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Chironomid responses (Insect: Diptera) to Younger Dryas and Holocene environmental changes in a river floodplain from northern France (St-Momelin, St-Omer basin)

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Abstract: Lateglacial to Holocene subfossil chironomids from the St-Omer basin at St-Momelin (northern France) were analysed. At the end of the Lateglacial, stratigraphic and chironomid sequences indicate a shallow, oligotrophic and slow-flowing freshwater stream, with abundant aquatic macrophytic vegetation. Cold-water adapted taxa indicate a cold climate. During the early Holocene, from about 9500 to 7700 conventional radiocarbon yr BP, climate improvement is marked by an increase in warm-water adapted taxa and a decrease in cold-water fauna. However, the cold-water fauna persist, probably because of both the instability and continentality of the climate. During the mid Holocene, from about 7700 to 6000 BP, the marine transgression strongly influenced the river's hydrological regime and consequently the chironomid assemblages. At that time, eutrophic, warm and shallow stagnant-water conditions occurred throughout the basin. From 6000 to 3200 BP, the St-Momelin basin was subjected to a marine regression. Chironomids indicate a hydrological regime marked by an alternance of phases with either a dominance of rheophilous or limnophilous fauna. During this period, equivalent percentages of warm- and cold-adapted taxa may be explained by cold-water input in context of a temperate climate.

Key words: Palaeoecology, palaeoclimate, Holocene, marine transgression, hydrological regime, river floodplain, North Sea, Chironomidae, northern France.

Introduction

The analysis of subfossil chironomids has been used frequently in palaeoecological investigations of Quaternary lacustrine sediments as they are excellent indicators for Quaternary palaeoenvironments and palaeoclimates (Lowe and Walker, 1997). Like coleoptera (Elias, 1994), chironomids

respond rapidly to environmental change, as a result of their short lifespan and the dispersive capacity of winged adults. For example, chironomids that have been well preserved in lake sediments (Hofmann, 1986), provide valuable reconstructions of: (i) palaeotemperature (eg, Lotter *et al.*, 1997; Brooks and Birks, 2000b); (ii) lake eutrophication and nutrients assessing (Lotter *et al.*, 1998; Langdon *et al.*, 2006); (iii) dissolved oxygen (Francis, 2001; Quinlan and Smol, 2001a) and; (iv) water-level changes (Hofmann, 1998; Korhola *et al.*, 2000). However, chironomid analysis in fluvial systems is

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poorly developed, despite its potential for palaeoecological (Gandouin *et al.*, 2005, 2006) and archaeological investigations (Ruiz *et al.*, 2006) of floodplains. For example, Gandouin *et al.* (2006) have illustrated for the River Aa (northern France) that mid-Holocene hydrodynamic variations (potentially induced by climate change) can be reconstructed from subfossil chironomids. In addition, a middle pleniglacial sequence in the Dinkel Valley (The Netherlands), was studied by Ran (1990) with the aid of chironomid subfossils in association with pollen analyses. The chironomids provided valuable ecological information on the functioning of the Dinkel River, in particular, concerning the aquatic vegetation cover and the rate of water flow.

Based on a large data set consisting of 127 chironomid taxa and 991 sites situated in running water in Italy, Rossaro (1991) suggests that chironomid species can be sorted according to their optimum water temperature, from cold stenothermal species to warm water species. It is therefore probable that river chironomid subfossils can also provide thermal information concerning past water temperatures that may potentially relate to climate change.

Previous studies (Van der Woude and Roeleveld, 1985; Sommé *et al.*, 1994) have identified thick early Weichselian, Lateglacial and Holocene sequences at Watten and St-Momelin in the St-Omer basin, northern France. The chronological depth of the sequences makes this subsiding area of the Flemish maritime plain an ideal place to analyse the functioning of the river system in connection with the variations in postglacial climate and sea-level rise. It also allows the investigation of land–ocean interactions in mid- and north-European latitudes.

In 2000 a multidisciplinary programme was launched (Gandouin, 2003) in order to reconstruct environment and climate change from the end of the Lateglacial to the mid Holocene. Thick sequences have been investigated through the analysis of multiple proxies, including sediment, pollen, molluscs, chironomids and coleoptera. The present paper focuses on the chironomid assemblage as other analyses are still in progress.

At a regional scale, the maritime plains from Great Britain, Belgium, The Netherlands and Germany are relatively well documented from pollen analysis (Mullenders *et al.*, 1972; Munaut and Paulissen, 1973; Bohncke and Vandenberghe, 1991; Waller, 1994), geomorphology and chronostratigraphy (Plater *et al.*, 2000; Streif, 2004), insects (Dinnin, 1997; Coope, 1998) and multiproxy investigations (Long *et al.*, 1996, 1998; Preece and Bridgland, 1999; Berendsen and Stouthamer, 2000). Valuable data on climate (Zagwijn, 1994; Brooks and Birks, 2000a; Davis *et al.*, 2003; Bedford *et al.*, 2004) and the postglacial sea level rise (Pirazzoli, 1991; Preece, 1995; Shennan and Andrews, 2000) are also available for northern Europe. However, the French coasts of the English Channel and the North Sea remain underdocumented because the only existing continuous records are located in a few inland sites, such as in the Paris basin (Van Zeist and Van der Spoel-Walvius, 1980) and at Verrières in the Seine Valley (Limondin and Rousseau, 1991).

The aims of this paper are: (i) to produce a palaeoenvironmental reconstruction based on chironomid assemblage dynamics, (ii) to produce a preliminary water temperature range estimation, and (iii) to compare the St-Omer record with other contemporaneous climate reconstructions for NW Europe.

Study site

The site (Figure 1) has already been described by Van der Woude and Roeleveld (1985) and Gandouin *et al.* (2005). The

St-Omer basin (Pas-de-Calais region, northern France) is located downstream of the Aa river. The 560 km² river catchment is predominantly located in a zone of subsidence (Mansy *et al.*, 2003) on a chalk substratum that extends into Eocene clay in its lower part at the St-Omer basin (from Arques to Watten). This basin (40 km²) is situated close to the North Sea. A single narrow outlet (about 1 km wide near Watten) connects the large catchment basin and the maritime plain. The gradient of the river along the basin is gentle, amounting to only around 0.1 m/km. Because of its very low elevation (2 m above sea level) the basin served as an estuary during the two major episodes of postglacial sea level rise; these were first described by Dubois (1924) and regionally named the Calais and Dunkerque transgressions, respectively. Subsequently, further subdivisions have been described that include more marine episodes within the North Sea basin: Calais I–IV and Dunkerque 0–III. The chronological position of each marine episode differs from one region to another according to complex glacio-hydro-eustatic readjustments and neotectonic processes (Denys and Baeteman, 1995; Lambeck, 1997; Waller and Long, 2003). A chronology for the Flemish-German plain is provided by Behre (2004) and a synthesis is given in Table 1 and by Gandouin (2003). During the marine regression, the basin was occupied by a fluvial and marsh system (Van der Woude and Roeleveld, 1985).

Today, the tempered oceanic climate of the St-Omer region is marked by an annual rainfall of c. 800 mm; the mean temperatures of the warmest and coldest months are about 18°C and 3°C, respectively, and the mean annual temperature is close to 10.5°C (Gehu, 1970). The modern landscape is a mosaic of cultivated and built up areas, with scattered remnants of semi-natural marsh vegetation consisting of willow and alder woodland, peat-bogs and wet grasslands.

Material and methods

Field work

Core sampling was carried out in the St-Momelin marsh. Two corers were used: (i) a 10 cm piston corer to extract the 'S2' core, which reached a depth of 1800 cm; and (ii) a 15 cm screw auger to extract a further core below S2, named 'P14'. The P14 profile allowed us to reach the Tertiary bedrock surface at a depth of 2000 cm, and therefore to complete the S2 profile. The two profiles are located 3 m apart. The deposits from 0–1 m were not sampled because of possible disturbance by agricultural activities. Sediments from 3–6 m, 9.64–10.05 m and 11.5–12 m were lost during coring operations. The sandy-silty sediments, from 1–3 m, 10.4–13 m and 15.5–17.5 m on the S2 profile, were sterile in terms of fossil preservation.

Chronology and lithostratigraphy

The radiocarbon ages obtained from bulk peat samples (Table 2) were calibrated with the INTCAL98 calibration curve, using the intercept method (Stuiver *et al.*, 1998). The lithological similarity of the S2 and P14 profiles (Figure 2) and radiocarbon dating allowed us to: (i) correlate the two profiles in order to draw a synthetic log and; (ii) chronologically place the sedimentary history of the site into a regional sedimentological context. The dates 8610±70 and 7740±60 BP are very close stratigraphically (P14 profile), situated at 1625 and 1600 cm, respectively, which suggests that a hiatus occurred that may be correlated with a probable emersion of the site. Similarly, in the S2 profile, the dates taken from the peat between 970 and 1050 cm are extremely close in the chronology, this is probably because this segment of the core corresponds to re-sedimented peat (Gandouin *et al.*, 2005).

