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The influence of atmospheric circulation on the mid-Holocene climate of Europe: a data–model comparison

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Abstract. The atmospheric circulation is a key area of uncertainty in climate model simulations of future climate change, especially in mid-latitude regions such as Europe where atmospheric dynamics have a significant role in climate variability. It has been proposed that the mid-Holocene was characterized in Europe by a stronger westerly circulation in winter comparable with a more positive AO/NAO, and a weaker westerly circulation in summer caused by anti-cyclonic blocking near Scandinavia. Model simulations indicate at best only a weakly positive AO/NAO, whilst changes in summer atmospheric circulation have not been widely investigated. Here we use a new pollen-based reconstruction of European mid-Holocene climate to investigate the role of atmospheric circulation in explaining the spatial pattern of seasonal temperature and precipitation anomalies. We find that the footprint of the anomalies is entirely consistent with those from modern analogue atmospheric circulation patterns associated with a strong westerly circulation in winter (positive AO/NAO) and a weak westerly circulation in summer associated with anti-cyclonic blocking (positive SCAND). We find little agreement between the reconstructed anomalies and those from 14 GCMs that performed mid-Holocene experiments as part of the PMIP3/CMIP5 project, which show a much greater sensitivity to top-of-the-atmosphere changes in solar insolation. Our findings are consistent with data–model comparisons on contemporary timescales that indicate that models underestimate the role of atmospheric circulation in recent climate change, whilst also highlighting the importance of atmospheric dynamics in explaining interglacial warming.

1 Introduction

Global Climate Models (GCMs) are essential tools for investigating future climate change but their ability to simulate future climate remains uncertain, especially at the regional scale (Hawkins and Sutton, 2009; Deser et al., 2012). One of the main sources of uncertainty in determining regional climate change in the mid-latitude regions such as Europe is the atmospheric circulation, a feature of the climate system that models have difficulty to simulate (Gillett, 2005; van Ulden and van Oldenborgh, 2006; Woollings, 2010; Vial and Osborn, 2012; Brands et al., 2013).

One way to reduce model uncertainty is to perform GCM simulations of past climates, which can then be independently evaluated using palaeoclimate archives. The mid-Holocene (MH, 6000 years BP) has become a standard benchmark time period for this kind of data–model comparison, being sufficiently distant in the past to be substantially different from the present but close enough that the model boundary conditions are well known and actual climate conditions can be reconstructed in some detail. Climate forcing during the MH was primarily the result of an amplified seasonal insolation cycle, which led to higher than present insolation (+5 % at 45° N) in summer and lower insolation (−5 % at 45° N) in the winter, while ice-sheet extent and trace gas concentrations were similar to modern-day pre-industrial values (Bonfils et al., 2004). The MH is also a period rich in palaeoecological records (Wanner et al., 2008), providing the spatial coverage suitable for continental-scale data–model comparison that is also comparable with the grid-box resolution of climate models (Davis et al., 2003).

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It is for these reasons that the MH has been the focus of major data–model comparison projects such as the Palaeo Model Intercomparison Project (PMIP) (Joussaume and Taylor, 1995; Masson et al., 1999), and its successors PMIP2 (Braconnot et al., 2007a, b) and PMIP3/CMIP5 (Braconnot et al., 2012), that aim at evaluating climate models and provide a better understanding of climate change and climate feedbacks. Previous data–model comparisons have shown that climate models fail to simulate the summer cooling observed by proxy data over Southern Europe that is contrary to the increase in summer insolation in the MH (Davis and Brewer, 2009), and the strong winter warming observed over parts of northern Europe (Masson et al., 1999; Bonfils et al., 2004; Brewer et al., 2007) that is also contrary to the decrease in winter insolation in the MH. Nevertheless, models have still been able to demonstrate high-latitude winter warming through the action of local feedbacks such as sea ice and vegetation (Wohlfahrt et al., 2004; Braconnot et al., 2007b; Otto et al., 2009).

Atmospheric circulation has been identified as a significant cause of recent changes in the climate of Europe in both summer and winter (Jones and Lister, 2009; Küttel et al., 2011; Della-Marta et al., 2007; Ionita et al., 2012). In summer, recent extreme warm events such as those that occurred during the summers of 2003 and 2010 (Barriopedro et al., 2011; Black, 2004) were mainly driven by a persistent blocking high-pressure system located over central and eastern Europe which led to stable cloud-free skies and warm air advection from the south (Della-Marta et al., 2007). In the late 20th century, winters in Europe were characterized by a persistent positive phase of the AO/NAO, which resulted in strengthened westerlies and mild, wet conditions over northern Europe, while southern Europe experienced drier, cooler conditions leading to severe drought in many parts of the Mediterranean (Hurrell et al., 2003).

Based on palaeoclimate reconstructions, previous studies have suggested that Europe may have experienced analogous changes in atmospheric circulation during the MH. Antonsson et al. (2008) showed that anticyclonic conditions over Scandinavia may have accounted for warmer summers reconstructed from pollen records in this region, whilst in winter, many authors have suggested the MH was characterized by a positive AO or NAO (Nesje et al., 2001; Davis and Stevenson, 2007; Rimbu et al., 2004; Davis and Brewer, 2009). Climate model simulations in contrast show little change in winter in the mean-state atmospheric circulation as well as in inter-annual and decadal AO/NAO (Arctic Oscillation, North Atlantic Oscillation) variability during the mid-Holocene (Gladstone et al., 2005; Lu et al., 2010), while changes in atmospheric circulation in summer have not been widely investigated using models (Bonfils et al., 2004; Braconnot et al., 2007a).

Here we investigate the potential role of changes in atmospheric circulation on the MH climate of Europe based on a new pollen-based reconstruction with a greatly improved 6 ka data set compared to previous studies. This includes improvements in the geographical coverage of sites that allow better resolution of the spatial patterns of climatic anomalies associated with changes in atmospheric circulation. We also reconstruct a broader range of climate parameters that includes winter and summer precipitation and temperature change based on a larger and higher-quality modern pollen calibration data set. The role of atmospheric circulation is investigated by comparing reconstructed climate with MH experiments performed by 14 GCMs as part of the CMIP5/PMIP3 project (Braconnot et al., 2012), and with analogous modern climate anomalies associated with seasonal atmospheric circulation modes over Europe.

