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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 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.

5   Motivated by such considerations, in this paper we present a set of high resolution-simulations for different time slices of 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 mid-to-late Holocene simulations against a new pollen-based climate reconstructions 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 mid-to-late Holocene, with the aim of giving physically plausible interpretations of the mismatches between model and reconstructions.

Focusing our analysis on near surface temperature, we demonstrate that concrete advantages arise 15 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 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, 20 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 25 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 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 regarding their sensitivity to changes in the external forcings (Collins and Allen, 2002; Yip et al., 2011). To improve our predicitions 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). 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 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 , over northern latitudes in general, changes in the total amount of insolation during the year (with respect to present days conditions) were negligible ($\leq$4.5 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 Jungclaus, 2011). 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 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-based reconstruction dataset constrained by lake-level data, that summer and winter temperatures were different over Northern and Southern Europe at mid-Holocene in comparison to present-day values: winters, in particular, were warmer over Northern Europe even if the insolation was reduced, 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 win-

ter atmospheric patterns and summer soil conditions had an important influence on 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 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 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 global climate model, however not being able to reproduce correctly the reconstructed data over the entire region of study. 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 at mid-Holocene was highly related to changes in atmospheric circulation both in winter and in summer. Specifically, 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 consense is 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 transient 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 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).

Under these considerations, 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 precipitation during the last interglacial. Fallah et al. (2015) 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.

100   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 neg-

105   ligible.

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

110   – 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 discussion is structured as follows: in section 2 the employed methodology, including a brief

115   description of the models and the pollen 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 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 adavantages related to the performance of highly resolved simulations

120   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

In this work we perform a set of climate simulations, covering several time-slices of mid-to-late

125   Holocene, employing models at different resolution. 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 ($\sim 3.75^o \times 3.75^o$). Further

130   informations 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 ($\sim 1.125^o \times 1.125^o$), 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 co-ordinates 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 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.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 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 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. Recent data 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.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 **E-OBS** (Haylock et al., 2008) and the Climate Research Unit (**CRU**) (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 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. 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.

Subsequently, the results of 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 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 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 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.

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, $\delta 18O$ 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

3.1 Model Validation and Evaluation for Present Days

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.

205 The simulation covers a 10 years period, between 1991 and 2000. Even if the length of this simu-
lation 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

210 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-
day control run are directly validated, through a Student's T-test, against the CRU and the E-Obs

215 datasets. The same test is conducted for evaporation and heat fluxes but against the GLDAS dataset
in Fig.5. 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 obser-
vations are instead represented with different colours. The results show that, for temperature, the

220 model performs well over Northern Europe in both winter and summer. Winter-time results are in
particularly good agreement with observations over Northeastern Europe and Scandinavia (Fig.3II).
However, larger deviations are present over Central Europe, Turkey and Northern Africa. In partic-
ular 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 deviations from

225 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.3IV).

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

It has been shown in previous works (Hagemann et al., 2004; Christensen et al., 2008; Kot-

230 larski et al., 2014; Jerez et al., 2010, 2012) that, in general, regional climate models poorly sim-
ulate southern european summer conditions. 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 spring-time precipitation or badly represented soil

235 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 anomalously warm and dry
conditions over a wide part of Southern Europe and the Mediterranean basin, during summer, as a

240 consequence of a wrong conversion of energy towards latent heat in these regions. This hypothesis
is supported by the heat fluxes and evapotranspiration maps (Fig5) presenting a spatial distribu-

tion of the anomalies resembling the ones of temperatures and precipitaion. In particular, the model underestimates latent heat flux and evapotranspiration, while overestimating sensible heat over corresponding area.

245   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 applications.

250   **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
255   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.
260   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
265   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
270   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, beeing, in every case, the data constrained by the coarser resolution models. Nev-
275   ertheless, while the highly resolved simulations allow to catch a warmer bias over Northern Europe

in winter, 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.

280   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.

285   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:

$$290 \quad CF^k_{mod} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \omega_i{}^k (T^k_{rec,i} - T^k_{mod,i})^2} \tag{1}$$

where CF^k_{mod} 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. $T^k_{rec,i}$ is the temperature of the proxy-data at every location *i*, while $T^k_{mod,i}$ is the corresponding temperature of the model simulation. Additionally, the parameter w^k_i takes into account

295   the uncertainties of the reconstructions at every location and time period. Its value is given by:

$$\omega^k_i = \frac{1}{(SE^k_i)^2 + 1} \tag{2}$$

where SE_i represents the standard error of the reconstructions at every grid box *i*. The corresponding uncertainties of model results are considerably small ($\sim 0.01^o C$) in comparison to the ones of the reconstructions, similarly to Goosse et al. (2006), and are indeed neglected. In this way

300   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 Cost Function computed for the CCLM is in almost all the cases smaller than the ECHAM5's one. In particular the

305   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.

310   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 re-
315   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 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
320   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   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.
325   After analyzing 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 of the evinced mismatches.

Fig.7 and Fig.8 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
330   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.7). The largest anomalies (in some cases up to $\sim 4^o C$) are
335   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 ($\sim 3^o C$) over different parts of Southern Europe and the Mediterranean basin
340   (Fig.8).

In addition to the previous analyses, the maps 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 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.

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 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 model results are characterized by a negative trend over most of the
domain (Fig.9c), highly correlated to changes in insolation. The pollen data, instead, show a signifi-
cant negative trend similar to the CCLM results only over part of Northern Europe, and an opposite
positive trend over most of the South (Fig.9d).

Since changes in atmospheric circulation have often been suggested as possible drivers of temper-
ature 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 in-
sights on 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 un-
derlying 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 sim-
ilar 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 anoma-
lies, 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, 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 corre-
lation 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 tem-

peratures 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 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 paticularly 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 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).

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 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, 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.

3.3.1 Other Modelling Studies

An important benchmark for the comparison of our results against other modeling 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 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-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, 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

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 model COSMO-CLM.

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 ($\sim +4^oC$ 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 simulations have been compared against a new pollen-based climate 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 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 coastline 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 driv-

ing 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, with the aim of proposing plausible phyisical 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 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.

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 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 climate modelling and, consequently, to the improvement of future climate change projections.

