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THE SPATIO-TEMPORAL PATTERN OF THE MID-HOLOCENE THERMAL MAXIMUM

LJUNGQVIST, F.C. (2011): The Spatio-Temporal Pattern of the Mid-Holocene Thermal Maximum. Geografie, 116, No. 2, pp. 91–110. – This article presents a review of the spatio-temporal pattern of the mid-Holocene Thermal Maximum as it occurs in 60 different reconstructions of annual mean temperature from locations around the globe. The geographical coherency of multi-centennial periods with annual mean temperatures at least 1°C and 2°C above the pre-industrial (~1750 AD) equivalents are presented. Although the reconstructions show a heterogeneous temperature pattern for the period c. 10–8 ka BP, a rather coherent period of temperatures exceeding the pre-industrial ones are seen for c. 8–4 ka BP. The onset of the Neoglaciation takes place 4–3 ka BP and cumulates during the Little Ice Age (c. 1300–1900 AD). Overall, our review points towards a more homogeneous mid-Holocene Thermal Maximum than hitherto reported. However, the still limited data coverage, especially for the Southern Hemisphere, restricts the possibility to draw any firm conclusion regarding the amplitude and spatio-temporal pattern of the maximum mid-Holocene warming.
KEY WORDS: Mid-Holocene Thermal Maximum – Neoglaciation – palaeoclimatic records – temperature proxy data – climate variability – temperature reconstructions – global warming.

Introduction

It has long been known that the earth experienced rather high temperatures during the mid-Holocene period (c. 8 to 5 ka BP), especially during the summer at high latitudes in the Northern Hemisphere (see, e.g., Lamb 1977). In some regions, such as Greenland, Scandinavia, the North Atlantic, northern Siberia, eastern China, and Tasmania, certain seasonal temperatures were several degrees Celsius higher than today (He et al. 2004; Kim et al. 2004; MacDonald et al. 2000; Seppä et al. 2009; Vinther et al. 2009; Xia et al. 2001). This warm period is usually referred to as the Mid-Holocene Thermal Maximum or the Mid-Holocene Climate Optimum (sometimes also referred to as Altithermal, Hypsithermal or Holocene Megathermal). This warming, and the subsequent cooling (the Neoglaciation), was primarily caused by changes in the Earth's orbital tilt and precession (Berger, Loutre 1991; Renssen et al. 2009; Wanner, Bütikofer 2008). The direct results of these orbital changes during the mid-Holocene, according to state-of-the-art General Circulation Models and Energy Balance Models, should have been a substantial warming during the Northern Hemisphere summer and perhaps a slight cooling during the winter, whereas the Southern Hemisphere should have experienced somewhat cooler summers and warmer winters (Solomon et al., eds. 2007). However, several strong positive feedbacks in the climate system (i.e. the ice-albedo feedback and the sea-ice insolation feedback) and a large-scale reorganization of the latitudinal heat transport seem to have caused a more global warming. Moreover, the orbital changes alone should have resulted in maximum Northern Hemisphere summer heating already c. 11 ka BP. However, this was not the case. The cooling effect of the remaining melting ice-sheets from the last glacial period led to a delayed mid-Holocene Thermal Maximum by several thousand years (MacDonald et al. 2000; Davis et al. 2003; Kaufman et al. 2004; Widmann 2009). In a recent review of available proxy records, Shakun and Carlson (2010) found that the warmest conditions during the Holocene occurred in the Northern Hemisphere c. 8 ± 3.2 ka BP and in the Southern Hemisphere c. 7.4 ± 3.7 ka BP.

No quantitative reconstruction of the Holocene temperature evolution on a global scale has yet been attempted and only one such reconstruction for the Northern Hemisphere has been published. The reconstruction of annual mean air temperature by Klimenko, Klimanov, Fedorov (1996) shows a variability of 4–5°C during the Holocene, with a maximum 1°C above modern temperatures shortly after 6000 BP, but has rarely been cited in the literature since no description is given of the method and data used. On the other hand, a number of quantitative reconstructions and syntheses of temperature (and/or precipitation) changes during the Holocene on a regional scale have been published during the last decade.

Cheddadi et al. (1997) attempted to estimate the climate in Europe 6000 BP from pollen data. They found that both summer and winter temperatures were considerably higher in northern Europe than now but also that the climate 6000 BP was much colder in the Mediterranean region than today. Davis et al. (2003) published a quantitative pollen climate reconstruction using a four-dimensional gridding procedure of more than 500 pollen sites that essentially confirmed the results from Cheddadi et al. (1997), although they found less mid-Holocene winter warming in northern Europe. Looking deeper into northern Europe, Seppä et al. (2009) presented a synthesis of the temperature variability in Scandinavia and the Baltic region from 36 individual pollen-derived July mean and annual mean temperature reconstructions. They found evidence of a clear mid-Holocene Thermal Maximum 8000–4800 BP, with annual mean temperatures about 2°C above pre-industrial ones. For the area covered by the former Soviet Union and Mongolia, Tarasov et al. (1999) reconstructed the climate at 6000 BP from pollen remains. They found that the winters in the whole region were about 2°C warmer than today and that the summers were warmer north of 60°N and in Mongolia, whereas in northern Kazakhstan and around the Black and Caspian Seas, summers were cooler than today. Cooler summers may also have existed in central Siberia.