2 Methods

Our climate reconstruction is based on an updated fossil and modern pollen data set compiled from the European Pollen Database (EPD) (Fyfe et al., 2009; Davis et al., 2013), the PANGAEA data archive, and digitized and raw count data from other sources (Collins et al., 2012). European MH climate was reconstructed at each site using a PFT-based Modern Analogue Technique following Davis et al. (2003) based on a training set of 4174 modern pollen samples and 4287 mid-Holocene samples from 756 sites. This data set represents a substantial improvement compared with data sets used in previous data–model comparisons. Our fossil pollen data set includes 48 % more sites compared with Davis et al. (2003) and used by Brewer et al. (2007), and 143 % more sites compared to Cheddadi et al. (1997), with this improvement in data coverage spread throughout Europe (Fig. 1). The modern pollen data set has 81 % more sites compared with Davis et al. (2003) and 221 % more sites compared with Cheddadi et al. (1997). Following Davis et al. (2003), we only used sites with chronologies based on radiometric or other independent dating (Giesecke et al., 2013). This contrasts with most previous studies (Huntley and Prentice, 1988; Guiot et al., 1993; Cheddadi et al., 1997; Wu et al., 2007; Bartlein et al., 2010) which have relied heavily on the data set of Huntley and Birks (1983) where around 35 % of the sites had no 14C dates or other independent dating control (Guiot et al., 1993). In addition to existing data quality checks on the surface sample training set (Davis et al., 2013) we also undertook a further check on the geo-referencing using a high-resolution digital elevation model (DEM) (Jarvis et al., 2008). Uncertainty in the geo-referencing was identified as unacceptable where the altitude for the site given in the metadata differed by greater than 250 m from that suggested by the latitude and longitude, leading to the exclusion of 440 sites from the Davis et al. (2013) data set.

The reconstructed climate anomalies for each of the fossil sites were calculated using the R package "rioja" (Juggins, 2013) then interpolated onto a uniform spatial grid using a 4-D thin plate spline from the R package "fields"

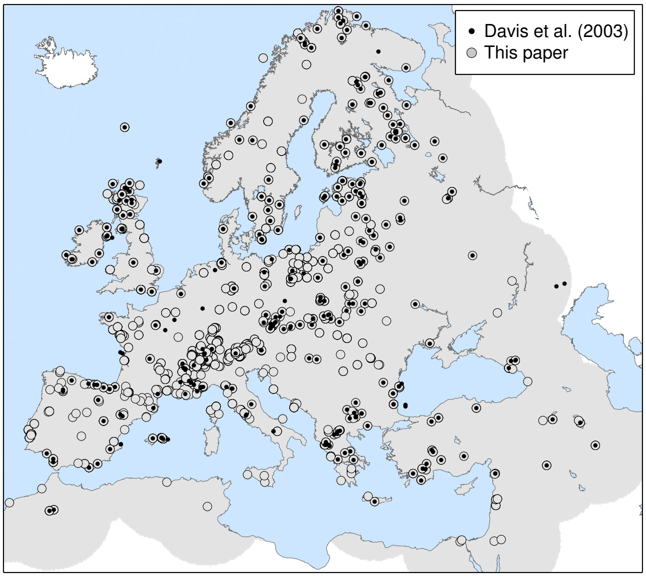

Figure 1. Spatial distribution of pollen sites (open circles) used to reconstruct the climate for the mid-Holocene. The number of sites analysed represents an increase of 48 % compared to Davis et al. (2003) (black dots). Interpolated climate values were limited to a distance of 500 km from the pollen site location (grey area).

(Fields Development Team, 2006), as also used by Davis et al. (2003). This method interpolates through time on to the chosen time slice (6000 BP), reducing the problem of temporal "blurring" associated with traditional methods that integrate all the samples within a wide time window, for instance 6000 BP ±500 years (e.g. Cheddadi et al., 1997). The latter time window approach can result in samples being treated as concurrent, when in fact they can be up to 1000 years distant from each other and up to 500 years from the target time. Using our 4-D method, we reconstructed the climate parameters of summer and winter temperatures and precipitation that have been widely used in previous pollen–climate studies (Bartlein et al., 2010). An evaluation of the climate reconstruction method based on n-fold leave-one-out cross-validation is shown in Table 1. This shows that our transfer function has robust skill in all parameters, although winter precipitation is significantly weaker than the other parameters. This can be attributed to the difficulty of reconstructing winter precipitation from areas where much of the precipitation falls as snow, such as northern Europe. However, comparisons with other reconstructions of winter precipitation based on other proxies from sites in northern Norway and Germany over the Holocene show good agreement (Mauri et al., 2014).

Uncertainties in our gridded reconstruction were calculated as a combination of (1) the standard error of the combined uncertainty of the samples within each grid square (Bartlein et al., 2010), and (2) the standard error of the interpolation (Fields Development Team, 2006). We also applied an interpolation limit of 500 km from the nearest data point, which represents a conservative boundary compared to the 1500 km limit established by Davis et al. (2003) for pollen-based climate reconstructions. Maps of uncertainty for the reconstructions are shown in Fig. 2 and indicate that uncertainties are generally lowest in areas with high site/sample density such as central Europe, and are highest where site/sample density is lowest such as in the far south and east of the study area.

Table 1. Performance of the pollen–climate transfer function based on n-fold leave-one-out cross-validation. For each climate variable we report the coefficient of determination (r^2), the root mean square error (RMSE) and the actual error (Birks and Seppa, 2004).

Climate parameter	Correlation (r^2)	RMSE	Uncertainty
$T_{(DJF)}$	0.85	2.78	±1.67 °C
$P_{(DJF)}$	0.49	28.8	±5.37 mm month^{-1}
$T_{(JJA)}$	0.71	2.59	±1.61 ºC
$P_{(JJA)}$	0.78	17.6	±4.20 mm month^{-1}

We compare our climate reconstruction with the results of MH experiments performed by 14 different GCMs as part of the PMIP3/CMIP5 project. The GCMs consist of nine fully coupled Ocean–Atmosphere (OA) models and five fully coupled Ocean–Atmosphere–Carbon (OAC) models (Table 2). In this paper we primarily compare our data-based reconstruction with the multi-model ensemble mean, which we believe provides the best illustration of general model behaviour (IPCC, 2013).

Modern teleconnection indices for the winter AO and the summer Scandinavian pattern (SCAND) were taken from NOAA (2011) based on Thompson and Wallace (1998) and Barnston and Livezey (1987) respectively.

The SCAND (also known as EU1 in Barnston and Livezey, 1987) is defined as the pressure gradient between Scandinavia and secondary areas extending from southwestern Europe through to eastern Russia and western Mongolia. A negative/positive SCAND is associated with lower/higher pressure over Scandinavia and western Russia, and higher/lower pressure in the surrounding secondary regions. A positive phase of the SCAND in summer usually results from a blocking anticylone over Scandinavia and western Russia resulting in warmer and drier conditions over Scandinavia and a southwards shift of the storm tracks accompanied by higher precipitation rates and lower temperatures over southern Europe (Fig. 3). Some authors have noted the limited nature of the SCAND teleconnection in summer when mid-latitude atmospheric circulation is at its weakest (Bueh and Nakamura, 2007), but others have found that it nevertheless has a significant effect on surface climate (Ionita et al., 2012; Macias-Fauria et al., 2012).

Table 2. Details of the 14 PMIP3/CMIP5 GCMs. Model types are either Ocean–Atmosphere (OA) or Ocean–Atmosphere–Carbon (OAC).