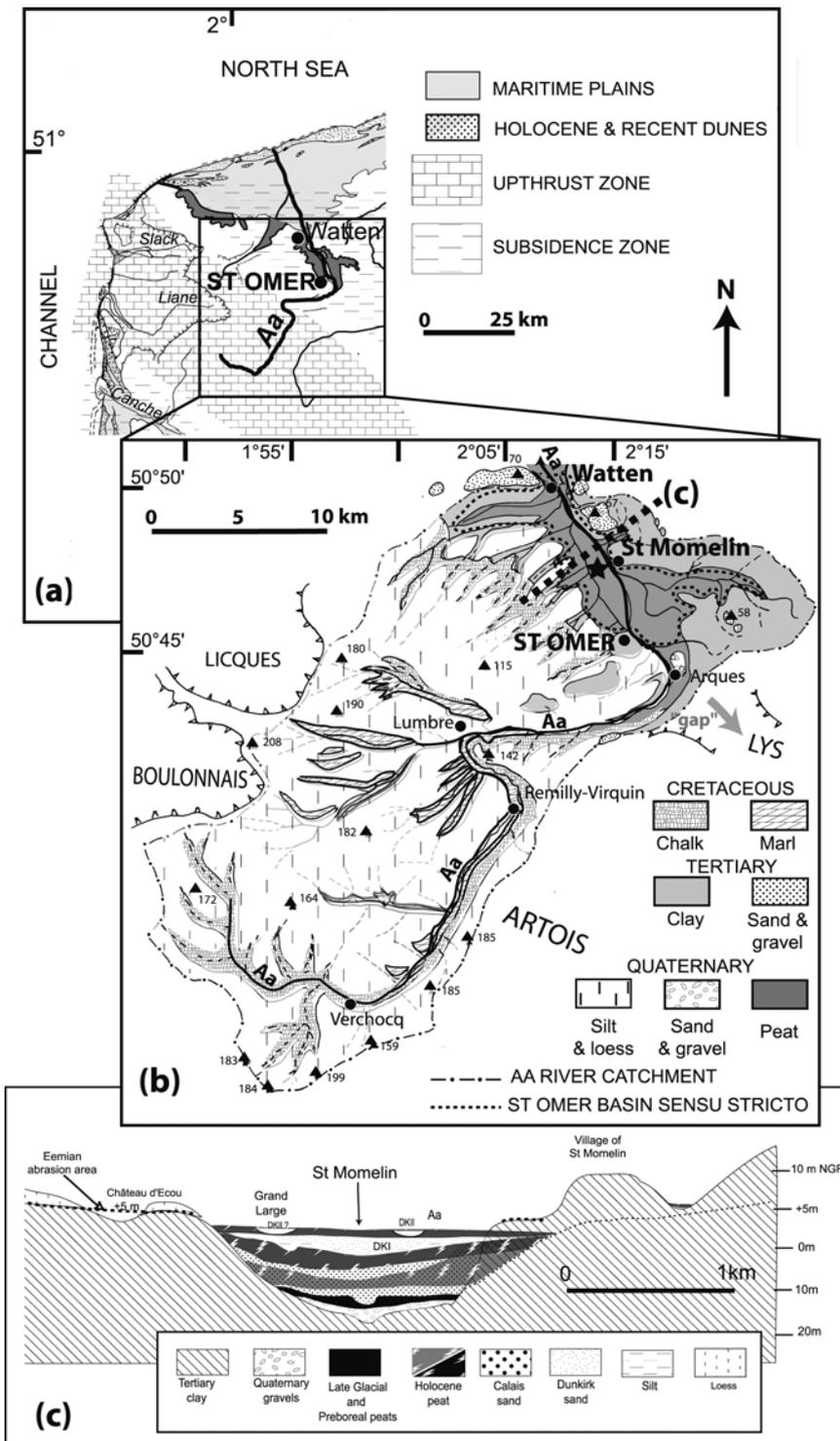


Figure 1 (a) Location of the St-Omer basin (northern France). (b) Drainage basin of the river Aa and coring site (black star). The St-Omer basin *sensu stricto* is delimited by a dotted line. (c) Lithology of the St-Omer basin cross-section at St-Momelin (Gandouin, 2003)

Subfossil chironomid analysis

Ninety-two samples of sediment weighing 150 to 500 g were collected, on average at 11 cm intervals, at depths ranging from 1900 to 600 cm. The laboratory methods for the extraction and identification of subfossil remains are described in Gandouin *et al.* (2005) and consisted of a coupled method, with successive sediment KOH-defloculation, water-washing over a 100 µm sieve (Hofmann, 1986) and paraffin flotation (Coope, 1986; Ruiz *et al.*, 2006). A minimum of 50 head capsules per sample must be picked out in order to provide realistic estimates of environmental conditions (Quinlan and Smol, 2001b). Taphonomic implica-

tions of floodplain and lake assemblages have been discussed by Ruiz *et al.* (2006). However, in higher energy environments mechanical fragmentation of the head capsules may make identification problematic. In floodplain sediments (silt, gyttja, charophytic mud and peat) from lower energy areas, head capsules were abundant and perfectly preserved, allowing reliable identification to be made to the genus level, and in some cases to the species or species-group level. The identification criteria were based on Bryce (1960), Bryce and Hobart (1972), Cranston (1982), Ferrarese and Rossaro (1981), Rieradevall and Brooks (2001), Rossaro (1982), Schmid (1993) and Wiederholm (1983).

Table 1 Calais and Dunkerque transgressions and their ages (conventional ^{14}C dates BP) at St-Momelin, in Netherlands (Hageman, 1969) and in Lower Saxony (Behre, 2004)

Transgression	St-Momelin (P14 and S2 profiles)	The Netherlands (Hageman, 1969)	Lower Saxony (Behre, 2004)
			500
			Dunkerque IIIb
			850
Dunkerque III	–	1150<	1100
			Dunkerque IIIa
			1250
Dunkerque II	–	1350	1600
		1700	1950
		2050	
		Dunkerque I	2100
Dunkerque 0–I	2510 ± 90	2550	2850
	3265 ± 70	2950	
		Dunkerque 0	
		3450	
		3750	3250
Calais IV	–	4550	3900
		4750	4400
Calais III	–	5250	5100
	5880 ± 80	5250	5300
Calais II	6990 ± 50	6250	6400
	7150 ± 90	6450	6400
Calais I	7740 ± 110	7950	7800

Table 2 ^{14}C dates assigned to sediments from St-Momelin

Profile: depth (cm)	Laboratory identification code	$^{13}\text{C}/^{12}\text{C}$ ratio	Conventional ^{14}C age BP	(2 σ) Calibrated BP	(2 σ) Calibrated BC
S2: 50–54	Hv–24816	–29.3 o/oo	1975±45 BP	1960–1870	10 BC–AD 80
S2: 76–79	Hv–24815	–31.9 o/oo	2510±90 BP	2745–2360	795 BC–410
S2: 600	Hv–24814	–29.7 o/oo	3265±70	3565–3385	1615–1435
S2: 800	Beta–161064	–29.0 o/oo	4850±70	5720–5460	3770–3510
S2: 900	Beta–161063	–30.0 o/oo	5830±100	6870–6410	4920–4460
S2: 1025	Hv–24813	–30.0 o/oo	5880±80	6840–6635	4890–4685
S2: 1400	Beta–161062	–28.5 o/oo	6990±50	7940–7700	5990–5740
S2: 1530	Hv–24812	–30.5 o/oo	7150±90	7990–7830	6040–5880
S2: 1723	Beta–161061	–28.3 o/oo	7740±110	8960–8940 / 8850–8840/ 8780–8350	7010–6980 / 6900–6890/ 6830–6400
P14: 650	Hv–24808	–28.9 o/oo	4180±45	4825–4575	2875–2625
P14: 700	Hv–24807	–29.0 o/oo	5040±55	5890–5720	3940–3770
P14: 1000	Hv–24806	–29.7 o/oo	5810±50	6710–6540	4760–4590
P14: 1600	Beta–161065	–28.1 o/oo	7740±60	8620–8400	6670–6450
P14: 1625–1630	Beta–161066	–28.2 o/oo	8610±70	9720–9500	7770–7550
P14: 1700	Beta–161067	–29.1 o/oo	9450±70	11 070–10 940 / 10 860–10 520	9120–8990 / 8910–8570

The calibrated age ranges were based on the INTCAL98 calibration procedure, using the intercept method (Stuiver *et al.*, 1998). All measurements were performed on bulk sediment with a conventional radiocarbon dating procedure.

Chironomid collection slides from the Natural History Museum of London (S.J. Brooks, unpublished works) were also consulted. The relative abundance of each chironomid taxon for each sample is presented as a percentage diagram (Figure 3). A constrained sum-of-squares cluster analysis (CONISS) for percentage data was performed to highlight major changes in

chironomid assemblage composition throughout the stratigraphy (Grimm, 1987). Correspondence analysis (CA) was performed on the n by p matrix of percentages to produce an ordination of the p taxa and of the n samples. Rare taxa were removed from the analysis. CA sample scores reflect the relative position of each sample (characterized by a specific faunal

