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Short Communication

Ancient water wells reveal a prolonged drought in the lower Yellow River area about 2800 years ago

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Proxy records from the North Atlantic realm reveal that large and rapid cooling known as the Bond events continued into the Holocene [1], repeatedly punctuating what is conventionally thought to have been a relatively stable climate. Given that the Holocene is the most recent interglacial period that has spurred the development of modern societies, scrutinizing climate variability during this period is important not only for predicting the trend of future climate changes, but also for better understanding the driving forces behind the rise and fall of ancient civilizations.

Our knowledge about the driving forces of Holocene climate variability is fragmentary. Triggers for the millennial-scale cooling during the early Holocene have been ascribed to the episodic freshwater perturbation on the North Atlantic thermohaline circulation [2]. However, the forcing mechanism of millennial-scale climate changes in the absence of major continental ice sheets during the second half of the Holocene remains highly uncertain. Although cold spells manifested as the Bond events have been widely reported in the North Atlantic sector during the second half of the Holocene, it is not clear whether or not there is a global expression of these events. Therefore, far-field proxy records are indispensable to pinpoint the geographical extent of these climate events. Here, we present archaeological evidence for a prolonged drought in the lower Yellow River area corresponding to Bond event 2 in the North Atlantic realm [1]. In addition to its societal relevance, this finding may deepen our insight into the mechanism behind late-Holocene climate variability.

The North China Plain (32°–42° N, 112°–122° E) is a topographically flat landmass built up by the deposits of the Yellow River and several other small rivers originating in Mts. Taihang and Tai within a Cenozoic saucer-shaped, rifted intraplate basin. It is also a cultural landscape with a long history of human settlement since the Neolithic period onward. Changes in the landscape during the late Holocene are closely related to the frequent channel displacement of the Yellow River. Lying in a seasonal frontal zone that separate highly contrasting air masses, this area is prone to flooding during summer, especially when the slow-drifting cold fronts collide with the moist and unstable subtropical-derived air masses, while extreme drought may occur when it is occupied by the western Pacific subtropical high for a prolonged period.

The archaeological site studied here is located at Liang'ercun (36°44′38″ N, 117°10′39″ E), a village around 15 km northeast of Jinan (Fig. 1a). Regulated by the East Asian monsoon, climate in this area exhibits a remarkable seasonality with coherent changes in temperature and precipitation (Fig. S1 online). Mean annual temperature is 14.83 °C and annual precipitation is 687 mm (1951–2015). The site was discovered unexpectedly during the construction of a new railway station. The site is situated at an alluvial fan on the northern flank of Mt. Tai (Fig. 1a), which is around 10 m above the floodplain and thus defines the second terrace of the Xiaoqing River (Fig. S2a online). Rescue excavations at this site revealed a detailed stratigraphical relationship of the cultural layers and the underlying natural sediments (Fig. S2b online). The permeable coarse sand has a high hydraulic conductivity, while the impermeable basal clay has a low hydraulic conductivity, which forms a shallow unconfined aquifer. Groundwater begins to flow out at the depth of ∼8 m below ground, yielding standing