Kaufman et al. (2004) investigated the spatio-temporal pattern of peak Holocene warmth in 140 sites across the Western Hemisphere of the Arctic. They found that summer temperatures during the mid-Holocene Thermal Maximum were 1.6 ± 0.8°C higher than the average of the 20th century, but that peak Holocene warmth occurred much earlier in western Canada and Alaska than elsewhere. The peak warmth occurred latest in Labrador due to the lingering Laurentide Ice Sheet. Viau et al. (2006) reconstructed the millennial-scale July temperature variability in North America from pollen distributions during the last 14000 years and found only small variability since the rapid 4–5°C warming of the deglaciation. Nevertheless, they reported a stable mid-Holocene Thermal Maximum 6000–3000 BP with a peak warming as late as c. 3200 BP. Viau et al. (2008) presented a January, July and annual pollen-derived temperature reconstruction for eastern Beringia and found a peak winter warming as early as 11000 BP and maximum summer and annual temperatures from 8000–7000 BP with little long-term change during the last ~6000 years. Viau and Gajewski (2009) reconstructed the Holocene January and July temperature variations of boreal and low-Arctic Canada with pollen data. They found the clearest Holocene temperature maximum, both in summer and winter, in central Canada c. 12000–8000 BP. In northern Quebec, temperatures peaked around 8000 BP and the mid-Holocene Thermal Maximum occurred, as in Kaufman et al. (2004), later and less pronounced along the Labrador coast.

There exist two important syntheses of sea surface temperature data covering the Holocene. Kim et al. (2004) investigated available Northern Hemisphere alkenone-derived sea-surface temperature records and demonstrated a Holocene cooling trend in the North Atlantic region but a warming trend in the North Pacific and Indian Ocean region. On lower latitudes at least, a mid-Holocene Thermal Maximum could only be seen in the North Atlantic region. Leduc et al. (2010) reviewed globally available alkenone- and foraminiferal Mg/Ca-derived sea surface temperature records for the Holocene. They found a cooling Holocene trend, and the existence of the mid-Holocene Thermal Maximum on high latitudes in both the Northern and Southern Hemisphere, but a warming trend in most tropical records. Though it should be noted the tropical records showed quite a heterogeneous pattern. For Africa, there are no quantitative large-scale temperature reconstructions but several reconstructions of annual precipitation exist. A model-data comparison by Peyron et al. (2006) showed that at 6000 BP Sahara-Sahel was 200–700 mm/year wetter than today but a longer dry season prevailed during the boreal winter near the equator. Wu et al. (2007) found that the climate was generally wetter in northern Africa at 6000 BP and, moreover, that it was significantly warmer than today in southern and eastern Africa yet cooler in tropical Africa.

The IPCC report (Solomon et al., eds. 2007) was inconclusive whether at least parts of the mid-Holocene Thermal Maximum experienced globally higher temperatures than the present ones. According to IPCC (Solomon et al., eds. 2007) the "spatial coverage, temporal resolution and age control of available Holocene proxy data limit the ability to determine if there were multi-decadal periods of global warmth comparable to the last half of 20th century". A major problem for our understanding of the mid-Holocene Thermal Maximum is the dominance of proxy records sensitive to specific seasons (e.g. summer) and the limited number of records from lower latitudes. This lack of appropriate quantitative palaeotemperature data, especially for the Southern Hemisphere, together with the inability of state-of-the-art General Circulation Models and Energy Balance Models to simulate global mean annual temperatures higher than those of today, have thus led to the conclusion that the mid-Holocene Thermal Maximum was very likely not a globally synchronous event. Increasingly more data to better address this question are becoming available, but a more comprehensive assessment of the global spatio-temporal pattern of the mid-Holocene Thermal Maximum has yet to be done. Here, we present a review of quantitative palaeotemperature records in order to give tentative answers to the following two questions: (1) What do we presently know of the spatio-temporal pattern of the mid-Holocene Thermal Maximum from available palaeotemperature reconstructions? (2) Did any multi-centennial period of the mid-Holocene Thermal Maximum likely experience a substantially (i.e. more than 1°C) higher annual mean temperature than the pre-industrial (~1750 AD) period according to available palaeotemperature reconstructions?

Data and method

Through a screening of the peer-reviewed literature for quantitative palaeotemperature reconstructions of annual mean air temperatures and annual mean sea-surface temperatures, 60 records with reasonably high temporal resolution covering the mid-Holocene to the pre-industrial period were selected for this study. In order to capture only annual changes in temperatures, all seasonal reconstructions were avoided. The temperature reconstructions were, when possible, obtained as digital data (either from http://www.ncdc.noaa.gov/paleo, http://www.pangaea.de or directly from the author) or otherwise digitized from the graphs appearing in the respective publications.

Essential information about each record is given in Table 1a–b: e.g., (1) name of the record, (2) exact latitude and longitude, (3) type of proxy, and (4) reference to the original publication where the record first appeared. The proxy records are presented in Table 1a–b in geographical order from north to south and the location of each record is shown on the map in Figure 1. For more detailed information about a specific record, the reader is referred to the respective reference. Out of the 60 records, 37 are terrestrial records and 23 are marine records. Of the terrestrial records, 14 are from northern high

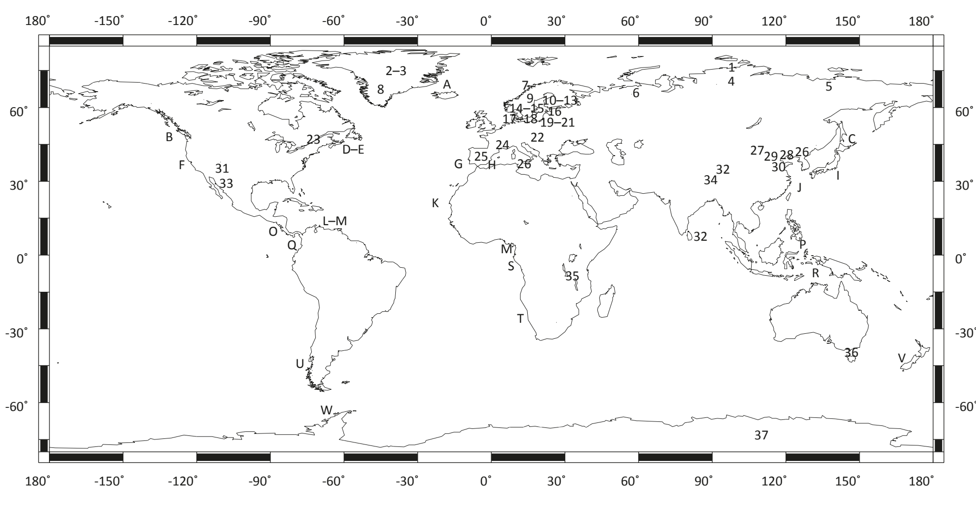


Fig. 1 – Map showing the location of the 60 palaeotemperature reconstructions presented in Table 1a–b and Figure 2a–b

