

Reply to  
**Referees' Comments**

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

Dear editor,

Thank you very much, again, for your effort in reviewing our paper.

Below we go point by point through the technical corrections suggested by the two referees, detailing how we dealt with their concerns reported in **Bold**.

Thank you.

Reply to  
**1st Reviewer**

- **Minor Comments**

As in the former version of the manuscript, there is an excess of too short paragraphs that could be merged to produce a more cohesive text. Examples of this are the first three paragraphs (that have not been merged despite my recommendation), lines 82-83, 143-145, 227-228, 258-259, 312-322, the four paragraphs between lines 347 and 366, and the two between 411 and 415, and finally even in the acknowledgements, which I'd merge into one single paragraph.

We agree.

We merged together the mentioned paragraphs and tried to make the text more cohesive.

In section 2 I think it would be clearer if method and different dataset are described in separate subsections. Something like 2.1 Models, 2.2 Observations, 2.3 Reconstructions, or something similar.

We agree.

We structured the section accordingly to the referee comment.

**In the discussion of the model performance, in page 7, I think the discussion should be more quantitative, providing more numbers drawn from the corresponding figures that quantify the disagreements that are being discussed. In this regard, it would be interesting to provide also numbers drawn from similar exercises in the literature, so it can be quantitatively argued how the errors are indeed within the margins "acceptable".**

We agree.

Also based on the comment of the second referee we made the discussion more quantitative, providing numbers quantifying the disagreements arising in the comparison between the different datasets.

**In Fig. 6, the anomalies are calculated over which period? Only one year, or are they averages over 10 years or longer?**

The anomalies are calculated over a 25-year period.

We added such information within the caption of the considered figure.

**In the discussion of Figure 6, it was argued that the warm bias in the North is present in the reconstructions, which happen in all models but in ECHO-G. However the figure is not shown. I think this is a quite important finding, and I'd advise the authors to reconsider showing the figure that is mentioned, because it's the only that can support that rather important claim.**

We agree.

We added the figure relative to the pollen reconstructions to the previous plot.

**I think Tables 2 and 3 should be merged.**

We agree.

We merged together the mentioned tables accordingly to the referee comment.

**Although the text is clearer, I found several mistakes or expressions that I do not think are very standard. However, I didn't review this aspect of the manuscript extensively since as I understand this will be eventually tackled at a latter stage by professional text reviewers prior final publication, which**

surely will amend these small mistakes and many other I could not possibly spot.

We agree.

As also suggested by the second reviewer, we had the text proofread by an english native speaker and we modified it accordingly to his corrections.

Reply to  
2nd Reviewer

- General Comments

Compared to the previous version, this version has much improved. For instance, in my view, the comparison of the CCLM results with ECHAM5, including the application of the cost function, has strengthened the manuscript considerably. However, there are still several points that must be addressed before this manuscript can be considered for publication. Concerning my first main comment in the previous review, I find that the manuscript is still rather poorly written. It still includes many language mistakes, so I am quite sure that the text has not been checked by a native speaker as I suggested. Such a check would significantly improve the readability of the manuscript, so I stress this issue once more here.

We agree with the second referee that the text was still requiring additional corrections and needed to be improved. This time the manuscript has been reviewed and corrected by an english native speaker, significantly improving its readability.

Furthermore, regarding my 5th previous comment, the authors have not really provided a more in-depth discussion of the uncertainty of the summer temperature reconstructions for Southern Europe. In addition, their reply to my comment is not clear to me on this point. The authors note that "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,

possibly 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". From the reply, it is not clear who "they" are, or what "previous analyses" the authors are referring to. Furthermore, Figure 4 presents maps of summer temperatures for the period 1991-2000, so not for the mid-to-late Holocene.

First of all we would like to clarify our previous response to the referee's 5th comment. With "the previous analyses of mid-to-late Holocene temperature evolution" we referred to the first analysis of the trends of temperature that we conducted. We think that the former analysis was misleading because it was obtained by simply averaging the data over two wide regions, not allowing to have a proper overview of the trends at different locations, possibly leading to a mismatch with other proxy-based reconstructions. The new maps (Fig. 9 of the Final Version of the manuscript) permit the comparison with independent reconstructions for different areas. In particular they present now a more heterogeneous behaviour, being in agreement this time with other reconstructions such as the one of Heiri et al. 2015 suggested by the referee, that showed that over the alps summer temperature was characterized by a decreasing trend during mid-to-late Holocene. Nevertheless, the new plots have been designed in order to carefully take into account the uncertainties of the reconstructions (as suggested by the referee) not only in summer but in both the seasons, for every single point of the domain (North and South), by means of a weighted least squares method. In addition, a detailed discussion on the pollen uncertainties and mismatches with some other reconstructions, as the ones based on chironomids, has been provided by Basil Davis in response to the second referee comment. However, despite all the efforts we made in order to carefully take into consideration the referee comment, we realized that our previous response was probably not accurate enough. Aware of this, considering the issue of reconstruction uncertainties a fundamental factor, we agree with the referee on the fact that a more in-depth discussion of the uncertainty of the summer temperature reconstructions for Southern Europe should be provided.