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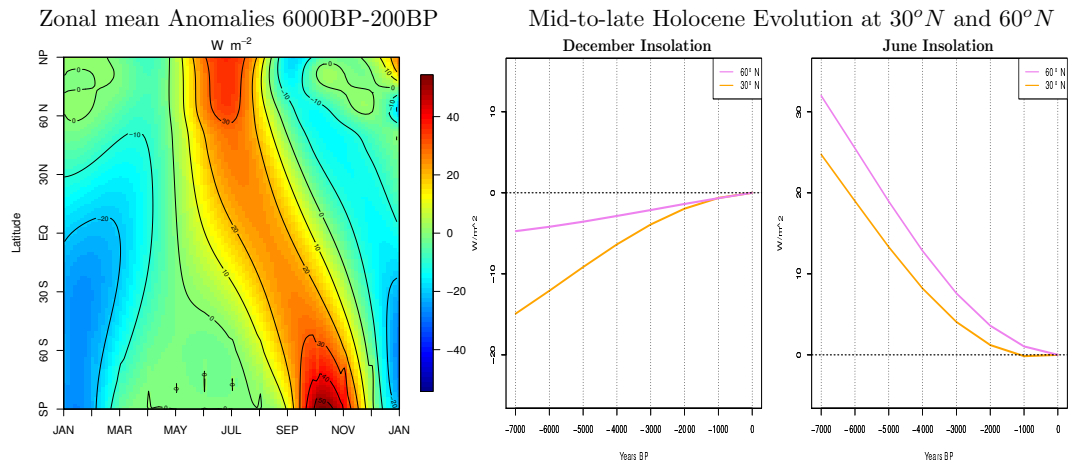
Figure 1. *(Left) Anomalies of zonal mean insolation on top of the atmosphere (TOA) between pre-industrial period (PI) and 6000 years BP. (Right) Mid-to-late Holocene trends of the anomalies, with respect to present-day values, of December and June TOA incoming insolation, calculated for 30 and 60 degrees North. Units are W/m^2.*

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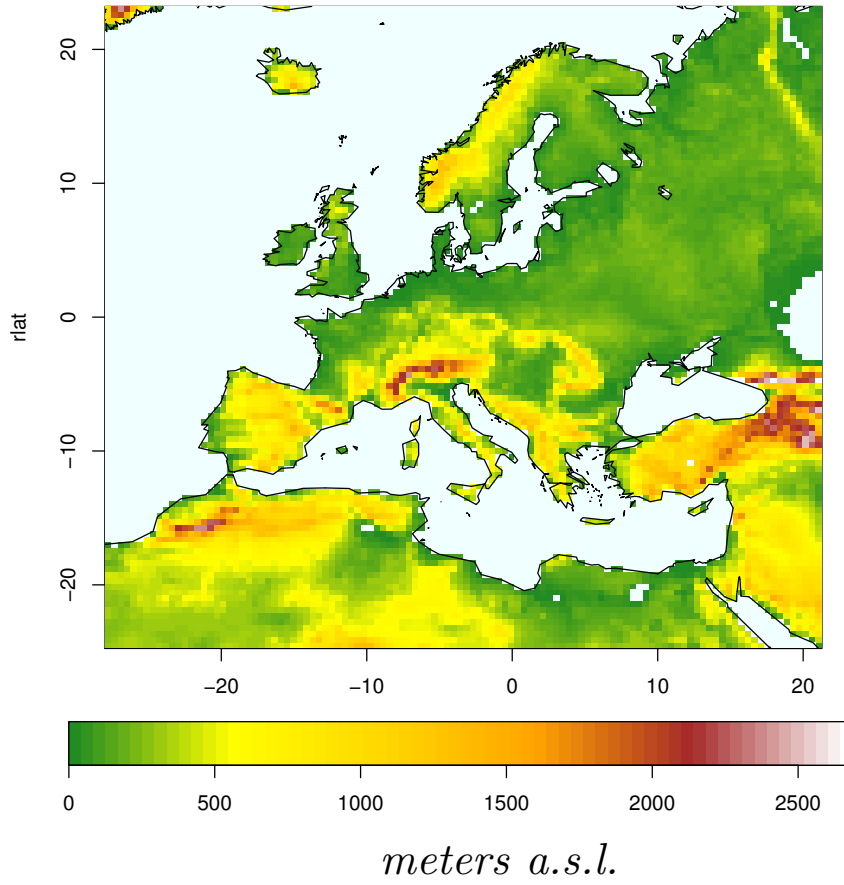
Figure 2. *Orography map of the COSMO-CLM simulation domain in rotated coordinates.*

Table 1. COSMO-CLM Main model configuration parameters

Convection	Tiedke
Time Integration	Runge-Kutta, ΔT=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
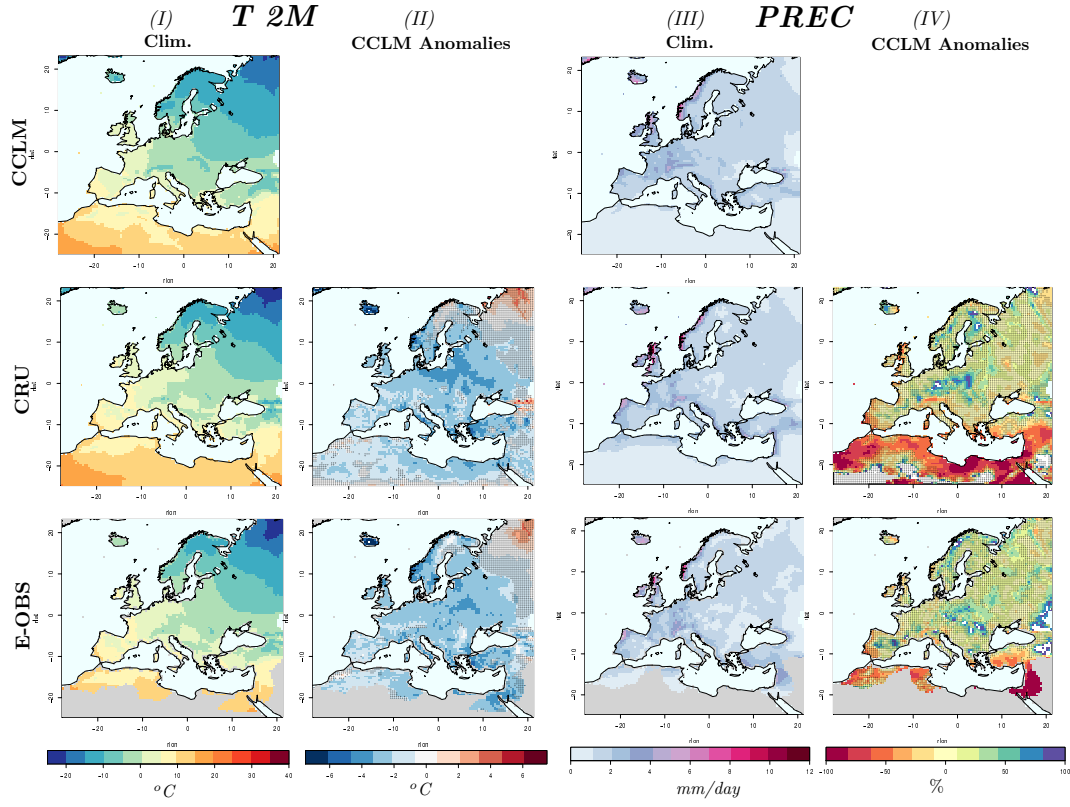
Figure 3. *Analysis of Winter seasonal means of 2 meter temperature (left panel) and Precipitation (right panel) for the period 1991-2000. The first column of each panel (I,III) shows the mean climatology for the investigated period as represented in the three considered datasets: the CCLM in the first row, the CRU in the second and the E-OBS at the bottom. The second columns show (II,IV), instead, 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%.*

