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A molluscan perspective on hydrological cycle dynamics in northwestern Europe

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Abstract

Shell aragonite $\delta^{18}O$ values of unionid freshwater mussels are applied as a proxy for past river discharges in the rivers Rhine and Meuse, using a set of nine shells from selected climatic intervals during the late Holocene. A single Meuse shell derives from the Subboreal and its $\delta^{18}O$ values are similar to modern values. The Rhine specimens represent the Subboreal, the Roman Warm Period and the Medieval Warm Period (MWP). These shells also show averages and ranges of aragonite $\delta^{18}O$ values similar to modern specimens. This indicates that environmental conditions such as Rhine river dynamics, Alpine meltwater input and drought severity during these intervals were similar to the 20th century. These shells do not record subtle centennial to millennial climatic variation due to their relatively short lifespan and the large inter-annual and intra-seasonal variation in environmental conditions. However, they are very suitable for studying seasonal to decadal scale climate variability. The two shells with the longest lifespan appear to show decadal scale variability in reconstructed water $\delta^{18}O$ values during the MWP, possibly forced by the North Atlantic Oscillation (NAO), which is the dominant mode of variability influencing precipitation regimes over Europe.

Keywords: bivalve, NAO, sclerochronology, *Unio*, Unionidae

Introduction

We present the application of freshwater bivalve oxygen isotope ($\delta^{18}O$) records as archives for past river discharge variation and source waters in the rivers Rhine and Meuse during selected intervals of the late Holocene. Accurate reconstructions of pre-industrial river conditions, including discharge seasonality and frequencies of floods and droughts, are essential for validation of models predicting future river dynamics. Questions arise such as: (1) what was the natural variation in discharge of the rivers Rhine and Meuse (between years and within one year) during the late Holocene; (2) are the recent changes in Rhine and Meuse river dynamics unique, or have these changes occurred previously during the late Holocene?

In order to answer these questions, palaeo-discharge records are needed, with sufficient resolution at the seasonal timescale. As instrumental records (e.g. of discharge, temperature and Alpine meltwater amounts) only go back to the early 20th century, the development of accurate proxy records at high temporal resolution is necessary. A potentially useful proxy record is provided by stable isotope profiles of growth increments in freshwater bivalves.

Sclerochronology of unionid freshwater bivalves has proven to be a powerful tool in palaeoclimate research. Ambient water $\delta^{18}O$ ($\delta^{18}O_w$) values are incorporated in seasonal growth increments of shell aragonite in isotopic equilibrium (Dettman et al., 1999; Kaandorp et al., 2003; Goewert et al., 2007). Shell aragonite $\delta^{18}O$ ($\delta^{18}O_{ar}$) values have successfully been applied as a proxy for rainfall patterns, water source or river discharge (Rodrigues et al., 2000; Kaandorp et al., 2005; Verdegaal et al., 2005; Gajurel et al., 2006; Goewert et al., 2007). Seasonal variability in $\delta^{18}O_w$ values is faithfully recorded in $\delta^{18}O_{ar}$ records of Unionidae in Northwest European rivers, with the exception of the winter season, when the shells do not grow.

We previously demonstrated that through the relationship between discharge and $\delta^{18}O_w$ values in the Meuse, unionid $\delta^{18}O_{ar}$ records reveal the occurrence of past low-discharge summers (Versteegh et al., 2010). Ricken et al. (2003) have suggested that for the Rhine, Alpine snowmelt events can be recognised in unionid $\delta^{18}O_{ar}$ records as excursions towards low $\delta^{18}O_{ar}$ values.

In this paper we examine what the $\delta^{18}O_{ar}$ records of selected freshwater bivalves from different late Holocene time intervals can tell about past climate and river condition variability. Research questions are:

1. Can centennial to millennial scale environmental variability in the rivers Rhine and Meuse be recognised in unionid $\delta^{18}O_{ar}$ records and corresponding reconstructed $\delta^{18}O_w$ records?
    a. Can we recognise late Holocene climatic oscillations?
    b. Is human influence, like embankment of the rivers or land-use changes, visible in these records?
2. Can we detect seasonal to decadal scale climatic oscillations in these shells?

We present $\delta^{18}O_{ar}$ records of unionid shells that lived under different climate regimes and associated river conditions during the late Holocene (see next paragraph). From the $\delta^{18}O_{ar}$ records, we reconstructed $\delta^{18}O_w$ profiles. These $\delta^{18}O_w$ profiles can provide insight into past river dynamics, such as an extreme frequency of seasonal droughts and meltwater pulses (Versteegh, 2009). The $\delta^{18}O_{ar}$ records in unionid bivalves would thus provide insight in seasonal aspects of changing river conditions, particularly during summer, as these bivalves cease growing and cannot record environmental variability during winter (Versteegh et al., 2009). Nine late Holocene shells from the time interval 4800 cal BP - 1700 cal AD were analysed. Unfortunately, material from the river Meuse was rare, comprising only one shell. This paper will thus mainly focus on the river Rhine.