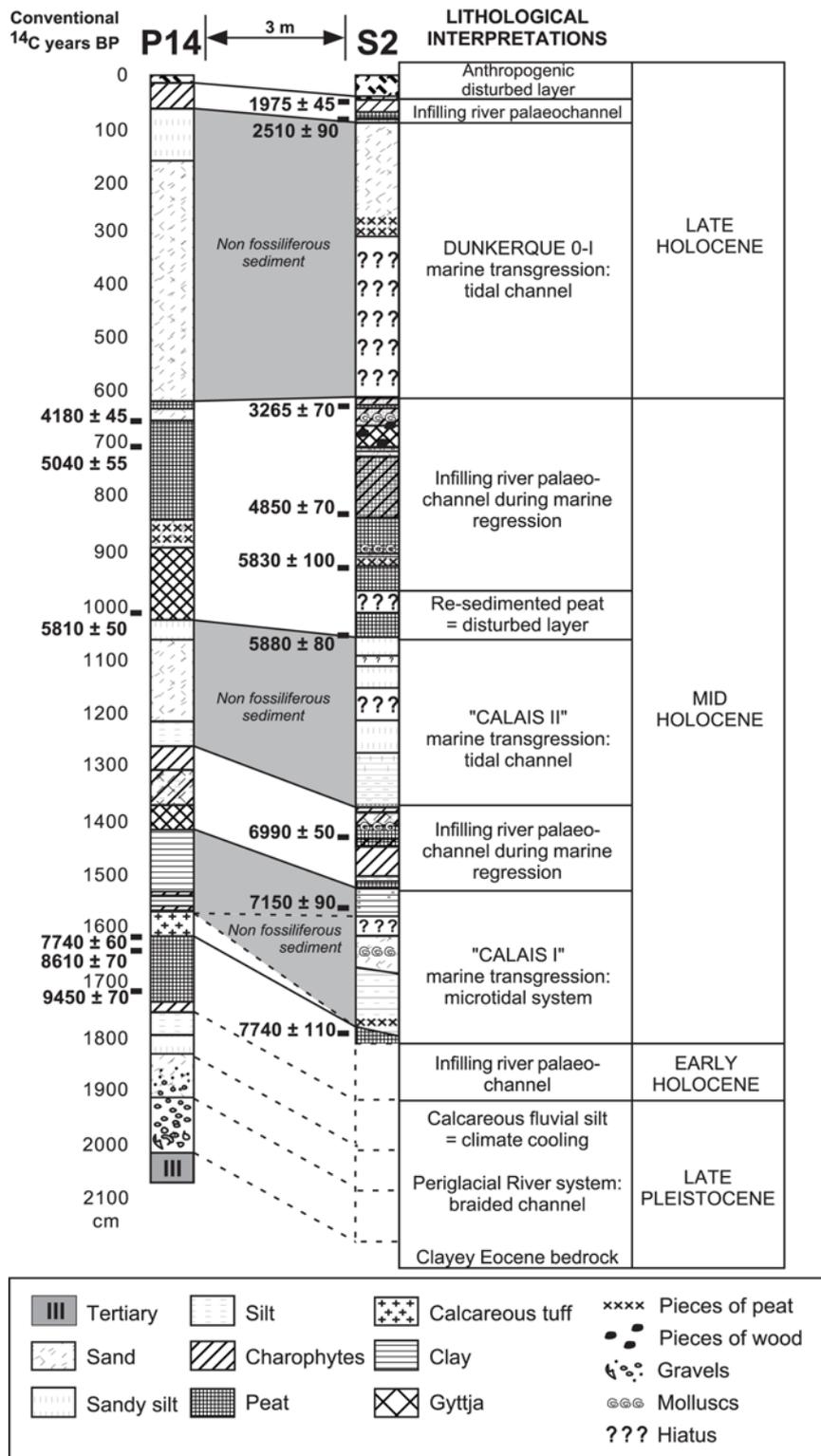


Figure 2 Lithological correlation between P14 and S2 sedimentary profiles

assemblage) among all samples in response to one or more environmental gradients. These scores give an estimate of the overall compositional change between two adjacent samples. The CA and its corresponding graphical plots (Figure 4) were performed in ADE-4 (Thioulouse *et al.*, 1997).

Chironomid ecological preferences and temperature estimates

The habitat preferences of flood plain chironomids are discussed in Gandouin *et al.* (2005, 2006). Following Gandouin

et al. (2006), the chironomid assemblages are grouped into four ecological categories (Figure 5): (i) lentic: chironomid genera associated with lentic habitats such as oxbow lakes, dead-arms, side channels temporarily connected with main channel; (ii) lotic: genera associated with lotic habitats such as the main channel and side channels, connected to the main river; (iii) ubiquitous: genera that can colonize all kinds of habitats available in the river floodplain; and (iv) unclassified: taxa that cannot be precisely identified and/or taxa with a distribution that is either unknown or unrelated to the flow rate of the current.

A second independent grouping is based on trophic and thermal preferences with: (i) eutrophic and warm-water adapted taxa; (ii) oligotrophic and cold-water adapted taxa; and (iii) indifferent taxa.

The method used here to produce temperature estimates is based on the only data set available in Europe, obtained by Rossaro (1991) and Rossaro *et al.* (2006), from an altitudinal range of 991 sites in running waters (northern Italy). Temperature estimates are represented graphically according to the Tukey boxplot method (Tukey, 1977; Wonnacott and Wonnacott, 1990).

Results: palaeoenvironmental reconstruction

One hundred and eleven taxa (see Gandouin, 2003) were identified from 92 levels. A mean number of 78 head capsules per sample were counted ($n_{\min}=53$ capsules, $n_{\max}=154$), totalling 7157 head capsules. Three major zones (Zone 1, 2 and 3) and 16 subzones (Subzone SMch-1 to SMch-16) were identified by the cluster analysis (Figure 3).

The first two axes of the CA (Figure 4A, B) account for nearly 25% of the total inertia contained in the 92 (samples) by 79 (taxa) matrix. The first axis shows a gradient between Zone 1 and 2, with Zone 3 located in an intermediary position. The first axis separates the warm-water adapted, eutrophic and limnophilous taxa, such as *Chironomus* spp. and *Dicoretendipes* spp., from the cold-water adapted, oligotrophic and rheophilous taxa, such as *Paracladius* sp., *Micropsectra* spp., *Diplocadius cultriger*, *Tanytarsus lugens* grp., *Eukiefferiella/Tvetenia* and *Cricotopus/Orthocladius/Paratrachocladius*. Hence, the first axis could be interpreted as a thermal gradient. Based on this interpretation, the thermal optimum occurs in the final part of Zone 2, and the cold maximum in Zone 1 (Figure 4C).

Zone-1 (1894–1747 cm) $\leq 9450 \pm 70$ BP

Zone-1 is characterized by *Cricotopus/Orthocladius/Paratrachocladius*, *Paracladius* sp., *Micropsectra* spp., *Eukiefferiella/Tvetenia* and *Tanytarsini* unidentified. These taxa are mostly adapted to cold water, and following Gandouin *et al.* (2006), they are considered to be a lotic community that is typical of a river floodplain.

In SMch-1 (1894–1846 cm), despite of the dominance of lotic taxa, the presence of lentic species, such as *Polypedium* spp. and *Microtendipes* spp. (which are usually located in lacustrine littoral areas) is consistent with shallow and slow water flow. Many stream species of the *Micropsectra* spp. and *Eukiefferiella/Tvetenia* genera are also known to be oligotrophic (Brodersen *et al.*, 2004) and cold-water adapted (Rossaro, 1991; Rossaro *et al.*, 2006), and indicative of good water quality (Mandaville, 2002). These characteristics are all consistent with cold climate conditions.

SMch-2 (1834–1786 cm) is characterized by a change in the assemblage, with a decrease of lotic taxa and a dominance of the cold-water adapted *Paracladius* (Brooks *et al.*, 1997; Walker *et al.*, 1997). Many cold-water adapted and oligotrophic taxa, such as *Diplocadius cultriger* (Oliver and Dillon, 1997), *Paracladopelma* sp. (Lotter *et al.*, 1997) and *Heleniella serratosioi* (Bulankova *et al.*, 2001) sporadically appear in this subzone. This faunal change could be linked to a cold maximum.

In SMch-3 (1761–1747 cm) the chironomid evidence suggests that climate conditions were still harsh, but relatively warmer than in SMch-2, with slightly higher percentages of eutrophic and warm-water adapted taxa.

The zone-1 dynamics of the chironomid assemblage allow us to: (i) discriminate two phases in the water flow rate, SMch-1 versus SMch-2 and 3, the latter two being more stagnant than the previous one; and (ii) suggest that a cold period is recorded in the St-Omer deposits, with a cold maximum during SMch-2.

Zone-2 (1737–1305 cm) from c. 9500 to 7000 BP

Zone-2 is contemporaneous with the early Holocene and the Calais transgression. In the lower and upper part of the Calais deposits (1800–1555 cm and 1300–1045 cm) of the S2 profile, no chironomids were found in the sandy deposits. This could be explained by either rapid sedimentation or poor conservation of chitinous remains resulting from oxidation and abrasion processes. Zone-2 is mainly characterized by *Chironomus* spp., *Dicoretendipes* spp., *Polypedium* spp., *Stempellina* sp. and *Microtendipes* spp. These taxa mostly fall within the category of 'lentic-ubiquitous' as they are eutrophic taxa that are adapted to warm water; as such, they mark the climatic improvement of the Holocene. Such assemblages also suggest that the habitat became progressively lentic and eutrophic by the organic infilling of the site. This probably would have resulted in a shallow oxbow lake or the dead arm of a stream with stagnant fresh water and a low dissolved oxygen content.

In SMch-4 (1737–1717 cm) the persistence of cold-water adapted *Parametrioctenemus/Paraphaenocladus* and *Linnophyes* taxa suggests that in spite of temperate summers, cold water probably persisted in spring, as a result of cold and long winters. These taxa are also semi-terrestrial (Wiederholm, 1983; Delettre, 2005) and their presence may be related to the lowering of water levels induced by the infilling of the site. Moreover, *Parametrioctenemus/Paraphaenocladus* are also taxa that are known to be typical of running-water (Heiri and Lotter, 2003), therefore the site was probably connected with the main channel during part of the year, explaining the cooler water inputs.

In SMch-5 (1710–1632 cm) the increase of *Microtendipes* spp., which is usually known as a littoral lacustrine taxon (Brooks, 2000), suggests that the infilling of the palaeochannel continued. The upper and lower limits of the subzone are marked by two isolated events. The first event, at the lower limit, corresponds to a peak of *Polypedium* spp. This ubiquitous taxon could suggest an intermediate stage between a predominantly 'lotic' system (cf. SMch-4) and a lentic and shallow hydrosystem (SMch-5). The second event is marked by a peak in the oligotrophic and cold-water adapted *Micropsectra* spp., which is also considered as lotic in a floodplain environment (Gandouin *et al.*, 2006). This may indicate a reconnection of the site with the river channel, probably as a consequence of a flood. No evidence of an abrupt flood event, such as a coarse minerogenic deposit, is given by the lithology, but a groundwater flood is probable. Moreover, groundwater, usually being cooler than surface water, would have enabled cold-water adapted taxa to appear. A climatic cooling could also be used to explain the peak of *Micropsectra* spp. and the occurrence of several cold stenothermous taxa, such as *Heleniella serratosioi* and *Conchapelopia melanops*.