Table 2. *Winter Temperature Cost Function estimates for the CCLM and the ECHAM5 models compared to the Proxy reconstructions for each time slice of mid-to-late Holocene. Values closer to 0 indicate a better agreement with proxy reconstructions.*

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	0.77	0.79
1000BP	0.61	0.61
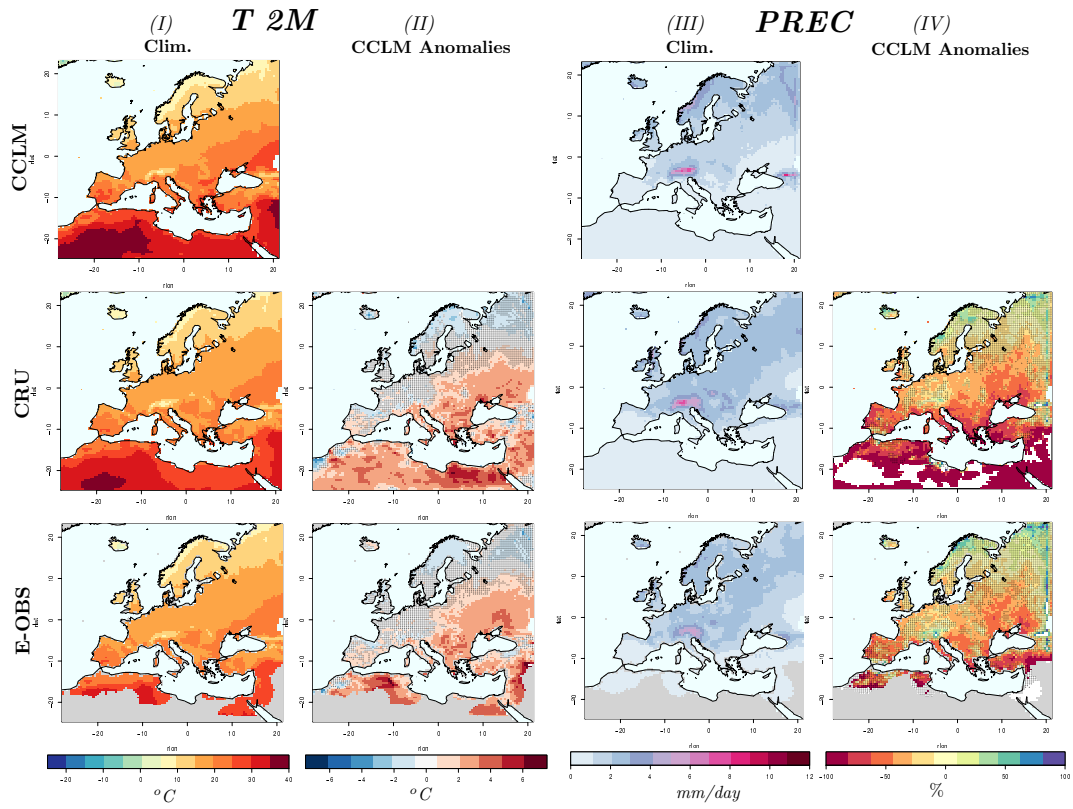
Figure 4. *As Fig3 but for Summer.*

