Supporting information to:

Implications of sub-monthly oxygen and carbon isotope variations in Late Pleistocene *Melanopsis* shells for regional and local hydroclimate in the Upper Jordan River Valley

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Supporting Text 1. Modeled shell temperature and $\delta^{18}O_{water}$ inputs for modern scenarios

Agamon Hula

Mean monthly water temperatures in Agamon Hula range from ~12 to 25°C (Gophen et al., 2016). Because the daily temperature range is slightly larger than the mean monthly temperatures, we used a range of 11-26°C to better capture the full variability. Few $\delta^{18}O_{lake}$ data are available. Litaor et al. (2008) measured $\delta^{18}O_{water}$ from the Agamon Hula outlet four times in 2001-2002, obtaining a range in $\delta^{18}O_{water}$ values of -5.23 to -1.92‰. However, these data only span a portion of the seasonal cycle (November to April) and most likely do not reflect the amplitude of the full seasonal cycle. Precipitation within the Hula Valley has variable $\delta^{18}O_{water}$ values. Gat and Dansgaard (1972) measured values from -6.5‰ to -5.5‰ while Gilad and Bonne (1990) measured -8.1‰, and Rindsberger et al. (1990) found values as low as -11‰. For the modeled shell, we used input $\delta^{18}O_{water}$ values of -7.7 to -1.7‰.

Dan Spring

Gat and Dansgaard (1972) measured Dan Spring $\delta^{18}O_{water}$ values 14 times from samples collected between 1959 and 1970, and found values ranging from -8.02 to -7.01‰, with higher values generally occurring during the rainy season and lower values during summer. However, Zaarur et al. (2016) found a much higher $\delta^{18}O_{water}$ value of -4.97‰ during their summer sampling campaign. We used the values from Gat and Dansgaard (1972) in the model (-8‰ in summer, -7‰ in winter). Water temperatures range from 15-16.2°C seasonally (Gur et al., 2003).

Upper Jordan River

The upper Jordan River typically exhibits $\delta^{18}O$ values of about -7.0 to -6.3‰, with higher values during summer months (Gat and Dansgaard, 1972; Litaor et al., 2008), but with high variability during spring flooding events (-7.6 to -5.54‰; Gat and Dansgaard, 1972). During the summer when the shell was collected, the $\delta^{18}O_{water}$ value was -4.42‰ and water temperature was 21°C (Zaarur et al., 2016). We used model $\delta^{18}O_{water}$ inputs varying from -7.25‰ in winter to -5.75‰ in summer, with temperature inputs varying from 15-21°C.

Modern – Sea of Galilee

The Sea of Galilee is a large lake with an annual overturning circulation, resulting in small seasonal changes in $\delta^{18}O_{water}$ from about -2‰ in winter to 0‰ in summer (Gat, 1970). Anthropogenic use of the water and restricted outflow may have led to higher $\delta^{18}O_{water}$ values in more recent years, with a summer $\delta^{18}O_{water}$ value of 0.5‰ and temperature of 24°C (Zaarur et al., 2016). We used $\delta^{18}O_{water}$ values of -1.25 to +0.25‰ in the model, with temperatures varying from 15-25°C.

Supporting Text 2. Detailed sclerochronological interpretations

Agamon Hula shell

Working backwards from the most recently precipitated sample at the aperture, changes in $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ values were interpreted over time in the shell (Fig. 3a). Assuming the shell aperture was growing at the time of collection, the sample closest to the aperture [sample 49] represents spring 2017. This sample has a $\delta^{18}O_{shell}$ value of -7.1‰, and likely precipitated during April-May, when mean temperatures in Agamon Hula are 18-22°C (Gophen et al., 2016), which correspond to $\delta^{18}O_{water}$ values of -6.9 to -6.1‰ following the equation of Kim et al. (2007). This is within the range of Hula Valley precipitation (-8.1 to -5.5‰; Gat and Dansgaard, 1972; Gil'ad and Bonne, 1990) and somewhat lower than the range in $\delta^{18}O_{water}$ values in Agamon Hula reported by Litaor et al. (2008), which range from -5.2 to -1.9‰. The high $\delta^{13}C_{shell}$ values prior [sample 47] are unexpected for a shell forming during winter when aquatic productivity is lower. Furthermore, a freshening trend in $\delta^{18}O_{shell}$ values is expected in winter due to the lake filling with rainwater, which has lower $\delta^{18}O_{water}$ values compared to lake $\delta^{18}O_{water}$ values. Instead, Growth Mark H may represent a hiatus or extreme slowdown in shell growth during the winter months, consistent with the interpretation of growth marks in *Melanopsis* specimens from Lake Pannon (Geary et al., 2012). Because no freshening trend is present, the slowdown of growth likely represents the entire wet season and, possibly, the early part of the subsequent dry season.