Based on these considerations we modified the text accordingly, considering a series of different references.

**A major outcome of the present paper is the mismatch between the CCLM model results in Southern Europe and the pollen-based**

reconstructions of Mauri et al. (2014), showing an opposite trends in summer. In Mauri et al. (2014), the pollen-based reconstruction is compared against independent reconstructions (their Figure 8), but this was not done for summer temperatures in Southern Europe, except for the Alps. In explaining the noted mismatch, Russo and Cubasch only consider a model bias in surface heat fluxes, but do not reflect on the possibility that the pollen-based reconstruction does not capture the right temperature trend in the Mediterranean area during the Holocene. The latter possibility has been discussed in the literature before as I mentioned in my review of the CPD manuscript, and I urge the authors again to make the readers aware of this discussion. As mentioned in Section 3.3.1., all PMIP3 models suggest warmer conditions in Southern Europe during the mid-Holocene (see also Table S2), so if the reconstruction of Mauri et al. (2014) is correctly indicating cooler conditions here, this implies that all these models are not capable of capturing the right climate response in Southern Europe under influence of astronomical forcing. An alternative to consider is that the reconstructions are incorrect. This important issue is still under debate, and in my opinion it is crucial to provide the arguments of both sides of this debate.

We agree with the referee that our discussion should be possibly expanded, taking into account his suggestions and trying to make the reader more aware of the possibility that the reconstructions could be incorrect, providing the arguments of both sides of the debate.

Bearing this in mind, taking into account the bibliography suggested by the referee and considering additional one, we developed the text accordingly.

Below we report in *italic* the text included into the discussion and developed according to the previous two points:

*It is important to mention that the behaviour of mid-to-late Holocene's summer temperature over Europe has been highly debated during recent years. While a dipole behaviour has been suggested by several studies based on pollen analyses ([1, 9, 2, ?, 10]) and others relying on a combination of different proxies, such as the one of Magny et al. 2013 [3], which suggested a North-South paleohydrological contrast in the central Mediterranean during the Holocene, other studies argued against such hypothesis. In particular Osborne et al. 2000 [4] proposed that reconstructions of summer tempera-*

ture based on pollen could be erroneous for the Mediterranean region, since here the vegetation distribution is mainly limited by effective precipitation, rather than by summer temperature. The latest hypothesis should be taken into account for the comparison between pollen-based reconstructions and model simulations. Nevertheless, additional investigations have shown that, when directly compared to the pollen record, the mid-Holocene vegetation simulated from the output of climate models is way too dry over Southern Europe, with an expansion of Mediterranean and steppe/desert vegetation and contraction in forest cover, a direct consequence of simulated warmer conditions ([2, 5, 6, 7, 8]). Based on these considerations, recognizing the dataset of Mauri et al. 2015 as a valuable source for the investigation of European temperature evolution during mid-to-late Holocene, we acknowledge the fact that joint efforts from specialists of different disciplines are still required in order to further clarify possible uncertainties.

- Minor Comments:

**L157: It is mentioned here that effects of greenhouse gas forcing is not considered in the analyses. Does this mean that the trace gas concentrations were kept fixed at their preindustrial values in all experiments? Or are the concentrations adjusted in the experiments based on ice-core measurements, but is the effect of this forcing not separated from the impact of insolation changes? Please clarify.**

In our analysis of temperature evolution during mid-to-late Holocene, since the impact on the radiative balance of changes in the concentration of greenhouse gases was considerably small compared to the effects of changes in insolation, in our discussion we did not separate them from the latter ones. Nonetheless, the values of GHGs were set in the experiment based on ice-cores measurements.

**L195: Please explain what you mean by 'satisfactory results'.**

With "satisfactory results" we referred to the fact that the data of Mauri et al. 2015 proved to be in good agreement with independent reconstructions derived from different proxies. The details of their analysis have already been enunciated in Mauri et al. 2015.

**L213 and L219: Why do you use "instead" in these sentences?**

We agree with the referee that "instead" in this context is not necessary.