		Resolution (lat, long, layers)			
Model	Type	Atmosphere	Ocean	Years	Institution
BCC-CSM1-1	OAC	64, 128, L26	232, 360, L40	100	BCC, China
CNRM-CM5	OA	128, 256, L31	292, 362, L42	200	CNRM-CERFACS, France
CSIRO-Mk3-6-0	OA	96, 192, L18	189, 192, L31	100	CSIRO-QCCCE, Australia
CSIRO-Mk3L-1-2	OA	56, 64, L18	128, 224, L21	100	CSIRO, Australia
FGOALS-g2	OA	60, 128, L26	196, 360, L30	100	LASG-CESS, China
FGOALS-s2	OA	108, 128, L26	196, 360, L30	100	LASG-IAP, China
HadGEM2-CC	OAC	145, 192, L60	216, 360, L40	102	MOHC, UK
HadGEM2-ES	OAC	145, 192, L38	216, 360, L40	35	MOHC, UK
IPSL-CM5A-LR	OAC	96, 96, L39	149, 182, L31	500	IPSL, France
MIROC-ESM	OAC	64, 128, L80	192, 256, L44	100	MIROC, Japan
MRI-CGCM3	OA	160, 320, L48	360, 368, L51	100	MRI, Japan
CCSM4	OA	192, 288, L26	320, 384, L60	1×301 $+1 \times 30$	NCAR, USA
GISS-E2-R	OA	90, 144, L40	90, 144, L32	2×100	NASA-GISS, USA
MPI-ESM-P	OA	96, 192, L47	220, 256, L40	2×100	MPI-M, Germany

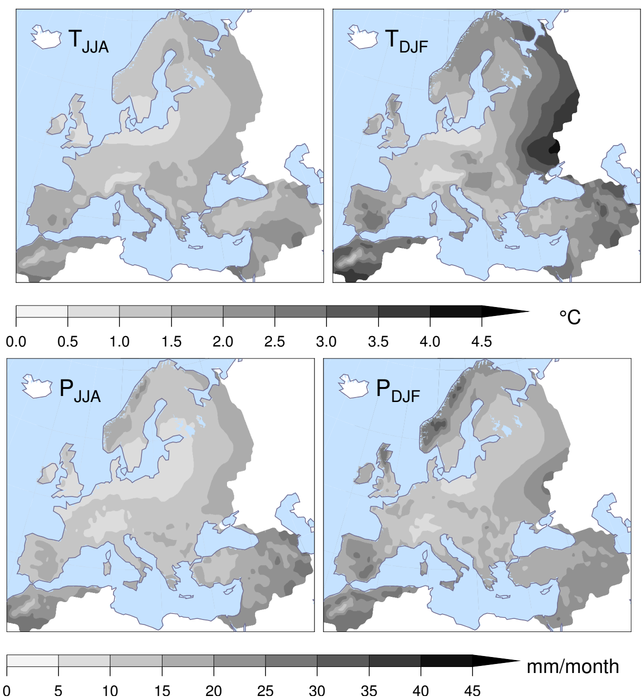

Figure 2. Uncertainties (standard error) associated with the mid-Holocene data based climate reconstructions shown in Figs. 4–9. These are based on the combined uncertainty of the interpolation and the pollen–climate transfer function (see methods).

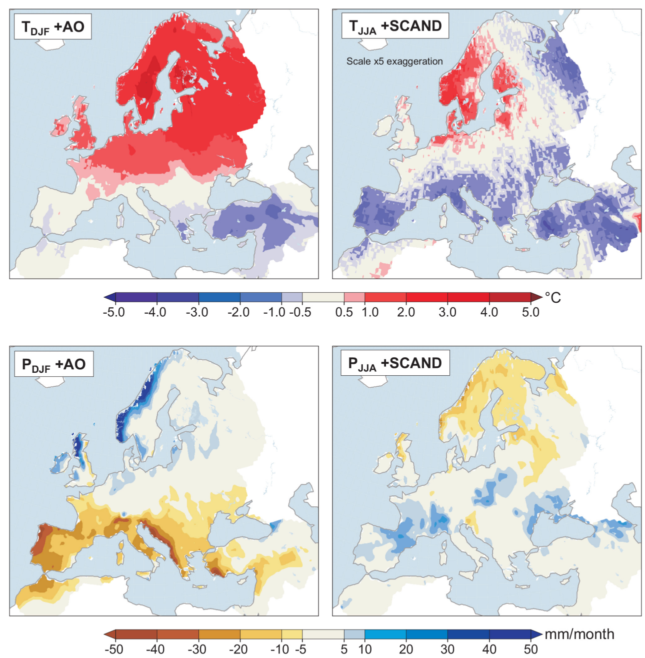

Figure 3. Modern temperature and precipitation anomalies associated with a positive Arctic Oscillation (AO) in winter and Scandinavian pattern (SCAND) in summer. Note that the SCAND temperature is scaled with a $\times 5$ exaggeration. These anomalies were calculated over the 1950–2000 period based on the mean of the years falling in the upper quartile of the teleconnection index.

The AO index is defined as the pressure gradient between polar and mid-latitude regions, with a negative/positive phase reflecting higher/lower pressure over the poles and lower/higher pressure over the mid-latitudes. In general, a positive phase means a stronger pressure gradient and a stronger zonal (westerly) circulation resulting in warmer and wetter conditions over northern Europe and cooler and drier conditions over southern Europe (Fig. 3). The AO is closely related to the NAO, which we consider here as the regional manifestation of the AO, although the exact relationship is subject to some debate (Ambaum et al., 2001).