Climatic background

Compared to the large glacial/interglacial oscillations during the Pleistocene, the Holocene is a climatically relatively stable time interval. Still, on a smaller scale, distinct oscillations can be recognised.

From ~5000 to 2800 cal BP western European climate was dominated by continental (warm and dry) conditions. This time interval is known as the Subboreal. Around 2800 cal BP this abruptly changed to more oceanic (cooler and wetter) conditions, known as the Subatlantic (Van Geel et al., 1996). During Roman times a warmer interval is postulated, the Roman Warm Period (RWP; ~2350 cal BP - 0 cal AD) (Hass, 1996; Frisia et al., 2005; Holzhauser et al., 2005). Climate reconstructions of the RWP indicate temperatures similar to or slightly warmer than today (Frisia et al., 2005). The RWP was followed by a colder phase between 400 and 700 cal AD, the Dark Ages (Hass, 1996). The Medieval Warm Period (MWP) lasted from about 950 until 1200 cal AD (Brázdil et al., 2005) and is characterised by warm, dry summers and wet winters (Lamb, 1965; Mann et al., 1999; Esper et al., 2002; Cook et al., 2004; Goosse et al., 2005; Goosse et al., 2006). The actual temperatures during the MWP were similar to those of the first half of the 20th century (−0.03 to +0.20°C) (Crowley and Lowery, 2000; Bradley et al., 2003).

The coldest phase of the late Holocene was the Little Ice Age (LIA). It consisted of several cold intervals between 1400 and 1900 cal AD (Mann et al., 1998) and is characterised by severely cold and dry winters. LIA summers were wetter and probably only slightly cooler (~−0.2°C) than today (Luterbacher et al., 2001; Cook et al., 2004; Luterbacher et al., 2004; Guiot et al., 2005).

In summary, the long-term summer temperature changes between the various different late Holocene climatic intervals probably did not exceed ~0.4°C. This is a small difference in comparison to the Late Glacial Maximum, when summer temperatures were 6-12°C below those of the present day (Wu et al., 2007). With respect to late Holocene precipitation regimes, true quantification is often problematic, but significant and synchronous shifts are suggested by peat bog records (Van Geel et al., 1996), glacier extension records and lake level changes (Holzhauser et al., 2005).

Influence of centennial to millennial timescale climate variability on $\delta^{18}O_{ar}$

It can be assumed that variations in late Holocene summer temperatures and summer precipitation regimes have influenced shell $\delta^{18}O_{ar}$ records from the selected time intervals. With respect to the direct influence of temperature on $\delta^{18}O_{ar}$ values during aragonite precipitation, $\delta^{18}O_{ar}$ values should be lower during warmer time intervals than during cold intervals. However, average summer temperature differences between cold and warm intervals during the late Holocene are only ~0.4°C, corresponding to very small differences in $\delta^{18}O_{ar}$ values, in the order of 0.1‰ (Grossman and Ku, 1986). For the Rhine and Meuse, both the intra-seasonal temperature variation (average temperature warmest week – temperature of growth cessation) and the inter-annual temperature difference (warmest day cold summer – warmest day warm summer) lie around 6°C. As such, the effect of centennial to millennial scale temperature variability on $\delta^{18}O_{ar}$ in late Holocene bivalves is an order of magnitude smaller than the seasonal variability. Detecting any long-term temperature trends by means of $\delta^{18}O_{ar}$ composition of these shells will be difficult.

Late Holocene climatic variations considerably influenced European hydrological regimes (Magny, 2004; Holzhauser et al., 2005). These hydrological changes, such as variations in precipitation regimes or the magnitude of Alpine snowmelt fluxes, are expected to show in unionid $\delta^{18}O_{ar}$ records (Ricken et al., 2003). At mid latitudes during summer there is a negative correlation between $\delta^{18}O_w$ and the amount of precipitation

(Dansgaard, 1964). This so-called amount effect influences river $\delta^{18}O_w$ values in such a way that high discharge summers result in lower $\delta^{18}O_w$ values (in the order of 1‰) compared to low discharge summers (Versteegh et al., 2010). Another factor that may have a large influence on (Rhine) river water is seasonal meltwater. Alpine meltwater pulses have relatively low $\delta^{18}O_w$ values (−12 to −17‰ (VSMOW); Mook, 2000), potentially lowering the overall Rhine $\delta^{18}O_w$ values up to 1‰ within a few days (Versteegh et al., 2009). The above examples show that late Holocene changes in precipitation regime and seasonal meltwater discharge are likely to change $\delta^{18}O_w$ values by more than 1‰, which arguably has a much higher impact on shell $\delta^{18}O_{ar}$ than the ~0.4°C (~0.1‰ in $\delta^{18}O_{ar}$) late Holocene long-term temperature variation.