We decided to take it out from the text.

**L219 to L228:** I suggest to make this section more quantitative, as it is very descriptive.

We agree.

We modified this part of the text accordingly.

**Section 3.3.1:** This new section on the results of PMIP3 experiments is a useful addition to the manuscript. However, it is very descriptive and it could be made more informative by making it more quantitative.

We agree.

We modified this subsection in order to make it more quantitative, accordingly to the referee suggestion.

**L270:** I suggest to use "proxy-based reconstructions", as the proxies themselves are not reconstructed.

We agree.

Corrected in proxy-based reconstructions.

**L281:** "The coastline is also better reproduced in this case, resulting in more suitable informations for possible comparison against proxy-data". Please clarify how a more detailed coastline would improve the model-data comparison. See also line 448 in the Conclusions.

We modified the text accordingly to the referee's comment, stressing out the fact that a better reproduced coastline allows for a more robust and precise representation of the surface and its physical processes. This would consequently lead to more suitable and robust information for the comparison against proxy-data.

**L283:** "CCLM shows better defined patterns as a consequence of higher resolution". What kind of patterns, please clarify. See also line 449 in the conclusions.

Although we took into consideration the referee's comment we preferred not to change the former sentence since we think it was already clear. With "CCLM shows better defined patterns as a consequence of higher resolution" we mainly referred to the fact that the spatial patterns of temperature deriving from the CCLM simulations are better defined in comparison to the ECHAM5's ones, since the RCM's spatial resolution allows to better discriminate higher spatial variability. Hence this could constitute added value.

**L287: Zhang et al. (2010) is missing in the reference list.**

We checked the previous version of the text and the mentioned reference was already present.

**L306: "It is important to mention that the scale considered in our analysis is closer to the resolution of ECHAM5 than the one of the CCLM". What scale are you referring to here? The scale of the reconstructions?**

In the previous sentence we referred to the resolution of the reconstructions. We tried to improve the text in order to make it clearer.

**L347: In Fig 9 the winter map for CCLM is gray (i.e. the trend is not significant) in Scandinavia, where the reconstructions show a strong, significant cooling trend. So here the model results do not match the proxy data, and I suggest to mention this here.**

We agree.

We modified the text accordingly to the referee's comment.

**L387: "the first CCA pair (Fig. 11 a,b)". Is this correct? The MSLP pattern explaining most of the variance is shown in Fig. 11c, so should Fig 11c,d not be the first CCA pair?**

Yes. It is correct. In CCA the order of the canonical pairs follows the values of correlation. The first pair of spatial patterns is the one with the highest correlation, followed by the second one and so on in a decreasing order.

**L409: "to capture this trend". What trend? In soil moisture during Summer? Or in winter or spring precipitation. Please clarify.**

We refer to the trend in temperature over Southern Europe.

We tried to make it clearer within the text.

**Figure1: In the caption, a reference for the presented data should be added.**

We agree.

We modified the caption accordingly.

**Caption Figure 5: Typo, "refernce period".**

Corrected.



**Figure 6: I suggest to use the same projection in all six panels to facilitate the inter-model comparison.**

Even if we agree with the referee on the fact that the use of the same projection would facilitate the inter-model comparison, we think that the best way to achieve this task would be by means of interpolation. We think that this could alterate the results leading us away from the original goal of the analysis. For this reason we preferred to leave the figure as it is. However we tried to be more accurate in the caption of the figure, adding further details.

**Figure 9: Please clarify what the unit of the slopes. Is it in C per 6kyr? Or C per kyr?**

We agree. The unit is °C/kyr. We modified the figure accordingly.

**Figure 12: In my view, this figure does not add much to the manuscript, so it could be described only, or it could be moved to the supplementary information.**

We do not agree with the referee and we do think that the figure should be included in the manuscript, as it gives important informations of the temporal expansion of the two variables into consideration and allows a substantial contribution to the developed discussion and conclusions.

Below we propose some additional bibliography that we will provide, in the revised version of the manuscript, accordingly to the referee's comments. Also some references already included in the manuscript and mentioned in these comments are reported.

## References

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With kind regards on behalf of the all authors,  
Emmanuele Russo

# 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 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 a few studies have tried to directly estimate the possible advantages of highly resolved simulations for the study of past climate change.

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

After proposing and testing a model configuration suitable for paleoclimate applications, ~~we compare the mentioned~~ the aforementioned mid-to-late Holocene simulations are compared against  
10 a new pollen-based climate ~~reconstructions~~ reconstruction dataset, covering almost all of Europe, with two main objectives: testing the advantages of high-resolution simulations for paleoclimatic applications, and investigating the response of temperature to variations in the seasonal cycle of insolation during the mid-to-late Holocene, with the aim of giving physically plausible interpretations of the mismatches between model and reconstructions.