Prior to Growth Mark H is a wide, bifurcated $\delta^{18}O_{shell}$ peak. Trends of increasing $\delta^{18}O_{shell}$ values [samples 33-39, 42-46] due to strong evaporation are interrupted by somewhat lower values [samples 40-42]. These more negative values likely represent artificial water-level adjustment at the end of the dry season, when water managers allow fresh Jordan River water to enter the lake. This allows for mixing between the heavily evaporated lake water and the river water less influenced by evaporation, resulting in lower $\delta^{18}O_{water}$ values in the lake (Gophen et al., 2016; Litaor et al., 2008). Steady, relatively low $\delta^{18}O_{shell}$ values [samples 28-32] likely represent the end of the rainy season or beginning of the dry season, prior to strong evaporation.

Prior to these samples, a pattern similar to the latter part of the shell, described above, occurs. Growth Mark G coincides with a large reduction in $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ values, and likely represents a hiatus or slowdown in growth during winter. A water-level adjustment [sample 25] allows for fresh Jordan River water with lower $\delta^{18}O_{water}$ values to enter the lake near the end of summer, creating a bifurcated peak in the data [samples 22-27]. A general trend of increasing $\delta^{18}O_{shell}$ values [samples 7-22] interpreted as the start of the evaporative season follows steady, lower values [samples 1-6]. This trend is interrupted by an event with low $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ values [sample 17], which could have been caused by a rain event in April 2015 (Fig. S2). Although a similar storm occurred the following year, this event is not seen in the shell, likely due to the subsampling process missing the part of the shell that was growing during and immediately after the storm.

Based on this interpretation, this shell records about two years of time, consistent with results from Zaarur et al. (2016) but contradicting age estimates from Elkarmi and Ismail (2006) of five years or more for a shell over 2 cm in length. Furthermore, growth occurs primarily in the summer, with growth marks indicating a slowdown or hiatus in growth during the wet winter season. Assuming that the winter growth marks denote a growth slowdown of about four months (November to February, corresponding to mean water temperatures of about 15°C and lower; Gophen et al., 2016), each sample represents approximately four to six days, with a four-to-six-day gap between samples. Because of rapid shell growth early in the mollusk's life, samples earlier in the shell may represent a shorter time frame, possibly under three days, while later samples represent a slightly longer period.

Layer 6 shells (approx. 20.0 cal ka BP)

Both Layer 6 shells exhibit changes in $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ values that tend to be small and gradual, (Fig. 3h, 3i) implying a large, hydrologically open lake. Unlike the modern shell results, the largest changes in $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ values often do not coincide. Instead, $\delta^{18}O_{shell}$ values remain high after $\delta^{13}C_{shell}$ values decrease. The significant lowering of $\delta^{13}C_{shell}$ values coinciding with a growth mark (for example, at Shell 1 Growth Mark B) likely indicates a winter hiatus. Here, aquatic productivity during summer prior to the growth mark left $\delta^{13}C_{DIC}$ values in the lake high. Then, organic matter decayed during winter, lowering the $\delta^{13}C_{DIC}$ values in the lake. Meanwhile, the relative lack of change in $\delta^{18}O_{shell}$ values could have occurred due to a change in precipitation regime within the catchment, where snow recharge to the springs lowered $\delta^{18}O_{water}$ values during the dry season relative to wet season precipitation falling as rain within the valley itself. This would have resulted in higher $\delta^{18}O_{water}$ values immediately after winter, which then lowered due to replacement with snow-fed spring water, and later became higher due to evaporation at the end of summer. Although changes in temperature could explain the gradual changes in $\delta^{18}O_{shell}$ values, it is unlikely that lowering temperatures would coincide with increasing $\delta^{13}C_{shell}$ values, which suggest aquatic production (for example, Shell 1 samples 11-18). Instead, the lake was likely recharged with local rainwater with higher $\delta^{18}O_{water}$ values during winter, and then lake-water $\delta^{18}O_{water}$ values gradually decreased due to the melt water inflow with lower $\delta^{18}O_{water}$ values during the early part of the dry season. In this case, a large lowering of $\delta^{13}C_{DIC}$ values due to organic matter decay in the winter months would coincide with higher $\delta^{18}O_{water}$ values of local precipitation.