Human influence

The palaeogeographic evolution of the Rhine-Meuse delta during the late Holocene is not expected to have had a major influence on $\delta^{18}O_w$, because the drainage basins of the rivers stayed the same. Human influence, through the clearing of forests and the beginning of agriculture started during the Neolithic (6400-3650 cal BP) and increased after the Roman Period. Human influence strongly proceeded from 1100 cal AD onwards with embankment of the rivers, which was completed around 1300 cal AD. (Berendsen and Stouthamer, 2001). During the 20th century several weirs were built to regulate water levels for shipping. Some authors suggest that deforestation caused increased discharges and a higher frequency of floods (Berendsen and Stouthamer, 2001; Ward et al., 2008). These discharge increases lie in the order of ~10% and it is doubtful if these caused significant changes in palaeogeography of the rivers (Erkens, 2009). If deforestation caused detectable changes in $\delta^{18}O_w$ values of river water, and related shell $\delta^{18}O_{ar}$, these values will have become gradually lower due to the decreased influence of evapo-transpiration in the drainage basin, and faster runoff of precipitation causing higher and more frequent peak discharges.

Methods and materials

Shells

Unionid freshwater bivalves commonly occur in both the Meuse and Rhine river systems. Historically three species of the genus *Unio* were present: *U. pictorum*, *U. tumidus* and *U. crassus nanus*. The latter has been extirpated since 1968 (Gittenberger et al., 1998), but is the most common species in archaeological finds. It is not entirely clear why these shells are found in archaeological context in the Netherlands. Although human consumption of unionid freshwater mussels is widely known from middens in Australia (Russell-Smith et al., 1997), Indonesia (Joordens et al., 2009), North America (Parmalee and Klippel, 1974; Peacock and James, 2002) and Africa (Plug and Pistorius, 1999), in Europe unionids were rarely eaten by humans. However they were sometimes used as cattle food (Tudorancea, 1972), in (pre-)historic tools and jewellery, or as a receptacle for paint (*U. pictorum*) (Gittenberger et al., 1998).

Nine shells ranging from ~300 to ~4900 years old were collected from different archaeological finds and cores in the Dutch Rhine-Meuse delta (Table 1). Based on palaeogeographic maps (Berendsen and Stouthamer, 2001), the Spijkenisse specimen likely originated from the Meuse, whereas the others derive from (former) distributaries of the Rhine.

Sampling and analysis of shells

All shells were embedded in epoxy resin and sections of 300 µm were cut perpendicular to the growth lines, along the dorso-ventral axis of the shell. The nacreous layer added each year to the ventral margin of the shell, was sampled with a Merchantek Micromill microsampler. Drill bit diameter was ~800 µm and sampling resolution was 100-500 µm corresponding to a time span of 6 days to >2 months, depending on growth rate. Drilling depth was ~250 µm. The samples were analysed for $\delta^{18}O_{ar}$ values on a Finnigan Delta+ mass spectrometer equipped with a GasBench-II. On both systems the long-term standard deviation of a routinely analysed in-house CaCO3 standard is <0.1‰. This $CaCO_3$ standard is regularly calibrated to NBS 18, 19, and 20 (National Institute of Standards and Technology).

River data

Data on the 1997-2007 $\delta^{18}O_w$ values of the river Rhine and Meuse, measured at Lobith and Eijsden, were obtained from the Centre for Isotope Research, University of Groningen. To reconstruct $\delta^{18}O_w$ values, an estimate of water temperature is needed. For the time interval 1908-1944, water temperature data were taken from Rijkswaterstaat (Dutch Directorate for Public Works and Water Management; *www.waterbase.nl*). This time interval was chosen, because of the limited influence of warming by industrial cooling waters. For the Meuse temperatures were measured at the gauging station at Borgharen, for the Rhine at Lobith.

Calculation of reconstructed $\delta^{18}O_w$

For the calculations of reconstructed $\delta^{18}O_w$ the equation by Grossman and Ku (1986) as modified by Dettman et al. (1999) was used as described in Versteegh et al. (2009).

The best indication for past water temperatures available, are the instrumental water temperature records measured before the profound warming (~3°C) by industrial cooling water (late Holocene long-term temperature differences are ≤0.2°C from modern-day values). Therefore, in $\delta^{18}O_w$ reconstructions, the average weekly water temperature in the time interval 1908-1944 was taken. For the Spijkenisse shell we used Meuse water

Table 1. Overview of the shell samples.