15 Focusing our analysis on near surface temperature, we can 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.

Additionally, our results reinforce previous findings showing that summertime temperatures during the mid-to-late Holocene were driven mainly by changes in insolation and that the model is  
20 too sensitive to such changes over Southern Europe, resulting in drier and warmer conditions. ~~In winter, instead~~ However, in winter, the model does not ~~reproducee-correctly~~ correctly reproduce 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  
25 two datasets in some areas are most likely due to high pollen ~~uncertanties~~ 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~~ the present day, 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~~ impact it could have on the life of our planet. Useful instruments for the study of climate change and its possible consequences are climate models. 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~~ particularly regarding their sensitivity to changes in the external forcings (Collins and Allen, 2002; Yip et al., 2011). To improve our ~~predictions~~ predictions of the future climate it is necessary to better understand such a 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 the mid-to-late Holocene (from 6000 years ago to present ~~days~~ day). The large number of proxy data available and the particular configuration of the Earth astronomical parameters, make it a useful period for the evaluation of the 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~~ During the mid-to-late Holocene, over northern latitudes in general, changes in the total amount of insolation during the year (with respect to present ~~days~~ day conditions) were negligible ( $\leq 4.5 \text{ W/m}^2$ ) when compared to the seasonal variations (up to more than  $30 \text{ W/m}^2$  for summer insolation at high latitudes) (Fischer and Jungclauss, 2011). Indeed, relevant variations in the seasonal values of surface variables would be expected. However, ~~evidences show~~ evidence shows that reconstructed climatic parameters, such as surface temperature, over Europe, did not always follow directly the 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~~ also been 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 the mid-to-late Holocene. Cheddadi et al. (1997) showed ~~as a result that the results~~ of a pollen-based reconstruction dataset constrained by lake-level data, indicated that summer and winter temperatures were different over Northern and Southern Europe at ~~mid-Holocene~~ the mid Holocene in comparison to present-day values: winters, in particular, were warmer over Northern Europe even if the insolation was reduced, while sum-

65 mers 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 seasonal changes of temperature and  
70 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 and dyn-  
amic vegetation ~~to better reproduce~~, better reproducing soil water storage and heat fluxes. They  
found that changes in ~~soil~~ the soil's physical properties of the model led to improved model results  
and hampered anomalies in surface variables, with respect to proxy-data, ~~of surface variables~~. Fis-  
75 cher and Jungclaus (2011) studied the evolution of the European seasonal temperature cycle in a  
transient mid-to-late Holocene simulation with an ocean-atmosphere global climate model, ~~however~~  
~~not being able~~ although they were unable to reproduce correctly the reconstructed data over the en-  
tire region of study. In particular, their results presented only a weak shift to a positive phase of the  
NAO at ~~mid-Holocene~~ mid Holocene in winter, resulting in colder conditions over Northern Europe  
80 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 con-  
ditions 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 at ~~mid-Holocene~~ the mid Holocene  
was highly related to changes in atmospheric circulation both in winter and in summer. Specifically,  
85 they proposed that in summer a major incidence of the "Scandinavian High" was most probably the  
reason for colder temperatures over Southern Europe 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~~ consensus is  
90 still missing on the correct explanation of the response of the climate system to changes in insolation  
for this period.

Within the mentioned studies, all the climate model applications have been conducted with tran-  
sient simulations or considering a single time slice with Global Circulation Models. In many cases  
the resolution of these simulations was not high enough to allow for an assessment of the climate  
95 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~~ information on surface and  
100 soil features (Feser et al., 2011).

~~Under these considerations~~Bearing this in mind, in recent years the application of regional climate models for 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~~African precipitation during the last interglacial. Fallah et al. (2015) investigated precipitations and 105 dry periods during the Little Ice Age and the ~~Middle-age~~Medieval Warm Period over central Asia. Wagner et al. (2012) compared ~~mid-Holocene~~the 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.

