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

Emmanuele Russo[1] and Ulrich Cubasch[1]

Institute of Meteorology - FU-Berlin Karl-Heinrich-Becker-Weg 6-10, 12165 Berlin (DE)

Correspondence to: Emmanuele Russo (emmanuele.russo@met.fu-berlin.de)

Abstract. The improvement in resolution of climate models is 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.

In this paper we present for the first time a set of high resolution simulations for different time slices of mid-to-late Holocene performed over Europe using a Regional Climate Model. Through a validation against a new pollen-based climate reconstructions dataset, covering almost all of Europe, we test the model performances for paleoclimatic applications and investigate the response of temperature to variations in the seasonal cycle of insolation, with the aim of clarifying earlier debated uncertainties, giving physically plausible interpretations of both the pollen data and the model results.

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

1 Introduction

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

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Useful instruments for the study of human impact on the climate system and its possible consequences are climate models. Climate models are not reality itself but the best possible physical representation of it.

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 past climatic conditions.

An important case of study is the evolution of European climate during mid-to-late Holocene (from 6000 years ago to present days). For this period a large number of proxy data are available and the particular configuration of the Earth orbital 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; Mauri et al., 2014).

During mid-to-late Holocene (in this study the period between 6000 years Before Present (BP) and the pre-industrial time), over northern latitudes in general, the changes in the total amount of insolation during the year were negligible (≤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). We expect that such changes would imply relevant variations in the seasonal values of surface variables.

However, evidences show that reconstructed climatic parameters, such as surface temperature, over Europe did not always follow directly the solar forcing: in fact their signals seem to have been also influenced by other complex processes (atmospheric circulation, geography, or land-surface interactions with the atmosphere).

Cheddadi et al. (1997) showed as a result of a pollen 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: in particular winters were warmer over Northern Europe even if the insolation was reduced, and summers were colder over Southern Europe despite the higher insolation. Similar results were obtained by Davis et al. (2003) who proposed an updated database of European pollen reconstructions for the entire Holocene. Bonfils et al. (2004), within the PMIP (Paleoclimate Model Intercomparison Project (Joussaume and Taylor, 1995)) collaboration, hypothesized that winter atmospheric patterns and summer soil conditions had an important influence on seasonality changes of temperature and precipitation. This has also been highlighted by a study from Starz et al. (2013) who performed a simulation for the mid-Holocene with a coupled soil-ocean-atmosphere circulation model with dynamic vegetation to better reproduce soil water storage and heat fluxes. They found that changes in soil physical properties of the model led to hampered climate anomalies and improved model results. Fischer and Jungclaus (2011) studied the evolution of the European seasonal temperature cycle in a transient mid-to-late Holocene simulation with an ocean-atmopshere global climate model, however not being able to reproduce correctly the reconstructed data over the entire region of study. Conversely in their recent work Mauri et al. (2014)

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suggested that the different response of surface variables to the solar forcing in mid-Holocene is caused by changes in atmospheric circulation patterns both in winter and in summer. In particular they proposed that during mid-Holocene, while in summer a more positive phase of a "Scandinavian pattern" of pressure anomalies caused a block situation over Northern Europe and the advection of colder air over Southern Europe, in winter 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. All the mentioned studies 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).

In this paper we employ for the first time a regional climate model, the COSMO-CLM (**CCLM**), for the investigation of the main climatic changes that characterized Europe during Mid-to-Late Holocene. A set of highly resolved simulations covering different time slices is performed and the results are compared and validated against a new pollen-based climate reconstruction dataset, which constitutes an update of the previous work of Davis et al. (2003), derived from a wider sample, covering a bigger area and adjusted with isostatic corrections.

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

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

No regional climate simulation, to our knowledge, has been ever performed for Europe during mid-to-late Holocene.

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Our work is structured as follow: in section 2 the employed methodology, including a brief description of the model and the pollen dataset, 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 evaluated and finally the interpretation of the paleo-results is presented.

2 Methods

Brewer et al. (2007), Renssen et al. (2001) and Fischer and Jungclaus (2011) have suggested that high resolution simulations of European climate during mid-to-late Holocene should help in getting more valuable results, useful for the comparison and evaluation against proxy data. In order to reduce the computational expenses of the simulations we employ the so called *time-slice* technique (Cubasch et al., 1995). The "modus operandi" consists of three steps:

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 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 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 order to set the orbital parameters corresponding to the mid-to-late Holocene configuration, we applied the routine of Prömmel et al. (2013), that allows the estimation of latitudinal and seasonal insolation at the top of the atmosphere based on Earth's orbital parameters calculated by Berger and Loutre (2002). 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

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Holocene changes in GHGs concentration to the radiative balance is negligible (less than 2W/m^2) in comparison to the effects of changes in insolation, and only the latest ones 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). For this study the model has been used 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. Table 1 shows the model configuration used in this study. Recent data of the Earth's surface physical parameters (e.g., orography, land use, vegetation fraction, and land-sea mask) were used for the simulations. The model domain shown in Fig. 1 is the one used for the Euro-CORDEX simulations (Jacob et al., 2014), extending from Southern Greenland to Western Russia in the North and from the Western Atlantic coast of Morocco to the Red sea in the South. Each simulation includes a 5 years spinup period used to let the model reach a semi-equilibrium state as suggested by Hollweg et al. (2008) .