Place	Location	Estimated shell age	Age based on	Channel belt (Berendsen & Stouthamer, 2001: their App. 1)	Species	Length (mm)	Height (mm)	Height along curve of shell (mm)	References
Spijkenisse	Hekelingen	4839-4437 cal BP	Associated archaeology		*Unio crassus nanus*	42.0	22.5	30	(Kuijper, 1990)
Montfoort	Tiendweg 'DAG 7'	4080-3915 cal BP	Calibrated age of abandonment	Zuid-Stuivenberg crevasse (#205)	*Unio crassus nanus*			32	(Verdegaal et al., 2005)
Houten	Tiellandt	2950-2736 cal BP	Calibrated age of abandonment	Houten (#74)	*Unio crassus nanus*	n.a.*	35.5	47	
Utrecht	Roman watchtower	40-70 cal AD	Associated archaeology	Oude Rijn (#133)	*Unio crassus nanus*		28.5	37	(Van der Kamp, 2007)
Vleuten - De Meern	Roman road	50-270 cal AD	Associated archaeology	Oude Rijn (#133)	*Unio sp.*		34.8	50	
Kerk-Avezaath 1	Huis Malburg	1050-1250 cal AD	Associated archaeology	Linge #97 (Daver crevasse)	*Unio tumidus*	54.5	31.5	41	(Oudhof et al., 2000)
Kerk-Avezaath 2	Huis Malburg	1050-1250 cal AD	Associated archaeology	Linge #97 (Daver crevasse)	*Unio crassus nanus*	69.5	36.0	50	(Oudhof et al., 2000)
Wijk bij Duurstede		~1200 cal AD	Associated archaeology	Nederrijn (#116)	*Unio crassus nanus*			43	(Verdegaal et al., 2005)
Gorinchem	Kazerneplein	1500-1700 cal AD	Associated archaeology	Waal/Merwede (#175)	*Unio crassus nanus*	50.5	31.0	41	

* This shell was broken, so the original length could not be measured.

temperatures and for the other shells we used Rhine water temperatures. The calculated $\delta^{18}O_w$ profiles provide insight into past river dynamics, such as extreme seasonal droughts and meltwater pulses or their frequencies (for methodology see Versteegh et al., 2010). The reconstructed $\delta^{18}O_w$ records are compared with $\delta^{18}O_w$ records covering the time interval 1997-2007.

Analyses and results

The ranges of $\delta^{18}O_{ar}$ values per shell and comparison with modern day data are presented in a box-whisker diagram in Fig. 1. In the background, the predicted $\delta^{18}O_{ar}$ values (± 1) for modern Meuse and Rhine shells (Versteegh et al., 2009) are given.

The single shell from the Meuse (Spijkenisse), can be clearly distinguished from the other shells both by its higher average (−6.5 ‰) and its smaller range in $\delta^{18}O_{ar}$ values. All other shells fall within the range of modern Rhine water with average $\delta^{18}O_{ar}$ values from −9.4 to −8.4‰ and ranges from ~−6.5 to ~−11.0‰ (Versteegh et al., 2009).

The seasonal $\delta^{18}O_{ar}$ records of the shells are presented in Figures 2a-i. All shells show the truncated sinusoidal pattern typical for seasonal growth. Sharp peaks represent winter growth cessations, whereas broad troughs represent fast growth during summer. Slow growth during spring and autumn causes the steep slopes of the peaks (Grossman and Ku, 1986; Dettman et al., 1999; Goodwin et al., 2003). This pattern is similar to that found in modern Unionidae from the Meuse and Rhine (Ricken et al., 2003; Verdegaal et al., 2005; Versteegh et al., 2009; Versteegh et al., 2010), and indicates that mainly summer conditions are recorded in the shells.

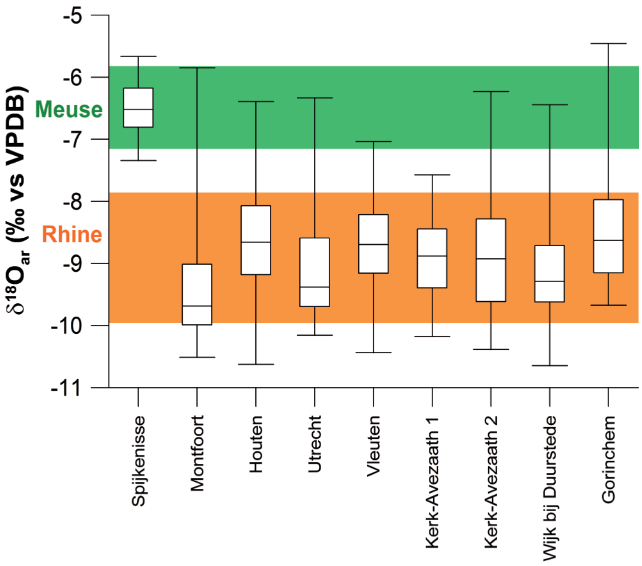


Fig. 1. Box-and-whisker diagram showing the range of $\delta^{18}O_{ar}$ data for all shells. Coloured bands indicate predicted modern values for the Meuse (green) and the Rhine (orange) according to Versteegh et al. (2009). The Spijkenisse shell clearly fits in the Meuse range; all other shells have mostly Rhine $\delta^{18}O_{ar}$ values. The Gorinchem shell grew in a mixture of Rhine and Meuse water.

