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Oman corals suggest that a stronger winter shamal season caused the Akkadian Empire (Mesopotamia) collapse

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ABSTRACT

The Akkadian Empire was the first united empire in Mesopotamia and was established at 4.6 kyr B.P. (where present is A.D. 1950). The empire abruptly collapsed in 4.2 ± 0.2 kyr B.P. Seasonal-scale climatic dynamics behind this collapse have not yet been resolved. Here, we present monthly climatic parameters (temperature and hydrology) inferred from fossil Omani corals that lived between 4.5 and 2.9 kyr B.P. Winter temperatures derived from a modern Omani coral correlate with winter shamal (western Asian dust storm) frequency. A fossil coral from 4.1 kyr B.P. shows a prolonged winter shamal season with frequent shamal days. This likely caused agricultural failures in Mesopotamia and contributed to the Akkadian Empire collapse, as this region depends on winter rainfall.

INTRODUCTION

Mesopotamian civilizations thrived following the development of irrigation and rain-fed agriculture between the Euphrates and Tigris Rivers (Jacobsen and Adams, 1958; Wilkinson et al., 1994; Macklin and Lewin, 2015) (Fig. 1A). The first united empire in the Mesopotamian region, the Akkadian Empire, was established around the metropolis Tell-Leilan under the rule of Sargon of Akkad in ca. 4.6 kyr B.P. (where present is A.D. 1950) (Weiss et al., 1993; Ristvet and Weiss, 2005). The Akkadian Empire linked the remote rain-fed agricultural lands of northern Mesopotamia with the irrigation-based southern Mesopotamian city-states. Archaeological ruins dated by radiocarbon isotopes show that the Akkadian Empire abruptly collapsed at ca. 4.2 kyr B.P., and its settlements were abandoned (Weiss et al., 1993, 2012; Ristvet and Weiss, 2005). Three-hundred (300) years after the collapse, new populations resettled in the region of the former Akkadian Empire.

Soil morphological investigations at Tell-Leilan suggest a sudden shift toward drier, more arid conditions at ca. 4.2 kyr B.P. (Weiss et al., 1993), while a sediment core from the Gulf of Oman, taken directly downwind of the Akkadian Empire, shows an abrupt increase in aeolian dust from the Mesopotamian region (Cullen et al., 2000). Taken together, these results suggest that the collapse of the Akkadian Empire was caused by an abrupt drought (Weiss, 2017), which involved strong surface winds blowing from western Asia toward the Gulf of Oman–Arabian Sea. However, the climatic processes behind the 4.2 kyr B.P. event still need to be resolved (Staubwasser et al., 2003; Walker et al., 2012; Kathayat et al., 2017). The agriculture of the Akkadian Empire depended on winter rainfall in the headwaters of the Euphrates and Tigris Rivers and on their seasonally varying river discharge (Fig. 1; Macklin and Lewin, 2015). To better constrain the climatic processes that caused the abrupt aridification at 4.2 kyr B.P. in the Mesopotamian basin and the collapse of the Akkadian Empire, paleoclimate reconstructions are required (deMenocal, 2001). Here we reconstruct wintertime temperatures and hydrological changes from six fossil *Porites* corals sampled in the Gulf of Oman. The fossil corals are from 4.5 to 2.9 kyr B.P.; i.e., they provide time windows of seasonal climate variations before, during, and after the collapse of the Akkadian Empire.

MATERIALS AND METHOD

We collected fossil *Porites* colonies from coastal tsunami deposits on the northeastern coast of Oman (city of Fins: 22°54.08′N, 59°13.37′E; Hoffmann et al., 2013; Fig. 1). The coral samples were sliced into 5-mm-thick slabs, which were X-rayed (Fig. DR1 in the GSA Data Repository[1]). We collected powder samples for geochemical analysis along the maximum growth axes of the corals at 0.2–0.9 mm intervals (Table DR1 in the Data Repository). All fossil corals were screened for diagenetic alteration using scanning electron microscope images and X-ray diffraction analysis (Fig. DR2; Table DR1). For geochemical analysis, we selected fossil corals that did not show any signs of diagenetic alteration. The ages of fossil corals were determined using a radiocarbon technique at the Accelerated Mass Spectrometry Center of Yamagata University (Yamagata, Japan). Ages were corrected for a local reservoir effect following Cullen et al. (2000) and then calibrated using the Marine13 program (Reimer et al., 2013; Table DR2). We used six fossil *Porites* corals from 4.5 to 2.9 kyr B.P., bracketing the 4.2 kyr B.P. event.