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
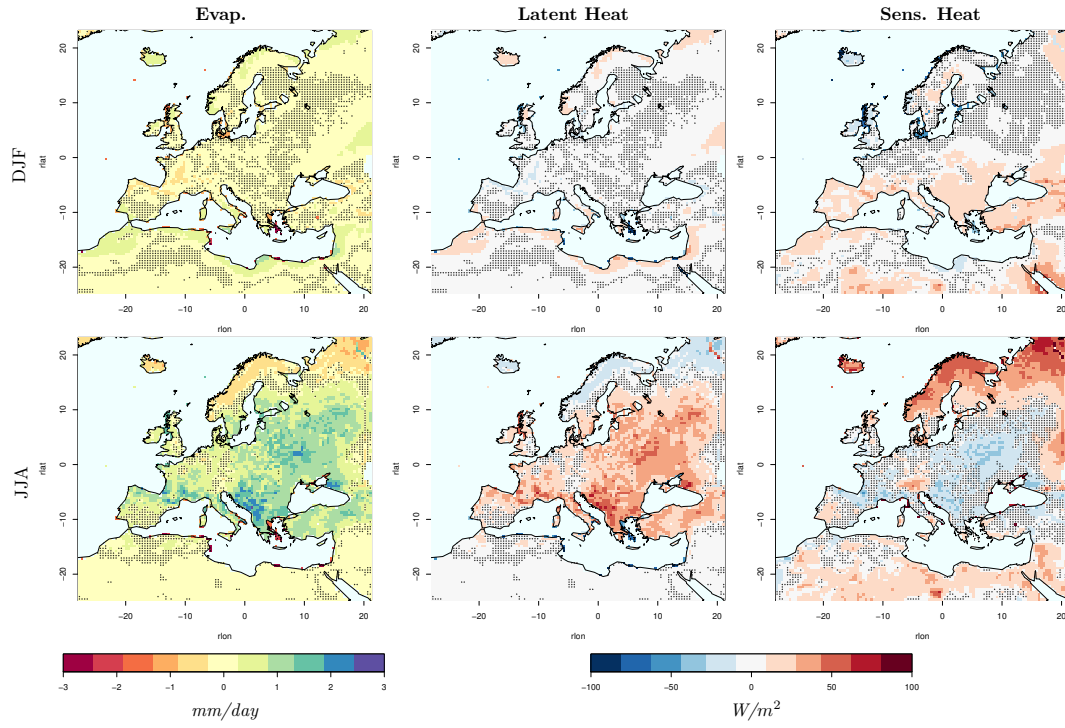
Figure 5. *Biases of seasonal means of Evapotranspiration (left), Latent (center) and Sensible Heat (right) fluxes, between the CCLM simulations and the GLDAS dataset, calculated for the refernce period 1991-2000. As in the previous figures, the area with a point represent the grid cells where the anomalies between the two datasets are not significant, according to a Student's T-test, at a significance level of 5%. Winter results are presented in the first row, and Summer results in the second.*
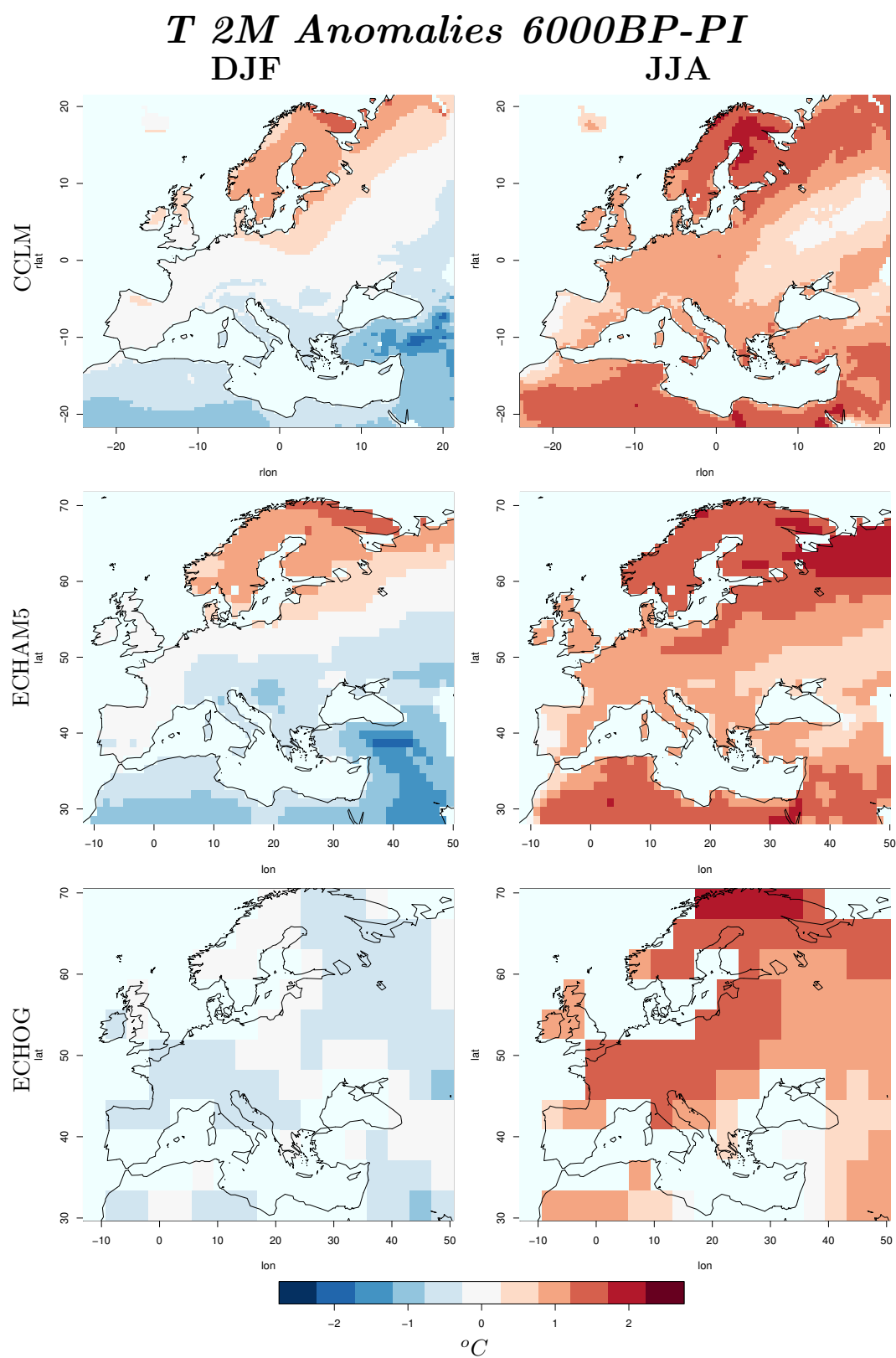
Figure 6. *Maps of Winter (left) and Summer (right) 2 meters temperature anomalies between 6000BP and the preindustrial period. The results of the three different models are presented: CCLM (top), ECHAM5 (center), ECHO-G (bottom).*