In several studies, regional simulations of European climate during different times of the mid-to-late 110 Holocene have been performed (~~(Gómez-Navarro et al., 2011),,,,,,~~)(Gómez-Navarro et al., 2012, 2013, 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**), 115 for the investigation of the main climatic changes that characterized Europe during multiple time-slices of the 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
- 120 – ~~Analyze~~Analyze proxy and model mismatches, providing plausible physical interpretations of the dynamical processes responsible for them

Our discussion is structured as follows: in section 2 the employed methodology, including a brief description of the models and the ~~pollen-proxy~~pollen-proxy datasets, is presented. Results are illustrated and discussed in section 3: first a validation of the data for present-day conditions is conducted in order 125 to test the performances of the model with the changes necessary for paleoclimate applications; then the mid-to-late Holocene simulations are compared against ~~the~~ pollen-based reconstructions, trying, in a first instance, to highlight the ~~advantages-related-to~~advantages of the performance of highly resolved simulations specifically for this case of study; finally, physically plausible ~~interpretations~~interpretation of the mismatches between the CCLM results and the reconstructions are proposed; 130 the results of other studies are additionally discussed.

## 2 Methods

### 2.1 Experimental Setup

In this work we perform a set of climate simulations, covering several ~~time-slices~~time slices of mid-to-late Holocene, employing models at different resolution.

135 The modus operandi consists of three 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  
140 ~~informations~~information on the simulation realization are provided in Wagner et al. (2007).
2. We then select ~~7~~seven 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~~30-year period, with  
145 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~~a horizontal resolution of 0.44 longitude degrees, using  
150 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  
155 studies.

In order to set the 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 astronomical parameters calculated by Berger (1978). In Fig.?? the anomalies of zonal mean insolation on top of the atmosphere (TOA)  
160 between the 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  
165 air trapped in ice ~~eore~~cores (Flückiger et al. (2002)). The ~~contribute of~~contribution of the 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 latter are considered in our ~~analyses~~discussion.

The setup of the COSMO-CLM is based upon the work of Hollweg et al. (2008) within the Euro-  
170 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 employed coupled to a Soil Vegetation Atmosphere Transfer  
scheme, the **TERRA ML**, a ~~multi-layer~~ ~~multi-layer~~ model with a constant temperature lower bound-  
ary condition that allows to reproduce the fluxes of heat, water and momentum between the soil-  
175 surface and the atmosphere. Recent data of the physical parameters of the Earth's surface ~~physical~~  
~~parameters~~ (e.g., orography, land use, vegetation fraction, and land-sea mask) are employed for the  
simulations. The model domain, shown in Fig.??, 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~~ Sea in the South. Each simulation includes a  
180 ~~5-years~~ ~~5-year~~ spinup period used to let the model reach a semi-equilibrium state as suggested by  
Hollweg et al. (2008) .

## 2.2 Observations

For the model validation for present climate, the **E-OBS** (Haylock et al., 2008) and the Climate  
Research Unit (**CRU**) (Harris et al., 2014) observational datasets are used as benchmarks for the  
185 comparison with the results of a COSMO-CLM control run covering the period 1991-2000 and  
driven by the ERAInterim (**ERAInt**) dataset (Dee et al., 2011). The validation is conducted with  
respect to the total precipitation and 2 meter temperature winter and summer seasonal means. Addi-  
tionally, CCLM heat fluxes and evapotranspiration values, from the same simulation, are validated  
against the **GLDAS** (Global Land Data Assimilation System Version 1 Products) dataset.

## 190 2.3 Proxy-Reconstructions

Subsequently, the results of the mid-to-late Holocene simulations are compared against the dataset of  
Mauri et al. (2015). This is the latest updated pollen-based climate reconstruction dataset for Europe  
and constitutes an upgrade of the results of Davis et al. (2003). It is derived with the same methodol-  
ogy, but with a wider number of fossil and surface-samples, following a more rigorous quality con-  
195 trol. The data cover a time slice every millennium for the entire Holocene and are derived through a  
4-dimensional 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~~ information on seasonal (winter and summer) and annual values of precipita-  
200 tion 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  $1 \times 1$  longitude degrees.

The choice of the dataset of Mauri et al. (2015) has been done for several reasons. First of all, it  
allows us to perform a comparison against the model results over most of the simulation domain,



considering different variables (even if we only focus on temperature in our discussion). Then, it  
205 covers exactly the same ~~time-slices~~ 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  
210 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

#### 3.1 Model Validation and Evaluation for Present ~~Days~~ Day

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

The simulation covers a ~~10-years~~ 10-year period, between 1991 and 2000. Even if the length of this  
220 simulation can be considered as "critical" for the model's validation, we want to acknowledge that,  
due to computational reasons, it was not possible to cover a longer period.