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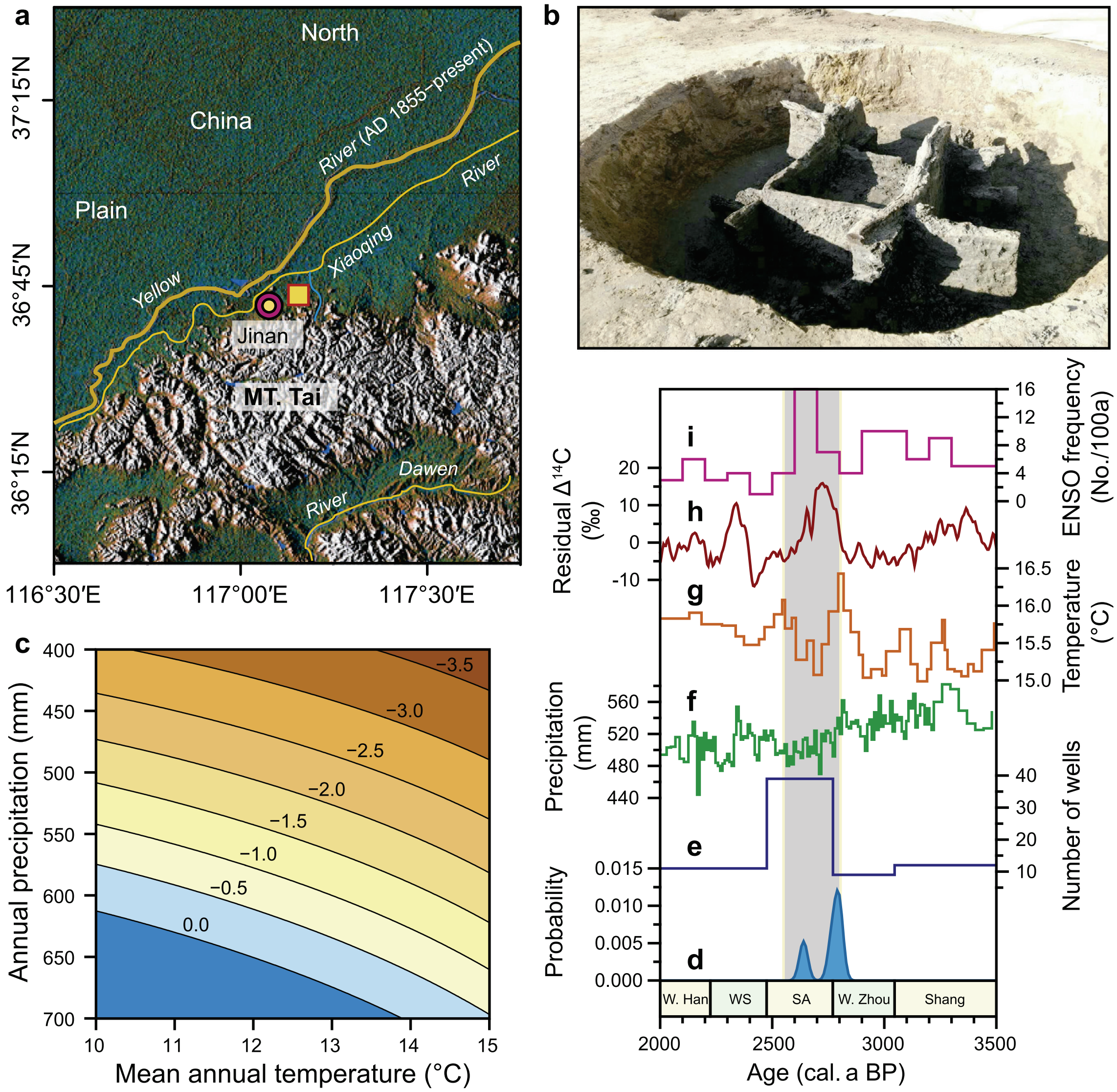

Fig. 1. Ancient water wells in the lower Yellow River area and palaeoclimatic implications. (a) Map showing the topographical features of the study area. Filled square indicates the location of the Liang'ercun archaeological site. (b) Outline of the wooden water well shaft. (c) Modeled anomaly of groundwater table with respect to that of today as a function of mean annual temperature and annual precipitation. (d) Probability distribution of calibrated radiocarbon ages of water wells at the Liang'ercun site. (e) Changes in the number of water wells in the middle and lower Yellow River areas during the Bronze and Iron Ages. (f) East Asian summer monsoon precipitation variability reconstructed using pollen data from Lake Gonghai on Mt. Taihang [3]. (g) Changes in surface temperature of the central southern Yellow Sea [4]. (h) Detrended atmospheric ^{14}C record showing the changes in solar output. The residual is linearly interpolated to the same spacing as IntCal04 and smoothed using a 1000-a moving window (http://www.radiocarbon.org/IntCal04.htm). (i) Variability of El Niño/Southern Oscillation activity within a 100-year-wide non-overlapping moving window (https://www.ncdc.noaa.gov/paleo-search/study/5488). SW = Spring and Autumn period (771–476 BCE), and WS = Warring States period (476–221 BCE). Vertical band highlights the timing of Holocene Bond event 2 in the North Atlantic realm [1].

water of ~1 m deep that defines the depth of modern groundwater funnel (Fig. S2b online).