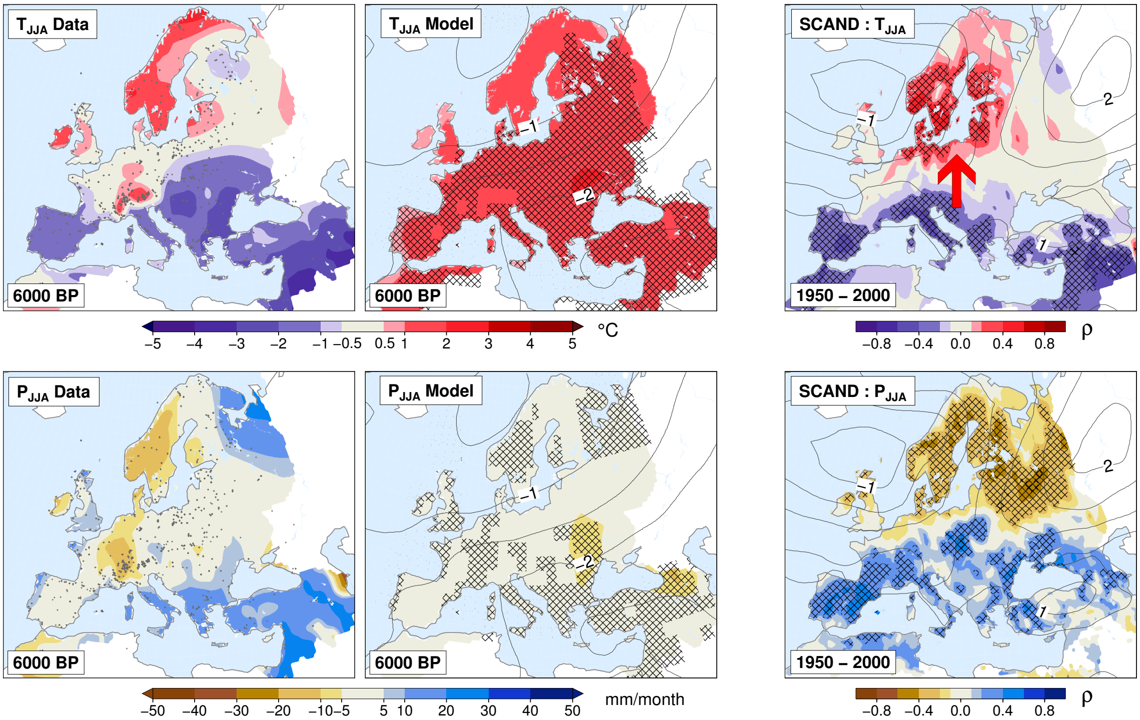

Figure 4. Summer temperature (upper panels) and precipitation (lower panels) as reconstructed from pollen data (left) and simulated (centre) by CMIP5/PMIP3 climate models represented here by the ensemble mean of 14 models. The cross-hatching indicates areas where the differences between the data and model ensemble mean exceed the uncertainties of the reconstruction as shown in Fig. 2. Also shown (right) is the correlation coefficient between modern climate and the SCAND teleconnection index for the period 1950–2000. The cross-hatching indicates areas where the correlation is significant (t test, $p = 0.05$, taking into account serial correlation). Isobars represent surface pressure anomalies (mbar) associated with the mid-Holocene simulations and positive SCAND. A positive SCAND leads to a southerly airstream (large arrow) bringing warmer and drier conditions to Scandinavia, while southern Europe is cooler and wetter. Palaeoclimate data were interpolated to the same grid resolution as the model. Black crosses represent pollen sites used to reconstruct the climate.

The effects of the AO and SCAND on modern temperature, precipitation and pressure over Europe were calculated from NCEP/NCAR Reanalysis data (Kalnay et al., 1996). Modern climate anomalies were calculated with respect to the long-term average for the period 1950–2000.

3 Results

3.1 Summer

A common feature of climate model simulations for the MH is a relatively uniform summer warming across the Northern Hemisphere extra-tropics (Braconnot et al., 2004, 2007b, Harrison, 2013). We also find this warming in the PMIP3/CMIP5 ensemble mean in Europe (Fig. 4) and as a robust feature in almost all of the 14 GCMs which all show little if any summer cooling (Fig. 5). In contrast, our reconstructed summer temperatures show a more complex pattern, with warming generally over the north of Europe and particularly over central Scandinavia, while large areas of Southern Europe show cooler conditions. This pattern of summer warming over the north and cooling over the south has also been shown in all previous summer temperature reconstructions using pollen data, including Davis et al. (2003), Huntley and Prentice (1988) and Wu et al. (2007). Summer precipitation in the model ensemble shows relatively little change except for some drier conditions in Eastern Europe, although individual models show much greater variability (Fig. 6). Our reconstruction also shows much greater variability in precipitation change than the model ensemble, with drier conditions occurring roughly in a line from central southern Scandinavia to the western Mediterranean, but with wetter conditions mainly to the east.

3.2 Winter

As with summer precipitation, winter temperature anomalies in the MH model ensemble show little change across Europe (Fig. 7), although this partly reflects a balance between some individual models that show warming whilst others show cooling (Fig. 8). At the Northern Hemisphere scale, the slight warming over the far north of Europe in the ensemble is part of a strong warming response over the Barents Sea, whilst a slight cooling to the south reflects a more general