Winter
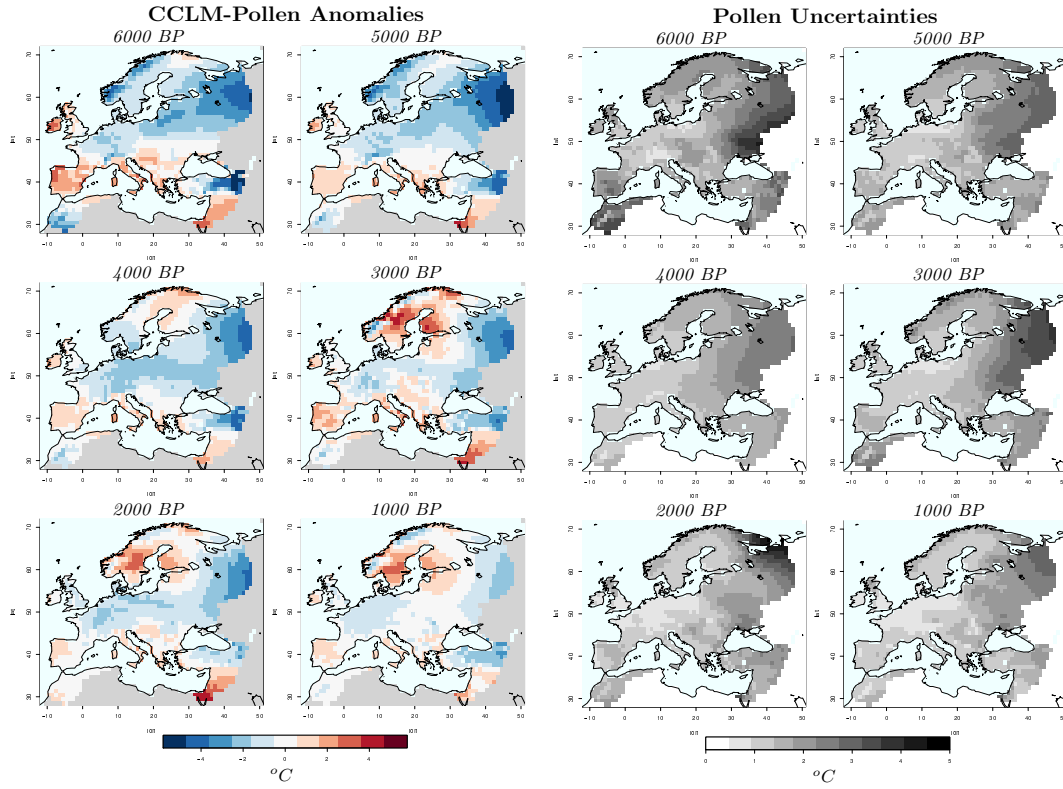
Figure 7. *Left: Maps of Winter 2 meters temperature anomalies between CCLM and Pollen-based Reconstructions for the different time slices of mid-to-late Holocene. Right: Standard error of winter temperature seasonal mean derived from the pollen-based reconstructions for each time slice of mid-to-late Holocene.*