Two water wells (hereafter referred to as J1 and J2) were uncovered during a rescue excavation. They are the earliest wooden water wells ever found in the lower Yellow River area. The water wells are square shaped with supports of four side walls (Fig. 1b), forming a shaft that exactly resembles the pictographic Chinese character "well". Each of the side walls was lined with wood logs, which were simply stacked up without corner joins (Fig. S3a online). The excavation was stopped at the present-day groundwater table; thus the bottom of the water wells was not reached. We determined the depth of the water wells by drilling boreholes. The interface of the primary fills and the natural sediments of coarse sand lies at 10.9 m at J1 and 10.8 m at J2 (Fig. S3b online). Assuming a constant depth of the groundwater funnel, we estimate that past groundwater table was approximately 10 m below ground (~3 m lower than that of today).

Shaft lining appears to be an important structure designed and constructed to resist the lateral pressure of sediments and thus to avoid collapse of a water well. Our finding suggests that the wood lining technique was not introduced to this area until the late Bronze Age. In addition to the assurance of structural stability, lining the side wall with wood logs may help deal with the hygienic concern. After seeping through the wood lined wall, the turbidity of groundwater would be reduced and thus the potability would be increased substantially.

A total of four radiocarbon ages were obtained (Table S1 online). Two samples collected from the side wall of each water well yield nearly identical ages of 2,600 a BP (Before Present) or 2,800–2,750 cal. a BP (Figs. S3 and S4 online), suggesting that the water wells were initially constructed during the late Western Zhou Dynasty (1046–771 BCE). One sample from the basal fills of J1 indicates that the water wells were abandoned no later than 2,480 ± 20 ^{14}C a BP (2,470–2,720 cal. a BP). This timing may be supported by one sample from a human skeleton preserved in the primary fills of J2 (Fig. S4 online), which yields an age of 2,540 ± 20 a BP (2,730–2,760 cal. a BP). We infer that the site was abandoned by the end of the Western Zhou period, but the precise timing of the abandonment was hindered by the Hallstatt radiocarbon plateau effect. The reasons for the abandonment of the water wells are not clear yet, probably the much worsened climate is the culprit.

Ancient water wells not only support the settled societies, but also contain rich information about past climate conditions. We model groundwater-table changes in a confined shallow aquifer using a box model of hydrological balance (Supplementary online text). Two conceptual reservoirs are included in this model (Fig. S5 online). An inverse modeling was conducted to infer past climate conditions (i.e., mean annual temperature and annual precipitation) from past groundwater table using the Markov Chain Monte Carlo (MCMC) method. A random-walk algorithm was used to browse the parameter space (Table S2 online) to find an optimal value from modern groundwater table under modern climate conditions. Inferred model parameters were presented in Table S3 (online). Our results show a strong dependence of groundwater table in the shallow aquifer on mean annual temperature and precipitation (Fig. 1c). Note that temperature affects evaporation in the topsoil, thus it has a negative effect on water-level changes in the aquifer. In contrast, precipitation governs the recharge, thus it has a positive effect on the water budget in the aquifer. Marine record from the southern Yellow Sea revealed a nearly 1.5 °C cooling at ~2,800 years ago [4]. Assuming the same magnitude of cooling occurred in the study area, annual precipitation of ~450 mm is required to attain the observed ~3 m drawdown of the groundwater table, equivalent to a ~250 mm reduction in annual precipitation with respect to that of today. The Yellow River channel frequently shifted during the late Holocene and such changes in the hydrological regime may affect the modeling results. We assumed that the piracy of the Daqing River by the Yellow River at AD 1,855 (Fig. 1a) would not alter the hydraulic boundary condition of the shallow aquifer. Therefore, the parameters inferred from modern data are valid for the past.