Table 1a – List of terrestrial temperature proxy records used for this study

Proxy location	Latitude	Longitude	Proxy type	Reference
1. Levison-Lessing	74.47°N	98.63°E	Pollen T_{Ann}	Andreev et al. 2003
2. GRIP	72.58°N	38.50°W	Borehole T_{Ann}	Dahl-Jensen et al. 1998
3. GISP2	72.59°N	38.46°W	Ice T_{Ann} $\delta^{18}O$	Alley 2000
4. Taymyr	70.77°N	99.13°E	Pollen T_{Ann}	Andreev, Klimanov 2000
5. Kazach'e	70.77°N	136.25°E	Pollen T_{Ann}	Andreev, Klimanov, Sulerzhitsky 2001
6. Khaipudurskaya	68°N	60°E	Pollen T_{Ann}	Andreev, Klimanov 2000
7. Søylegrotta	66.62°N	13.68°E	Stalagmite $\delta^{18}O$	Lauritzen, Lundberg 1999
8. Dye-3	65.18°N	43.83°W	Borehole T_{Ann}	Dahl-Jensen, Morgan, Elcheikh 1998
9. Klotjärnen	61.82°N	16.53°E	Pollen T_{Ann}	Seppä et al. 2009
10. Nautajärvi	61.80°N	24.68°E	Pollen T_{Ann}	Ojala et al. 2008
11. Laihalampi	61.48°N	26.07°E	Pollen T_{Ann}	Heikkilä, Seppä 2003
12. Kuivajärvi	60.80°N	23.80°E	Pollen T_{Ann}	Seppä et al. 2009
13. Arapisto	60.58°N	24.08°E	Pollen T_{Ann}	Sarmaja-Korjonen, Seppä 2007
14. Gilltjärnen	60.08°N	15.83°E	Pollen T_{Ann}	Antonsson et al. 2006
15. Lilla Gloppsjön	59.83°N	14.58°E	Pollen T_{Ann}	Seppä et al. 2009
16. Raigastvere	58.58°N	26.65°E	Pollen T_{Ann}	Seppä, Poska 2004
17. Trehörningen	58.55°N	11.60°E	Pollen T_{Ann}	Antonsson, Seppä 2007
18. Flarken	58.55°N	13.67°E	Pollen T_{Ann}	Seppä et al. 2005
19. Lake Viitna	59.45°N	26.08°E	Pollen T_{Ann}	Seppä, Poska 2004
20. Lake Ruila	59.17°N	24.43°E	Pollen T_{Ann}	Seppä, Poska 2004
21. Rouge	57.73°N	26.75°E	Pollen T_{Ann}	Seppä et al. 2009
22. NW Romania	47.80°N	23.52°E	Pollen T_{Ann}	Feurdean et al. 2008
23. Quebec	45.50°N	73.67°W	Pollen T_{Ann}	Muller et al. 2003
24. Central Massif	44.00°N	4.00°E	Pollen T_{Ann}	Guiot 1987
25. Quintanar	42.03°N	3.01°W	Pollen T_{Ann}	Peñalba et al. 1997
26. Mt. Changbai	41–42°N	128°E	Pollen T_{Ann}	He et al. 2004
27. Loess Plateau	41–34°N	101–114°E	Pollen T_{Ann}	He et al. 2004
28. S. Liaoning	40°N	122°E	Pollen T_{Ann}	He et al. 2004
29. Beijing	39.55°N	116.25°E	Pollen T_{Ann}	He et al. 2004
30. East Hebei	38°N	117°E	Pollen T_{Ann}	He et al. 2004
31. Montezuma Well	34.65°N	111.75°W	Pollen T_{Ann}	Davis, Shafer 1992
32. Qilian Mountains	34.00°N	97.20°E	Pollen T_{Ann}	Herzschuh et al. 2009
33. Sierra Madre	29.00°N	111.00°W	Pollen T_{Ann}	Ortega-Rosas et al. 2008
34. Core HL1	29.00°N	92°E	Pollen T_{Ann}	Tang et al. 1999
35. Lake Malawi	9°S	34°E	TEX_{86} T_{Ann}	Powers et al. 2005
36. Wairehu	39.03°S	175.70°E	Pollen T_{Ann}	Wilmshurst et al. 2007
37. Law Dome	68.4°S	112.21°E	Borehole T_{Ann}	Dahl-Jensen et al. 1999