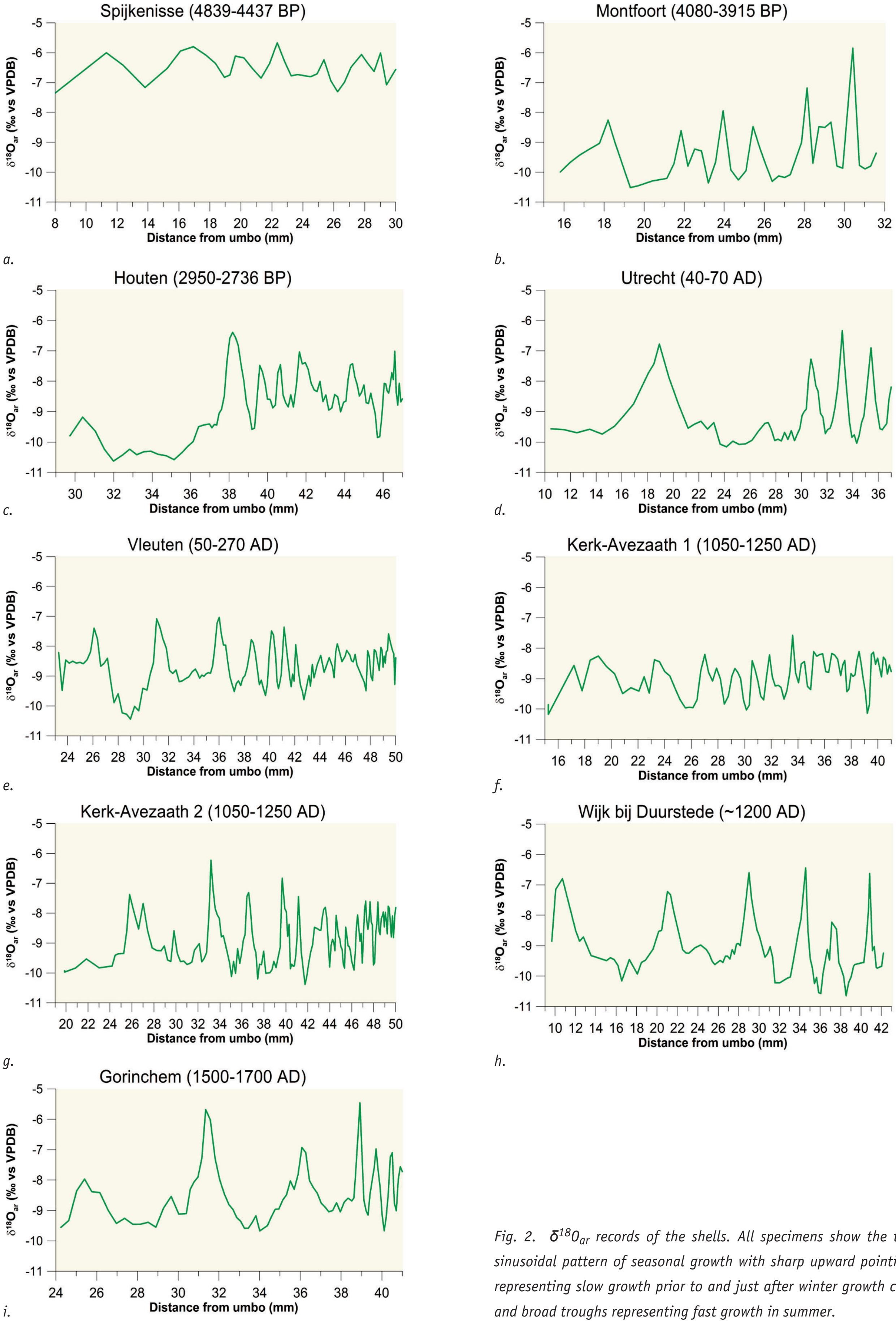


Fig. 2. $\delta^{18}O_{ar}$ *records of the shells. All specimens show the truncated sinusoidal pattern of seasonal growth with sharp upward pointing peaks representing slow growth prior to and just after winter growth cessations and broad troughs representing fast growth in summer.*

Discussion

$\delta^{18}O_{ar}$ records

Since both the ranges and the seasonal patterns in $\delta^{18}O_{ar}$ values (Fig. 2a-i) are very similar to those of modern-day shells, it appears that possible differences in seasonal patterns between these late Holocene shells and their recent equivalents, caused by climate change or human influence, are too small to be readily detected in these $\delta^{18}O_{ar}$ records.