For the model validation for present climate, the ERA-Interim (**ERAInt**) reanalysis dataset (Dee et al., 2011) and the Climate Research Unit (**CRU**) observations dataset (Harris et al., 2014) 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 ERAInt dataset, with respect to the total precipitation and 2 meter temperature. 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 and evaluated against the dataset of Mauri et al. (2015). This is the latest updated pollen-based climate reconstruction dataset for Europe and constitutes an improvement of the results of Davis et al. (2003). It is derived with the same methodology, but with a wider number of fossil and surface-samples following a more rigorous quality control. The data cover a time slice every millennium for the entire Holocene and are derived through a 4-dimensional interpolation in time and space. They are deduced with an analogue transform method and corrected with postglacial isostatic readjustment. Along with the data, a standard error estimate derived from the transform and the interpolation methods is also provided. Reconstructions contain informations on winter, summer and annual precipitation and temperature as well as a measure of moisture balance and of growing degree days over 5 degrees and are provided on a regular grid with a resolution of 1×1 longitude degrees.
In our analysis we focus only on the seasonal changes of temperature.

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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 day values of orbital parameters and greenhouse gases (sec.2), in order to test the ability of the model to properly reproduce present day climate. Additionally, this provides further knowledge about the spatial distribution of the model performances.

Temperature and Precipitation values from the present-days control run are validated, through a Kolmogorov-Smirnov (KS) non-parametric significance test at a significance level of 0.05, against the CRU and the ERA Interim datasets. The same test is conducted for evaporation and heat fluxes but against the GLDAS dataset. In (Fig. 2;Fig. 3;Fig. 4) the black dots represent the grid cells where the compared datasets are significantly not different, while coloured are the anomalies. The results show that, for temperature, the model performs well over Northern Europe during summer and winter. Winter-time results are in particularly good agreement with observations and the ERA-Interim re-analysis over Northeastern Europe and Scandinavia. However, larger deviations are present over Central Europe, Turkey and Northern Africa. In particular the model tends to simulate generally colder conditions over these regions (Fig. 2, upper row). Winter precipitation results seem to be in good agreement over a major part of the domain, with some deviations from the observations over regions with particularly complex orography, in the Northern African coasts of the Mediterranean Sea and in regions that are normally highly affected by westerlies(Fig. 3, upper row).

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

It has been shown in previous works (Hagemann et al., 2004; Christensen et al., 2008; Kotlarski et al., 2014) that, in general, regional climate models poorly simulate Southern European summer conditions. They suggest that this is most likely related to deficiencies in soil-atmosphere coupling (Seneviratne et al., 2006; Fischer et al., 2007; Seneviratne et al., 2010). In soil moisture-controlled evaporative regimes, such as the Mediterranean basin, low soil moisture contents (due probably to an underestimation of precipitations 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.

Based on these considerations, we suggest that the model reproduces warmer conditions over a wide part of Southern Europe and the Mediterranean basin, as a consequence of a wrong conversion of energy towards latent heat. This hypothesis is supported by the heat fluxes and evapotranspiration maps (Fig 4) presenting a spatial distribution of the anomalies resembling the one of temperatures. In particular the model underestimates latent heat flux and evapotranspiration, while overestimating sensible heat over corresponding area.

In summer the role of local and surfaces processes, in particular land surface evaporation, is also important for the variability of regional precipitation, while the role of atmospheric moisture advection is disminished Zveryeav and Allan (2010). Indeed wrong estimates of evapotranspiration are expected to have an high influence on local precipitation.

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

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

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

In a second step, after a validation of the model results against the pollen dataset of Mauri et al. (2015) through a KS-test for winter and summer temperature, we divide Europe in two regions, one North from 55N to 72N and one South from 35N to 50N with the goal of discriminating the effects of possible shifts in the westerlies and changes in their intensity. Analyzing the temporal evolution of temperature and the effect of the forcings, we try to assess to what extent the changes in circulation are the responsible for climatic changes in both seasons.

The validation maps (Fig. 5) show that, when compared to the pollen dataset, the CCLM performs well during summer over Northern Europe and during winter over Southern Europe with the highest anomalies over Northeastern Europe in winter ($\sim 4^oC$) and over Southern Europe in summer ($\sim 3^oC$). In accordance with these results the time evolution plots of temperature (Fig. 6) show that the data are in good agreement for winter over Southern Europe and for summer over Northern Europe. In these cases the two datasets show similar trends. The most interesting situations arise in summer over Southern Europe and in winter over Northern Europe. In the first case not only the model simulates always warmer conditions, but the trend of the two datasets are anticorrelated. In the second, instead, the trends are both negative, but the slopes in the two cases are significantly different, suggesting the fact that the driving process could be the same but probably the model is underestimating its effects or variability.

3.3 Interpretation of the Paleo-Results

In this section possible interpretations of the differences arising between the pollen dataset and the CCLM outputs are proposed by means of correlations with trend of insolation and changes in atmospherical circulation patterns.

The trends of northern european summer temperature present both for the pollen and the CCLM data a negative trend (Fig. 6). This suggests that their response in this case could be highly related to the changes in insolation (Fig. 7). Over Southern Europe instead, while the CCLM data seem to be driven by the insolation changes, the pollen data present an opposite trend.

According to Bonfils et al. (2004) and Starz et al. (2013), the presence of more moisture in the soil during mid-Holocene, due to more precipitation, is responsible, as a direct effect of higher insolation, for cooler conditions due to stronger latent heat transfer. According to the previous analyses of model's heat-fluxes we suggest that the reason why the model does not manage to capture this trend could be most probably due to a wrong reproduction by the model of soil-atmosphere heat exchanges.

