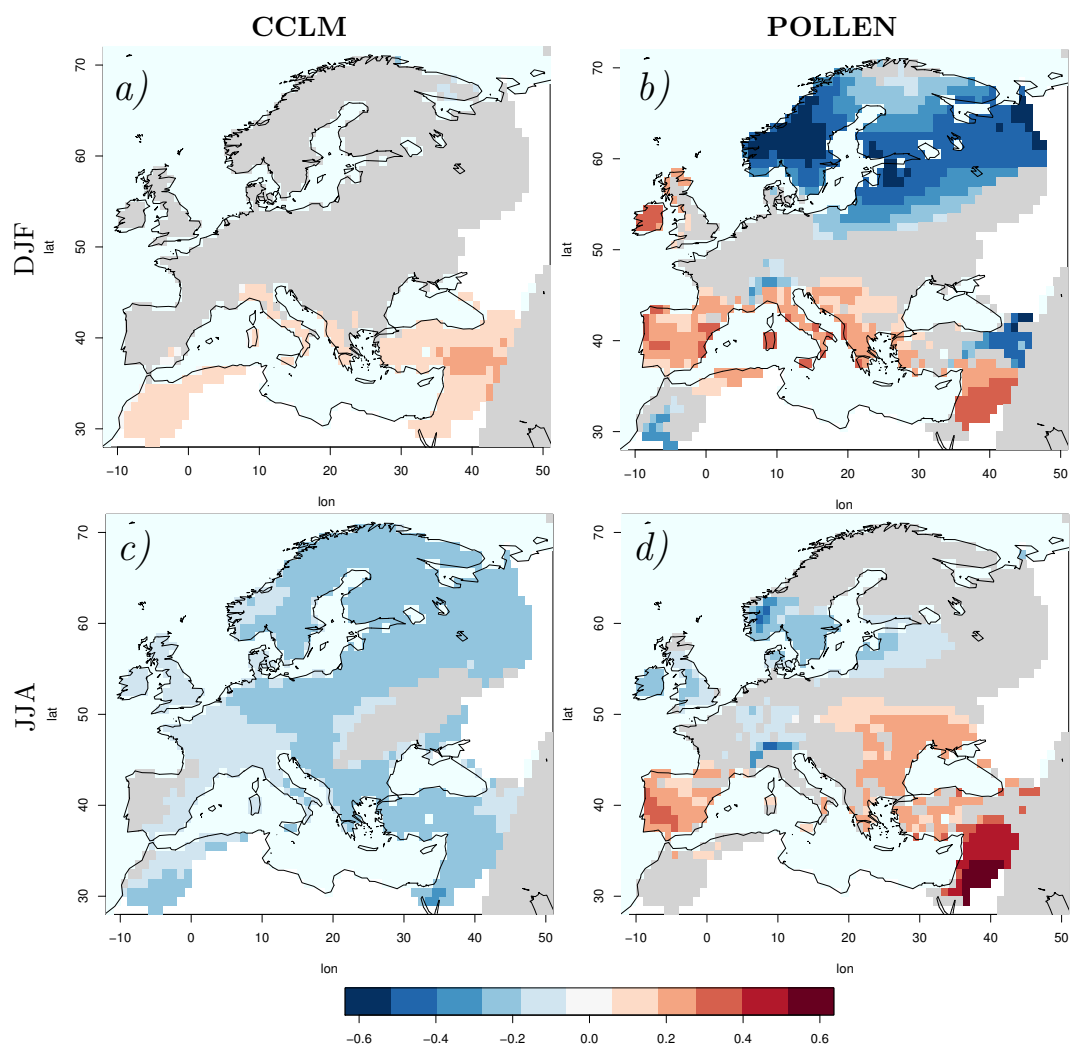


Figure 9. Time expansion of Principal Components of the first two EOFs, respectively for **summer**(upper row) and **winter**(lower row) Mid-to-late