We developed paired, monthly resolved records of coral strontium/calcium ratios (Sr/Ca) and stable oxygen isotopes ($\delta^{18}O_{coral}$) to reconstruct sea-surface temperature (SST) and oxygen isotopes in seawater ($\delta^{18}O_{sw}$, a proxy for hydrological variations; e.g., Gagan et al., 1998). We estimated $\delta^{18}O_{sw}$ by subtracting the SST contribution inferred from Sr/Ca from $\delta^{18}O_{coral}$ following Ren et al. (2003) (see the Data Repository for analysis and calculations in detail). For calibration of fossil corals, we used the 26-yr-long record from the modern *Porites* coral drilled in

[1]GSA Data Repository item 2019385, sample information and detailed methods, is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.

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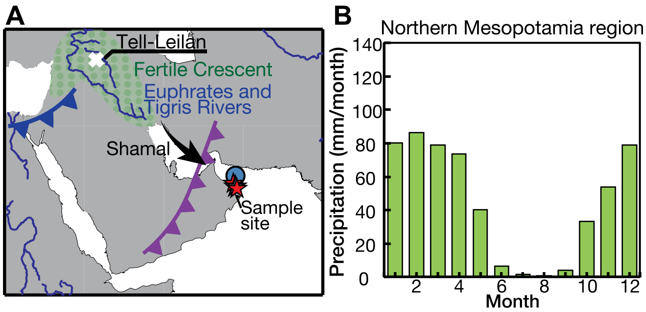

Figure 1. (A) Map of western Asia. Blue circle shows location of sediment core in the Gulf of Oman (Cullen et al., 2000). White cross marks the archaeological site of the metropolis of Tell-Leilan from the Akkadian Empire. Green dots delineate the Fertile Crescent, i.e., Mesopotamian region. Red stars show our coral sample site and location of *in situ* wind-speed record. (Sample site of fossil corals: 22°54′5″N, 59°13′22″E; modern coral core: 23°30′N, 58°45′E). Gray star shows location of in situ wind-speed record. Blue and purple lines with triangles schematically indicate the position of cold fronts before and during shamal development, respectively. (B) Precipitation climatology (at 37°–38°N, 41°–42°E) in the Mesopotamian region during the past 27 years (data from Global Precipitation Climatology Project Climate Data Record, Monthly, Version 2.3, https://catalog.data.gov/dataset/global-precipitation-climatology-project-gpcp-climate-data-record-cdr-version-2-3-monthly92511).

a small bay nearby in February 2013 (Bandar Khayran: 23°30′N, 58°45′E; Watanabe et al., 2017, 2019).

Age models for the fossil coral records were developed by setting the maximum Sr/Ca value in any given year to 13 February, when the coldest day of the year on average was recorded in satellite SSTs spanning the past 27 yr. We linearly interpolated between these anchor points to obtain a monthly resolved time series using the AnalySeries software (Paillard et al., 1996). We centered each proxy time series by subtracting their mean values. Mean seasonal cycles were estimated from these proxy anomaly time series. Past changes in seasonality were estimated by calculating the difference between the mean seasonal cycle of each fossil coral and the modern coral, hereafter referred to as relative change in seasonality (increase or decrease). We applied one-way analysis of variance (ANOVA) to the coral proxy records before, during, and after 4.1 kyr B.P. using the R software (R Core Team, 2017).

To discuss the history of Mesopotamia, we compared the land area of cities and villages around Tell-Leilan measured on the basis of archaeological surveys (Ristvet and Weiss, 2005) with our coral data. To assess the frequency of anomalously strong northwesterly winds (known locally as "shamals"), we compared the modern coral record (Watanabe et al., 2019) and in situ wind speed-data from the Port Sultan Qaboos, Gulf of Oman (23°37′N, 58°34′E). Days with winter shamals, which typically associate with dust storms in Mesopotamia, were defined as days with wind speeds >8.75 m/s (Rao et al., 2001).

RESULTS

The centered, monthly resolved fossil coral records are shown in Figure 2A. In winter, deviations of $\delta^{18}O_{coral}$ and Sr/Ca from their mean range from –0.13‰ to –0.06‰ and –0.02 to –0.11 mmol/mol, respectively (Figs. 2A and 3). The 4.1 kyr B.P. coral shows the highest winter Sr/Ca and $\delta^{18}O_{coral}$ anomalies (0.06‰ ± 0.1‰ and 0.11 ± 0.06 mmol/mol, respectively), indicating a colder winter climate compared to the modern coral (Fig. 2B). Winter $\delta^{18}O_{sw}$ anomalies estimated from the 4.1 kyr B.P. coral are the lowest of all corals, indicating a more humid climate (–0.31‰ ± 0.28‰ compared to the modern coral record) (Figs. 2B and 3). The anomalous winter coral values recorded by the 4.1 kyr B.P. coral are outside the range of the modern coral data (>2σ standard deviations; Fig. 3). Before and after 4.1 kyr B.P., winter anomalies of $\delta^{18}O_{coral}$, Sr/Ca, and $\delta^{18}O_{sw}$ are comparable to modern values. The anomalous winter anomalies in 4.1 kyr B.P. are significantly different from those of other Holocene records based on ANOVA analysis (P <0.01; Table DR4).