Summer
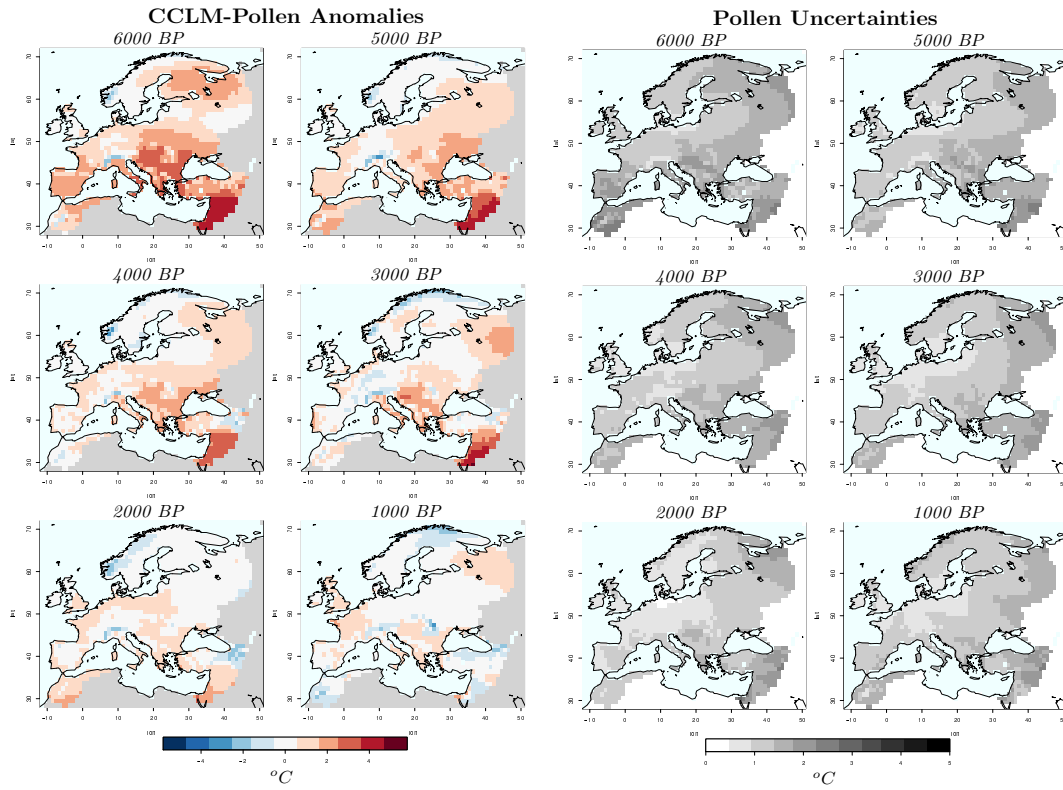
Figure 8. *As in Fig.7 but for Summer seasonal means.*
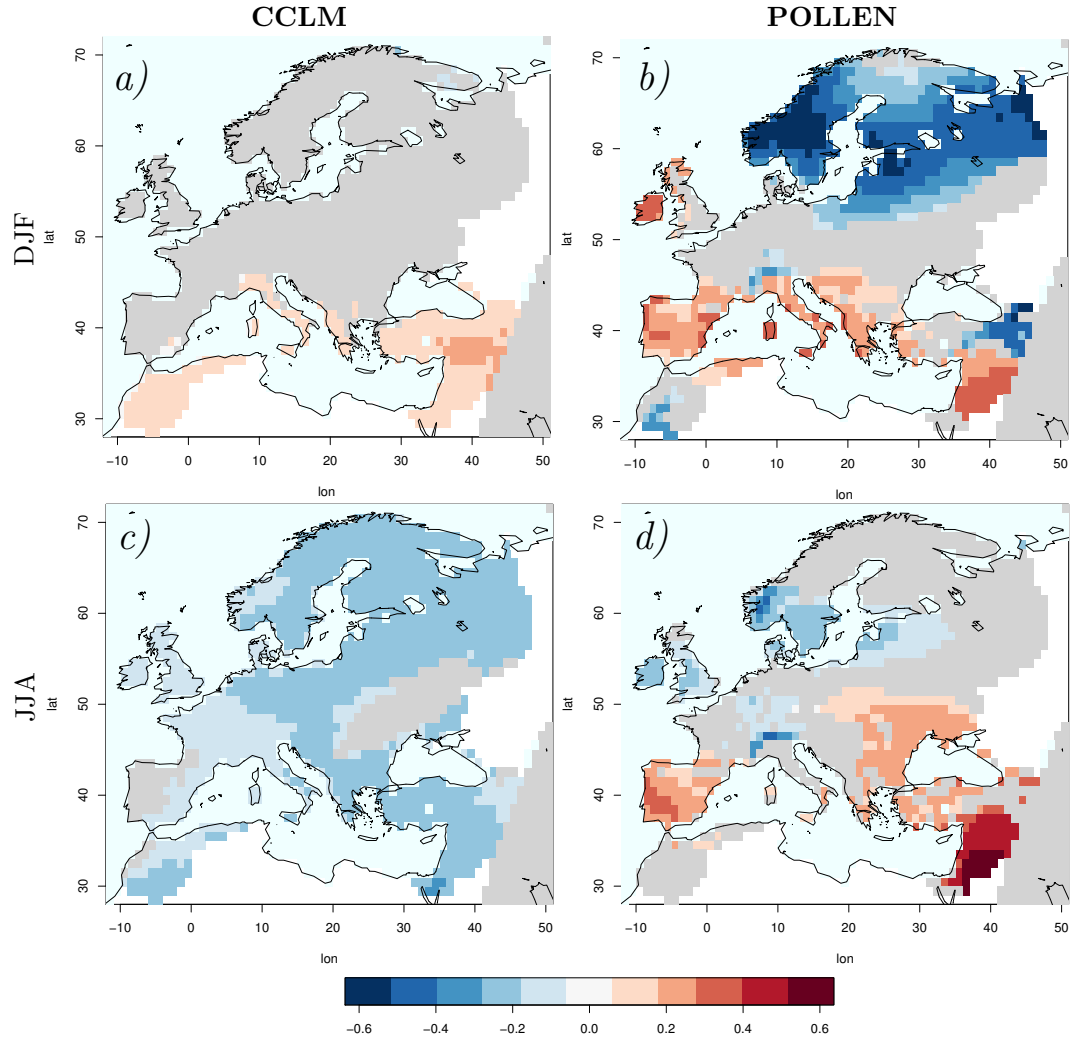
Figure 9. *Mid-to-late Holocene temporal Evolution of the anomalies, with respect to the pre-industrial period, of near surface temperature winter (first row) and summer (second row) seasonal means, derived from the CCLM simulations (left) and the pollen-based reconstruction (right). The maps show the slopes of the linear trends calculated, for every grid box, taking into