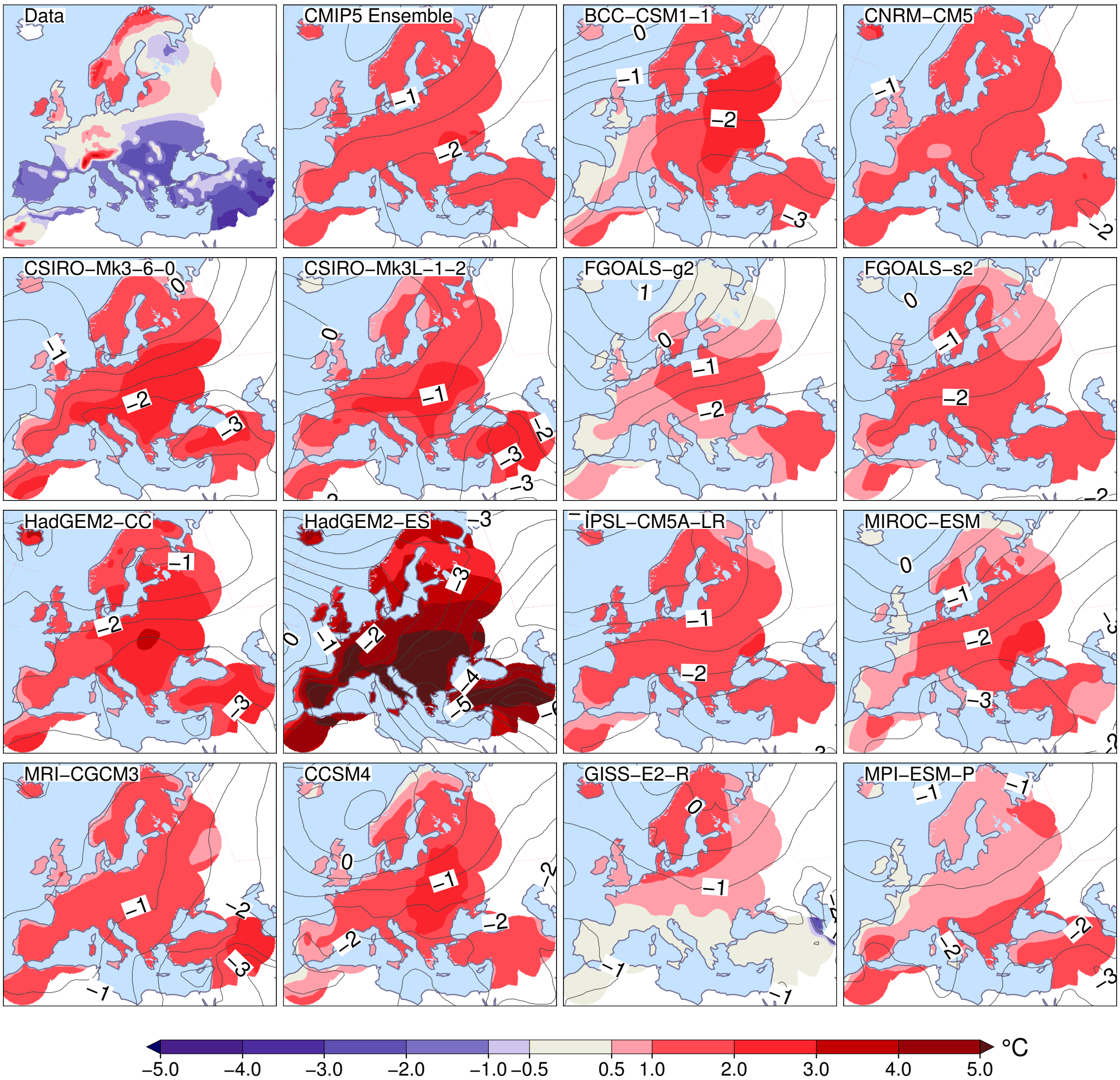

Figure 5. Results of all of the 14 PMIP3/CMIP5 mid-Holocene GCMs showing summer temperature (°C) and pressure (mbar) anomalies.

cooling over lower mid- and tropical latitudes, both of which are typical of PMIP3/CMIP5 and earlier models (Braconnot et al., 2004; Harrison et al., 2013). Neither the ensemble nor individual PMIP3/CMIP5 models show the pattern of winter temperature anomalies shown by the reconstruction, which indicates a more extensive and relatively strong warming extending over much of northern and central Europe, together with a strong but somewhat less extensive cooling over southern Europe. This pattern of high-latitude warming and low-latitude cooling is comparable with previous mid-Holocene winter temperature reconstructions (Cheddadi et al., 1997; Brewer et al., 2007; Wu et al., 2007). Precipitation changes in winter in the model ensemble are limited, as it is in all of the model simulations (Fig. 9). The data in contrast show more significant changes in winter precipitation than the models, with wetter conditions over Central Europe and eastern Scandinavia, whilst northeastern Iberia and the Middle East show drier conditions.

4 Discussion

4.1 Summer

The warmer and mainly drier summer climate shown in the model ensemble can be attributed to a direct thermal response to the increase in summer insolation across Europe during the MH (Braconnot et al., 2004). This simple direct response to top-of-the-atmosphere change in solar energy results in a relatively uniform summer warming across all latitudes of Europe in model simulations, while reconstructed summer temperatures indicate a more complex pattern of regional warming and cooling (Fig. 4). It has been suggested

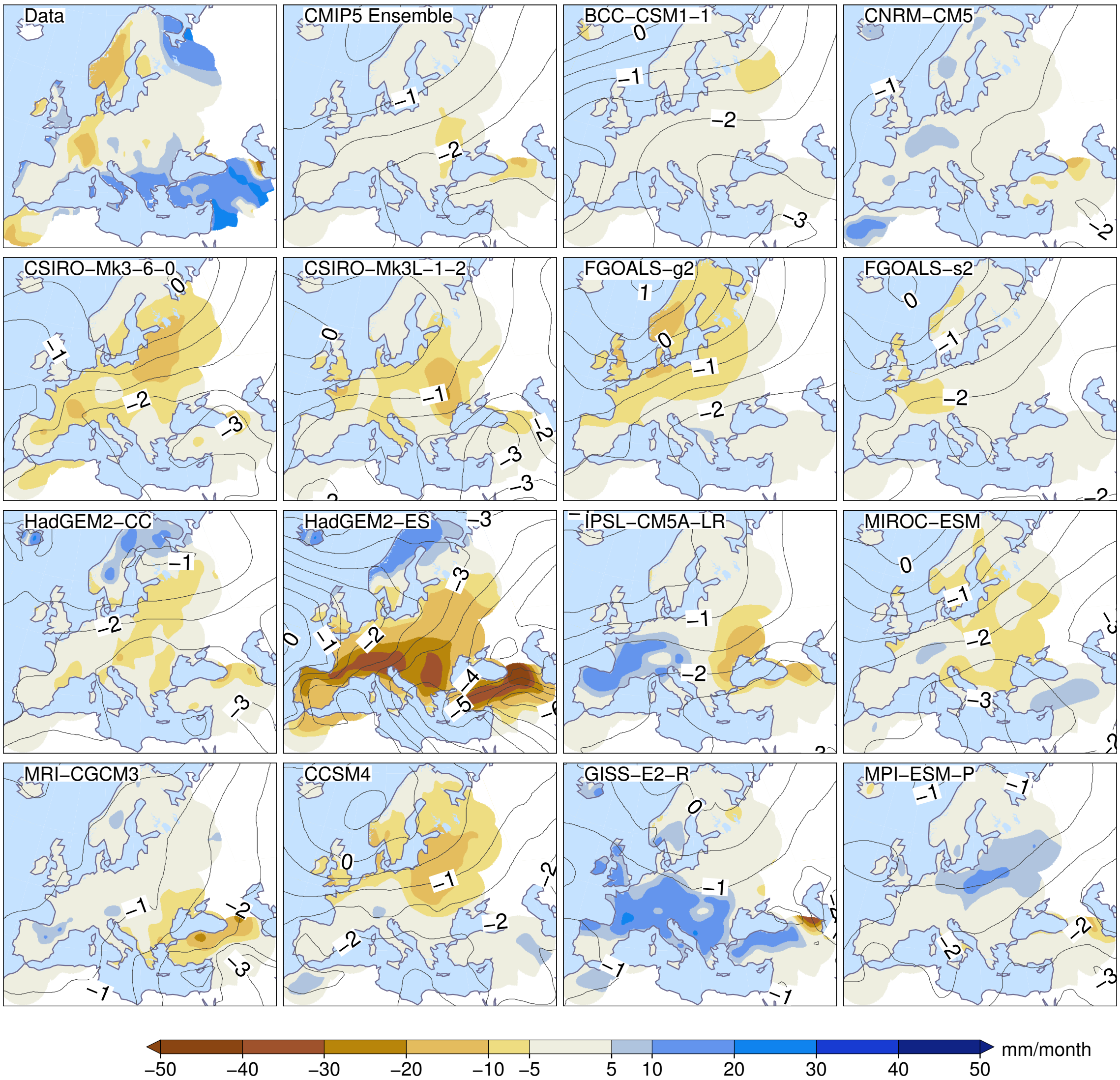

Figure 6. As for Fig. 5 but showing summer precipitation anomalies (mm month^{-1}).

(Antonsson et al., 2008; Seppa and Birks, 2001) that warmer and drier conditions during the MH over Scandinavia were the result of anticyclonic blocking over Northern Europe leading to warm air advection from southern latitudes and clear skies that promoted radiative heating. This is also consistent with isotopic evidence from lake sediments that suggest a more meridional circulation over Scandinavia in the MH associated with anticyclonic blocking (Jonsson et al., 2010).