In winter, instead, the situation is inverted. While in the North the trend of the simulated temperature, even if slightly negative, does not correctly agree with the highly negative trend exhibited by the pollen data, in the South, the results are particularly close and show a much more similar behaviour. While over northeastern Europe the wide bias is likely related to high pollen data uncertainty (Fig. 5) , partly due to the fact that seasonal values derived from pollen in this area are biased towards the winter season, in the other cases the anomalies are likely to be connected to a wrong representation by the model of the variability of atmospheric circulation patterns.

In order to investigate changes in atmospheric circulation during mid-to-late Holocene, in Fig. 8 we present the Empirical Orthogonal Function (**EOF**) analysis of the anomalies of mean sea level pressure standardized to the pre-industrial period and in Fig. 9 the trends of the time expansion of their principal components. In summer the first EOF shows that the model reproduces similar conditions in atmospheric circulation between mid-Holocene and pre-industrial times. Nevertheless, the second pattern arising from the EOFs resembles the positive phase of the Summer North Atlantic Oscillation (SNAO) (Folland et al., 2009). The negative trend of the time expansion of the principle component of this pattern suggests that clearer skies were present over Northern Europe at mid-Holocene that, together with higher insolation, would justify not only the observed warmer conditions over this area but also the good agreement between pollen data and model results. For southern Europe instead, the changes in the circulation alone would not be enough to justify the observed changes in surface temperature in comparison to the changes in the radiation budget ($\sim 30W/m^2$) and the role of land-atmosphere coupling needs to be considered (Seneviratne et al., 2006). Our hypothesis differs from that of (Mauri et al., 2014) in that enhanced soil moisture at mid-Holocene, resulting from the excessive summer precipitation linked to the SNAO presence, together with increased summer insolation, strongly augmented latent cooling, amplifying the surface temperature anomalies. 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 drier and warmer conditions.

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

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

In winter, the hypotheses of Mauri et al. (2014), of a more pronounced positive phase of the North Atlantic Oscillation during mid-Holocene, are supported by the maps of the mid-to-late Holocene linear trends of temperature derived from the pollen dataset(Fig. 11).

From the EOF analysis of MSLP anomalies we can affirm that the model seems to reproduce well the spatial pattern of the NAO when compared to present day configuration calculated from ERAInterim reanalysis for the period 1979-2013 (not shown) and, according to the correlation maps, even its effects. Nevertheless, the model simulates a lower weight of the NAO ($\sim 40\%$) for mid-to-late Holocene in comparison to present-days conditions ($\sim 55\%$), with a minor influence of westerly winds. Additionally, the trend of the temporal evolution of the principal components of the first EOF, even if negative, seems not to be pronounced enough in order to reproduce a response in temperature comparable with the respective results of pollen data. At the same time a high impact of the second circulation pattern, consisting in this case in a blocking system centered over the Baltic area would justify the pattern of the anomalies between the two datasets in winter, with colder conditions over central Europe and a warmer climate over part of Southern Europe, Scandinavia and British Isles.

4 Conclusions

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

The performances of the model are tested for present day conditions. Then the temperature values from mid-to-late Holocene "time slice" simulations are compared against a new pollen-based climate reconstructions dataset, covering almost all of Europe. Along with the test of model performances for paleoclimate applications, the response of the climate system to changes in the seasonal cycle of insolation is also investigated, in order to give a new interpretation of the proxy data and to confirm or deny previously affirmed theories.

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

Over Southern Europe wintertime temporal behaviour and spatial distribution of temperature in the two datasets are comparable. A significant cold bias, instead, is present 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.

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 prediction.

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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

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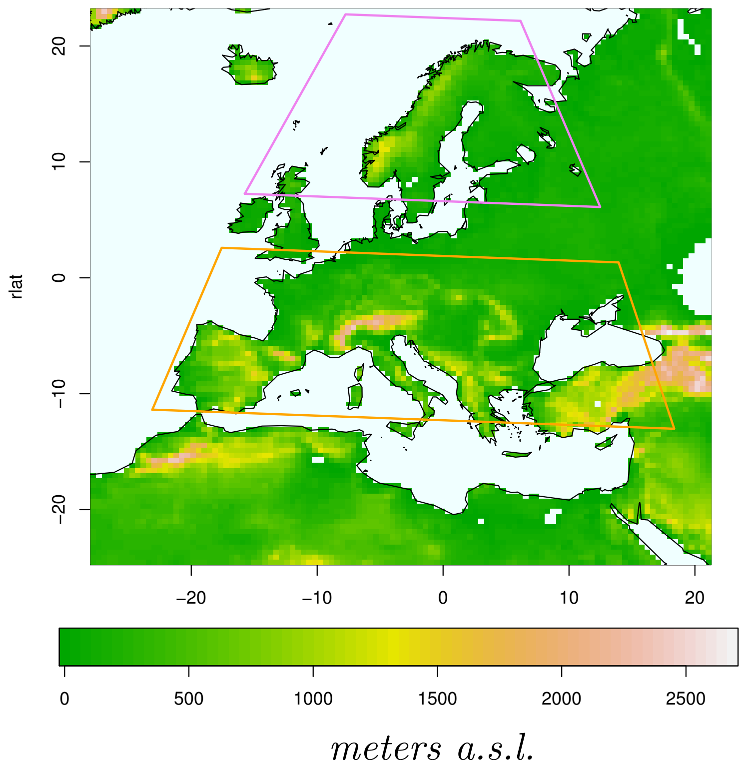

Figure 1. *Orography Map of the COSMO-CLM simulation domain in rotated coordinates. Highlighted are, in* ***orange*** *, the area comprised between 10W:40E and 35N:50N and, in* ***purple****, the area comprised between 10W:40E and 55N:72N, for which field means of surface variables derived from the two datasets are compared.*