Table 1b – List of marine temperature proxy records used for this study

Proxy location	Latitude	Longitude	Proxy type	Reference
A. JR51-GC35	67°N	17.96°W	Alkenone T_{Ann} SST	Bendle, Rosell-Melé 2007
B. JT96-09	48.54°N	126.53°W	Alkenone T_{Ann} SST	Kienast, McKay 2001
C. MD01-2412	44.53°N	145.04°E	Alkenone T_{Ann} SST	Harada et al. 2006
D. OCE326-GGC30	44.00°N	63.00°W	Alkenone T_{Ann} SST	Sachs 2007
E. OCE326-GGC26	43.48°N	54.87°W	Alkenone T_{Ann} SST	Sachs 2007
F. ODP Site 1019	41.68°N	124.93°W	Alkenone T_{Ann} SST	Barron et al. 2003
G. Iberian Margin	37.77°N	10.18°W	Alkenone T_{Ann} SST	Bard 2002
H. 161-977	36.03°N	1.95°W	Mg/Ca T_{Ann} SST	Martrat et al. 2004
I. Japan margin	35.00°N	141.00°E	Alkenone T_{Ann} SST	Isono et al. 2009
J. Okinawa	27.82°N	126.98°E	T_{Ann} SST	Jian et al. 2000
K. ODP658C	20.75°N	18.58°W	T_{Ann} SST	deMenocal et al. 2000
L. M35003-4	12.08°N	61.25°W	Alkenone T_{Ann} SST	Rühlemann et al. 1999
M. Cariaco Basin	10.77°N	64.77°W	Mg/Ca T_{Ann} SST	Lea et al. 2003
N. GeoB4905-4	9.39°N	11.22°E	Alkenone T_{Ann} SST	Schefuß, Schouten, Schneider 2005
O. MD02-2529	8.20°N	84.12°W	Mg/Ca T_{Ann} SST	Leduc et al. 2007
P. MD81	6.18°N	125.50°E	Mg/Ca T_{Ann} SST	Stott et al. 2004
Q. KNR176-JPC32	4.85°N	77.96°W	Alkenone T_{Ann} SST	Pahnke et al. 2007
R. MD76	5.00°S	133.26°E	Mg/Ca T_{Ann} SST	Stott et al. 2004
S. GeoB6518-1	5.58°S	9.39°E	Alkenone T_{Ann} SST	Weldeab et al. 2007
T. ODP 1084B	25.52°S	13.03°E	Mg/Ca T_{Ann} SST	Farmer, Demenocal, Marchitto 2005
U. Off S. Chile	41.00°S	74.45°W	Alkenone T_{Ann} SST	Kaiser, Lamy, Hebbeln 2005
V. SO136-011GC	43.44°S	167.85°E	Alkenone T_{Ann} SST	Barrows et al. 2008
W. W. Antarctic Peninsula	64.51°S	64.12°W	TEX_{86} T_{Ann} SST	Shevenell, Ingalls, Domack 2007

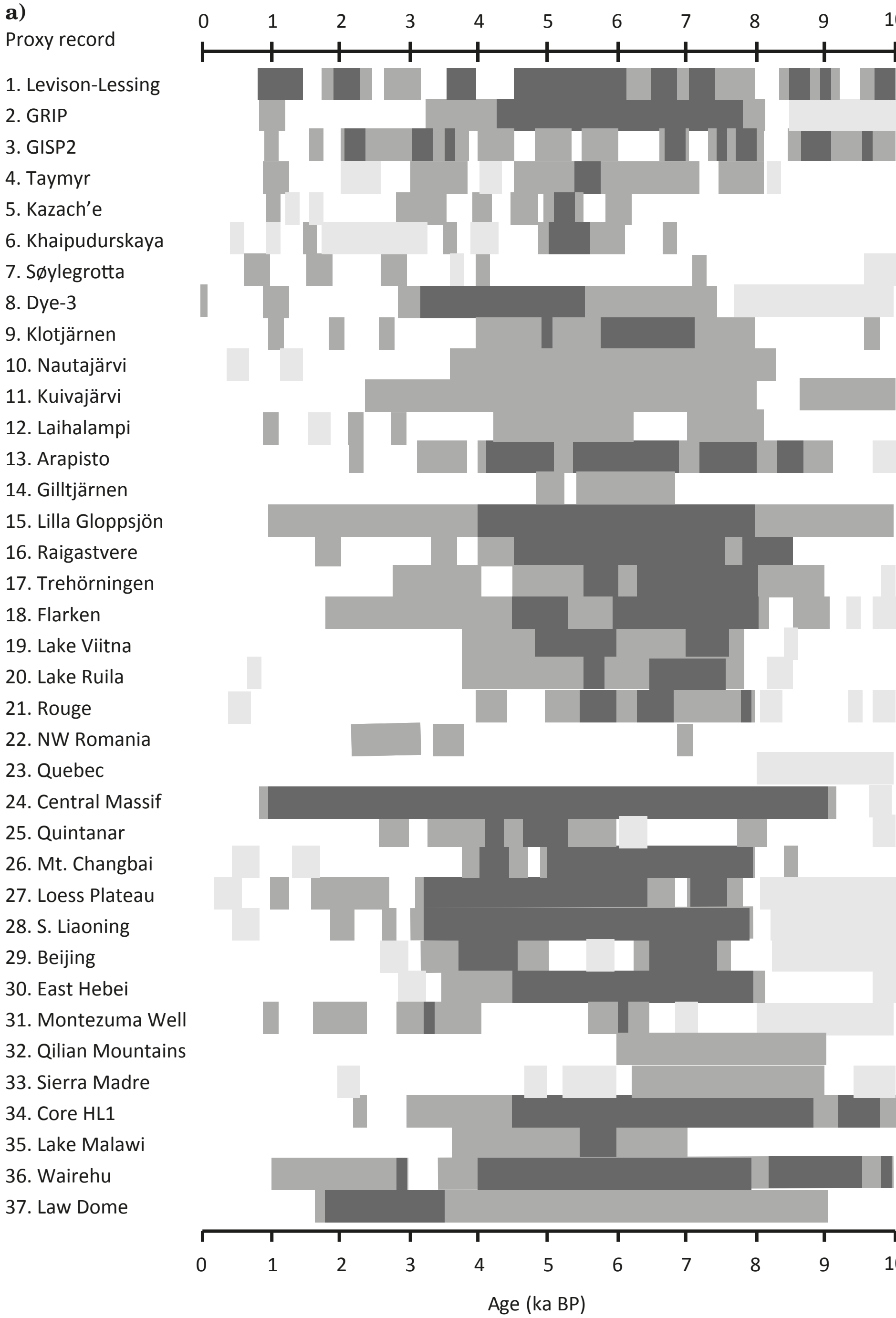
latitudes (90–60°N), 18 from northern mid latitudes (60–30°N), 2 from northern low latitudes (30–0°N), and 1 record each from the southern low (0–30°S), mid (30–60°S), and high latitudes (60–90°S). Of the marine records, 1 is from northern high latitudes, 8 are from northern mid latitudes, 9 from northern low latitudes, 3 from southern low latitudes, 2 from southern mid latitudes, and 1 is from southern high latitudes. Altogether, 51 out of the 60 records are from the Northern Hemisphere, reflecting the relative lack of palaeotemperature data from the Southern Hemisphere.