In Fig.?? and Fig.??, winter and summer seasonal means of temperature (left panel) and pre-  
cipitation (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  
225 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-  
day control run are directly validated, through a Student's T-test, against the CRU and the E-Obs  
datasets. The same test is conducted for evaporation and heat fluxes but against the GLDAS dataset in  
230 Fig.?. In these figures the black dots represent the grid cells where the 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 in both winter and summer. Winter-time results are in particularly good  
235 agreement with observations over Northeastern Europe and Scandinavia (Fig.??II). However, larger  
deviations (up to 4°C in some cases) are present over Central Europe, Turkey and Northern Africa.  
In particular the model tends to simulate generally colder conditions over these regions. Winter  
precipitation results seem to be in good agreement over a major part of the domain, with some

240 deviations from the observations over regions with particularly complex orography, in regions that are normally highly affected by westerlies and in the Northern African coasts of the Mediterranean Sea and in regions that are normally highly affected by westerlies (where the biases are particularly pronounced, and the model results diverge by almost 100% from the values of the observations) (Fig.??IV).

245 In summer, instead, the main discrepancies are found over Southern Europe both for temperature and precipitation (Fig.??). In particular the temperature anomalies reach 4°C over most of the mentioned area.

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~~ European summer conditions. This seems to be most likely related to deficiencies in 250 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 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, 255 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 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??) presenting a spatial distribution 260 of the anomalies resembling the ones of temperatures and ~~precipitaion~~ precipitation. In particular, the model underestimates latent heat flux and evapotranspiration, while overestimating sensible heat over corresponding area.

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; 265 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 applications.

### 3.2 Possible added Value of Highly Resolved Simulations for Paleoclimate Studies

270 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~~ 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  
275 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:

- 280
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.

285 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~~proxy-based reconstructions.

In Fig.?? we present the anomalies of temperature summer and winter seasonal means between  
290 6000BP and the Pre-industrial period, as reproduced by the different models and the pollen-based reconstructions. From these maps we first notice ~~as~~, in both the seasons, that a similar signal of climate change is present in all the simulations. This is expected, ~~being~~being, in every case, the data constrained by the coarser resolution models. Nevertheless, while the highly resolved simulations allow ~~to catch us to detect~~ a warmer bias over Northern Europe in winter, also present in the proxy  
295 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~~Sea area, Southern Italy and Scandinavia are partly or completely masked-out in this case.

Consequently, we focus further ~~analyses~~analysis on the comparison between the ECHAM5 and  
300 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~~a better detailed representation of the land-sea contrast, a more precise reproduction of surface processes and, consequently, leading to more suitable information for possible comparison against proxy-data. Nonetheless, the CCLM shows better defined patterns as a consequence of higher resolution, being  
305 able to discriminate higher spatial variability.

On the ~~base~~basis 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  
 310 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 cor-  
 315 responding 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 corre-  
 sponding uncertainties of the model results are considerably small ( $\sim 0.01^\circ C$ ) in comparison to the  
 320 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.??~~. Values closer  
 to 0 indicate a better agreement with proxy reconstructions.

As we can notice, even if not particularly large differences are present, the Cost Function com-  
 325 puted for the CCLM is in almost all the cases smaller than the one for 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~~ of the pollen-based reconstructions, considered  
 for 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  
 330 ~~with to~~ their horizontal resolution, it seems natural that the results depend on the 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  
 335 proxy-reconstructions.

Nonetheless, the motivation behind producing higher resolution climate simulations is not only re-  
 lated 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 adap-  
 tation or environmental response to past climatic changes would be investigated. ~~The~~ Accordingly,  
 340 the need for climate information at very fine scales, for ~~application applications~~ such as archaeol-

ogy 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~~ motivation for the choice of conducting RCM simulations for this particular case ~~of study-~~ study.

### 345 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~~ analysing the differences between the two datasets and their temporal evolution, we propose, by means of correlations with trends of insolation and changes in atmospherical circulation patterns, physically plausible ~~interpretations~~ interpretation of the evinced mismatches.

350 Fig.?? and Fig.?? present the 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.

355 In winter, generally colder conditions ~~over northern regions~~ are reproduced by the model over northern continental Europe, with slightly warm biases over most of the South (Fig.??). In Scandinavia a negative bias is present for the first two millennia, after which the situation then reverses. 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.

360 In ~~Summer~~ summer, instead, CCLM results present a positive bias over most of the domain, with particularly pronounced anomalies ( $\sim 3^{\circ}C$  in some case larger than  $\sim 4^{\circ}C$ ) over different parts of Southern Europe and the Mediterranean basin (Fig.??).

In addition to the previous analyses, the maps of temperature temporal evolution are presented 365 in Fig. ???. They show the slope of the mid-to-late Holocene linear trends of temperature anomalies with respect to the 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~~ grey.