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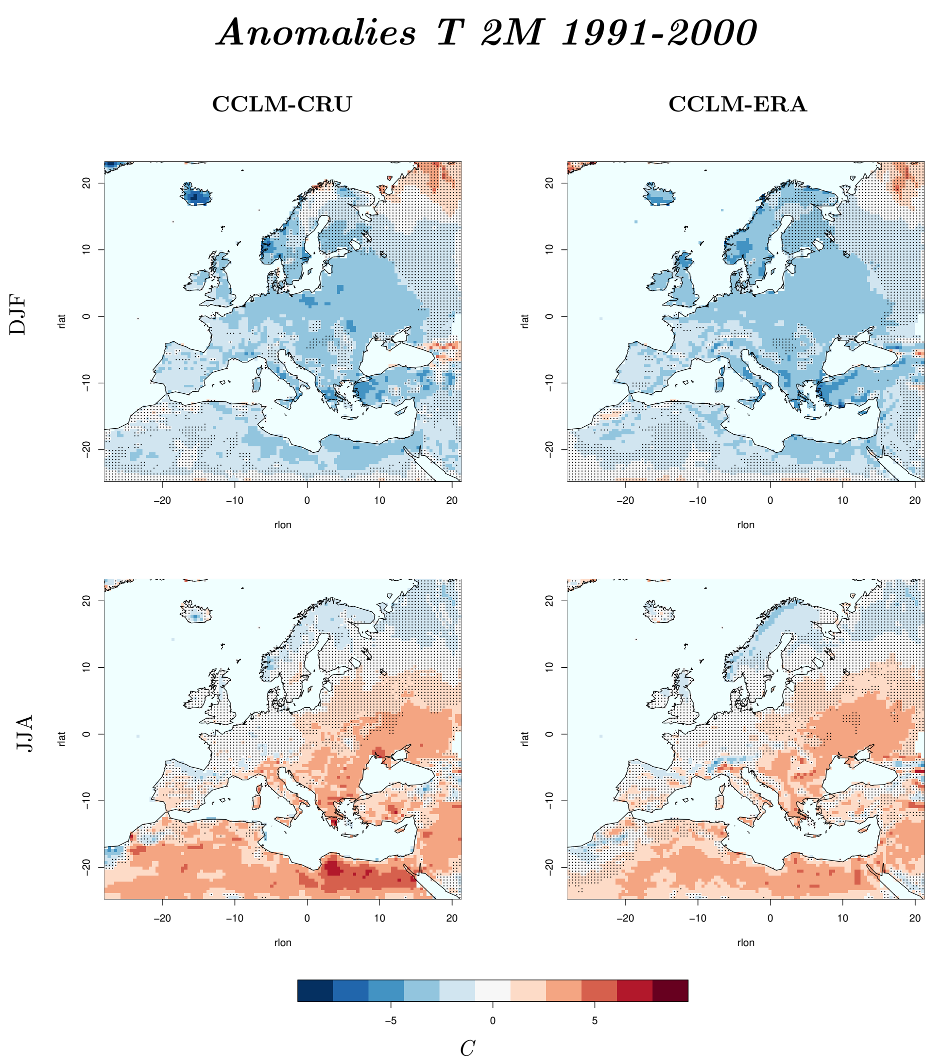

Figure 2. *2 meter temperature anomalies between model results, CRU (left) and ERA-Interim dataset (right). The area with a point represent the grid cells where the anomalies between the two datasets are not significant, according to a KS-test at a significance level of 0.05.*

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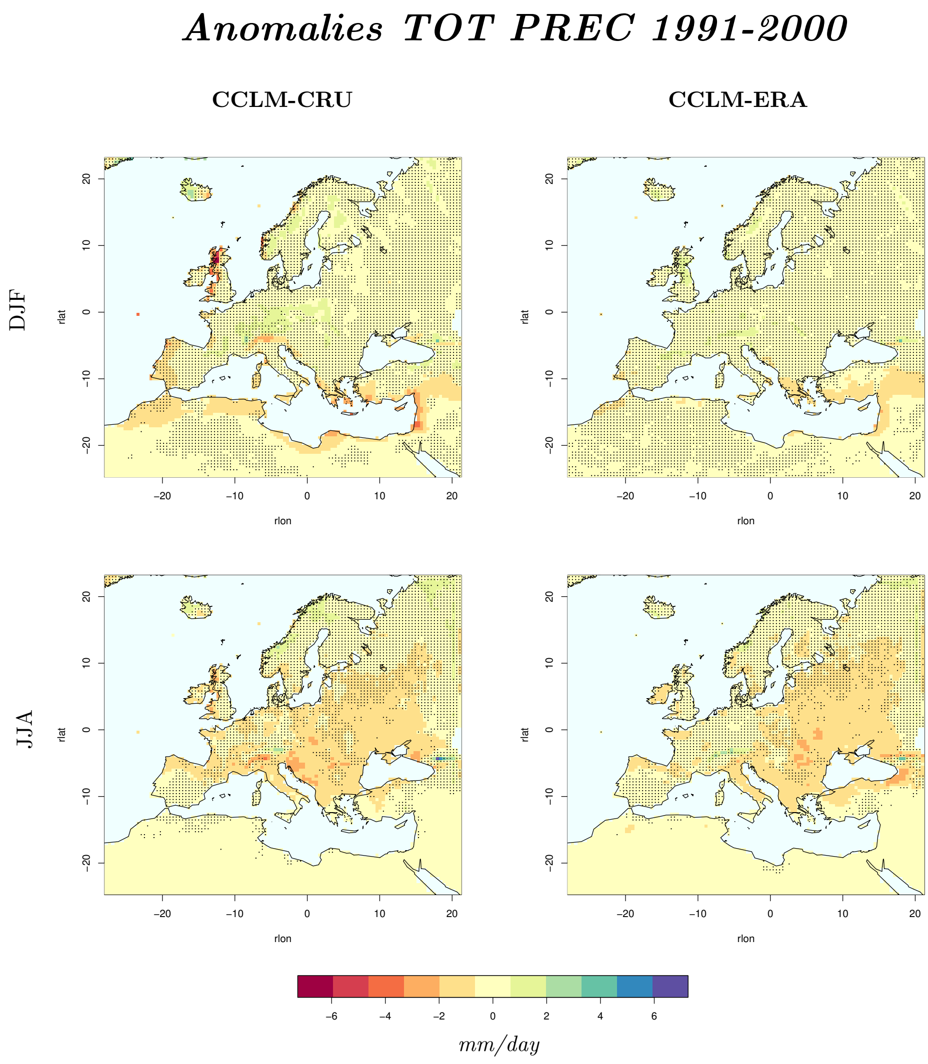