SMch-6 (1625–1611 cm) is characterized by the ubiquitous *Chironomus* spp. and *Polypedium* spp. The site was probably situated between the lotic and lentic habitats of the river floodplain. Many species of the *Chironomus* and *Polypedium* taxa are associated with mesotrophic to eutrophic environments and large amounts of fine organic matter (Millet, 2004). In lakes from low-arctic West Greenland, Brodersen *et al.* (2004) have shown that *Chironomus* larvae have a high oxy-regulatory capacity and are thus able to spend a proportion of their life-cycle under hypoxic or apoxic conditions. This could indicate a

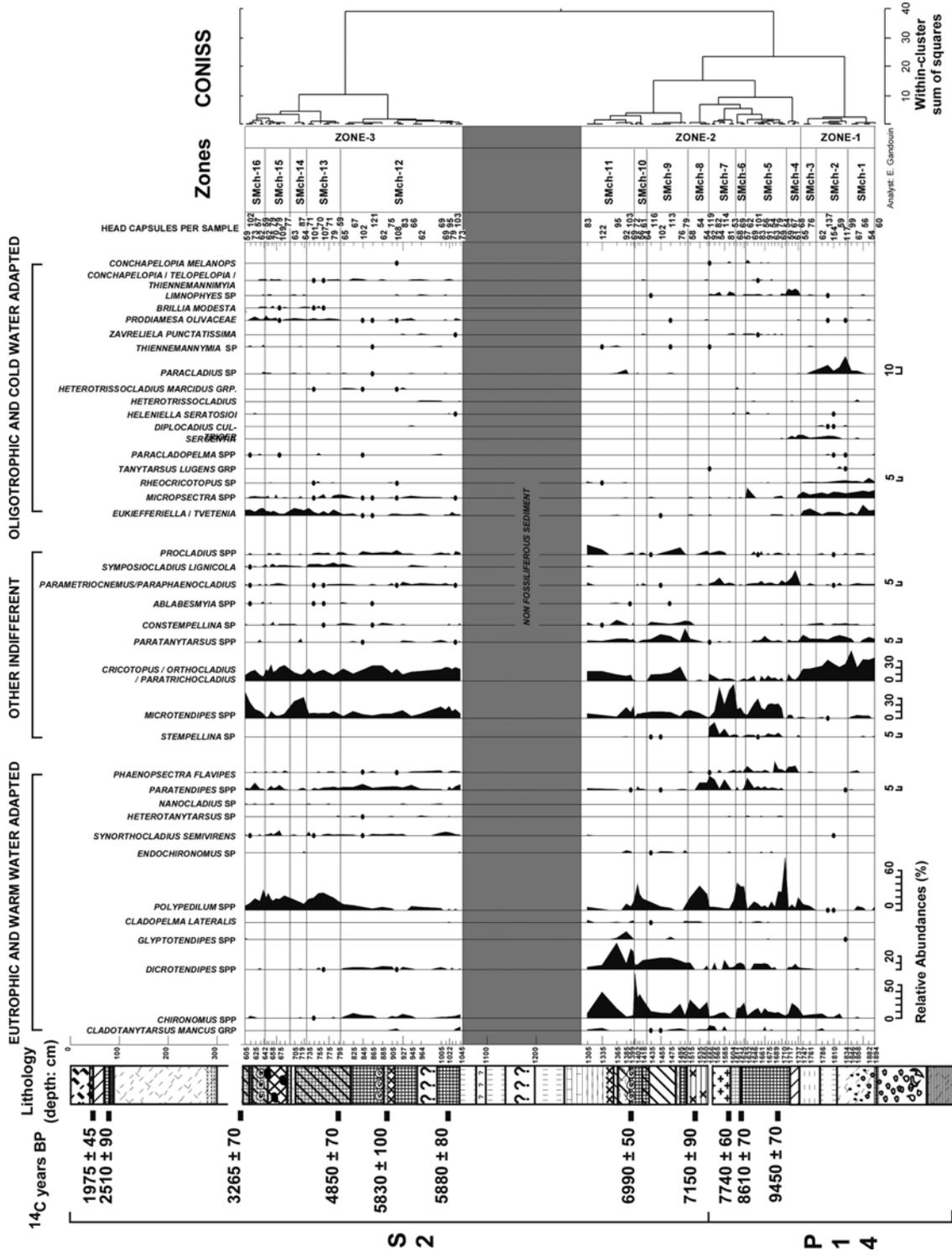


Figure 3 Lithology of the St-Momelin sequence and chironomid diagram showing relative abundances (%) of chironomid taxa (the dots on the vertical lines indicate $\leq 1\%$ occurrence) versus depth (cm). The present diagram shows the 39 main chironomid taxa out of a total number of 111 identified taxa (cf. Gandouin, 2003). Sandy sediments between 1305 cm and 1045 cm are devoid of chironomid sub-fossil. When morphological characteristics of different genera were too similar for more precise identification to be made, some taxa have been classified in fairly broad taxonomic categories eg, *Cricotopus/Orthocladius/Paratrichocladius*. When the head capsules were damaged, the individuals were classified at the family, subfamily or tribe level, followed by the term 'unidentified'. Selected taxa have been divided into three ecological categories: eutrophic and warm-water adapted taxa, oligotrophic and cold-water adapted taxa, and other indifferent taxa (eurythermous taxa + eurytope taxa + unknown preference), according to Wiederholm (1983); Larocque *et al.* (2001); Lotter *et al.* (1997); Rossaro *et al.* (2006); Brooks (2000) and Brooks and Birks (2000b). Gandouin *et al.* (2005) have previously subdivided the faunal assemblage sequence from the mid-Holocene peat (1035 cm to 600 cm) into five subzones: SMch-1, -2, -3, -4 and -5. For these subzones to be consistent with rest of the sequence they have been renamed, and subsequently become subzones SMch-12, -13, -14, -15 and -16 respectively.