One of the most common teleconnection patterns for this type of blocking is a positive or high index phase of the SCAND pattern, which causes warming over central Scandinavia as well as cooling over southern Europe. The pattern of climate anomalies generated by this pressure pattern is very similar to that observed over Europe during the MH, suggesting that anticyclonic blocking provides a plausible explanation for the MH summer climate not just over northern Europe but also southern Europe. Climate model simulations however do not reproduce this kind of high-pressure blocking pattern, where modelled pressure anomalies indicate a decrease, not increase, in atmospheric pressure over continental Europe (Figs. 4–6). A dynamic explanation for the cooling observed over Southern Europe in the data in summer differs from that proposed by Bonfils et al. (2004) who suggest cooling may be the result of a greater proportion of the radiative energy being released as latent heat due to increased winter soil moisture. This may indeed be a factor, but evidence of low water levels in groundwater-fed lakes in Spain suggests decreased (not increased) winter recharge in the MH in southern Europe (Davis and Stevenson, 2007), consistent with our pollen-based reconstruction which also shows drier winters across much of the region. Dry winters and resulting

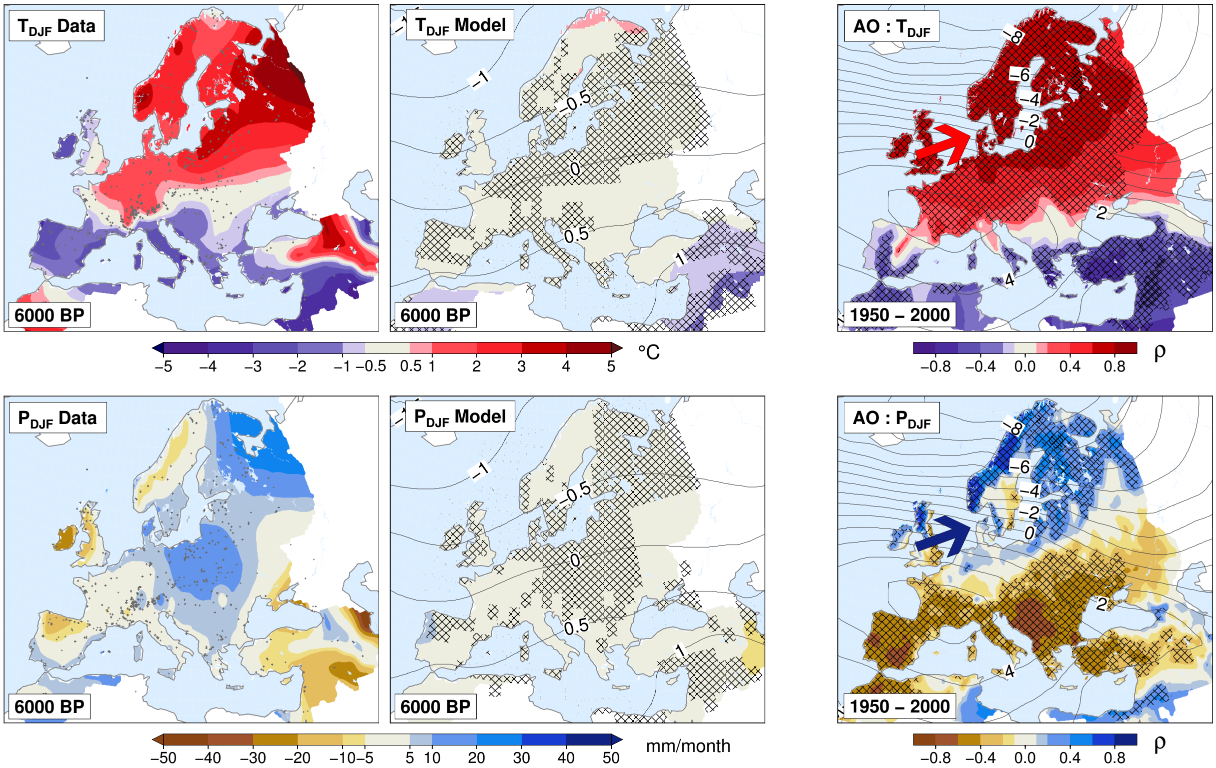

Figure 7. As for Fig. 4, but for winter and using the Arctic Oscillation (AO) teleconnection index. A positive AO leads to stronger westerly winds bringing warmer (large red arrow) and wetter (large blue arrow) conditions over northern Europe, whilst southern Europe experiences relatively cooler and drier conditions.

soil moisture deficits over southern Europe in spring have also been identified as one of the factors in promoting summer heat waves over northern Europe (García-Herrera et al., 2010).

4.2 Winter

Modern inter-annual variability of the winter climate of Europe is largely a function of the AO (regionally expressed as the NAO) teleconnection pattern, which influences the strength and position of the westerly atmospheric circulation and accompanying storm track (Hurrell et al., 2003). A number of authors have suggested that the AO/NAO was in a positive or high index phase during the MH based on Holocene temperature gradients across Europe (Davis and Brewer, 2009), water levels in groundwater-fed lakes in the Mediterranean (Davis and Stevenson, 2007), the distribution of Arctic driftwood (Funder et al., 2011), the mass-balance of Norwegian glaciers (Nesje et al., 2001), and the pattern of Atlantic sea surface temperatures (Rimbu et al., 2004). Strong westerly winds such as those experienced under a positive AO/NAO were also proposed by Vork and Thomsen (1996) to explain the occurrence of thermophilious Mediterranean ostracods around the coast of Denmark in the MH, as well as by Harff et al. (2011) to explain the elevated salinity of the Baltic Sea at this time. The study by Vork and Thomsen (1996) suggested that winter sea surface temperatures were around 5–6 °C above present around Denmark in the MH in order to explain the observed ostracod fauna, supporting our reconstruction of much higher than present winter temperatures over northern Europe at this time.