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

375 In particular, over Scandinavia, while the pollen-based reconstructions show a strong, significant cooling trend, no significant trend is evident for the model results. Conversely, in summer, the model results are characterized by a negative trend over most of the domain (Fig.??c), highly correlated

to changes in insolation. The pollen data, instead, show a significant negative trend similar to the CCLM results ~~only~~ over part of Northern Europe only, and an opposite positive trend over most of the South (Fig.??d).

380 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~~ in order to obtain further insights into the causes of the evinced biases, we conduct a Canonical Correlation Analysis (CCA) of model's mean sea level pressure and temperature anomalies, with respect to the pre-industrial period, for winter and summer seasons.

The Canonical Correlation Analysis is particularly suitable for our purposes since it helps to 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 pre-industrial 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~~ 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.

400 Fig.?? and Fig.?? 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.??c). 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.??c), 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~~ Sea. The trend of the expansion coefficients of this pattern is slightly positive but again not particularly pronounced.

410 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.?? a,b) seems to be highly related to changes in insolation (Fig.?? 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  
415 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.?? c) resembles the positive  
420 phase of the Summer North Atlantic Oscillation (SNAO) (Folland et al., 2009). The trend (Fig.?? c)  
of its expansion coefficients is again not particularly pronounced. As a consequence, the changes in  
the corresponding temperature pattern (Fig.?? d), are also not ~~particularly remarkable.~~ remarkable.

Consequently, we suggest that in summer, during mid-to-late Holocene, the changes in circulation  
alone would not have been enough ~~in order~~ to justify the variations in surface temperature, as recon-  
425 structed 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,~~ Southern Europe, however, the  
role of land-atmosphere coupling needs to be considered (Seneviratne et al., 2006).

According to Bonfils et al. (2004) and Starz et al. (2013), over Southern Europe, the presence  
430 of more moisture in the soil during mid-Holocene 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 the reconstruction temperature~~  
435 trend, could most probably be 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, to drier and warmer  
conditions.

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

It is important to mention that the behaviour of mid-to-late Holocene's summer temperature over  
Europe has been highly debated during recent years. While a dipole behaviour has been suggested by  
several studies based on pollen analyses (Huntley and Prentice, 1988; Cheddadi et al., 1997; Prentice  
et al., 1998; Davis et al., 2003; Mauri et al., 2015) and others relying on a combination of different  
445 proxies, such as the one of Magny et al. (2013), which suggested a North-South paleohydrological  
contrast in the central Mediterranean during the Holocene, other studies argued against such hypothesis.  
In particular Osborne et al. (2000) proposed that reconstructions of summer temperature based on  
pollen could be erroneous for the Mediterranean region, since here the vegetation distribution is  
mainly limited by effective precipitation, rather than by summer temperature. The latest hypothesis  
450 should be taken into account for the comparison between pollen-based reconstructions and model

simulations. Nevertheless, additional investigations have shown that, when directly compared to the pollen record, the mid-Holocene vegetation simulated from the output of climate models is way too dry over Southern Europe, with an expansion of Mediterranean and steppe/desert vegetation and contraction in forest cover, a direct consequence of simulated warmer conditions (Prentice et al., 455 1998; Wohlfahrt et al., 2004; Gallimore et al., 2005; Benito Garzon et al., 2007; Kleinen et al., 2010).

Based on these considerations, recognizing the dataset of Mauri et al. (2015) as a valuable source for the investigation of European temperature evolution during mid-to-late Holocene, we acknowledge the fact that joint efforts from specialists of different disciplines are still required in order to further 460 clarify possible uncertainties.

### 3.3.1 Other Modelling Studies

An important benchmark for the comparison of our results against other modeling-modelling studies is represented by the outcomes of the PMIP3 experiment (Braconnot et al., 2011), for which several simulations have been performed, with different coupled circulation models, for the mid-Holocene 465 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 ~~for the PMIP3 simulations as well as each of ours~~. The results are presented in two tables, provided as supplementary material, in which the corresponding values derived from the pollen-based 470 reconstructions are also included. Two main features arise from such analysis: first of all a common positive bias ( $\sim +1^{\circ}C$ ) over Southern Europe in summer for all the models is evident. ~~It,~~ while the reconstructions present a negative value ( $\sim -1.2^{\circ}C$ ). This 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~~ pre-industrial period. Additionally, another feature that seems to be common 475 to all the models is represented by the failure in representing winter anomalies in both the regions and it is attributable to a wrong reproduction of changes in the amplitude of NAO (Fischer and Jungclaus, 2011; Strandberg et al., 2014).

