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Sclerochronological evidence of pronounced seasonality from the Pliocene of the southern North Sea Basin, and its implication

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Various elements of the biota of the early Pliocene Coralline Crag Formation (southern North Sea Basin, eastern England) have been taken to indicate a warm temperate marine climate, with summer surface temperatures above 20 °C and winter temperatures above 10 °C [1]. However, summer and winter temperature estimates from oxygen-isotope ($\delta^{18}O$) sclerochronology of benthic invertebrates are typically in the respective cool temperate range when calculated using a plausible modelled value for water $\delta^{18}O$ of +0.1‰. For instance, examples of the bivalve mollusc *Aequipecten opercularis* from the Ramsholt Member indicate summer maximum temperatures of 11.0–15.7 °C and winter minimum temperatures of 4.4–7.1 °C [2]. Amongst other evidence, the pattern of microgrowth-increment variation in Ramsholt-Member *A. opercularis* points to a depth below the summer thermocline, hence the temperatures recorded for that season provide an underestimate of surface temperature; this may well have been in the warm temperate summer range [2], as suggested by the pelagic dinoflagellate biota [3]. However, the cool temperate benthic winter temperatures indicated by isotopic data are likely also to have obtained at the surface, pointing to a greater seasonal range in surface temperature (perhaps > 15 °C) than in the modern North Sea (< 13 °C) [2]. This conclusion is not changed by adoption of a different (invariant) value for water $\delta^{18}O$ and also follows from data for a specific late Pliocene interval (Mid-Piacenzian Warm Period) elsewhere in the southern North Sea Basin (Belgium, Netherlands [4]). Here we present isotopic evidence of a seasonal range in surface temperature higher than now at other times in the late Pliocene. Examples of *A. opercularis* from several horizons in the Lillo Formation (Belgium) and the Oosterhout Formation (Netherlands) indicate seasonal ranges in benthic temperature of 10–14 °C. Seasonal variation in water $\delta^{18}O$ can only plausibly account for about 1 °C of these ranges. Taking into consideration microgrowth-increment evidence of a setting below the summer thermocline, the seafloor ranges imply that the surface seasonal range was sometimes 17 °C or more. Other bivalves (*Atrina fragilis*, *Arctica islandica, Pygocardia rustica*, *Glycymeris radiolyrata*) do not indicate such a high seasonal range in benthic (and hence

surface) temperature but this can be attributed to inadequate sampling—time-averaging or a failure to recover evidence of seasonal extremes because of growth breaks. The high surface temperature range could reflect a reduction in vigour of the North Atlantic Current and hence diminished oceanic supply of heat in winter.

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