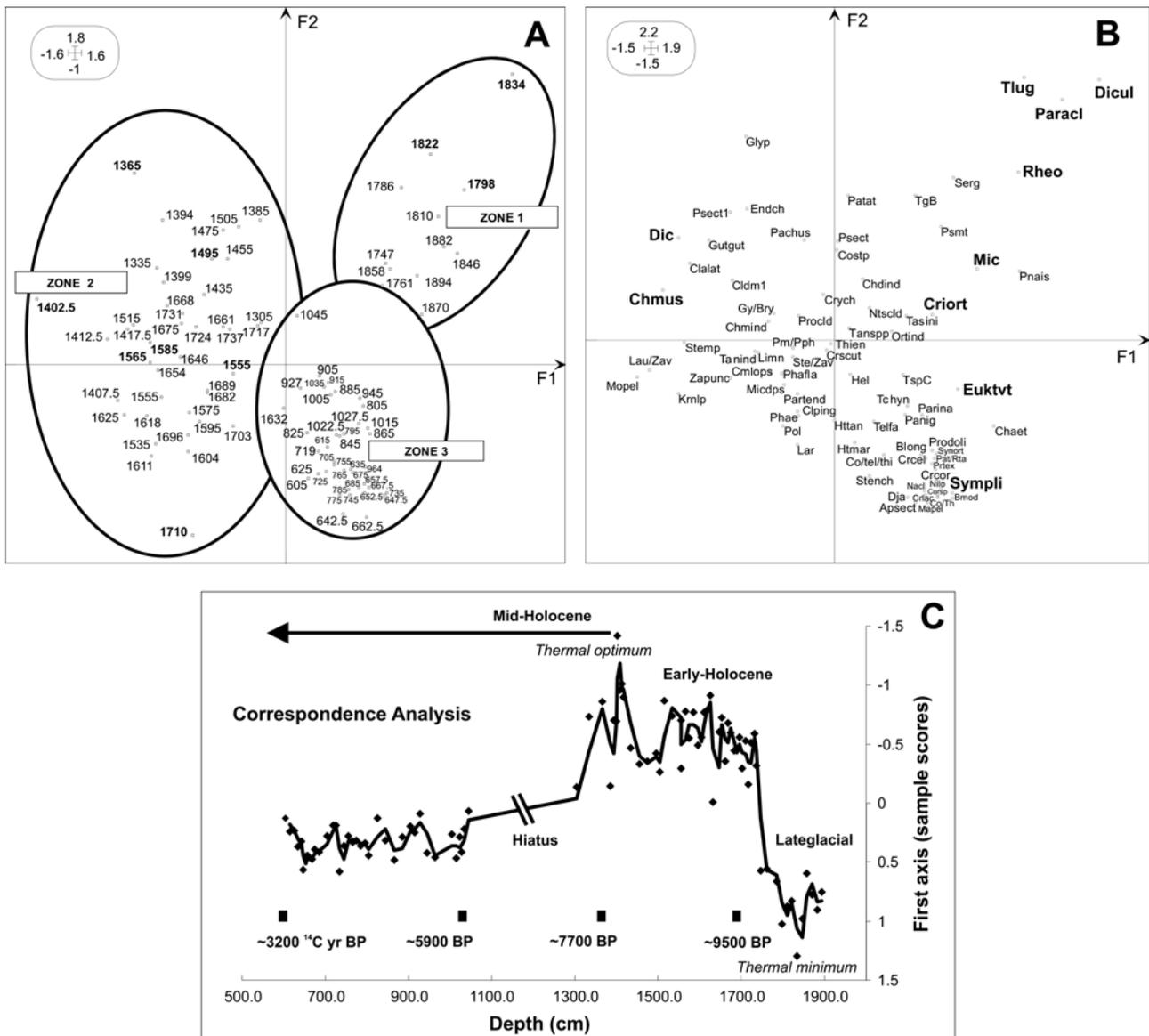


Figure 4 Factorial plane F1-F2 (accounting for 25% of the total inertia) from a Correspondence Analysis. (A) Plot of axes F1 and F2 for the 92 analysed samples. (B) Plot of axes F1-F2 of the chironomid taxa ($n=76$; rare taxa have been excluded from the analysis). (C) Correspondence Analysis sample scores for F1 axis. In bold: taxa that contribute to the first axis. Abbreviations: Apsect, *Apsectrotanypus trifascipennis*; Blong, *Brillia longifurca*; Bmod, *Brillia modesta*; Chaet, *Chaetocladius* sp; Chdind, unidentified Chironomidae; Chmind, unidentified Chironomini; Chmus, *Chironomus* spp.; Clalat, *Cladopelma lateralis*; Cldm1, *Cladotanytarsus mancus* group; Clping, *Clinotanypus pinguis*; Cmlops, *Conchapelopia melanops*; Co/Tel/Thi, *Conchapelopia/Telopelopia/Thiennemannimyia*; Co/Th, *Corynoneura/Thiennemania*; Corcp, *Corynoneura* sp.; Costp, *Constempellina* sp.; Crcl, *Corynoneura celeripes* (cf. *antennalis*); Crclac, *Corynoneura lacustris*; Crscut, *Corynoneura scutellata* type; Crych, *Cryptochironomus* sp.; Dic, *Dicotendipes* spp.; Dicul, *Diplocadius cultriger*; Endch, *Endochironomus* sp.; Euktvt, *Eukiefferiella/Tvetenia*; Glyp, *Glyptotendipes* spp.; Gutgut, *Guttipelopia guttipennis*; Gy/Bry, *Gymnometriocnemus/Bryophaenocladus*; Hel, *Heleniella seratosioi*; Htmr, *Heterotrissocladus marcidus* grp.; Htscl, *Heterotrissocladus* sp.; Httan, *Heterotanytarsus* sp.; Krnlp, *Krenopelopia* sp.; Lar, *Larsia* sp.; Lau/Zav, *Lauterborniella/Zavreliella*; Limn, *Limnophyes* sp.; Mapel, *Macropelopia*; Mic, *Micropsectra* spp.; Micdps, *Micotendipes* spp.; Mopel, *Monopelopia tenuicalcar*; Nacl, *Nanocladus* sp.; Nilo, *Nilotanypus dubius*; Ortind, unidentified Orthoclaadiinae; Pachus, *Parachironomus* sp.; Paracl, *Paracladius* sp.; Panig, *Paralauterborniella nigrohalteralis*; Parina, *Paramerina* sp.; Partend, *Paratendipes* spp.; Pat/Rta, *ParalRheo-tanytarsus*; Patat, *Paratanytarsus* spp.; Phae, *Phaenopsectra* sp.; Phafla, *Phaenopsectra flavipes*; Pm/Pph, *Parametriocnemus/Paraphaenocladus*; Pnais, *Paracladopelma nais*; Pol, *Polypedilum* spp.; Procl, *Procladius* spp.; Prodoli, *Prodiamesa olivaceae*; Prtex, *Paratrisocladus excerptus*; Psect, *Psectrocladius* spp.; Psmt, *Pseudosmittia* sp.; Rheo, *Rheocricotopus* sp.; Serg, *Sergentia* sp.; Stel/Zav, *Stempellinella/Zavrelia*; Stemp, *Stempellina* sp.; Stench, *Stenochironomus* sp.; Sympli, *Symposiocladius lignicola*; Synort, *Synorthocladus semivirens*; Tanind, unidentified Tanytopodinae; Tanspp, *Tanytarsus* spp.; Tchyn, *Tanytarsus Chyniensis*; Tasini, unidentified Tanytarsini; Telfa, *Telopelopia fascigera*; TgB, *Tanytarsina* sp.; Thien, *Thiennemannimyia* sp.; Tlug, *Tanytarsus lugens* grp.; TspC, *Tanytarsina* sp. C; Zapunc, *Zavreliella punctatissima*

possible depletion of oxygen in the water column, probably during a phase of water stagnation.

SMch-7 (1604–1556 cm) is marked by the dominance of *Microtendipes* spp., which could suggest shallow standing water, as observed in SMch-5. However, SMch-7 differs by having higher percentages of *Stempellina* sp. and *Paratendipes* spp. These taxa prefer high pH values (Mousavi, 2002), which are consistent with the contemporaneous chalky deposits (calcareous tuff layer in Figure 2). These sediments may have been the result of carbonate precipitation due to evaporation processes in a thin water film, or to intense bacterial activities. The abundance of the detritivores *Paratendipes* and *Microtendipes* (Stribling *et al.*, 1998) suggests that plenty of organic matter was available, a condition favourable to such bacterial activities. In SMch-7 the cold-water adapted taxa such as *Limnophyes* sp. and *Conchapelopia menalops* suggest the possibility of a temporary phase of cold water that was induced by the persistence of cool climate conditions.

SMch-8 (1555–1515 cm) is characterized by the same assemblages as those of SMch-6 and by the dominance of ubiquitous *Chironomus* spp. and *Polypedilum* spp., which are also oxygen-regulators, and adapted to eutrophic and warm waters. During SMch-8, almost all oligotrophic and cold-water adapted taxa disappear. Throughout this subzone, water was probably eutrophic and relatively warm, with low oxygen content because of a highly productive ecosystem, where metabolic activities of plants and micro-organisms are stimulated by nutrient profusion and warm summer waters. Such assemblages also could have been induced by brackish conditions (Tourenq, 1975) due to probable marine water influx (tidal or storm activity).

In SMch-9 (1505–1435 cm) the percentages of eutrophic and warm-water adapted taxa are still very high, whereas the high occurrence of *Dicrotendipes* spp. indicates considerable abundance of macrophytic vegetation (Hofmann, 1984), as also suggested by charophyte deposits.

SMch-10 (1418–1402 cm) is characterized by chironomid assemblages similar to those from SMch-8, with an abundance of *Chironomus* spp. and *Polypedilum* spp.

SMch-11 (1399–1305 cm) possesses the same chironomid assemblages, and hence similar ecological conditions, to that of SMch-9. At the end of SMch-11, *Dicrotendipes* spp. is replaced by *Chironomus* spp. This could have been induced by maximal oxygen depletion, and/or an increasing marine influence associated with brackish conditions. The latter is supported by the lithology, with the blue-grey silty clay being typical of tidal palaeochannels.

Zone-3 from c. 5900 to 3200 BP

Zone-3 is marked by the abundance of both standing- (or slowly moving) and running-water taxa. These ecologically contrasting groups are not necessarily incompatible. The presence of both groups suggests a river meandering across its floodplain between pools and riffles. The fact that the sediment included members of both communities suggests that they were accidentally brought together, for instance, at the time of a flood.

Faunal successions throughout zone-3 (from SMch-12 to SMch-16) indicate fluctuations in the hydrological regime, oscillating (Figure 5) between periods with a dominant lentic fauna (SMch-12, SMch-14 and SMch-16) and those with a dominant lotic fauna (SMch-13 and SMch-15). These fluctuations probably indicate that there were alternating episodes of rapid flow interspersed with calmer periods. Gandouin *et al.* (2005) have already discussed the correlation of the St-Omer lotic phases with several European climatic events known to have occurred during this period, such as alternations between dry and wet periods (Magny *et al.*, 2003). Since the sea level was relatively stable and the coastline was fairly distant from

the basin in this part of the mid Holocene, Gandouin *et al.* (2005) assumed that climate may have been responsible for these fluctuations in the hydrological regime of the River Aa. However, with a possible overestimation of the effects of precipitation due to some orographic processes (the Aa river catchment being located between the 'Boulonnais' and the 'Artois' reliefs), rainfall and flooding may have been concentrated in the lowest part of the river (the St-Omer basin).

This paper adds additional paleoenvironmental information about zone-3. Comparison between the zone-3 faunal assemblage and the two other subjacent zones reveal the following. (i) Eutrophic and warm-water adapted taxa are always dominant in zone-3, but that cold-water taxa reappear, suggesting that water temperatures were probably lower in zone-3 than in zone-2. (ii) The presence of high numbers of xylophagous taxa, such as *Symposiocladius lignicola*, *Brillia modesta* and *Synorthocladius semivirens* (Rossaro, 1982; Wiederholm, 1983; Walker and Mathewes, 1989) suggests that accumulations of plant debris, probably deposited during floods, were available nearby (this hypothesis is confirmed by the occurrence of wood fragments in the sediment). These data suggest a forest expansion within the catchment basin.

Discussion

Dating of the basal part of the sequence, based on radiocarbon, sediment and chironomid evidence

According to Antoine *et al.* (2000), fluvial silts with a high calcareous content are characteristic of Lateglacial cold periods (Oldest and Younger Dryas). Over much of NW Europe, where valleys cut through the chalk, calcareous muds were produced at this time by substrate gelifraction that accumulated in the valley bottoms (Ponel *et al.*, 2005). In Belgium and The Netherlands such fine and calcareous sand layers underlying early Holocene peat (Munaut and Paulissen, 1973; Berendsen and Stouthamer, 2000) have been dated to the Younger Dryas. However, some Lateglacial minerogenic deposits (some of which have a high calcareous content) are associated with entirely temperate insect assemblages (Coope and Brophy, 1972; Coope, 1998). Thus minerogenic sedimentation alone should not necessarily be taken as an indicator of cold conditions, but independent evidence, such as that derived from the chironomid assemblages, is clearly indicative of cold conditions that, in this case, are in agreement with the sedimentary interpretation. Based on this evidence there can be little doubt that samples from faunal unit SMch-1 to SMch-3 date from the Younger Dryas and that the sudden warming at SMch-4 marks the start of the Holocene.