For Layer 6 Shell 1, a trend of increasing $\delta^{13}C_{shell}$ values [samples 2-18] and abrupt decrease [Growth Mark B] is interpreted as aquatic productivity and subsequent decay after a winter-growth hiatus. The $\delta^{18}O_{shell}$ increase [samples 9-18] is interpreted as summer evaporation. High $\delta^{18}O_{shell}$ values after Growth Mark B (-6.2‰) indicate winter rain with relatively high $\delta^{18}O_{water}$ values that filled the lake, and the trend of decreasing $\delta^{18}O_{shell}$ values toward ~-7.5‰ [samples 19-28] reflects inflowing water replacing local rainwater in the lake during spring or a slow increase in temperature through the summer. Growth Mark C may represent a winter hiatus similar to Growth Mark B.

A similar interpretation can be applied to Layer 6 Shell 2. Growth Marks B, C, D, and E possibly represent winter growth hiatuses. These marks are preceded by increases in both $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ values, followed by an abrupt but small decline in $\delta^{13}C_{shell}$ values and a more gradual trend of decreasing $\delta^{18}O_{shell}$ values. Growth Mark G could also represent winter, suggesting that the individual grew for five years.

Layer 5 shells (19.3 – 17.3 cal ka BP)

Shells from Layer 5 (Fig. 3f, 3g) exhibit similar patterns to those from Layer 6. Because these shells also formed during glacial climate conditions, similar interpretations are appropriate.

The $\delta^{18}O_{shell}$ pattern in Layer 5 Shell 1 exhibits three peaks that occur after rapidly lowered $\delta^{13}C_{shell}$ values [samples 6, 25, 33]. These are associated with Growth Marks A, E, and F. Whereas the latter two show a gradual $\delta^{18}O_{shell}$ trend toward ~-7.5‰ after the peak and are interpreted as winter growth marks, $\delta^{18}O_{shell}$ values fall rapidly after Growth Mark A. Because of the high temporal resolution in this part of the shell, it can be suggested that it represents a storm event that washed allochthonous organic matter with low $\delta^{13}C$ values into the water body. The subsequent peak in $\delta^{18}O_{shell}$ [sample 14], which does not coincide with a growth mark, may also be an early spring storm event. However, it is also possible that Growth Mark A is a winter growth hiatus.

Layer 5 Shell 2 is the smallest shell used in this study, and the specimen may have lived for a shorter period of time. Growth Marks A, C, and D coincide with decreases in $\delta^{13}C_{shell}$ values and could represent winter growth hiatus. It is also possible that the first maximum in $\delta^{18}O_{shell}$ values [sample 4] resulted from a storm event due to the short time period represented in this early part of the shell and lack of an associated observable growth mark.

Layer 4 shells (17.5 - 15.8 cal ka BP)

Rapid, large changes in $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ values in both shells indicate a small, poorly buffered water body (Fig. 3d, 3e). The complexity in the patterns could also suggest more frequent storms, interannual variability in the source or amount of rain, or variability in $\delta^{13}C_{DIC}$ values due to processes other than aquatic productivity and decay, such as input of soil carbon from wind erosion and storm runoff.

In Layer 4 Shell 1, Growth Marks A, B, E, G, I, and J coincide with decreases in $\delta^{13}C_{shell}$ values. However, changes at Growth Marks B, E, I, and J are small decreases compared to the variability of $\delta^{13}C_{shell}$ values in the shell, and $\delta^{13}C_{shell}$ values continue to decrease after Growth Mark E. The lack of a consistent change in $\delta^{13}C$ values across these growth marks could mean that these are not all winter marks or that the DIC in the lake is strongly influenced by other controls than seasonal aquatic growth and decay. Still, each of these growth marks is followed by relatively high $\delta^{18}O_{shell}$ values, which may suggest that a regime of low $\delta^{18}O_{water}$ values in inflowing water and higher local $\delta^{18}O_{water}$ values in local precipitation is present, similar to the interpretations of shells from layers 5 and 6.