Average $\delta^{18}O_{ar}$ values and ranges for all shells are plotted along a time axis (Fig. 3), including previously published data on recent shells (collected between 1918 and 2005) (Versteegh et al., 2009; Versteegh et al., 2010). The oxygen isotopic difference between the Rhine and the Meuse waters (Versteegh et al., 2009) is clearly visible in bulk shell $\delta^{18}O_{ar}$ values and appears to be similar throughout the late Holocene.

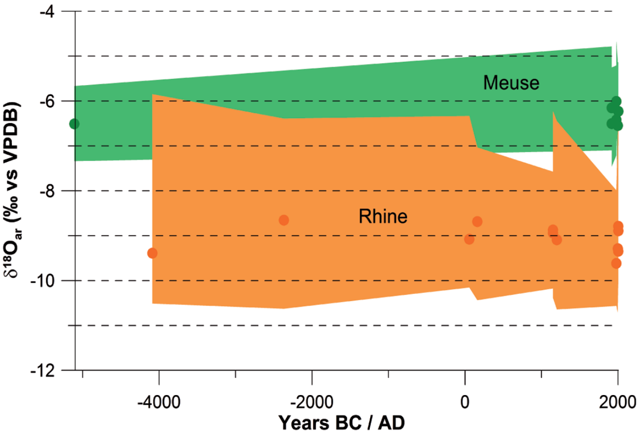


Fig. 3. Time line indicating average $\delta^{18}O_{ar}$ values for the Meuse (green dots) and the Rhine (orange dots) and ranges (light green and orange bands) for the shells presented here and several previously analysed modern shells (Versteegh, 2009; Versteegh et al., 2009). There is no significant trend in either average or range of $\delta^{18}O_{ar}$ values.

The average and range of $\delta^{18}O_{ar}$ values of the Meuse specimens (Subboreal-Spijkenisse and recent) are very similar. River conditions in the Meuse during this time interval thus appear similar to today. This is in agreement with our expectations, since the Subboreal is known as a relatively warm and dry episode, comparable to our recent reference time interval (1997-2007).

The $\delta^{18}O_{ar}$ data of the Gorinchem (1500-1700 cal AD) shell are similar to those of the Rhine shells, but also overlap with Meuse values (Fig. 1). This individual likely lived in a mixture of Meuse and Rhine waters, since the Meuse was connected to the Rhine system by the 'Afgedamde Maas' (dammed Meuse) just upstream of Gorinchem during its lifetime (Berendsen and Stouthamer, 2001). Due to this mixing it is not possible to draw conclusions on river discharge or meltwater input from the $\delta^{18}O_{ar}$ values of this shell, and we will not include this specimen in our discussion.

We established that the influence of temperature on the seasonal range of $\delta^{18}O_{ar}$ values is subordinate to that of $\delta^{18}O_{w}$. This means that minimum $\delta^{18}O_{ar}$ can be an indication for meltwater input and maximum $\delta^{18}O_{ar}$ can give insight in drought events. All Rhine shells in Figure 3 have average, minimum and maximum $\delta^{18}O_{ar}$ values that fall within the range of recent specimens. There thus appear to be no large climate-related differences in meltwater amounts or droughts, compared to the present day. A possible explanation for this observation can be that all specimens originate from relatively warm and dry intervals in the Holocene (Subboreal, RWP and MWP), which may have had similar river conditions to the present day with respect to the amount of precipitation, discharge values and the influence of evapo-transpiration.

Furthermore, it is likely that in comparison to inter-annual and intra-seasonal variation in both temperature and $\delta^{18}O_{w}$, the centennial to millennial scale climate variations are too subtle to readily be recognised in these records.

With respect to human influence by deforestation and embankment of the rivers, there is no sign of gradually decreasing $\delta^{18}O_{ar}$ values due to increasing discharges and flooding frequencies or a decreasing influence of evapo-transpiration. If any of these effects is present, it is too small to be recognised in these bivalve time series.

The above findings imply that these high-resolution / short time-span records are not suitable for studying subtle centennial millennial scale climate- or human-induced environmental variations, but are very appropriate for examining higher frequency climatic variability, especially on decadal to sub-seasonal time scale.

Reconstructed $\delta^{18}O_{w}$ values

We established that the $\delta^{18}O_{ar}$ records presented show no obvious variation or trends that might be related to Holocene climate or land use changes, and that these subtle long-term trends are probably overshadowed by higher frequency climate variation. We now examine these records for decadal to seasonal scale variability and proceed by reconstructing $\delta^{18}O_{w}$ values and comparing these to modern day $\delta^{18}O_{w}$ data from the Rhine and Meuse.