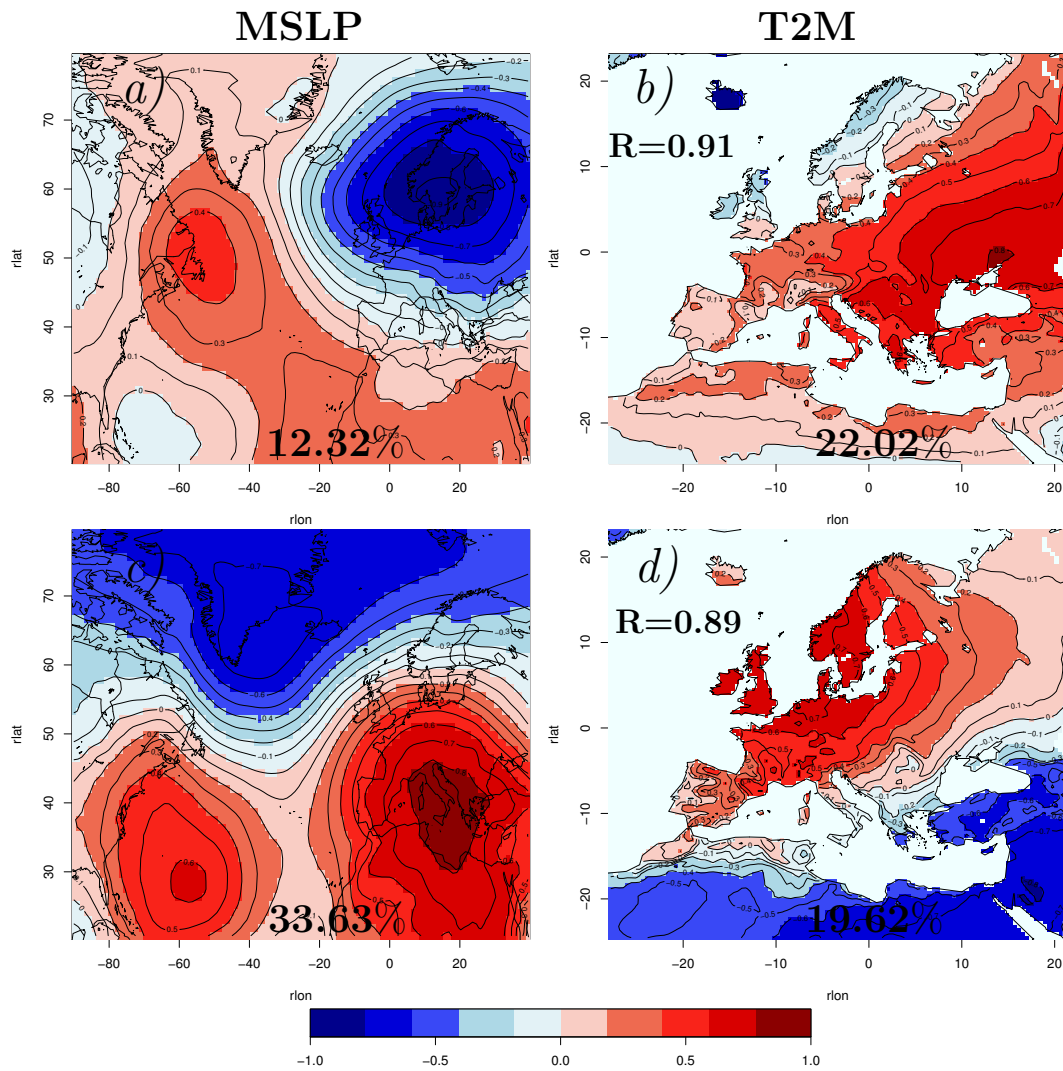


Figure 10. Kendall correlation maps between time evolution of **summer**(bottom) and **winter**(top) 2 meter-temperatures and the time-expansion of Canonical correlation pattern pairs of MSLP (left) and T2M (right) in Winter, calculated according to the Barnett and Preisendorfer (1987) method.

