Clim. Past Discuss., 9, 5569–5592, 2013
www.clim-past-discuss.net/9/5569/2013/
doi:10.5194/cpd-9-5569-2013

Climate of the Past
Discussions
Open Access

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

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Received: 9 September 2013 – Accepted: 22 September 2013 – Published: 7 October 2013

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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 (positive SCAND). We find little agreement between the reconstructed anomalies and those from a climate model simulation, which as with most model simulations shows a much greater sensitivity to local radiative forcing from 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 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 simulating (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 by evaluating climate models against past known climates, such as the mid-Holocene (MH, 6000 yr BP) which was 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).

It is for these reasons that the MH has been the focus of major data-model comparison projects such as Palaeo Model Intercomparison Project (PMIP) (Joussaume and Taylor, 1995; Masson et al., 1999), and its successors PMIP2 (Braconnot et al., 2007a, b) and lately PMIP3 (Braconnot et al., 2012), that aim to evaluate climate models and provide a better understanding of climate change and climate feedbacks. These 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 winter during the late 20th Century, a persistent positive phase of the AO/NAO resulted in strengthened westerly's over Northern Europe, which experienced mild wet winters, while Southern Europe experienced drier cooler winters leading to drought conditions in many parts of the Mediterranean (Hurrell et al., 2003).

It has been suggested based on palaeoclimate data that Europe may have experienced similar 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 characterised 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 AO/NAO in 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 dataset 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 dataset. The role of atmospheric circulation is investigated by comparing

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the reconstructed climate with that shown in a high-resolution climate model simulation of mid-Holocene climate (Singarayer et al., 2011), and 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 dataset 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 dataset represents a substantial improvement compared with datasets used in previous data-model comparisons. Our fossil pollen dataset 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 dataset has been improved by 81 % compared with Davis et al. (2003) and 221 % 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 dataset 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). Uncertainty in the geo-referencing was identified as unacceptable where the altitude in the meta-data 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) dataset.

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The reconstructed climate anomalies for each of the fossil sites were calculated using the R package “rioja” (Juggins, 2012) then interpolated onto a uniform spatial grid using a four-dimensional thin plate spline from the R package “fields” (Fields Development Team, 2006), as also used by Davis et al. (2003). This method interpolates through time as well as 3-D space, reducing the problem of temporal “blurring” associated with traditional methods that integrate all the samples within a wide time window, usually ±500 yr (e.g., Cheddadi et al., 1997). Using this 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., 2013).

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.

Our climate reconstruction is compared with a MH climate simulation using a coupled atmosphere-ocean climate model HadCM3 that has a resolution of 2.5° in latitude and 3.75° in longitude (Singarayer et al., 2011). This model does not include vegetation feedbacks, although vegetation is not thought to have a significant effect on the MH climate of Europe (Braconnot et al., 2007b; Otto et al., 2009), including the magnitude of the simulated AO response (Gladstone et al., 2005). Modern teleconnection indices for

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the winter AO and the summer Scandinavian pattern (SCAND) were taken from NOAA (NOAA, 2011) based on Barnston and Livezey (1987). The AO is a measure of the zonal flow, while the SCAND is more a measure of meridional flow and blocking. 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). Modern temperature and pressure data were taken from NCEP/NCAR Reanalysis (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 MH climate model simulations is a relatively uniform summer warming across all parts of Europe (Braconnot et al., 2004, 2007b), a feature that is also found in the HadCM3 simulation shown here (Fig. 2). 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 simulation is also shown to be uniformly reduced across Europe during the MH, but our reconstruction shows a different pattern with drier conditions in a line from central southern Scandinavia to the western Mediterranean, but with wetter conditions mainly to the east.

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3.2 Winter

Winter temperature anomalies in the MH model simulation show a different pattern to the model summer anomalies, with localised regional warming over the far north of Scandinavia and a general cooling over the remainder of Europe to the south (Fig. 3). This pattern is typical of model simulations, with maximum warming centered over the Barents Sea and extensive cooling over mid to low latitudes (Braconnot et al., 2004). This is quite different to the reconstructed winter temperature anomalies that show a much more extensive warming extending over much of northern and central Europe, and with a 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). The contrast between model and data is also shown in the winter precipitation anomalies, with areas shown as drier in the model simulation such as northern Scandinavia and the Middle East being wetter in the reconstruction, and areas in Southern Europe that are drier in the reconstruction are shown as wetter than today in the model simulation.

4 Discussion

4.1 Summer

The warmer and mainly drier summer climate shown in the model simulation can be attributed to climate model sensitivity to the increase in summer insolation across Europe during the MH (Braconnot et al., 2004). This simple direct thermal response to top-of-the-atmosphere change in solar energy results in 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. 2). It has been suggested (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 (also known as EU1) pattern, in which high pressure develops over Western Russia resulting in stable 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. 2). 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. In contrast, this high-pressure blocking pattern is not shown in the HadCM3 climate model simulation, where pressure anomalies indicate a decrease, not increase, in atmospheric pressure over continental Europe. This 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.