Impact of Holocene sea level fluctuations on chironomid assemblages

Some Chironomids, such as *Chironomus salinarius*, are able to live in full marine conditions (Pinder, 1995; Hofmann and Winn, 2000), and the influence of marine incursions near the estuary of a river is likely to have had effects further upstream, for example in the increase of salt-tolerant species of chironomids. In the sequence sampled at St-Omer there is no chironomid evidence for the durable presence of truly marine conditions. However, from a lithological point of view, there are several types of clay-silt and sand that are characteristic of marine environments (see Allen, 2003, for detailed lithological description and interpretation of tidal palaeochannel deposits). SMch-8, SMch-10 and the top of the SMch-11 may be related to only probable marine water influx induced by short tidal episodes or storm activity. These short marine episodes should

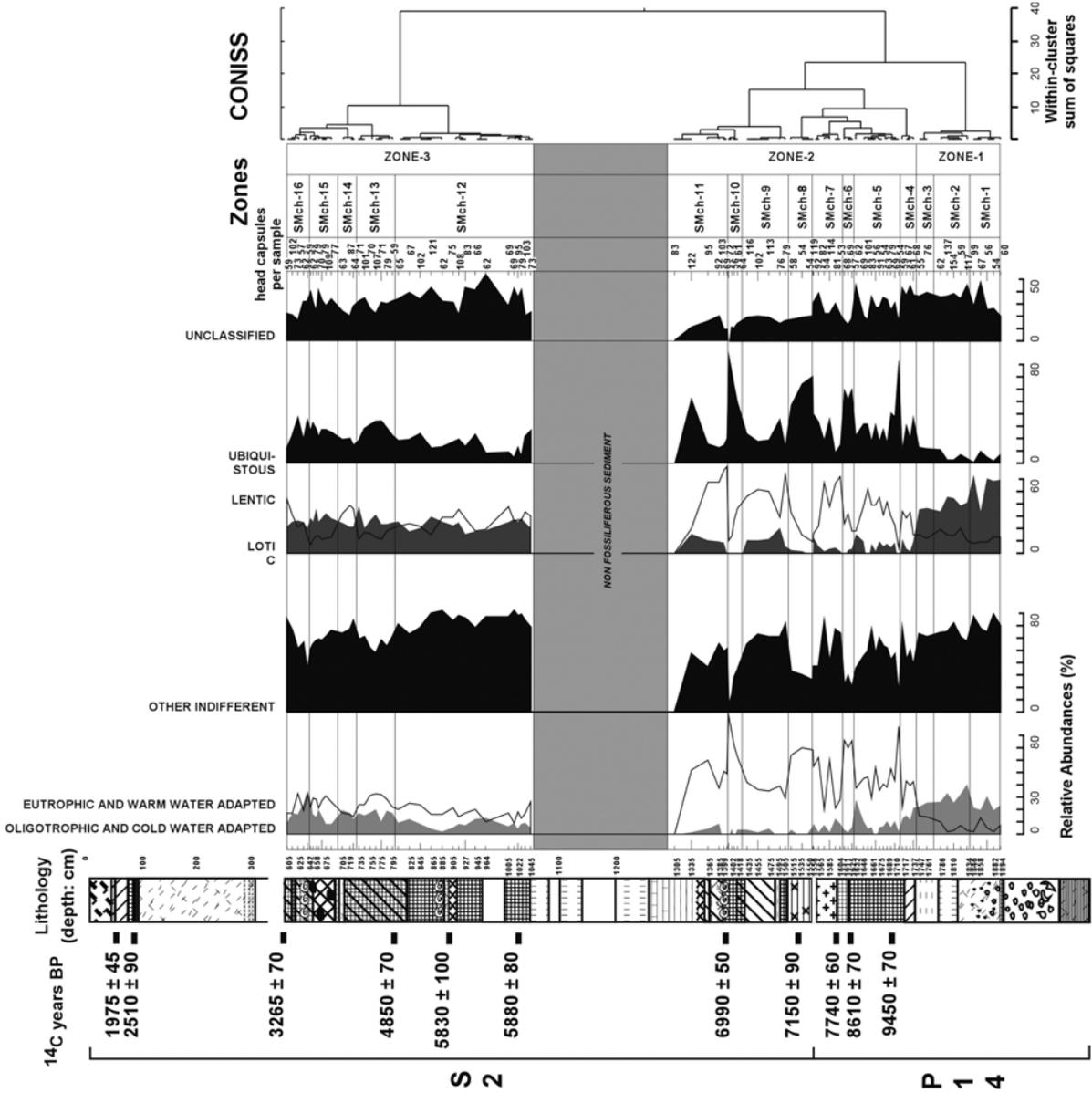


Figure 5 Synthetic chironomid diagram of relative abundances (%) of categories of cold-water adapted, warm-water adapted, eurythermous, lotic, ubiquitous, lentic and other unclassified chironomid taxa versus depth (cm). Cold-water adapted, warm-water adapted and other indifferent taxa are given in Figure 3. Lotic, ubiquitous, lentic and other unclassified categories have been established according to Gandouin *et al.* (2006). Lentic taxa: *Ablabesmyia* spp., *Cladopelma lateralis*, *Dicrotendipes* spp., *Endochironomus* sp., *Glyptotendipes* spp., *Kiefferullus tendipediformis*, *Limmophyes* sp., *Microtendipes* spp., *Paratanytarsus* spp., *Phaenopspectra flavipes*, *Tanytarsus* spp. Ubiquitous taxa: *Chironomus* spp., *Cladotanytarsus mancus* grp., *Paratendipes* spp., *Polypedilum* spp., *Procladius* spp., *Prodiamesa olivaceae*. Lotic taxa: *Brillia modesta*, *Cricotopus/Orthocladius Paratrichocladius*, *Eukiefferiella Tvetenia*, *Micropsectra* spp., *Nanocladius* spp., *Paracladopelma* spp., *Rheocricotopus* sp., *Synorthocladius semivirens*

have been favourable to the maintenance of brackish conditions into the basin and the dominance of brackish water tolerant taxa such as *Chironomus* and *Polypedilum* (Tourenq, 1975).

At St-Omer, the impact of Holocene sea level fluctuation on chironomid assemblages is therefore especially indirect. Change in the hydrological regime of the basin may have been induced in the following way. (i) A rise in groundwater level during the early Holocene in response to sea level rise; this would have led to the peat infilling of the Lateglacial palaeochannels (Berendsen and Stouthamer, 2000) and water stagnation throughout the basin. (ii) A substantial retreat of the sea from the area at about 6000 BP would have led to an increase in the water flow of the river, and the development of a vast freshwater marshy environment with a great diversification of habitats throughout the Aa river floodplain (Van der Woude and Roeleveld, 1985; Gandouin *et al.*, 2005).

Climatic interpretation and estimation of summer water temperatures

The present palaeoenvironmental reconstruction shows that chironomid assemblages are primarily dependent on hydrological conditions and river morphology. It is, however, possible to deduce climatic data from chironomid assemblage changes, not only because river morphology is dependent on major climate changes, but also indirectly since such assemblages are in equilibrium with water temperatures, the latter being a key variable for midge adult emergence and thus driving chironomid species distribution (Rossaro, 1991; Rossaro *et al.*, 2006).

Contrary to lake ecosystems, no chironomid transfer function is available for fluvial systems, since factors such as current speed, cool water inputs, sediment erosion, vegetation, transport and deposition are probably more constraining than in lake environments (Gandouin *et al.*, 2006). It is however possible to estimate a range of water summer temperatures from the data set available in Rossaro (1991) and Rossaro *et al.* (2006), using the Tukey boxplot graphic method (Tukey, 1977; Wonnacott and Wonnacott, 1990). Optimum water temperature was estimated for each chironomid species present in the data set from northern Italy. For each dominant genus occurring in subfossil assemblages at St-Omer, corresponding species values from the Rossaro data base (Table 3) are plotted on a diagram (Figure 6) showing graphically the ordinate distribution of temperatures within the different quartiles. Despite the southern location of the chironomid data base, its use in more northerly areas is made possible because of the wide altitudinal range spanned by the 991 sampling sites (from mid-Po fluvial plain to high summits of the Italian Alps). Moreover, the northern Italian chironomid fauna is very similar to the French fauna, according to Serra-Tosio and Laville (1991).

In Zone-1, the modern thermal requirements established in running water for species belonging to the *Cricotopus/Orthocladius/Paratrichocladius* group, *Micropsectra* spp. and *Eukiefferiella/Tvetenia* group enable us to estimate the thermal conditions that prevailed at St-Momelin: mean water temperatures ranged from 5°C to 21°C, with a median (Q2) of about 11°C and an interquartile range between 9°C (Q1: first quartile) and 16°C (Q3: third quartile). No modern river data are available for the dominant taxa *Paracladius*. However, according to a data set compiled by Lotter *et al.* (1997), *Paracladius* reaches a maximum abundance in Swiss alpine lakes, up to an altitude of 1500 m, with T°_{Jul} air temperatures ranging from 7.0°C to 9.6°C. This is consistent with reconstructed water temperatures ranging from 9°C to 11°C (interval between Q1 and Q2), since there is a strong correlation between surface water temperature and air temperature (Olander *et al.*, 1999).

In Zone-2, mean water temperatures deduced from the main taxa during the early Holocene ranged from 4°C to 22°C with a median of about 18°C and an interquartile range between 13°C and 21°C, and 50% of species had a mean water temperature ranging between 18°C and 22°C. Figure 4C shows a possible temperature optimum at the onset of the mid Holocene during the Calais transgression.

In Zone-3, summer water temperatures may have been cooler than in Zone-2, since they ranged from about 4°C to 22°C with a median value of about 12°C, and an interquartile range between 9° and 17°C.

Comparison with other European palaeoenvironmental and palaeoclimatical data

The Younger Dryas

During the Younger Dryas, fossil beetle data suggest summer air temperatures (T_{MAX}) between 5°C and 11°C in Britain (Coope, 1998) and between 10° and 11°C in The Netherlands (Bohncke *et al.*, 1987; Van Geel *et al.*, 1989). A pollen record from Luxembourg (Guiot and Couteaux, 1992) provided T°_{Jul} of 9°C, whilst pollen and plant macrofossils from central and NW Europe data sets (Isarin and Bohncke, 1999; Bogaart, 2003) suggest that the climate was characterized by cool summers with temperatures between 12° and 14°C. Rensen and Isarin (2001) characterized the major climate transitions in Europe during the last glacial–interglacial transition by comparing maps of January and July temperatures obtained by simulations with an atmospheric general circulation model (ECHAM model) and reconstructions based on geological and palaeoecological data (including beetle and pollen evidence). According to Rensen and Isarin (2001), the St-Omer basin is located between the 10° and 15°C isotherms, this is despite an overestimation of summer temperatures by the ECHAM model and the error margin (1–2°C) of the pollen-based temperature reconstructions (Isarin and Bohncke, 1999). These data are thus consistent with mean water temperatures ranging from 9°C to 11°C, estimated from the chironomids of St-Momelin, since there is a strong correlation between surface water temperature and T°_{Jul} (Olander *et al.*, 1999).

Chironomid results from St-Momelin are also in agreement with chironomid-based temperature reconstructions from Britain with summer air temperatures during the Younger Dryas (Loch Lomond stadial) between 9°C and 10°C at Hawes Water (Bedford *et al.*, 2004) and between 7.5°C and 9°C at Whitrig Bog (Brooks and Birks, 2000a; Brooks, 2006). Elsewhere in Europe, other chironomid-inferred temperatures for the Younger Dryas provide summer air temperatures of between 9.5°C and 10°C at Krakenes, Norway (Brooks and Birks, 2000b; Brooks, 2006) and of between 10.4°C and 10.9°C at the end of the Younger Dryas in the Swiss Alps (Heiri and Lotter, 2003; Heiri *et al.*, 2003).