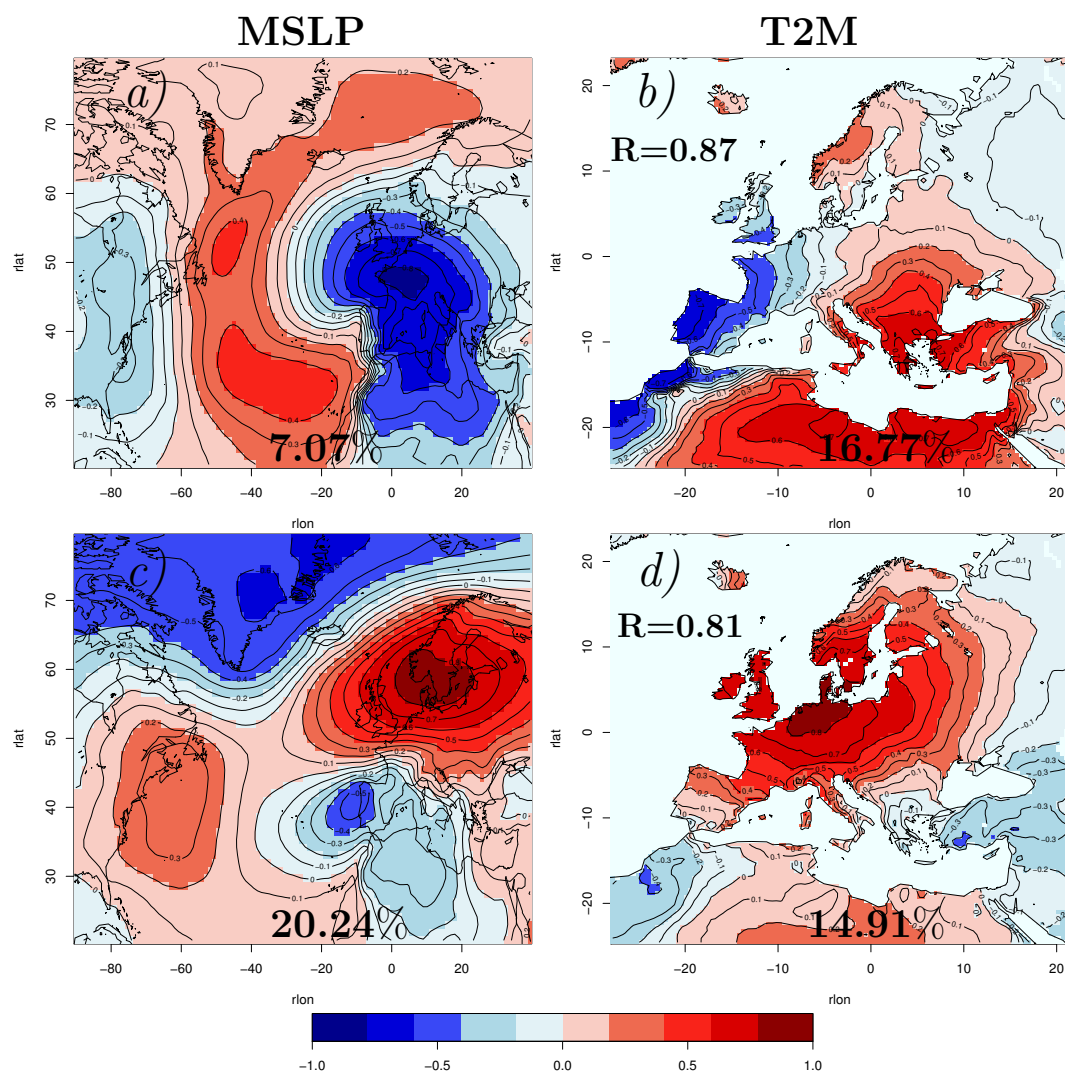


Figure 11. *Linear trend maps of winter 2-meter temperatures over mid-to-late Holocene. As in Fig. 10 but for Summer season.*