Model simulations of MH climate based on the earlier PMIP2 GCMs showed little change in AO (Lu et al., 2010), with just a few models showing only a weak shift to a positive phase of the NAO (Gladstone et al., 2005; Fischer and Jungclaus, 2011). Felis et al. (2004) also show a shift to a more positive AO/NAO in a model simulation of the last Interglacial, but the level of winter warming over central Europe shown in this simulation is not shown in other simulations using other models (Lunt et al., 2013; Otto-Bliesner et al., 2013). This is also consistent with the latest PMIP3/CMIP5 models shown here for the MH, which generally indicate a decrease in pressure over Iceland and increase in pressure to the south equivalent to a positive AO/NAO, but of insufficient strength to translate into a strong westerly circulation over northern Europe (Figs. 7–9). The winter warming shown in a few models over northern Europe appears to be the result of alternative mechanisms such as sea-ice feedbacks in the Barents Sea area (Fischer and Jungclaus, 2011), or the release in winter of sensible heat over Europe as a result

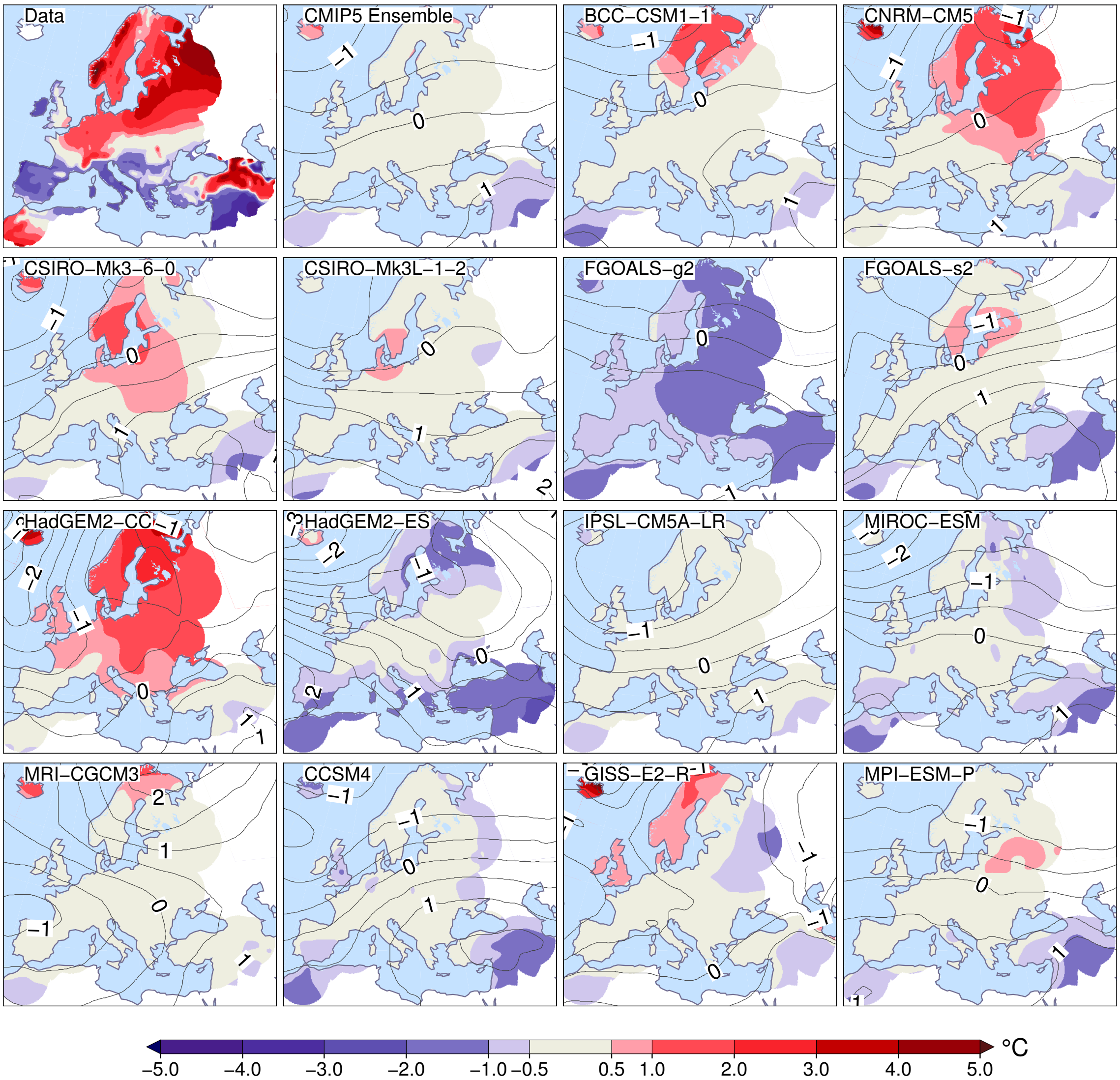

Figure 8. Results of all of the 14 PMIP3/CMIP5 mid-Holocene GCMs showing winter temperature (°C) and pressure (mbar) anomalies.

of warmer summer land and sea temperatures. This warming over northern Europe is also different from that shown in the data because it is not accompanied by substantial cooling over southern Europe and the Middle East (Fig. 8). This cooling is indicative of a strong positive AO/NAO, which advects warmer and wetter maritime air from the west and south over a large area of northern Europe, while at the same time cooler and drier air is advected from the north and east over southern Europe (Fig. 7). A somewhat limited cooling over southern Europe is also shown in the model ensemble, but in this case it can be attributed to the decrease in winter insolation across the mid- and lower latitudes of the Northern Hemisphere at this time which results in a general cooling over these areas in most model simulations (Davis and Brewer, 2009; Harrison et al., 2013). Reconstructed precipitation anomalies are also consistent with a positive AO/NAO, showing wetter conditions over northern Europe and drier conditions over southern Europe. This is also different from the few model simulations which show winter warming over northern Europe, where this warming in contrast was not accompanied by wetter conditions.

4.3 The atmospheric circulation

Many of the recent and historical periods of climatic warming in Europe have been explained by changes in atmospheric circulation. For instance, much of the warming that occurred in the late 20th century in Europe has been attributed to the increased number of winters with a high-index AO/NAO (Hurrell, 1995; Visbeck et al., 2001). High-index AO/NAO conditions are also thought to have occurred during the Medieval Climate Anomaly, providing a dynamic explanation for the winter warmth experienced over Europe at this time