consideration the uncertainties associated to the two datasets, by means of a weighted least squares method. The area masked out in gray, are the area where the trends are not significant, according to a F-test at a significance level of 10%.*
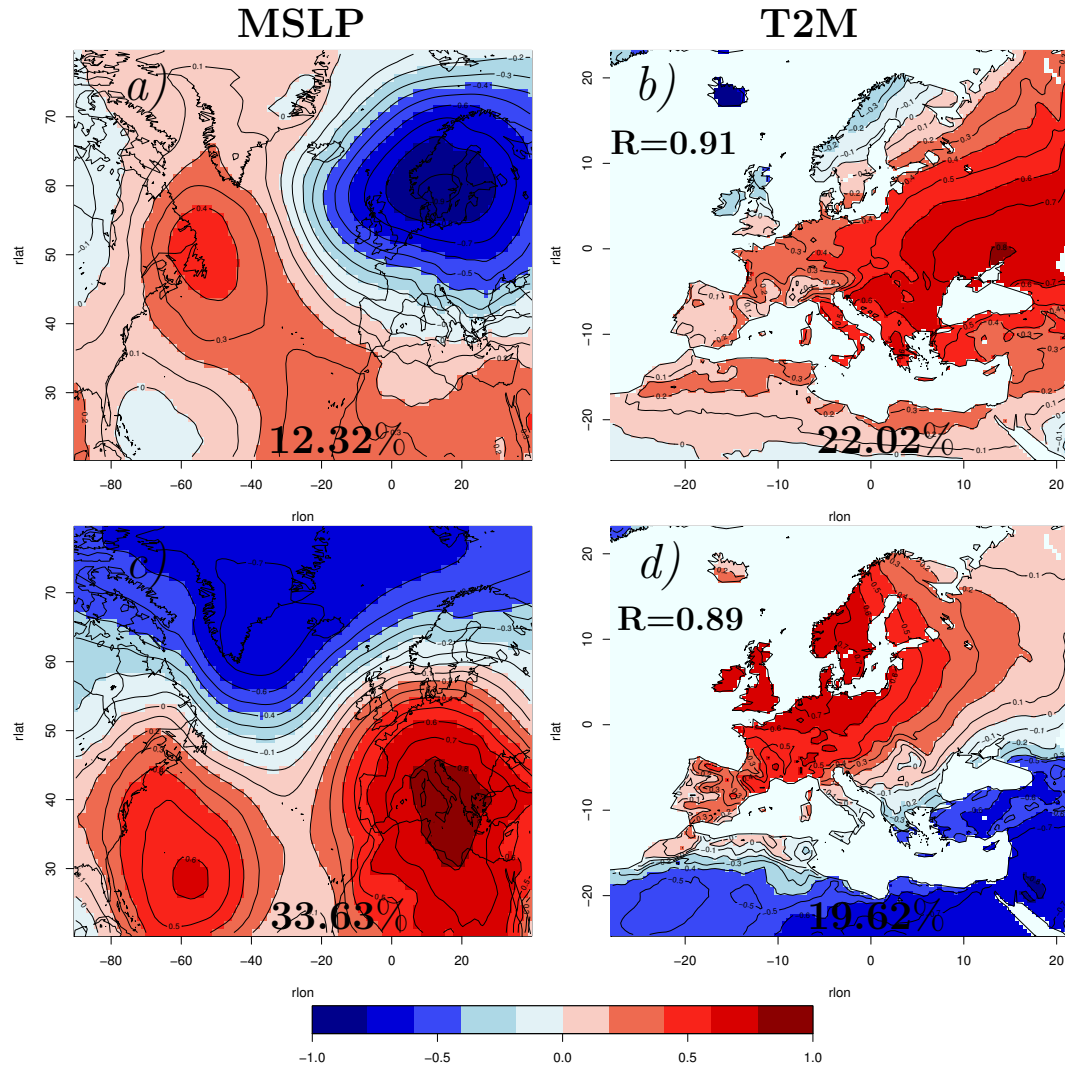
Figure 10. *Canonical correlation pattern pairs of MSLP (left) and T2M (right) in Winter, calculated accordingly to the Barnett and Preisendorfer (1987) method. Each panel illustrates the percentage of variance explained by the patterns and the