The Younger Dryas in central and NW Europe is known to be subdivided into an earlier colder and wetter phase followed by a relatively warmer and drier phase (Walker *et al.*, 1994; Isarin *et al.*, 1998; Magny, 2001; Bogaart, 2003). Previous studies of floodplain chironomid subfossils (Gandouin *et al.*, 2005) provided evidence for a close correlation between river hydrological regimes and precipitation; chironomid assemblages characteristic of lotic phases apparently correspond to precipitation increases, whilst lentic phases correspond to precipitation decreases. Our results show a good correlation with this climatic subdivision since the first phase (SMch-1) of the Younger Dryas has a maximum of lotic taxa, whereas the second phase (SMch-2 and 3) is marked by a rise in the lentic taxa.

Table 3 Correspondence between main chironomid taxa in each zone from St-Momelin and taxa from Rossaro's temperature data base (Rossaro, 1991; Rossaro *et al.*, 2006)

Main taxa present at St-Momelin	Taxa present in Rossaro data base	Mean water temperature (°C)	
Zone-1			
<i>Paratrichocladius</i>	<i>Paratrichocladius nivalis</i>	6.4	
	<i>Paratrichocladius skirwithensis</i>	6.6	
<i>Orthocladus</i>	<i>Paratrichocladius rufiventris</i>	10.5	
	<i>Orthocladus frigidus</i>	8.5	
	<i>Orthocladus</i> sp. A	11.1	
	<i>Orthocladus rubicundus</i>	11.8	
	<i>Orthocladus excavatus</i>	12.0	
	<i>Orthocladus</i> spp.	12.3	
	<i>Orthocladus</i> pe 1	13.0	
<i>Cricotopus</i>	<i>Cricotopus</i> sp.	10.3	
	<i>Cricotopus fuscus</i>	11.6	
	<i>Cricotopus triannulatus</i>	13.4	
	<i>Cricotopus trifascia</i>	14.8	
	<i>Cricotopus vierriensis</i>	16.6	
	<i>Cricotopus annulator</i>	17.0	
	<i>Cricotopus</i> spp.	17.5	
	<i>Cricotopus tremulus</i>	18.0	
	<i>Cricotopus bicinctus</i>	18.9	
	<i>Cricotopus sylvestris</i>	19.9	
	<i>Cricotopus laricomalis</i>	20.9	
	<i>Micropsectra</i> spp	<i>Micropsectra notescens</i>	9.8
		<i>Micropsectra atrofasciata</i>	10.4
<i>Eukiefferiella</i>	<i>Eukiefferiella claripennis</i>	5.5	
	<i>Eukiefferiella brevicealcar</i>	7.0	
	<i>Eukiefferiella devonica</i>	7.0	
	<i>Eukiefferiella fittkaui</i>	7.4	
	<i>Eukiefferiella</i> spp.	8.0	
	<i>Eukiefferiella minor</i>	8.2	
	<i>Eukiefferiella tirolensis</i>	9.6	
	<i>Eukiefferiella fuldensis</i>	9.7	
	* <i>Eukiefferiella hospita</i>	10.7	
	* <i>Eukiefferiella brehmi</i>	11.8	
	<i>Eukiefferiella lobifera</i>	12.6	
<i>Eukiefferiella clypeata</i>	16.4		
<i>Tvetenia</i>	<i>Tvetenia bavarica</i>	7.7	
	<i>Tvetenia calvescens</i>	10.0	
	<i>Tvetenia verralli</i>	17.5	
Zone-2			
<i>Chironomus</i> spp.	<i>Chironomus</i> spp.	17.4	
	<i>Chironomus riparius</i>	17.6	
	<i>Chironomus plumosus</i>	20.4	
<i>Polypedilum</i> spp.	<i>Polypedilum quadriguttatum</i>	11.1	
	<i>Polypedilum laetum</i>	17.4	
	<i>Polypedilum cultellatum</i>	19.2	
	<i>Polypedilum convictum</i>	20.6	
	<i>Polypedilum (Tripodura)</i> spp.	20.9	
	* <i>Polypedilum acifer</i>	21.0	
	<i>Polypedilum</i> spp.	21.4	
	<i>Polypedilum nebulosum</i>	21.7	
<i>Dicrotendipes</i> spp.	<i>Dicrotendipes nervosus</i>	20.0	
	<i>Paratendipes</i> spp.	17.3	
<i>Paratendipes</i> spp.	<i>Paratendipes nudisquama</i>	3.8	
	<i>Microtendipes</i> spp.	8.9	
<i>Microtendipes</i> spp.	<i>Microtendipes pedellus</i>	8.9	
	<i>Microtendipes</i> spp.	9.1	
Zone-3			
<i>Polypedilum</i> spp.	<i>Polypedilum quadriguttatum</i>	11.1	
	<i>Polypedilum laetum</i>	17.4	
	<i>Polypedilum cultellatum</i>	19.2	
	<i>Polypedilum convictum</i>	20.6	
	<i>Polypedilum (Tripodura)</i> spp.	20.9	
	* <i>Polypedilum acifer</i>	21.0	
	<i>Polypedilum</i> spp.	21.4	
	<i>Polypedilum nebulosum</i>	21.7	
<i>Paratendipes</i> spp.	<i>Paratendipes</i> spp.	17.3	
	<i>Paratendipes nudisquama</i>	3.8	

<i>Microtendipes</i> spp.	<i>Microtendipes pedellus</i>	8.9
	<i>Microtendipes</i> spp.	9.1
<i>Paratrichocladius</i>	<i>Paratrichocladius nivalis</i>	6.4
	<i>Paratrichocladius skirwithensis</i>	6.6
	<i>Paratrichocladius rufiventris</i>	10.5
<i>Orthocladus</i>	<i>Orthocladus frigidus</i>	8.5
	<i>Orthocladus</i> sp. A	11.1
	<i>Orthocladus rubicundus</i>	11.8
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	<i>Cricotopus annulator</i>	17.0
	<i>Cricotopus</i> spp.	17.5
	<i>Cricotopus tremulus</i>	18.0
	<i>Cricotopus bicinctus</i>	18.9
	<i>Cricotopus sylvestris</i>	19.9
	<i>Cricotopus laricomalis</i>	20.9
<i>Eukiefferiella</i>	<i>Eukiefferiella claripennis</i>	5.5
	<i>Eukiefferiella brevicealcar</i>	7.0
	<i>Eukiefferiella devonica</i>	7.0
	<i>Eukiefferiella fittkaui</i>	7.4
	<i>Eukiefferiella</i> spp.	7.8
	<i>Eukiefferiella minor</i>	8.2
	<i>Eukiefferiella tirolensis</i>	9.6
	<i>Eukiefferiella fuldensis</i>	9.7
	* <i>Eukiefferiella hospita</i>	10.7
	* <i>Eukiefferiella brehmi</i>	11.8
	<i>Eukiefferiella lobifera</i>	12.6
<i>Eukiefferiella clypeata</i>	16.4	
<i>Tvetenia</i>	<i>Tvetenia bavarica</i>	7.7
	<i>Tvetenia calvescens</i>	10.0
	<i>Tvetenia verralli</i>	17.5

*Species absent in modern chironomid fauna from France (Serra-Tosio and Laville, 1991).

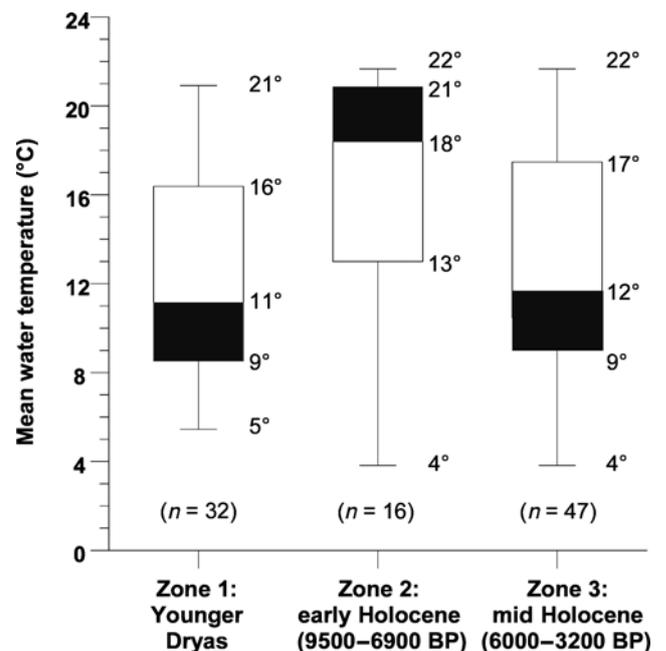


Figure 6 Tukey boxplots from a data set of mean water temperatures (Table 3) based on data from Rossaro (1991) and Rossaro *et al.* (2006). This preliminary graphic approach allows us to estimate possible mean water temperatures (black area) at St-Momelin during the Lateglacial and Holocene

At St-Omer, a possible control of the hydrological regime by sea level variations during the Lateglacial can be ruled out for the following reasons. (i) The palaeocoastline was located far away from the St-Omer basin (Scourse and Austin, 1995; Shennan *et al.*, 2000). (ii) Antoine *et al.* (2000) show that in the Somme and Seine valleys, close to the St-Omer basin, the middle part of river systems are beyond the impact of sea level variations and show detailed responses to climatic variation, especially during the Middle and Upper Pleistocene. (iii) A strong climatic impact on the dynamics of the NW European rivers is observed during the Lateglacial (eg. Starkel, 1991; Huisink, 2000). The climatic factor may be predominant until the early Holocene, since Scourse and Austin (1995) have shown that until *c.* 9000–8000 years BP, the Southern Bight of the North Sea and the eastern end of the English Channel were both shallow embayments with microtidal processes, and thus are unlikely to have affected the hydrological processes in the St-Omer Basin.