Figure 3. *As Figure 3 but for Total Precipitations anomalies.*

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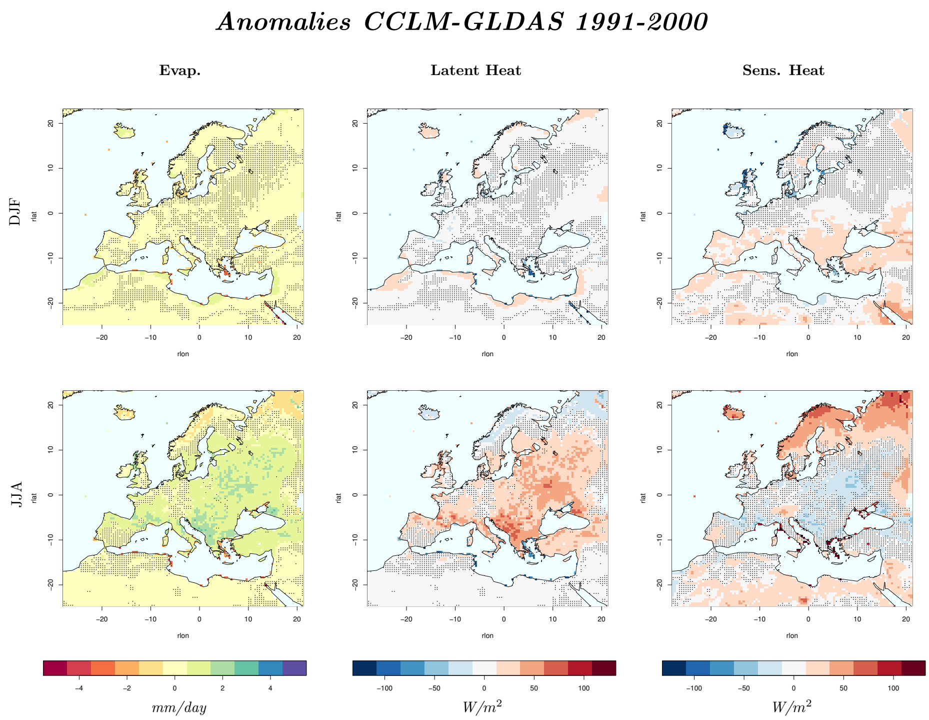

Figure 4. *As Figure 3 but for surface evapotranspiration and heat fluxes anomalies between CCLM results and the GLDAS dataset. The sign of the fluxes is taken negative when their direction is upwards. Positive (negative) biases indicate that the model underestimates (overestimates) the simulated variable.*

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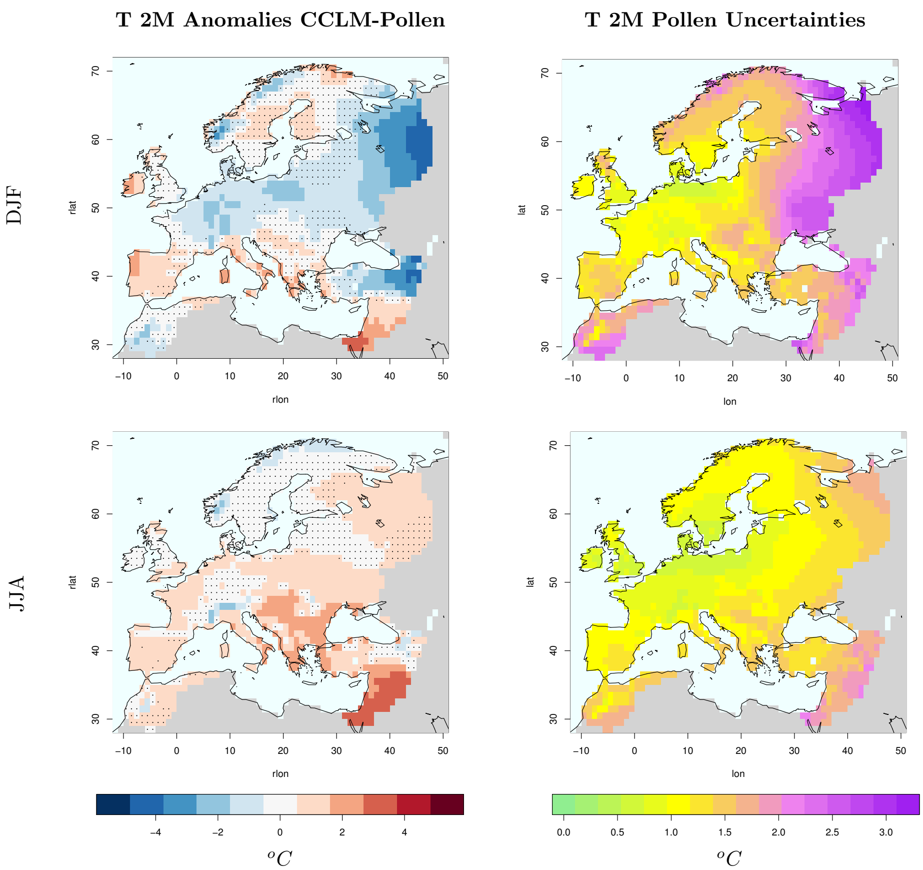