4.2 Winter

Modern inter-annual variability of the winter climate of Europe is largely a function of the Arctic Oscillation (regionally expressed as the North Atlantic Oscillation) teleconnection pattern, which influences the strength and position of the westerly atmo-

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spheric 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 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 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 however largely show 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). This includes the HadCM3 model shown here, but although the pressure changes are consistent with a positive AO/NAO, this does not translate into a strong westerly circulation over Northern Europe (Fig. 3). Rather, the winter warming shown in models (including HadCM3) over Northern Europe appears to be primarily the result of sea-ice feedbacks in the Barents Sea area (Fischer and Jungclaus, 2011), which brings about a localized warming in northern Scandinavia due to the release in winter of sensible heat stored in summer as a result of reduced sea ice. The warming over Northern Europe shown in the data is much more extensive than that shown in the model and extends much further south. This is more consistent with a strong positive AO/NAO, which advects warmer and wetter maritime air from the west and south over a large area of Northern Europe. At the same time, cooler and drier air is advected from the north and east over Southern Europe (Fig. 3), a feature that is also shown in the MH reconstruction. A similar

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cooling over Southern Europe is also shown in the model simulation, but in this case is much more extensive and more uniform, and can be attributed to the decrease in winter insolation across the Northern Hemisphere at this time (Davis and Brewer, 2009). Reconstructed precipitation anomalies are also consistent with a positive AO/NAO, showing wetter conditions over Northern Europe and drier conditions over Southern Europe. This contrasts with the model simulation, which shows that the warming simulated over Northern Europe was associated with drier conditions, and cooling over Southern Europe with largely 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 (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 conventional ideas about the simple role of Northern Hemisphere high latitude summer insolation in driving interglacial climates. It could also lend support to alternative orbital forcing's such as the winter latitudinal insolation gradient that has 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).

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 training set that is greatly improved in both size and quality compared with previous studies. This climate reconstruction has been compared with a coupled atmosphere-ocean climate model simulation (HadCM3) 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 simulation. We explain these differences in terms of atmospheric circulation, which appears strongly imprinted on the reconstructed climate, but subsumed in the model 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 characterised by a strong zonal circulation in winter consistent with a 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 block-

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ing 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.

The poor representation of changes in MH atmospheric circulation in models 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.

Acknowledgements. The authors would like to thank Joy Singarayer and Paul Valdes for providing the HadCM3 model simulation, and Steve Juggins for the RIOJA software used to make the pollen-climate reconstruction. This study would not have been possible without the resources provided by the European Pollen Database and the PANGAEA data archive. Funding was provided by grants from the Swiss National Science Foundation (PP0022_119049) and the Italian Ministry of Research and Education (FIRB RBID08LNFJ).

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Table 1. Performance of the pollen-climate transfer function based on n-folds-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 °C
$P_{(JJA)}$	0.78	17.6	±4.20 mm month^{-1}

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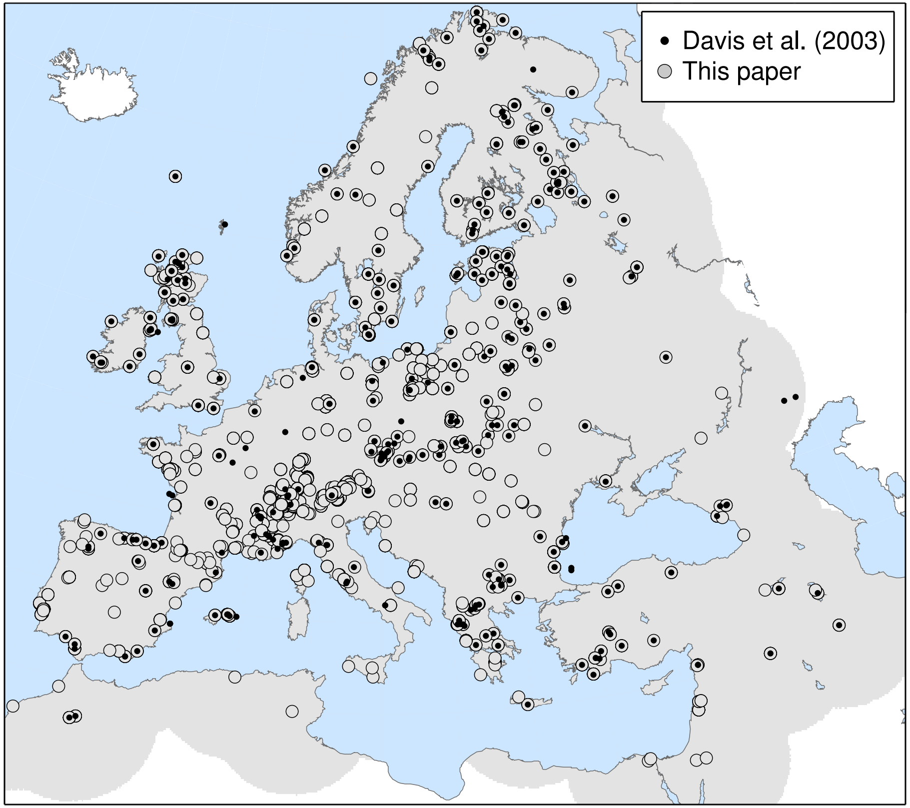