The early Holocene

The climatic improvement and the change in the fluvial regime of the Holocene are also clearly recorded in the chironomid assemblages. They are seen by the replacement of cold-water adapted and rheophilous taxa by warm-water adapted and limnophilous taxa. Although it is difficult to evaluate the timing of the climate change at St-Momelin because of possible hiatuses, the warming in summer-water temperatures inferred from chironomids (Figure 4C), appears to be related to the rapid warming of the early Holocene reported from fossil beetle data in Great Britain (Atkinson *et al.*, 1987; Coope and Lemdahl, 1995; Coope, 1998), from pollen data in Luxembourg (Guiot and Couteaux, 1992) and, broadly, all over central and NW Europe (Starkel, 1991; Renssen and Isarin, 2001; Davis *et al.*, 2003). This rapid warming is also recorded in fossil chironomid data from more northerly British sites at Hawes Water (Bedford *et al.*, 2004) and Whitrig Bog (Brooks and Birks, 2000a; Brooks, 2006), with summer air temperatures of 13.2°C and about 12°C, respectively. Also, at Kråkenes, Brooks and Birks (2000b) have reconstructed temperatures of 12–13°C or more at about 9570 BP, however these temperatures are possibly too low because of calibration problems concerning the temperature-inference model.

At St-Momelin, the persistence of cold-water adapted taxa during the early Holocene may be related to a possible temporary switch to a lotic environment marked by colder running water, which is favourable to cold-water adapted species. However, there is no sedimentologic evidence that such a lotic environment existed. The persistence of cold-water adapted taxa may also be explained by two aspects of climate.

(i) Relatively cool temperatures during spring were probably induced by long and cold winters. This explanation is consistent with the January and July isotherms estimated by Zagwijn (1994) at –2°C and 16°C, which have been based on the presence of indicator species in the pollen records from 9500 to 9000 BP. Zagwijn (1994) located the –2°C January isotherm further south of the St-Omer basin (in the mid-latitudes), whereas the 16°C July isotherm was located slightly north of the St-Omer basin. The climate reconstruction for NW Europe proposed by Davis *et al.* (2003) clearly shows that winter temperatures remained relatively low during the early Holocene whereas summer temperatures were already close to those of the present. This climatic continentality is consistent with the inland position of the St-Omer basin between about 9500 and 8000 BP, as shown by a number of studies (eg. Scourse and Austin, 1995; Shennan *et al.*, 2000).

(ii) Climate instability and abrupt climatic events, such as the Preboreal Oscillations (PBO), around 11 300–11 150 cal. yr BP (Björck *et al.*, 1997) and the 8200 cal. yr BP event, have been detected at many locations in Europe (Haas *et al.*, 1998; Brooks, 2000; Magny *et al.*, 2001; Björck *et al.*, 2002). Björck *et al.* (2002) suggest that this period is marked by complex climatic processes, with several short climate oscillations, which may be related to the influx of cold meltwaters from both the North American and European ice sheets and their associated impacts on the North Atlantic thermohaline circulation (Clark *et al.*, 2001; Fisher *et al.*, 2002; Teller *et al.*, 2002). Magny (2004) has noted that additional climate variations between the PBO and the 8200 cal. yr BP event can be also observed in palaeoclimatic records from the North Atlantic area. In north-west England, at Hawes Water, Bedford *et al.* (2004) have already described a short-lived resurgence of cold water chironomid taxa into the early Holocene, suggesting a period of cooler conditions (maybe PBO). These resurgences, or persistence of cold-water adapted taxa, are also recorded elsewhere in Europe, such as in Norway (Velle *et al.*, 2005), northern Fennoscandia (Korhola *et al.*, 2000, 2002), Britain (Sadler and Jones, 1997), the Swiss Alps (Heiri and Lotter, 2003; Heiri *et al.*, 2003), the Jura (Millet, 2004) and the Southern French Alps (Gandouin and Franquet, 2002). It has therefore been established that chironomids are able to respond to the rapid climatic events that occurred in the early Holocene. A detailed review of these events is given by Brooks (2006).

The mid Holocene

During the Calais transgression, climate interpretations may be blurred by the impact of sea level rise on the hydrological regime of the St-Omer basin. The abundance of chironomids associated with both macrophytic vegetation and stagnant water is related to the early Holocene transgression. This transgression induced the rise of the groundwater table, the infilling of the palaeochannel and the slowing down of the river flow by the flooding of the basin and the possible water stagnation (Berendsen and Stouthamer, 2000). Regional precipitation increases at the start of the Atlantic (Guiot and Couteaux, 1992) and also may have contributed to the waterlogging of the St-Omer basin.

Summer-water temperatures of between 18°C and 22°C at St-Momelin are in agreement with Zagwijn (1994) and Guiot and Couteaux (1992) who obtained summer air temperatures close to 18°C between 8000 and 7000 BP. However, our values are probably slightly overestimated, as stagnant and shallow waters tend to warm up easily. In addition, high summer insolation during the first part of the Holocene (Mayewski *et al.*, 2004) could have reinforced this warming of the summer waters (and may have also favoured dense vegetation by stimulating photosynthetic processes). Despite this thermal overestimation, the maximum of warm-water adapted taxa (and CA axis 1 scores on Figure 4C) at the onset of the mid Holocene corresponds to the summer thermal optimum reported from fossil chironomid data in Norway (Velle *et al.*, 2005; Brooks, 2006) and all over Europe from palaeobotanical data sets (Zagwijn, 1994; Davis *et al.*, 2003).

From 6800 BP onwards, the chironomids and floodplain vegetation suggest that the St-Omer hydrographic system consisted of a river system that weakly meandered through a vast marshy region (Van der Woude and Roeleveld, 1985). At this time, this type of hydrographic system was widespread throughout northern France (Antoine *et al.*, 2000). The indirect impact of climate, and especially the hydrological regime (precipitation), on chironomids is discussed by Gandouin *et al.* (2005, 2006). According to these authors, lotic phases (SMch-13 and

SMch-15) are correlated with a wetter mid-European climate (Magny *et al.*, 2003) whereas lentic phases (SMch-12, SMch-14 and SMch-16) are correlated with a drier climate.

Additional information is provided by the present study, which shows that cold-water adapted taxa reappear from about 6800 BP. This return can be explained by several hypotheses.

(i) A probable sea level fall or a slowing in the rate of relative sea level rise could be also envisaged for the St-Omer basin and surrounding area (Berendsen and Stouthamer, 2000; Van Vliet-Lanoë *et al.*, 2004) based on evidence from elsewhere around 5000 conventional radiocarbon yr BP (Bard *et al.*, 1990; Ybert *et al.*, 2003). This event may have induced an increase in the Aa river gradient and in the water flow throughout the basin. By comparison with standing water, running water is less easily warmed during spring and summer, allowing cold-water adapted taxa to emerge.

(ii) The decrease in the rate of the sea level rise induced the development and closing of a coastal barrier (Berendsen and Stouthamer, 2000). In back barrier areas, extensive peat formation is generated by the high groundwater table (Kiden, 1995). The groundwaters may have acted as a thermal buffer on lotic systems during water-table flooding, since they are usually colder than surface water in summer.

(iii) The presence of woodland on the riverbanks is suggested by numerous pieces of wood preserved in the sediments along with wood-mining chironomids. Cool water temperatures could persist because of shading effects.

(iv) Slight cooling in T_{Jul}° from 6000 BP in NW Europe (Huntley and Prentice, 1988; Hammarlund *et al.*, 2002; Davis *et al.*, 2003), combined with a solar radiation decrease (Berger and Loutre, 1991) and neoglaciation in the Northern Hemisphere (Magny *et al.*, 2003) corresponds to the cool water phase indicated by the reappearance of cold-water adapted taxa. Similar trends in declining temperatures obtained from fossil chironomid data are also reported by Velle *et al.* (2005) and Heiri *et al.* (2003) in Norway and the Swiss Alps, respectively, and from multiproxy evidence including chironomids in various Swedish lakes (Rosén *et al.*, 2001, 2003; Bigler *et al.*, 2002, 2003).

(v) It is highly probable that a simultaneous occurrence of all of these environmental factors occurs at St-Momelin, and leads to a return of cold-water adapted taxa. At present the respective roles of these factors is difficult to evaluate without additional multiproxy evidence.

Conclusion

Our results suggest that chironomids are an efficient tool for palaeoenvironmental reconstructions in river floodplains since they are strongly influenced by hydrological changes induced by Lateglacial and Holocene climate change. Such change is particularly well marked at the Lateglacial/Holocene transition through the replacement of cold-water adapted and rheophilous taxa by warm-water adapted and limnophilous taxa in a river switching from a braided to a meandering system.

Despite the influence of the hydrological factor, the present paper has clearly shown that river chironomid assemblages are also controlled by water temperatures. At St-Omer, the impact of climate on chironomid assemblages from the end of the Lateglacial to c. 3200 BP can be summarized as follows.

(i) During the final part of the Lateglacial, rheophilous-oligotrophic and cold-water adapted taxa are dominant, and water temperature may have ranged from 9°C to 11°C. (ii) During the early Holocene, the rapid and early climate

improvement is clearly shown by the expansion of warm-water adapted taxa, whilst persistence of cold-water adapted species may be related to climate instability and continentality. (iii) During the mid Holocene, the warm-water adapted taxa are correlated to the mid-Holocene climate optimum. (iv) From 6000 BP, the reappearance of many cold-water adapted taxa may have been induced by a slight global decline of summer temperatures.

Chironomids are therefore able to provide useful palaeoclimatic indications, especially in regions where continuous lacustrine sedimentary records are not available. This is especially the case for the French coastal plains of the North Sea where the Lateglacial and Holocene periods are poorly documented. Encouragingly, Brooks (2006) notes that fossil chironomids are now acknowledged as an essential component in most multiproxy palaeoenvironmental studies. However, further developments in Quaternary chironomid analysis, and especially the establishment of transfer functions adapted to river floodplain environments, require a better knowledge of modern ecological variables, such as thermal requirements and the geographical distribution of river taxa.

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