Figure 5. *Left: Map of the differences between the seasonal values of* ***winter*** *and* ***summer*** *2 meter temperature averaged over all the mid-to-late Holocene time slices. Again the black dots represent the grid cell for which the two datasets are not significantly different, according to a KS-test, at a significance level of 0.05. Right: Maps of temperature Standard Error derived from the Pollen data.*

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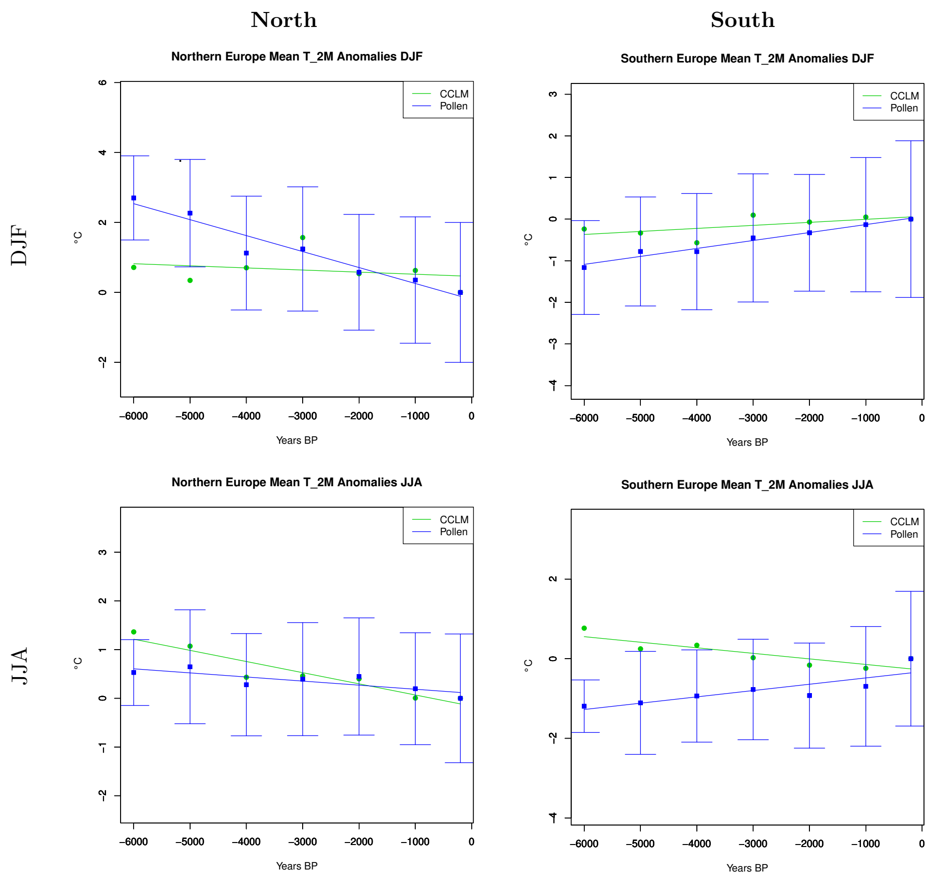

Figure 6. *Mid-to-late Holocene seasonal trends of 2 meter Temperature for Pollen and CCLM results; in the upper row is represented the regional mean for the area in between -10W:40E and 55N:72N, while in the lower row are shown the regional means for the area in between 10W:40E and 35N:50N. The bars represent the regional standard error associated to the pollen results.*

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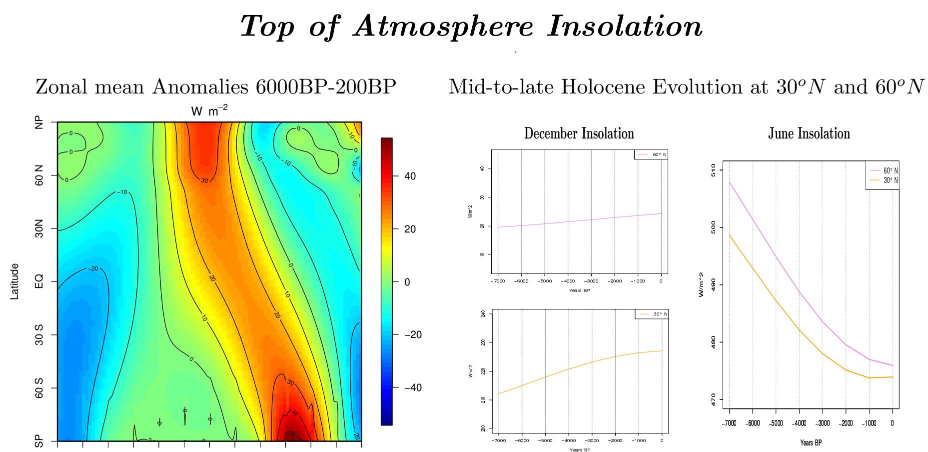