Many potentially useful records unfortunately cannot be used in this study since they either represent seasonal temperatures or end before the pre-industrial period AD ~1750. The latter is, for example, the case with most of the marine records presented in Kim et al. (2004) and Leduc et al. (2010) and also with some terrestrial records (e.g., Bordon et al. 2009; Jiang et al. 2006; Tierney et al. 2008). Most of the high-latitude records, including virtually all of those from Canada and Alaska, reflect summer temperatures and thus have not been useful here (for a review of the Arctic records, see Sundqvist et al. (2010)). Many other records also reflect seasonal temperatures (primarily summer and/or winter) and not annual temperatures, for instance Chase et al. (2008), Cheddadi et al. (1998), Heiri et al. (2003), Potito et al. (2006), and Tarasov et al. (2007). Only reconstructions from specific sites have been utilized and no regional reconstructions have been considered here. Hence, the data used for instance in Davis et al. (2003), Nakagawa et al. (2002), Viau et al. (2008), and Viau, Gajewski (2009) cannot be used here since they are not published as site-specific reconstructions.

The review of the spatio-temporal pattern of the mid-Holocene Thermal Maximum is achieved by assessing the coherency between the records of multi-centennial periods during the last 10 ka BP with annual mean temperatures exceeding three different threshold values: (1) at least 1°C above pre-industrial (~1750 AD) values, (2) at least 2°C above pre-industrial values, and (3) at least 1°C below pre-industrial values. Periods with temperatures that diverge less than 1°C from the pre-industrial temperatures will be considered "equal" to them. The results are visually presented in Figure 2. Low temporal resolution and uncertain dating of most of the reconstructions necessarily limit our assessment to warm and cold periods lasting several centuries. Hence, we are only concerned here with the temperature evolution over longer time-scales.

Results

As the graphical presentation in Figures 2a–b and 3a–b show, both hemispheres experienced mid-Holocene temperatures above pre-industrial (~1750 AD) values during several millennia on most locations where data are available. The larger amount of data makes this result more robust for the Northern Hemisphere than for the Southern Hemisphere. The 60 reviewed reconstructions suggest that the mid-Holocene Thermal Maximum culminated c. 8–4 ka BP, with the warmest temperatures occurring c. 6–5 ka BP (Figure 3a–b). This is in line with what was reported by Klimenko, Klimanov and Fedorov (1996). The onset of the Neoglaciation seems to occur c. 4–3 ka BP. In some records, mainly but not exclusively from the high northern latitudes, a new multi-centennial period of temperatures exceeding those of the pre-industrial (~1750 AD) period by more than 1°C seems to have occurred during the Medieval Warm Period (c. 800–1300 AD; see, e.g., Bradley et al. 2001, 2003; Broecker 2001; Esper, Frank 2009; Ljungqvist 2009). This brief interruption of the Neoglaciation was followed by the Little Ice Age (c. 1300–1900; see, e.g., Grove 1988; Matthews, Briffa 2005; Wanner et al. 2008), which the reconstructions suggest was the coldest period since at least c. 8 ka BP. Shorter periods of colder climate, notably the 8.2 ka BP event (Alley, Ágústsdóttir 2005), are not visible in Figures 2a–b and 3a–b due to the low temporal resolution and uncertain age control for most of the records. Nor have the much discussed quasi-cyclical c. 1470 ± 500 year climate oscillations known as the Bond Cycles, first observed in the North Atlantic region but recently also elsewhere, been clearly detected in the reconstructions (Wanner et al. 2008; Wanner, Bütikofer 2008). The reason behind this could partly be uncertain dating, but also that at



a)
Proxy record
1. Levison-Lessing
2. GRIP
3. GISP2
4. Taymyr
5. Kazach'e
6. Khaipudurskaya
7. Søylegrotta
8. Dye-3
9. Klotjärnen
10. Nautajärvi
11. Kuivajärvi
12. Laihalampi
13. Arapisto
14. Gilltjärnen
15. Lilla Gloppsjön
16. Raigastvere
17. Trehörningen
18. Flarken
19. Lake Viitna
20. Lake Ruila
21. Rouge
22. NW Romania
23. Quebec
24. Central Massif
25. Quintanar
26. Mt. Changbai
27. Loess Plateau
28. S. Liaoning
29. Beijing
30. East Hebei
31. Montezuma Well
32. Qilian Mountains
33. Sierra Madre
34. Core HL1
35. Lake Malawi
36. Wairehu
37. Law Dome
0 1 2 3 4 5 6 7 8 9 10
Age (ka BP)