While some models present a value similar to the one of reconstructions for Southern Europe ( $\sim +0.5^{\circ}C$ ), in the North the differences are significant, with the pollen-based reconstructions 480 presenting a warm bias ( $\sim +2.5^{\circ}C$ ), and the models having slightly positive values (between 0 and  $+1^{\circ}C$ ) in some cases, and negative (up to  $\sim -1^{\circ}C$ ) in the others.



## 4 Summary and Conclusions

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, by means of the state-of-the-art regional climate  
485 model COSMO-CLM.

~~In~~As 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  
490 drier conditions ( $\sim +4^{\circ}C$  for temperature and  ~~$\sim -50\%$~~  $\leq -50\%$  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 simulations have been compared against a new  
495 pollen-based climate reconstruction dataset. Winter and summer seasonal means of near surface temperature have been considered for our analysis.

~~In a first instance~~To begin with, the possible advantages of higher resolution models for paleoclimate applications 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  
500 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~~ reasons for choosing to conduct highly resolved simulations for this particular case ~~of~~ study.

505 Finally, the CCLM results are used in order to investigate the response of the climate system to changes in the seasonal cycle of insolation, with the aim of proposing plausible ~~physieal~~physical interpretations of the mismatches arising in the comparison against the reconstructions.

The results show that, in winter, over Southern Europe temporal behaviour and spatial distribution of temperature in the two datasets are comparable. Conversely, the model tends to reproduce  
510 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  
515 area.

In summer, the simulated northern conditions ~~are in good agreement~~agree well 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  
520 data exhibit an opposite trend. According to the results of previous works and to the analysis of  
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 over this area.

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

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725 **List of Figures**

**Figure1:** ( Left) *Anomalies of zonal mean insolation on top of the atmosphere (TOA) between pre-industrial period (PI) and 6000 years BP.*(Right) *Mid-to-late Holocene trends of the anomalies, with respect to present-day values, of December and June TOA incoming insolation, calculated, according to Berger 1978, for 30 and 60 degrees North. Units are  $W/m^2$ .*

730 **Figure2:** *Orography map of the COSMO-CLM simulation domain in rotated coordinates.*

**Figure3:***Analysis of Winter seasonal means of 2 meter temperature (left panel) and Precipitation (right panel) for the period 1991-2000. The first column of each panel (I,III) shows the mean climatology for the investigated period as represented in the three considered datasets: the CCLM in the first row, the CRU in the second and the E-OBS at the bottom. The second columns show (II,IV), in-*

735 *stead, the biases between the CCLM results and the respective observational datasets. The area with a point represent the grid cells where the anomalies between the two datasets are not significant, according to a Student's T-test, at a significance level of 5%.*

**Figure4:** *As Fig?? but for Summer.*

**Figure5:** *Biases of seasonal means of Evapotranspiration (left), Latent (center) and Sensible Heat (right) fluxes, between the CCLM*

740 **Figure6:** *Maps of Winter (left) and Summer (right) 2 meters temperature anomalies between 6000BP and the preindustrial period*

**Figure7:** *Left: Maps of Winter 2 meters temperature anomalies between CCLM and Pollen-based Reconstructions for the different time slices of mid-to-late Holocene. Right: Standard error of winter temperature seasonal mean derived from the pollen-based reconstructions for each time slice of mid-to-late Holocene.*

745 **Figure8:** *As in Fig.?? but for Summer seasonal means.*

**Figure9:** *Mid-to-late Holocene temporal Evolution of the anomalies, with respect to the pre-industrial period, of near surface tem*

**Figure10:** *Canonical correlation pattern pairs of MSLP (left) and T2M (right) in Winter, calculated accordingly to the Barnett and Preisendorfer (1987) method. Each panel illustrates the percentage of variance explained by the patterns and the canonical correlation associated with the pair.*

750 *The results are calculated for the mid-to-late Holocene, from 6000BP to Pre-industrial times. Note that the MSLP has been obtained directly from the driving GCM, since the window of interest lies outside the RCM domain. For both the variables the analysis has been conducted on the standardized anomalies with respect to the pre-industrial period. Red (blue) areas indicate positive (negative) correlations, for each grid point, between the data and the corresponding canonical score series.*

755 **Figure11:** *As in Fig.?? but for Summer season.*

**Figure12:** *Canonical score series of the first two pairs of Canonical Correlation patterns of, respectively, MSLP (left column) and 2 meter temperature (right column) winter seasonal mean anomalies* **Figure13:** *As in Fig.?? but for summer*

**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



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

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