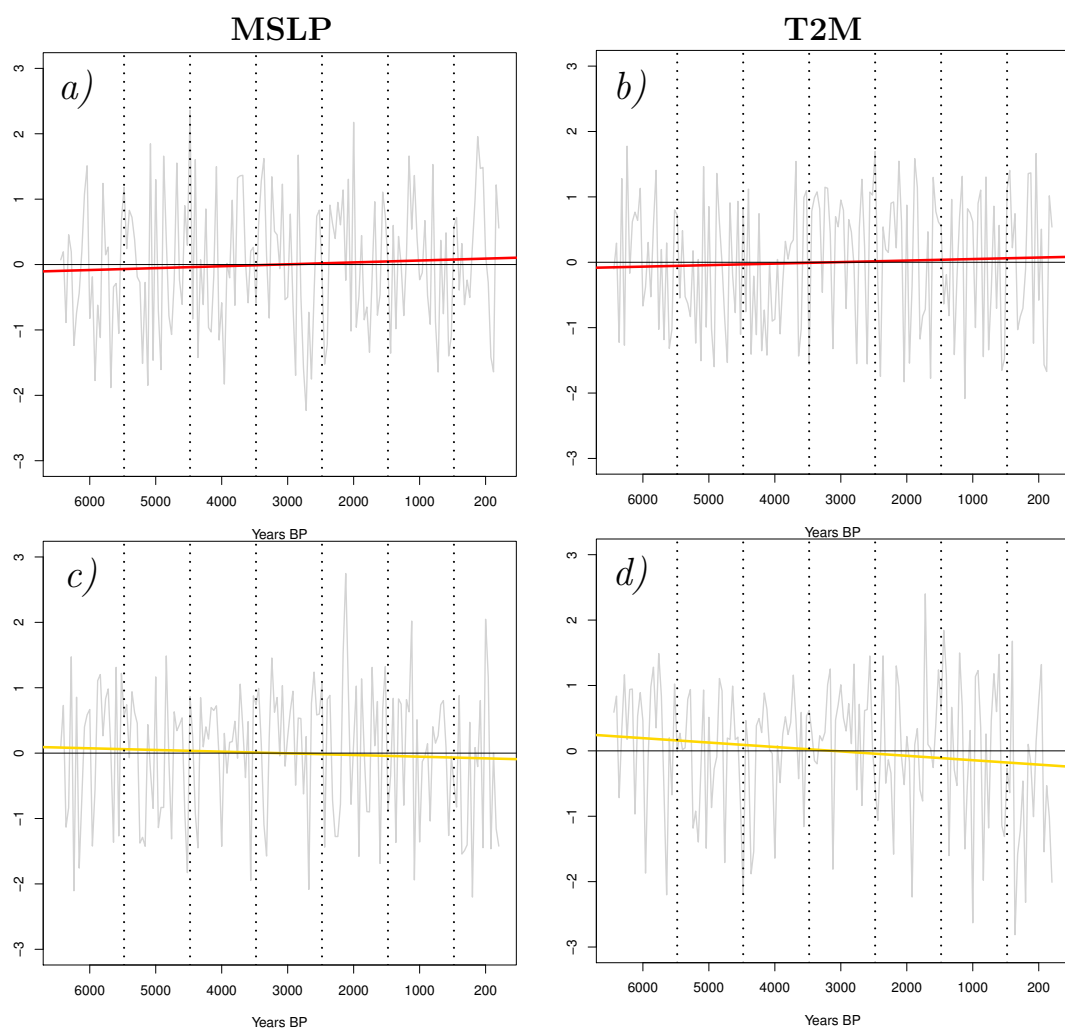


Figure 12. Canonical score series of the first two pairs of Canonical Correlation patterns of, respectively, MSLP (left column) and 2 meter temperature (right column).