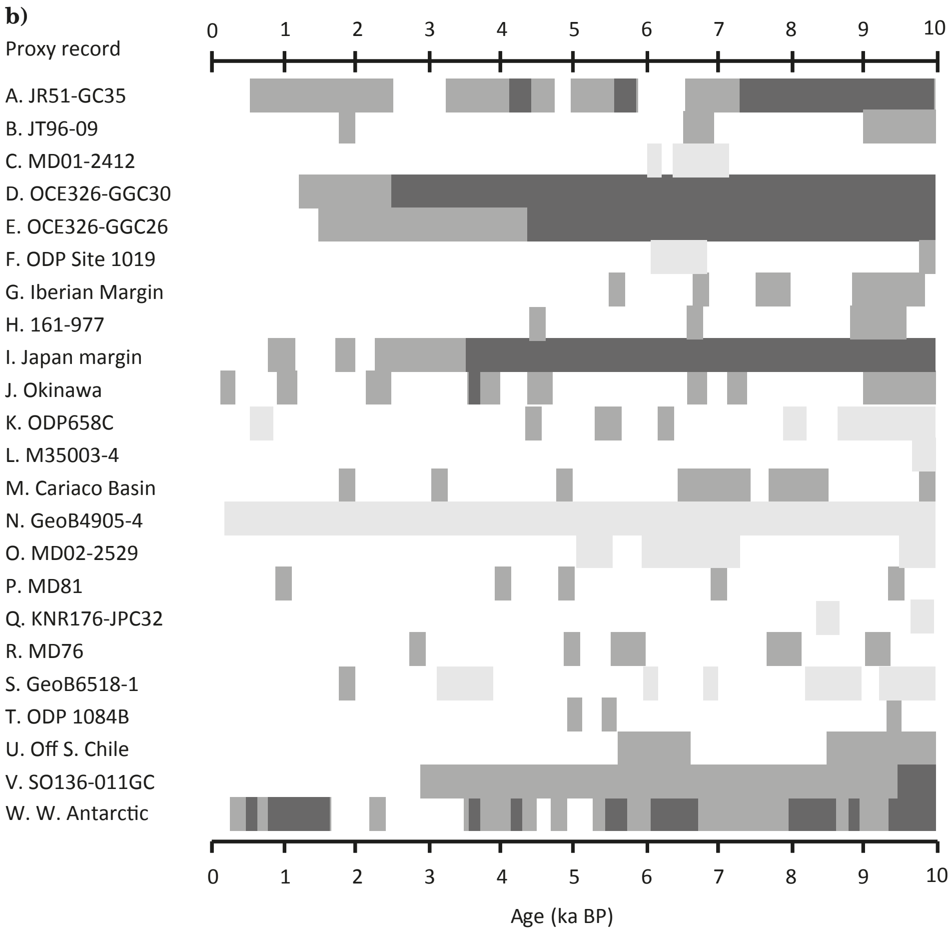


Fig. 2 – Periods marked in dark grey: at least 2°C above pre-industrial temperatures. Periods marked in grey: at least 1°C above pre-industrial temperatures. Periods marked in light grey: at least 1°C below pre-industrial values. Periods with temperatures that diverge less than 1°C from the pre-industrial temperatures are not shown.

most locations many of the Bond cycles probably had an amplitude of less than the threshold value of 1°C used here.

Perhaps surprisingly, no distinct spatio-temporal pattern of the mid-Holocene Thermal Maximum is noticeable in the 60 geographically widely scattered reconstructions (Figure 2a–b). Differences between reconstructions from the same region actually seem to be about as big as those between different hemispheres, regions or latitudes. Previous research has indicated that high latitudes in the Southern Hemisphere experienced a mid-Holocene Thermal Maximum earlier than the Northern Hemisphere (Masson et al. 2000; Williams et al. 2004). This assumption is not supported by the data presented in Figures 2a–b and 3a–b. Instead, both hemispheres seem to have experienced the mid-Holocene Thermal Maximum at about the same time, in line with the results of a recent study by Shakun and Carlson (2010). Keeping

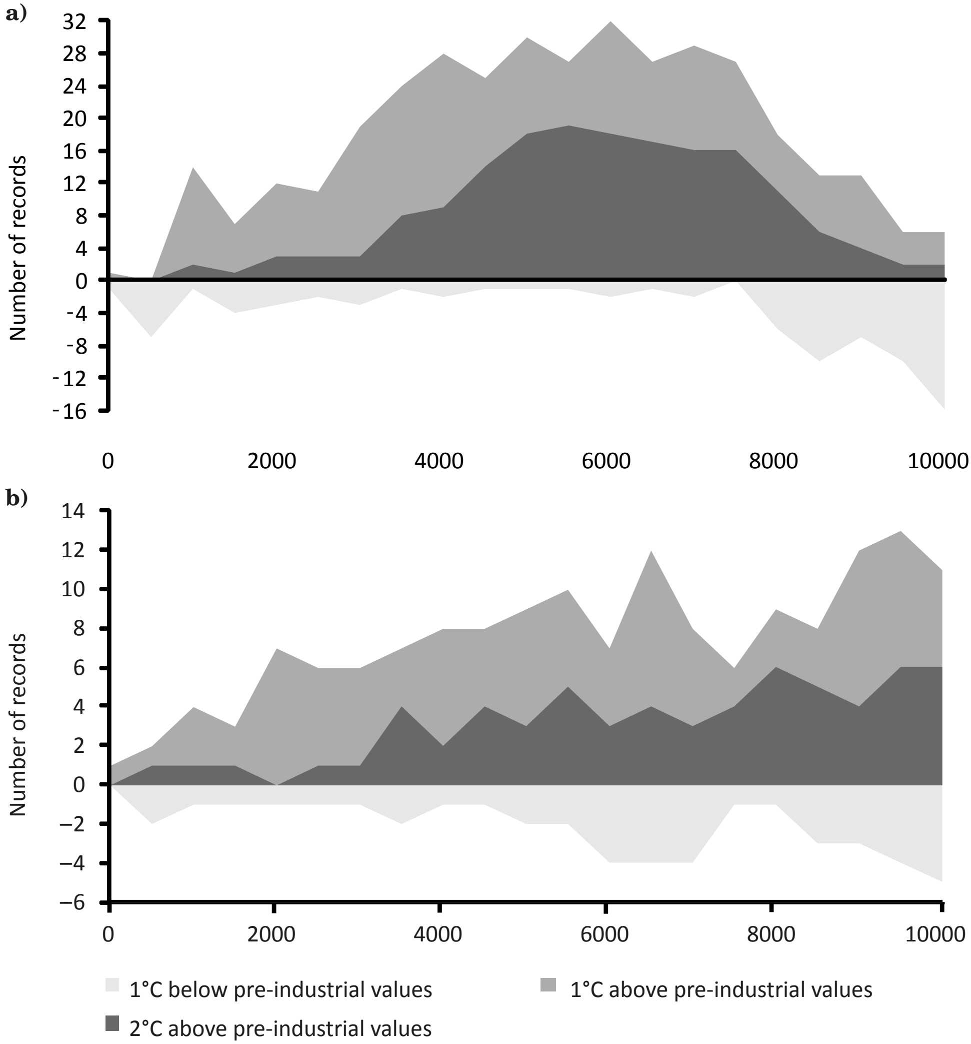


Fig. 3 – Number of records during different periods being at least 2°C above, at least 1°C above or at least 1°C below pre-industrial values

in mind the limited data available from the Southern Hemisphere, we can conclude that the amplitude of this warming seems to have been equivalent in both hemispheres and smallest in the tropical regions.