Figure 7. *(left) Anomalies of zonal mean insulation on top of the atmosphere between pre industrial period* **PI** *and 6000 years BP. (Right) Trends of* ***December*** *and* ***June*** *Incoming radiation on top of the Atmosphere.*

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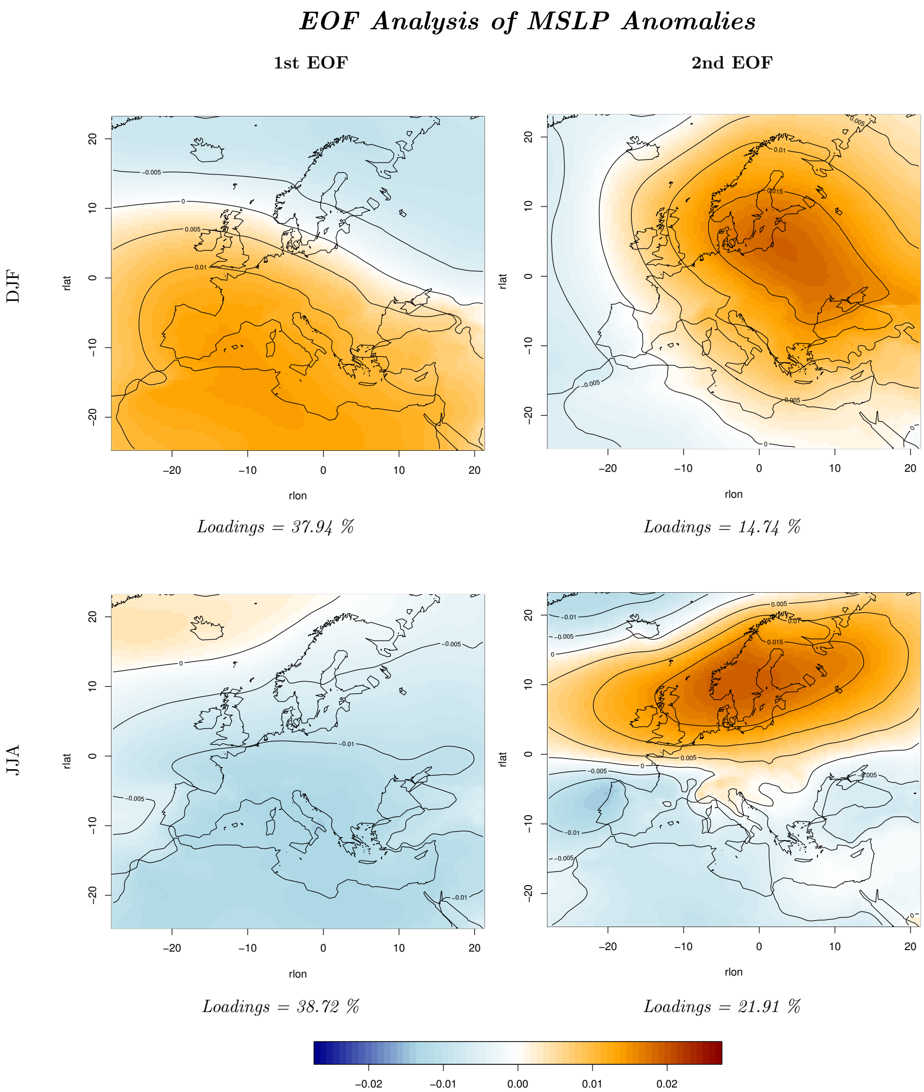

Figure 8. *First two EOFs of Mean Sea Level Pressure anomalies, derived from the CCLM simulations, standardized to the pre-industrial time, for* **summer***(upper row) and* **winter***(lower row)*

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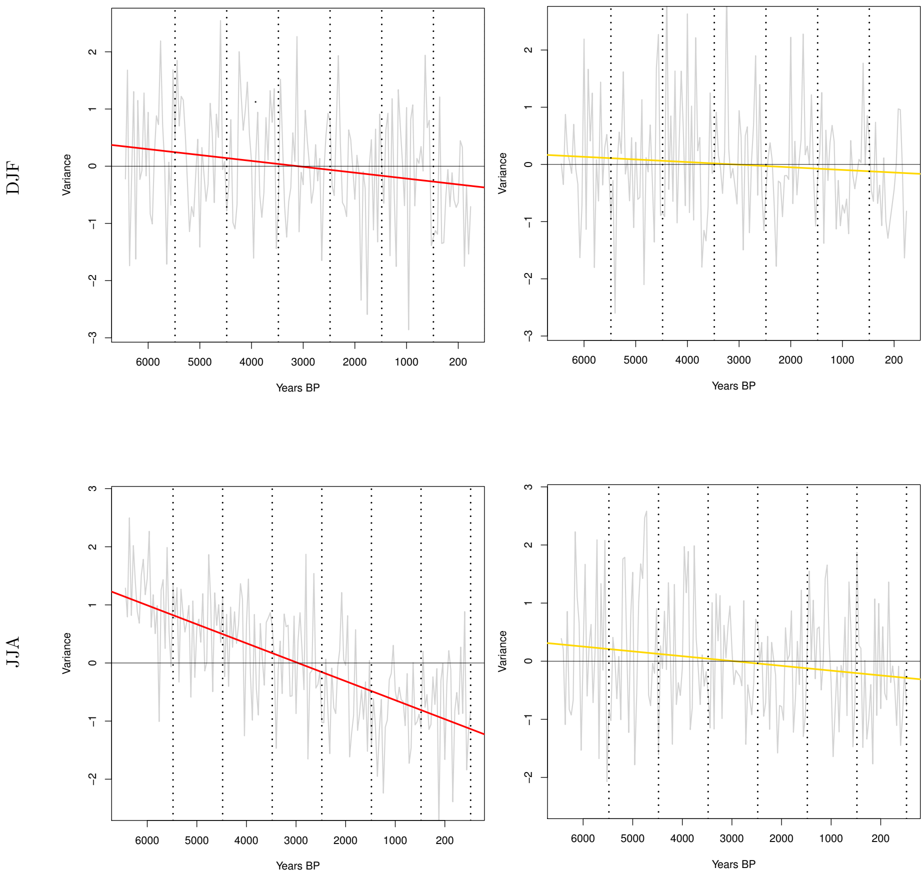