DISCUSSION

Our fossil coral records suggest a significant change in seasonality in the Gulf of Oman during the 4.2 kyr B.P. event. The observed anomalous cold and wet winters in the Gulf of Oman are consistent with 4.2 kyr B.P. anomalies inferred from low-resolution proxy records dated by both radiocarbon and U-Th dating (Cullen et al., 2000; Carolin et al., 2019). A sediment core from the Gulf of Oman records a dramatic increase in aeolian carbonates originating from

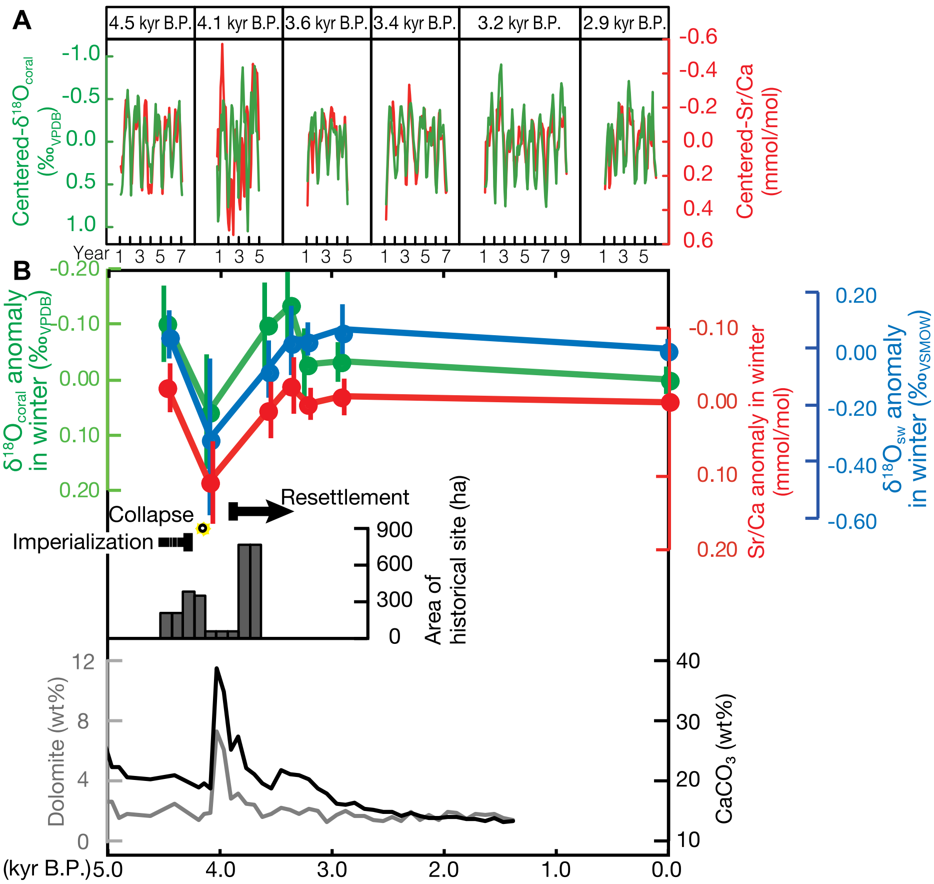

Figure 2. (A) Monthly centered records of Sr/Ca and $\delta^{18}O_{coral}$ data from fossil coral skeletons, Oman. Sr/Ca is shown in red; $\delta^{18}O_{coral}$ in green. Y-axis indicates number of annual cycles. (B) Top panel: Winter Sr/Ca anomalies (red), winter $\delta^{18}O_{coral}$ anomalies (green), and winter seawater $\delta^{18}O$ ($\delta^{18}O_{sw}$) anomalies (blue) from 4.5 kyr B.P. to present day (anomalies: relative to present values). Error bars indicate standard error of each proxy in each time period. Middle panel: Civilization history of Mesopotamia and the Akkadian Empire (Risvet and Weiss, 2013). Ages of historical sites are determined with ^{14}C. Bottom panel: Mineralogical records of a sediment core from the Gulf of Oman (Cullen et al., 2000; see Fig. 1 for location). VPDB—Vienna Peedee belemnite; VSMOW—Vienna standard mean ocean water.