For reconstruction of $\delta^{18}O_{w}$ values we calculated an average water temperature for every week of the year in the time interval 1908-1944. We assumed the shells started and ceased growing in the week that average water temperature reached 13.5°C (Versteegh, 2009). Because no detailed non-linear growth models are available for these species so far, we chose to assume constant growth throughout the growing season, and linearly interpolate $\delta^{18}O_{ar}$ samples between these two dates. Subsequently, reconstructed $\delta^{18}O_{w}$ values were calculated. As expected, an approach using slightly elevated summer temperatures for a warmer phase like the MWP (+0.2°C) or lower temperatures for the LIA (−0.2°C; Guiot et al., 2005) yielded comparable results. We illustrate this in Fig. 4, where reconstructed $\delta^{18}O_w$ values are shown for the Kerk-Avezaath 1 specimen, calculated using 20th century temperatures, and 0.2°C elevated temperatures, respectively.

The reconstructed $\delta^{18}O_w$ records are presented as box-whisker diagrams in Fig. 5a-i. Similar to recent specimens, considerable inter-annual variation in average, minimum and maximum $\delta^{18}O_w$ values can be observed.

The two shells with the longest lifespan (Kerk-Avezaath 1 and 2; 1050-1250 cal AD; Fig. 5f-g) appear to show decadal scale variability in reconstructed $\delta^{18}O_w$ values with a period of ~7-10 years. This possibly reflects decadal scale variations in precipitation regimes in the Rhine drainage basin. A likely candidate causing this type of variations in European climate records is the North Atlantic Oscillation (NAO), an important mode of variability influencing Western European precipitation

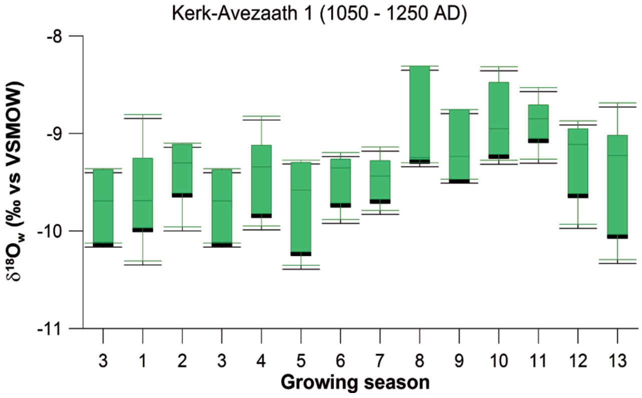
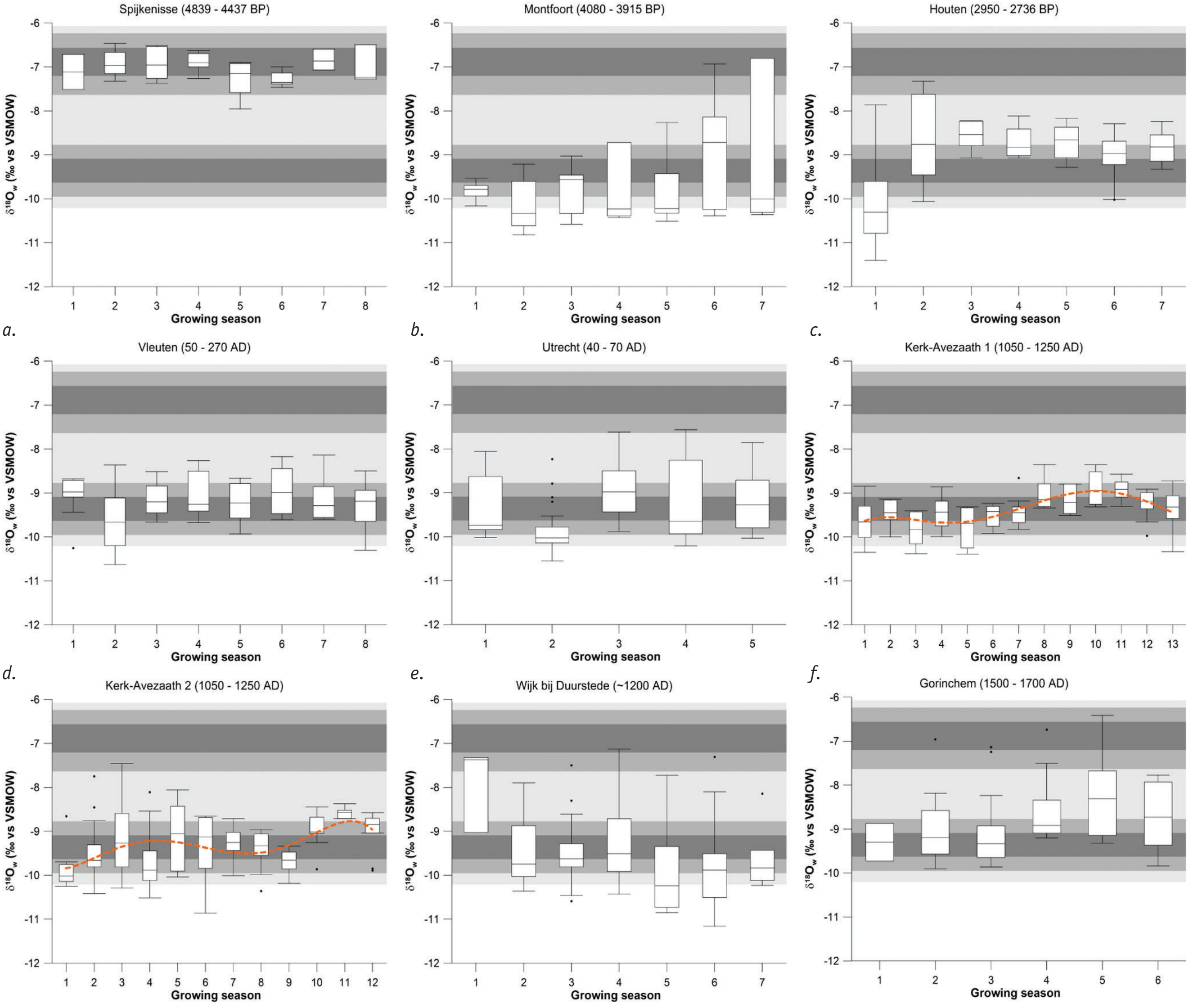