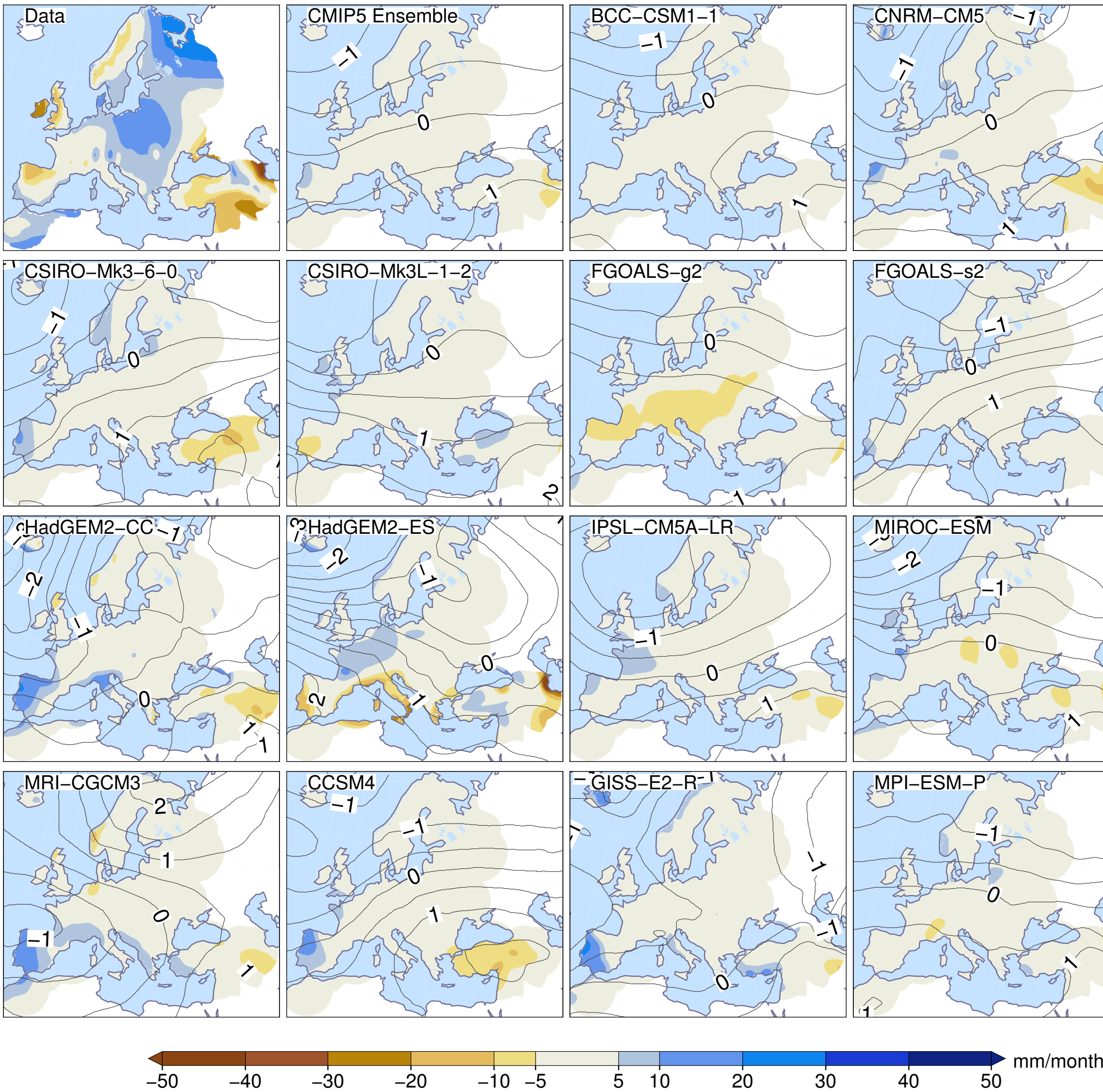

Figure 9. As for Fig. 8, but showing winter precipitation anomalies (mm month^{-1}).

(Trouet et al., 2009). Similarly in summer, the increased occurrence of heat waves in recent years has been shown to be the result of anomalous atmospheric circulation associated with blocking anticyclones (Kysely and Huth, 2006). This pattern has also been shown to underlie summer warming on longer timescales in the late Holocene (Della-Marta et al., 2007; Trouet et al., 2012; Yiou et al., 2012).

Changes in atmospheric circulation have a significant influence on European climate (Sepp and Jaagus, 2002; van Ulden and van Oldenborgh, 2006; Hoy et al., 2013), but many climate models have difficulty reproducing this aspect of modern climate (van Ulden and van Oldenborgh, 2006; Woollings, 2010; Kjellstrom et al., 2011; Brands et al., 2013). The warming in Europe during the mid-Holocene simulated in climate models differs fundamentally from that shown in the data, and indicates a high sensitivity in models to the effects of the amplified seasonal insolation cycle experienced at this time, showing greater warming (cooling) in summer (winter) in response to increased (decreased) summer (winter) insolation. Our reconstructed climate in contrast shows a greater warming in winter than in summer at the European scale, and a spatial pattern of anomalies that is more consistent with changes in atmospheric circulation rather than simple direct radiative forcing by insolation. This suggests a greater role for atmospheric dynamics in explaining interglacial warming, and a challenge to traditional ideas about the simple role of Northern Hemisphere high-latitude summer insolation in driving interglacial climates (Milankovitch, 1941). The greater importance of winter over summer warming could lend support to the role of the winter latitudinal insolation gradient in driving interglacial warming, having an identical orbital signature to summer insolation, and which could influence the atmospheric circulation through its control of the latitudinal temperature gradient (Davis and Brewer, 2009, 2011).

5 Conclusions

We have presented a new seasonal (summer and winter) gridded temperature and precipitation reconstruction for Europe during the MH, based on a fossil pollen and modern pollen data set that is greatly improved in both size and quality compared with previous studies. This climate reconstruction has been compared with the latest PMIP3/CMIP5 GCM simulations and with the modern winter AO/NAO and summer SCAND that represent potential analogues of modes of climate variability connected with atmospheric circulation during the MH.

Our data–model comparison highlights significant differences between the reconstruction and the model simulations. We explain these differences in terms of atmospheric circulation, which appears strongly imprinted on the reconstructed climate, but subsumed in climate models in favour of a simple direct radiative response to the change in the amplitude of the seasonal insolation cycle. We suggest that the MH climate of Europe was characterized by a strong zonal circulation in winter consistent with a present-day positive or high index AO/NAO teleconnection. This brought milder wetter conditions into northern Europe and cooler drier conditions to many parts of southern Europe. In summer, we suggest that the zonal circulation was weak, and that anti-cyclonic blocking occurred close to Scandinavia, comparable with a positive or high index SCAND teleconnection. This caused a more meridional circulation, which brought clear skies and dry and warm conditions to northern Europe, but relatively cooler and somewhat wetter conditions to many parts of southern Europe. Both of these seasonal changes in atmospheric circulation have been suggested by previous authors, and particularly in the case of the winter AO/NAO, are supported by a large number of studies based on many different proxies (Vork and Thomsen, 1996; Nesje et al., 2001; Rimbu et al., 2004; Davis and Stevenson, 2007; Davis and Brewer, 2009; Jonsson et al., 2010; Funder et al., 2011). Here we have provided evidence that the changes in atmospheric circulation suggested by these studies for the mid-Holocene can also explain the pattern of winter and summer temperature and precipitation anomalies across Europe at this time. These mutually supporting convergent lines of evidence also provide support for the reliability of our reconstruction, and particularly in those areas where we show large transfer-function uncertainties but which nevertheless conform to the pattern of expected circulation anomalies.

Evidence that climate models may have difficulty simulating MH atmospheric circulation is consistent with similar model deficiencies found on contemporary timescales, and may be important in understanding why Europe has recently been warming faster than predicted (van Oldenborgh et al., 2009). It also suggests that the atmospheric circulation may be more important in driving interglacial warming than previously considered based on model experiments that appear too sensitive to direct insolation forcing. Future work will extend this MH reconstruction to the complete Holocene, and investigate this problem by comparing this climate record with transient Holocene model simulations.

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