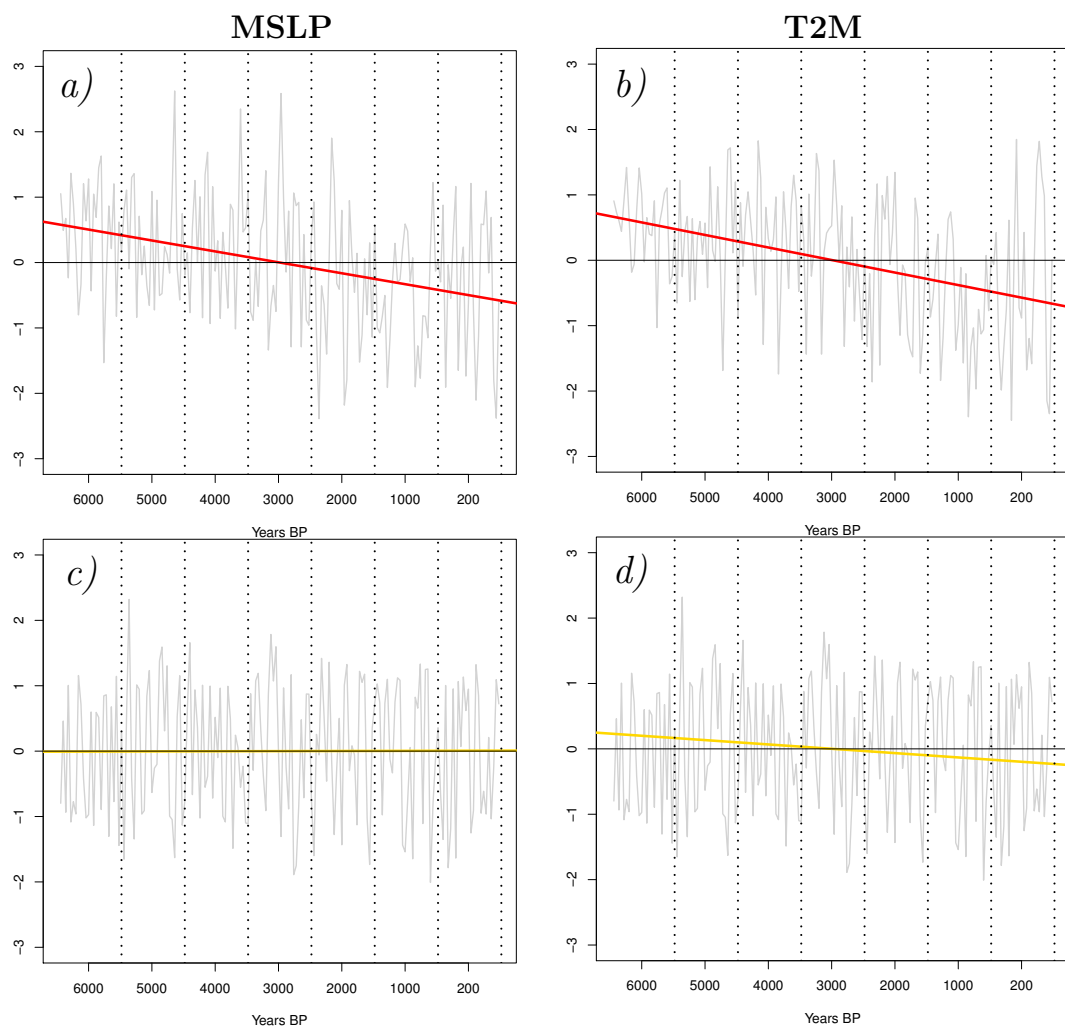


Figure 13. *As in Fig.12 but for summer*