Archaeological findings in Europe revealed a long history of groundwater exploitation [5]. Based on detailed radiocarbon dating, we provide evidence for water well constructions in the lower Yellow River area during ~2,800–2,500 year ago (Fig. 1d). To better understand the history of groundwater mining in the middle and lower Yellow River areas, we compiled archaeological findings of water wells from published literature (Tables S4 and S5 online). Most of the water wells are located on the foothills of Mts. Taihang, Mang, and Tai (Fig. S6 online), where the unconfined aquifers are much shallower than those in the Yellow River floodplain and they were not experienced groundwater over exploitation. The earliest water well construction in the lower Yellow River area can be traced back to the Beixin period (7,500–6,500 cal. a BP). These water wells are generally shallow and the side wall was not lined. The number of water wells began to increase from the late Neolithic period and culminated during the Bronze Age (Fig. S6 online). However, a dramatic increase in the number of water wells occurred during the Spring and Autumn period (771–476 BCE), suggesting that water well construction was a widespread phenomenon in the middle and lower Yellow River areas during the late Bronze Age (Fig. 1e) due probably to the introduction of the iron smelting technology as well as increasing population pressure.

In addition to the aforementioned socioeconomic factors, we ascribe this extensive groundwater exploitation accompanied by a substantial lowering of the groundwater table to a prolonged dry event ~2,800–2,500 years ago as revealed by proxy records from the alpine and marine settings in this area (Fig. 1f and g). The groundwater-table slope is usually in an order of 1:1,000. Therefore, a groundwater-table drawdown of ~3 m caused by the arid climate would further lead to the desiccation of surface waters such as the Xiaoqing and Daqing Rivers (Fig. S2a online), thereby driving the ancient settlers to seek alternative water sources. This event, also known as Holocene Bond event 2 in the North Atlantic sector [1], has been observed in the neighboring areas and elsewhere of the world [3,4,6,7]. The synchronicity suggests a global expression of this event, which in turn implies a common forcing mechanism. The close correlation of this climate event with a grand solar minimum (Fig. 1h) supports the hypothesis of solar forcing [8].

El Niño/Southern Oscillation (ENSO) plays a pivotal role in the hydrological cycling of this area (Fig. S7 online). Specifically, strong ENSO may result in extreme drought in this area, and vice versa. The dry and cold event ~2,800–2,500 year ago also occurred under a prolonged strong ENSO condition (Fig. 1i). The closely linked climate anomaly, solar activity, and ENSO cycle demonstrated here supports the notion that stochastic resonance in the tropical ocean processes could amplify the solar signal and thus regulate the meridional shift of the intertropical convergence zone (ITCZ) and the westerlies on millennial time scales [9].

This climate event, occurring in a period of a marked shift of the Earth's climate system towards colder and drier conditions, is of great societal relevance for early historic China. The late phase of the Western Zhou Dynasty represents the Bronze-Iron Age transition, which was accompanied by many profound political and social changes. Multiple written records showed that the worsened climate has caused a widespread famine in the Yellow River valley during the reign of the last four Western Zhou kings. Frequent civil rebellions and intrusions of the nomads such as the Quanrong tribe accelerated the collapse of the royal authority and Zhou had to reallocate to the wetter and warmer southeast [10], thereby leading to an episode of political and social turmoil known as the Spring and Autumn period (771–476 BCE) in early Chinese history.

We infer past climate conditions from ancient water wells under an assumption that the depth of the water wells represents a long-term average of the groundwater table while the water wells were in use. Our result is subject to several uncertainties. For example, an accurate estimate of past groundwater table is hindered by the time-varying groundwater funnel depth. Also, the solution of this inverse problem is not unique – both precipitation and temperature cannot be estimated simultaneously. Nevertheless, our finding highlights that water well construction represents a major technical invention in human history, which can sustain the sedentary society at times when dry climate prevailed and surface water resources were depleted. Our results also provide a historical analogue of the linked climatic and societal changes, with which the socio-economic response to potentially large climate changes in the future can be better understood.

Conflict of interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scib.2018.09.017.

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