canonical correlation associated with the pair. The results 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.*
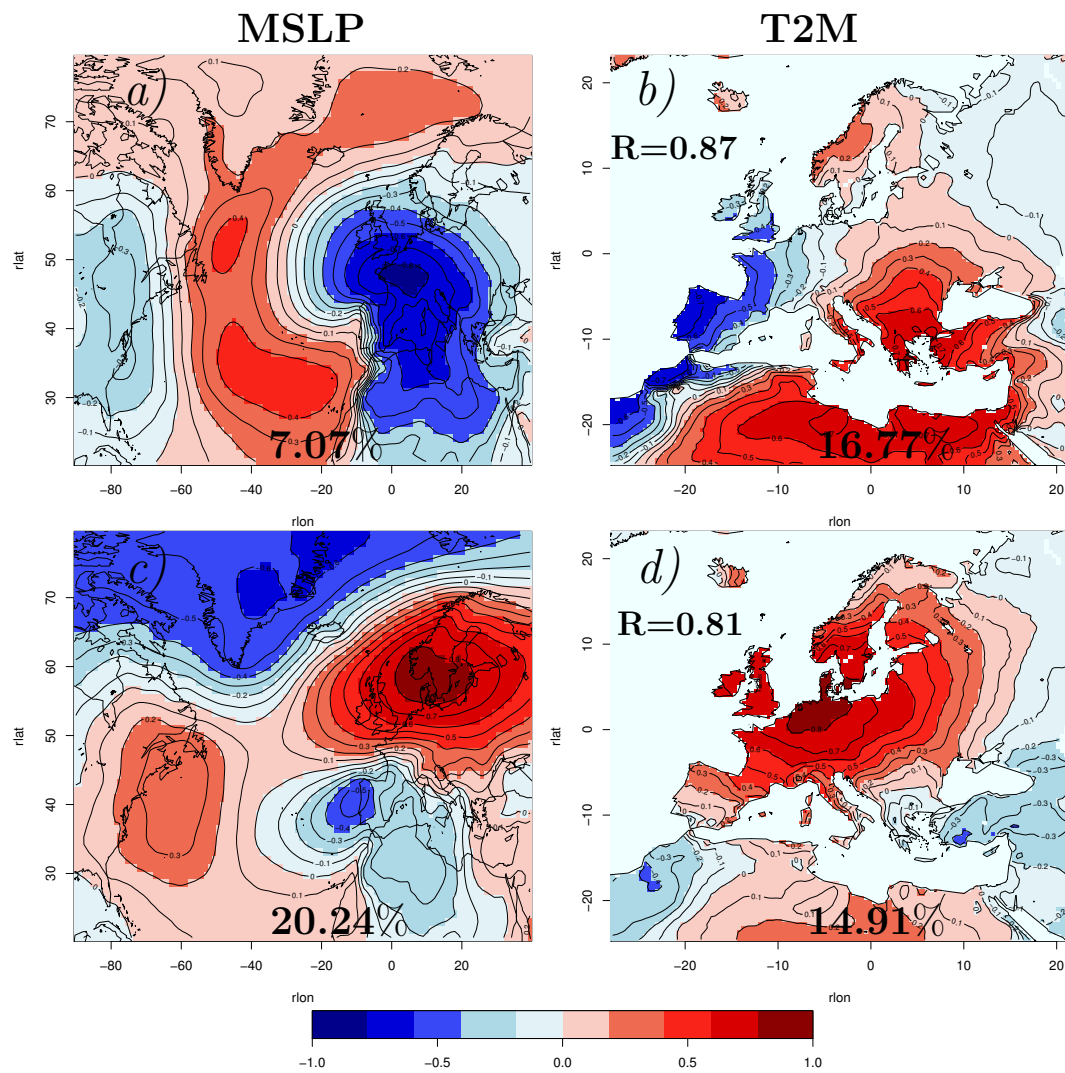
Figure 11. *As in Fig.10 but for Summer season.*
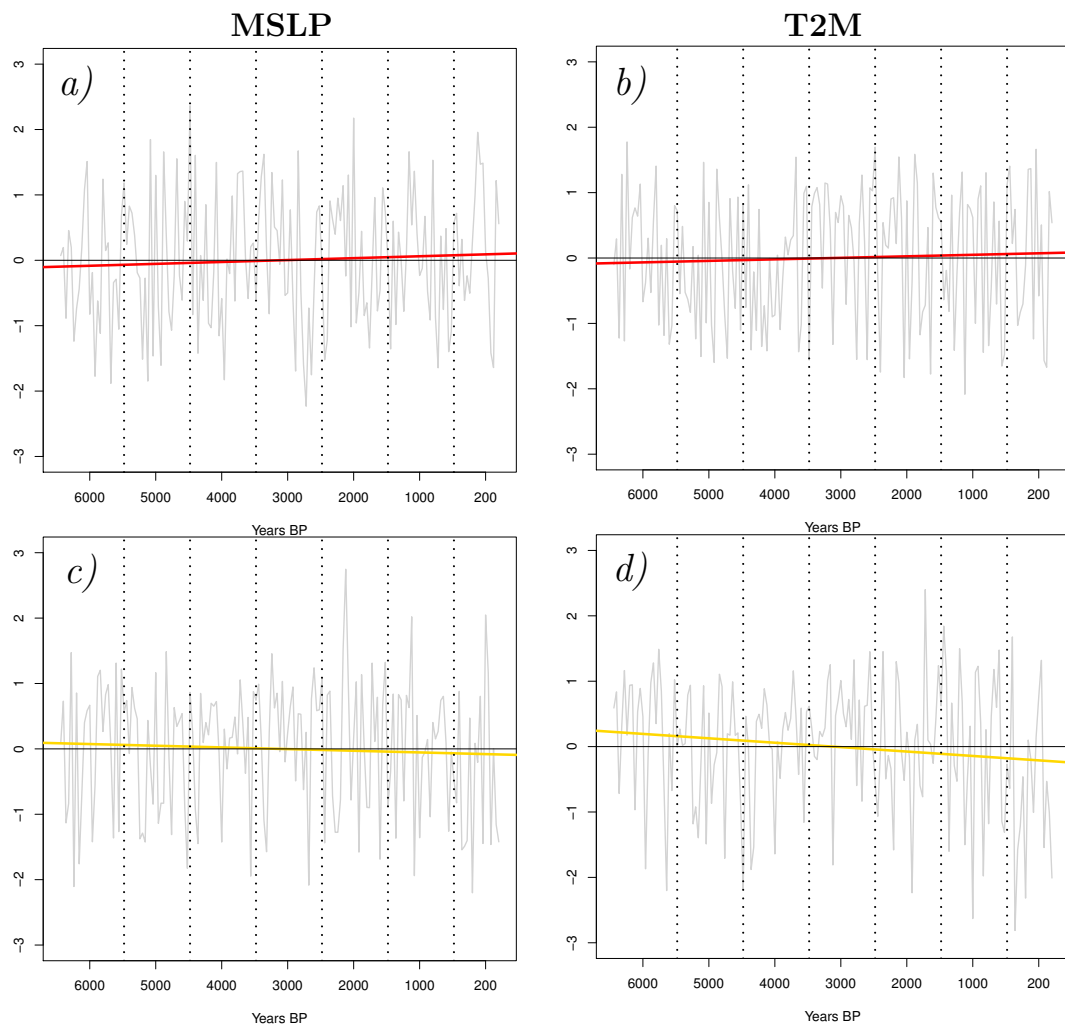
Figure 12. *Canonical score series of the first two pairs of Canonical Correlation patterns of, respectively, MSLP (left column) and 2 meter temperature (right column) winter seasonal mean anomalies*
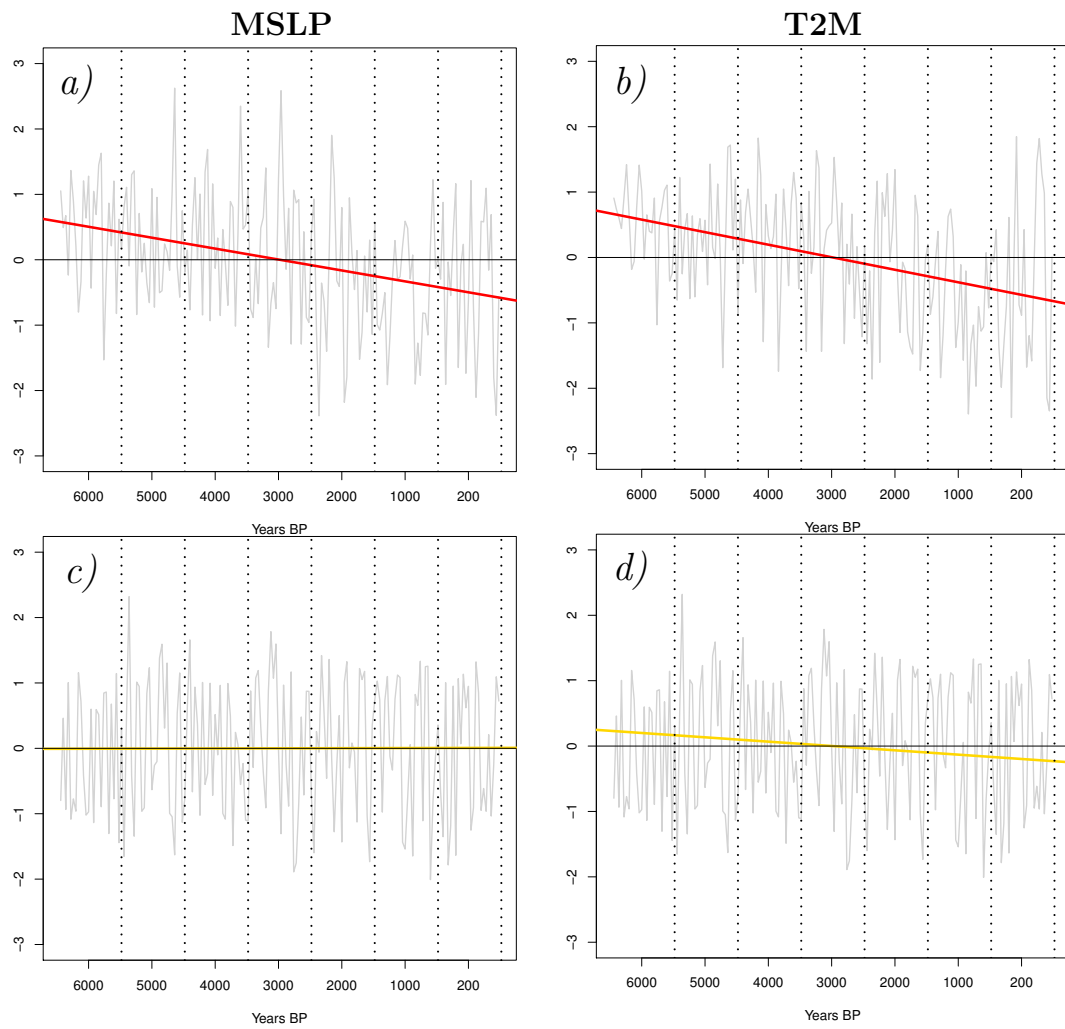
Figure 13. *As in Fig.12 but for summer*