Fig. 4. Comparison of reconstructed $\delta^{18}O_w$ values for one of the MWP shells with average weekly water temperatures from the 1908-1944 time interval (black) and 0.2°C elevated temperatures (green). The two approaches yield similar results.



a. b. c.

d. e. f.

g. h. i.

Fig. 5. Reconstructed $\delta^{18}O_w$ of the shells (using 1908-1944 weekly average temperatures). Grey areas indicate $\delta^{18}O_w$ values from the 1997-2007 summer record for both rivers. Dark grey indicates 50% of the data, intermediate shading is the 90% interval and lightest grey indicates 96% of the data. Orange dashed lines in the Kerk-Avezaath shells indicate decadal-scale variability in $\delta^{18}O_w$ values.

regimes (Hurrell, 1995; Hurrell et al., 2003) and related river runoff (Kiely, 1999; Hanninen et al., 2000; Straile et al., 2003). It has previously been demonstrated that NAO related climate variability can be recorded by marine (Schöne et al., 2004, 2005a, b; Dunca et al., 2009; Wanamaker et al., 2009), as well as freshwater bivalves (Dunca et al., 2005). Unionids are also known to record similar time scale ENSO-related precipitation variability (Schöne et al., 2007). It thus does seem likely that the Kerk-Avezaath shells recorded $\delta^{18}O_w$ variations that are related to NAO variability during the MWP.

The question arises if similar decadal-scale patterns are visible in the shorter records of the other shells in this study. This cannot be determined conclusively, since these shells were too short-lived to capture a full wavelength of $\delta^{18}O_w$ variability. However, several specimens (e.g. Houten, Fig. 5c; Wijk bij Duurstede, Fig. 5h) do show trends that could be part of decadal scale oscillations as observed in the Kerk-Avezaath shells.

Conclusions

We aimed to find out if centennial to millennial scale climate variations and land use changes during the late Holocene can be detected in freshwater bivalve $\delta^{18}O_{ar}$ records. It appears that environmental variability between the time intervals studied are too subtle to readily be recognised in these records. All shells have average, minimum and maximum $\delta^{18}O_{ar}$ values that fall within the range of recent specimens. There appear to be no large differences in meltwater amounts or severity of droughts in comparison to the present day. River conditions during several time intervals of the late Holocene were probably similar to those of the present day.

Two medieval shells show decadal-scale variation in reconstructed $\delta^{18}O_w$ values, with a period of ~7-10 years. These possibly reflect NAO variability, which is strongly linked to European spring-summer atmospheric circulations and related river runoff (previously suggested by Verdegaal et al. (2005)).

River $\delta^{18}O_w$ values and water temperature can be influenced by local factors, such as habitat (e.g. river bed, lake connected to the river) or water levels. On a regional scale climate variables can vary greatly between seasons and influence for example mixing proportions of different source waters or the influence of evapo-transpiration on river $\delta^{18}O_w$ values. It appears that the high-resolution / short-time window archive of unionid $\delta^{18}O_{ar}$ values is not very suitable for detection of long-term climatic trends, but very useful for studying decadal to seasonal scale environmental variability.

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