Fig. 1. Spatial distribution of pollen sites (open circles) used to reconstruct the climate for the mid-Holocene. The number of sites analysed represents an increase of 48 % compared to Davis et al. (2003) (black dots). Interpolated climate values were limited to a distance of 500 km from the pollen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

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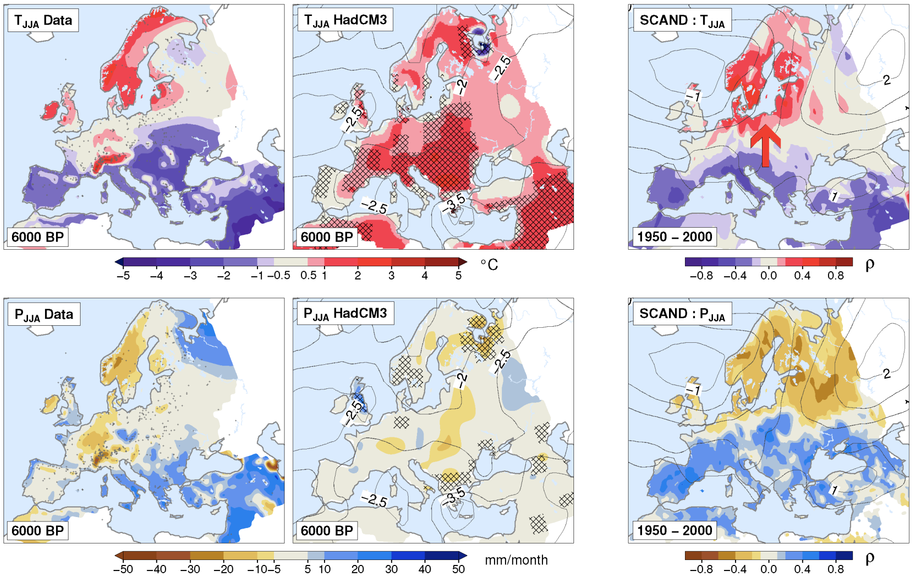

Fig. 2. Summer temperature (upper panels) and precipitation (lower panels) as reconstructed from pollen data (left) and simulated (center) by the Hadley Centre coupled atmosphere-ocean climate model HadCM3. Also shown (right) is the correlation coefficient between modern climate and the SCAND teleconnection index for the period 1950–2000. 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 was interpolated to the same grid resolution as the model. Black crosses represent pollen sites used to reconstruct the climate. The isolines are sea level pressure anomalies SLPa (mbar).

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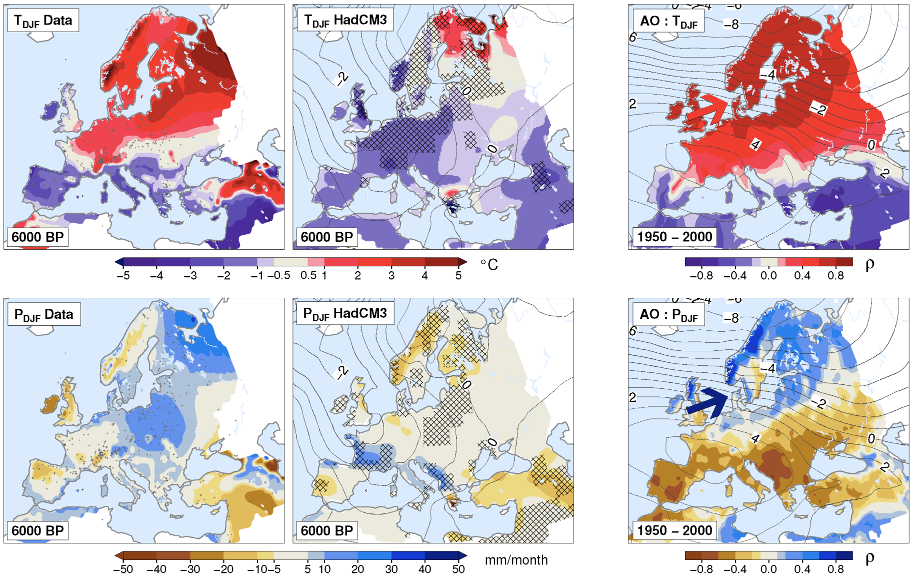

Fig. 3. As Fig. 2 but for winter and using the AO teleconnection index. A positive AO leads to stronger westerly winds bringing warmer (large red arrow) and wetter (large blue arrow) conditions over Northern Europe, whilst Southern Europe experiences relatively cooler and drier conditions.

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