Discussion

As highlighted in the IPCC report (Solomon et al., eds. 2007), our knowledge of the global or hemispheric temperature evolution during the Holocene period is still very inadequate. This is a serious shortcoming concerning our ability to predict the future climate and the relative influence of different natural and anthropogenic forcings. Our review of the timing of periods during mid- and late-Holocene with annual mean temperatures 1°C and 2°C above those in the pre-industrial (~1750 AD) period indicates that the mid-Holocene Thermal Maximum was more temporally coherent around the globe than generally thought. This in turn implies that the earth during the Holocene period perhaps experienced larger long-term changes in global mean temperature than usually acknowledged. One notable feature observed in the 60 records discussed here is that there is an earlier maximum warming in many of the marine records compared to the terrestrial records. It ought to be an important question for subsequent research to investigate if the mid-Holocene Thermal Maximum occurred earlier in oceans than on land or if this is just an artefact of insufficient data quality or of uneven geographical coverage.

This study represents the first systematic attempt to collect a larger number of globally distributed proxy records of annual mean temperature from different archives and synthesize their spatial-temporal information. Previous studies, tracking the mid-Holocene Thermal Maximum, have either been more restricted geographically or limited to a single type of proxy archive. The most important gain with this study is to bring together the information from 60 site-specific annual mean temperature reconstructions in order to get an improved overview of what currently available data show. Our main result is that site-specific reconstructions of annual mean temperature tend to indicate a more spatially coherent warm pattern during the mid-Holocene than usually thought.

State-of-the-art General Circulation Models and Energy Balance Models are unable to simulate a significant change in the global mean temperature due to changes in orbital forcing, or to any other changes in natural forcing known to have occurred during the Holocene (Hewitt, Mitchell 1998; Ganopolski et al. 1998; Kitoh, Murakami 2002; Masson-Delmotte et al. 2005; Wanner et al. 2008). On the other hand, composites of temperature measurements from boreholes drilled into the Earth crust indicate a mid-Holocene Thermal Maximum with temperatures more than 2°C warmer than during the pre-industrial period (Huang, Pollack, Shen 2008). If the mid-Holocene Thermal Maximum indeed represented a considerable global warming, it presupposes strong positive feedbacks in the climate system that are still poorly understood.

The spatio-temporal pattern of the Mid-Holocene Thermal Maximum, evident from Figures 2a–b and 3a–b, can briefly be discussed in the light of glaciological evidence. Beginning with the northern high latitudes, glaciers were much reduced on Frans Josef Land and Svalbard ~10–3 ka BP (Svendsen, Mangerud 1997; Lubinski, Forman, Miller 1999). Local coastal glaciers on Greenland were at approximately the same time reduced in size (Kelly, Lowell 2009) and Icelandic glaciers were significantly smaller than today ~8–4.5 ka BP (Geirsdóttir et al. 2009). The evidence is somewhat more inconclusive from the Canadian Arctic Archipelago but Briner, Davis, Miller (2009) have shown evidence of reduced glaciers on Baffin Island 7.5–4 ka BP. Scandinavian mountain glaciers were absent or much reduced ~9.5–3 ka BP (Nesje 2009), and although the picture from Alaska is somewhat less clear, glaciers in southern Alaska were smaller than today before the Neoglaciation 4.5–4.0 ka BP (Barclay, Wiles, Calkin 2009). Moving to the northern mid-latitudes, Ivy-Ochs et al. (2009) concluded that glaciers in the European Alps 10.5–3.3 ka BP were smaller than they are today. A similar glacial history for the Canadian Cordillera was found by Menounos et al. (2009). Röthlisberger and Geyh (1985) concluded that the glaciers in the Himalaya and Karakoram ranges of Asia were smaller than today ~7–4.5 ka BP. Evidence is sparser for the tropics and the Southern Hemisphere but Rodbell, Smith, Mark (2009) found that few, if any, significant glacier advances occurred during the Holocene in the Andes prior to the Neoglaciation ~4.5 ka BP. Glaciological data from Antarctica and the Sub-antarctic Islands indicate a generally reduced mid-Holocene glacier extent but also point to glacier advances ~8–7 ka BP and ~5.5–4.5 BP (Hall 2009). All in all, the glaciological evidence seems to broadly support the spatio-temporal pattern of periods with temperatures at least 1°C and 2°C, respectively, above the pre-industrial level.

To this date, there exist no direct quantitative temperature reconstructions on a global scale longer than 2000 years, except borehole temperature measurements (Solomon et al., eds. 2007; NRC 2006). To accomplish such reconstructions, preferably with quantitative error bars, ought to be an urgent challenge for the palaeoclimatological community now that sufficient data are becoming increasingly available to make such reconstructions feasible. However, in order to better understand the spatio-temporal pattern of the mid-Holocene Thermal Maximum, we have need of more quantitative temperature reconstructions from regions where little palaeoclimatological work has been done so far (e.g., Africa, Australia, and South America). It is also important to make more of existing and future data digitally available in publicly accessible and searchable databases such as http://www.ncdc.noaa.gov/paleo and http://www.pangaea.de. As it is now, much valuable palaeoclimatological data is unavailable for use in multi-proxy syntheses and for comparisons of various kinds.