In Layer 4 Shell 2, decreases in $\delta^{13}C_{shell}$ values coincide with Growth Marks B, D, E, and F. Of these, Growth Marks B and E exhibit the clearest decreases in $\delta^{13}C_{shell}$ values and are the most likely to represent a winter growth hiatus. After Growth Marks B and D, the $\delta^{18}O$ values are relatively high, then decrease, suggesting that winter rain with relatively high $\delta^{18}O_{water}$ values filled the lake, followed by decreasing $\delta^{18}O_{water}$ values due to inflowing water replacing local rainwater in the lake during spring or a slow increase in temperature through the summer, similar to the interpretation of shells from Layers 5 and 6. After Growth Mark E, the $\delta^{18}O_{shell}$ values are not as high as prior samples, have a slight uptick, then decrease. Due to the lower temporal resolution in the later area of the shell, interpretations of Growth Marks E and F are more uncertain.

Layer 3C shells (15.0 – 13.9 cal ka BP)

Shells from Layer 3C (Fig. 3b, 3c) exhibit large-magnitude, closely related changes in $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ values and may reflect a longer residence time and stronger evaporation of the lake water during the Bølling-Allerød as compared to the LGM. Because of the warmer climate and $\delta^{18}O_{water}$ values in precipitation more similar to present (Bar-Matthews et al., 2003), we would expect $\delta^{18}O_{water}$ values in local precipitation to be similar to those in inflowing water, as they are today. The

$\delta^{18}O_{shell}$ patterns in these shells more closely resemble those from the modern shell and the Zaarur et al. (2016) Sea of Galilee shell, and have a similar absolute range to the Sea of Galilee shell.

Large, concurrent lowering of $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ values occurs in Shell 1 at Growth Marks B, C, and I, which resemble Growth Marks G and H in the modern shell and likely represent winter growth hiatuses. Growth Marks A and E also coincide with decreases in $\delta^{13}C_{shell}$ values but show little change in $\delta^{18}O_{shell}$ values. Since $\delta^{18}O_{water}$ values in rainwater can vary between storms (Gat and Dansgaard, 1972) these may represent storms with relatively high rainwater $\delta^{18}O_{water}$. During late winter and early spring floods, Jordan River waters can have highly variable $\delta^{18}O_{water}$ values, with some high $\delta^{18}O_{water}$ values associated with heavy floods (Gat and Dansgaard, 1972), another possible explanation for these features. The small change in $\delta^{13}C_{shell}$ at Growth Mark A suggests that this is the result of a storm that altered the $\delta^{18}O_{water}$ and $\delta^{13}C_{DIC}$ values slightly. At Growth Mark E, the change in $\delta^{13}C_{shell}$ is similar in magnitude to changes at Growth Marks B, C, and I, which could suggest that it represents a winter growth hiatus. However, this area of the shell includes several growth marks where only one sample was collected between possible pauses in shell growth. As a result, the temporal resolution and interpretation is highly uncertain.

Due to the damaged area in Shell 2, the $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ patterns are more difficult to interpret. Prior to the damaged area, the $\delta^{18}O_{shell}$ values climb steadily, then rapidly, and decrease, while the $\delta^{13}C_{shell}$ values climb early to a stable plateau, and begin to fall. This pattern may indicate an earlier start of aquatic productivity, where the steady increase in $\delta^{18}O_{shell}$ reflects mild evaporation during spring, intensifying during summer. The fall in $\delta^{13}C_{shell}$ during intense evaporation could indicate organic matter decay in late summer. Growth Mark A then coincides with a drop in $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ values prior to the damaged area of the shell, possibly indicating a winter pause in growth. Between Growth Marks B and C, the $\delta^{13}C_{shell}$ values shift rapidly to higher, then lower values, while $\delta^{18}O_{shell}$ values increase. This might indicate spring productivity interrupted by a storm or flood event bringing low-$\delta^{13}C$ soil carbon to the lake and altering $\delta^{18}O_{water}$. The area between Growth Marks C and D exhibit a similar pattern to the earlier part of the shell, with $\delta^{13}C_{shell}$ values climbing rapidly to a plateau and $\delta^{18}O_{shell}$ values increasing slowly, then more rapidly. Growth Mark D coincides with decreases in $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ values and likely represents a winter growth hiatus.

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