Figure 9. *Time expansion of Principal Components of the first two EOFs, respectively for* ***summer****(upper row) and* ***winter****(lower row)*

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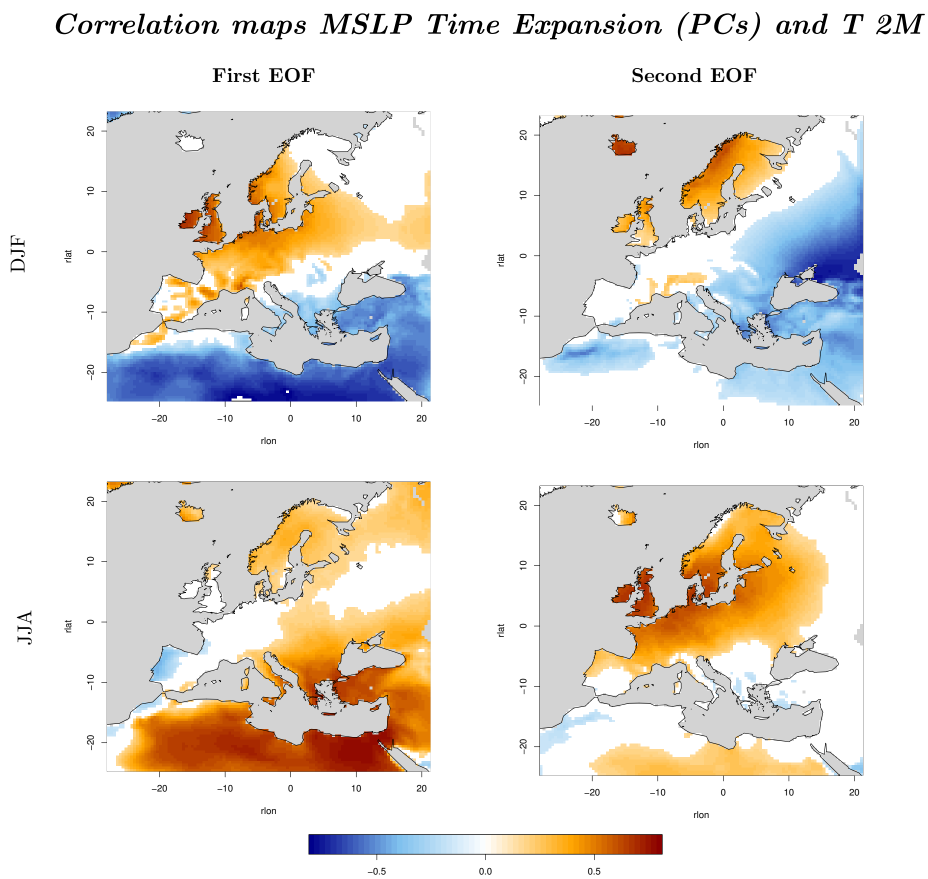

Figure 10. *Kendall correlation maps between time evolution of* **summer***(bottom) and* **winter***(top) 2 meter temperatures and the time expansion of the principal components of the respective first two EOFs of the MSLP anomalies. The area where the correlation is not significant at a level of 0.05 is masked in white.*

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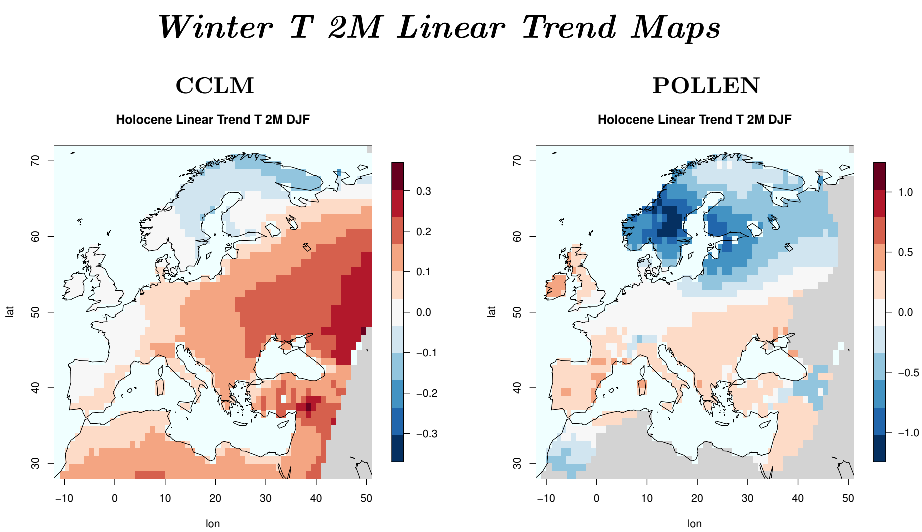

Figure 11. *Linear trend maps of winter 2 meter temperatures over mid-to-late Holocene.*