Conclusions

Our assessment of 60 annual mean temperature reconstructions from different locations around the globe indicate a more coherent mid-Holocene Thermal Maximum than hitherto reported. Focusing on the first question posed in the introduction, we can from the palaeotemperature reconstructions presented here conclude, in line with Solomon et al., eds. (2007), that the absolute peak temperatures during the mid-Holocene Thermal Maximum likely occurred at different times in different regions. Moreover, even proxy records from the same regions show a different temporal pattern of maximum warming, which limits our possibility to investigate to what degree the warming was synchronous. Although the early part of the mid-Holocene (10–8 ka BP) exhibits a very heterogeneous pattern, with some locations showing temperatures much higher than the pre-industrial (~1750 AD) period and others showing much lower temperatures, the latter part of the mid-Holocene (7–4 ka BP) shows more homogeneously higher temperatures than those of the pre-industrial period except for perhaps in the tropical region (see Figure 2a–b and Figure 3a–b).

This leads us to the second question posed in the introduction, namely whether there were periods during the mid-Holocene that likely experienced more than 1°C higher annual mean temperature than in the pre-industrial period. We find no indications that support the IPCC (Solomon et al., eds. 2007) conclusion that global annual mid-Holocene temperatures were not warmer than today or that the earth during the mid-Holocene Thermal Maximum only experienced increased temperatures during the summer season and on higher latitudes in the Northern Hemisphere.

On the contrary, our survey suggests that annual mean temperatures were higher in large areas of the globe in both hemispheres, although the temperature increase was amplified on high latitudes, especially in the Northern Hemisphere. The warming is less clear in some locations at low latitudes, where a few records show a cooling during some intervals of the mid-Holocene. Our conclusions are, arguably, somewhat weakened by the low resolution of much of the data and the considerable dating uncertainties of many of the records as well as the lack of data from some regions (e.g., Southern Europe), shown in other studies (e.g., Bartlein et al. 2011), likely to have had lower temperatures during the mid-Holocene. We would cautiously suggest, in agreement with borehole temperature composites (Huang, Pollack, Shen 2008), that it is very likely that the earth experienced multi-centennial periods during the Holocene with global mean temperatures at least 1°C above the pre-industrial temperatures and possibly even more. However, more reliable conclusions in this matter cannot be reached until more data have become available for low latitudes and the Southern Hemisphere.

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S h r n u t í

ČASOPROSTOROVÝ MODEL TEPLOTNÍCH MAXIM STŘEDNÍHO HOLOCÉNU

Jak je zdůrazněno v usnesení Mezivládního panelu pro změny klimatu (IPCC) z roku 2007, jsou naše znalosti o vývoji teplot během období holocénu v globálním i regionálním měřítku stále omezené. Víme, že během středního holocénu byla teplotní maxima (přibližně 8–5 tisíc let před současností) některých oblastí, alespoň během určitých období, o několik stupňů Celsia vyšší než dnes, a to v důsledku změn dráhových elementů Země. Časoprostorový model tohoto oteplování však není stále ještě dostatečně jasný. Hlavním problémem při porozumění klimatu středního holocénu je převaha paleoklimatických záznamů specifických pro určitá období (např. léto) a omezené množství údajů z nižších zeměpisných šířek. Tento nedostatek adekvátních kvantitativních paleoklimatických dat, obzvláště z jižní polokoule, spolu s neschopností obecných modelů cirkulace a energetické bilance simulovat globální průměrné teploty vyšší než současné, vedl k závěru, že teplotní maximum středního holocénu se v globálním měřítku s velkou pravděpodobností neobjevilo synchronně. Dostupné teplotní rekonstrukce však samy o sobě nejsou v tomto ohledu přesvědčivé, mnohé z nich naznačují, že teplotní maximum středního holocénu se objevilo zároveň v různých částech světa.

Článek předkládá posouzení časoprostorových modelů teplotního maxima středního holocénu v 60 rekonstrukcích ročních teplot z posledních 10 tisíc let před současností z různých oblastí světa, které byly v posledních letech publikovány v odborné literatuře. Z těchto 60 záznamů je 37 pevninských a 23 mořských. Analýza zhodnotila souvislosti mezi záznamy s teplotami minimálně o 1, resp. o 2 °C vyššími než preindustriální (kolem roku 1750). Abychom zachytili pouze změny v ročních teplotách, vyhnuli jsme se všem sezónním rekonstrukcím. Na počátku středního holocénu (10–8 tisíc let před současností) se projevuje silně heterogenním model s oblastmi teplot jak mnohem vyšších, tak mnohem nižších než preindustriální (kolem roku 1750). Poslední období středního holocénu (7–4 tisíc let před současností) však vykazuje náznaky jistým způsobem více koherentního globálního teplotního maxima, než se doposud uvádělo.

Těchto 60 posuzovaných záznamů naznačuje, že průměrné roční teploty středního holocénu mohly překročit preindustriální teploty nejen během léta ve vyšších zeměpisných šířkách, ale také během ostatních období a v dalších částech světa. Tento výsledek se dobře shoduje s paleoteplotními záznamy z vrtů, které ukazují, že průměrné globální teploty ve středním holocénu byly pravděpodobně alespoň o 1 °C vyšší, než preindustriální. Pozornost zasluhuje skutečnost, že v těchto 60 diskutovaných záznamech se maximum oteplení projevilo dříve v mnoha záznamech mořských než kontinentálních.

Obr. 1 – Rozmístění 60 paleoteplotních rekonstrukcí uvedených v tabulce 1a–b a na obrázku 2a–b.

Obr. 2 – Období vyznačená tmavě šedou: nejméně 2 °C nad preindustriálními teplotami. Období označená šedě: nejméně 1 °C nad preindustriálními teplotami. Období vyznačená světle šedě: nejméně 1 °C pod hodnotami preindustriálními. Období s teplotami, které se od preindustriálních liší o méně než 1 °C, nejsou uvedena.

Obr. 3 – Počet záznamů během různých období s hodnotami nejméně 2 °C nad, nejméně 1 °C nad nebo nejméně 1 °C pod preindustriálními hodnotami.

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