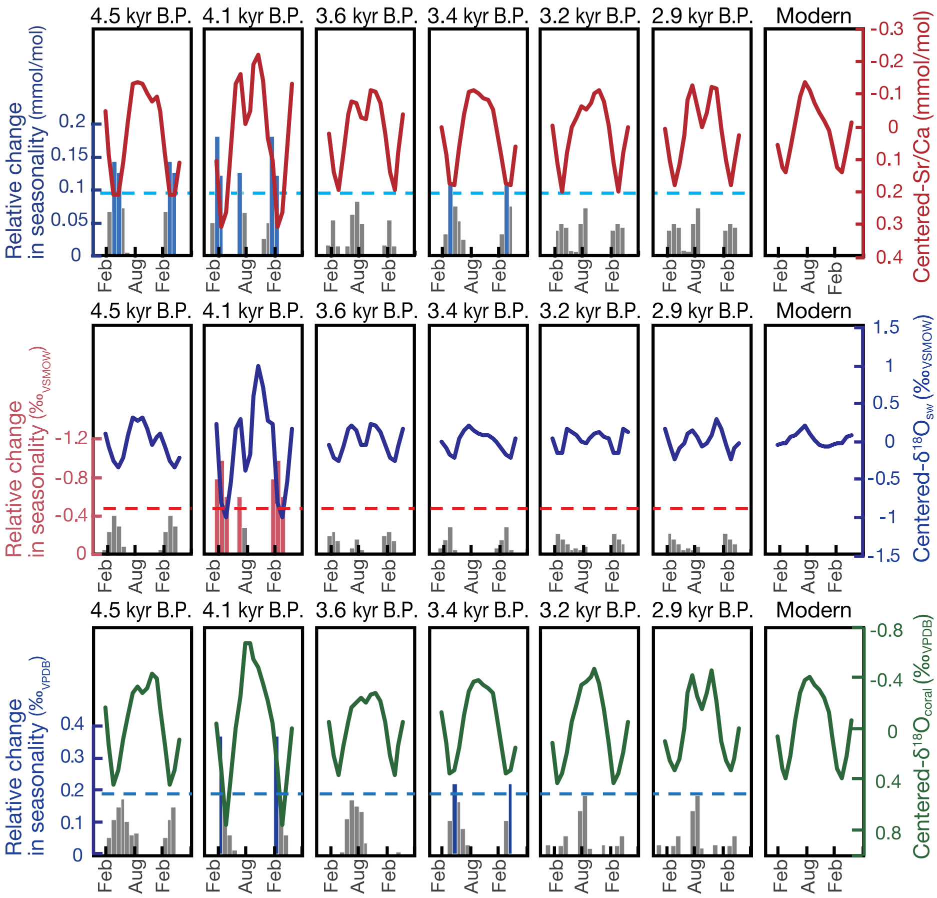

Figure 3. Mean seasonal cycles calculated from coral proxy records from Oman (red lines, Sr/Ca; green lines, $\delta^{18}O_{coral}$; blue lines, seawater $\delta^{18}O$ [$\delta^{18}O_{sw}$]) and change of seasonality of each record relative to modern coral (colored and gray bars). The threshold for anomalous increase or decrease of Holocene coral seasonality is >±1 standard deviation of the modern proxy seasonal cycle (dotted lines); months with anomalous climate relative to present are indicated by colored bars. VSMOW—Vienna standard mean ocean water; VPDB—Vienna Peedee belemnite.

Mesopotamia in 4.2 kyr B.P. (23°23.40′N, 59°2.50′E; Cullen et al., 2000; Figs. 1 and 2). Active dust transportation in 4.2 kyr B.P. is indicated by a decadal-resolution speleothem record dated by U-Th time series (35°50′N, 52°0′E; Carolin et al., 2019). Following the 4.2 kyr B.P. event, winter values recorded by the fossil corals are stable and comparable to present-day values, as are the carbonate contents in the Oman sediment core. Taken together, this suggests an abrupt intensification of surface winds, which caused an anomalous cold and/or wet winter climate in the Gulf of Oman. The abrupt intensification of surface winds would have caused aridification during winter in the Mesopotamia region, where the winter season is critical for agriculture today. This anomalous state in 4.09 kyr B.P. also coincides with the abandonment of cities and villages around Tell-Leilan between 4.1 and 3.8 kyr B.P. (Fig. 2B). Cities and villages around Tell-Leilan increased in size again after 3.8 kyr B.P., when both fossil corals and the sediment core from the Gulf of Oman record stable climates comparable to the present day. The winter climate event in 4.1 kyr B.P. may have triggered the collapse of the Akkadian Empire. In the following section, the climatic processes involved in the Akkadian Empire collapse are discussed based on an analysis of modern climate and coral proxy data from the Gulf of Oman.

Winter Shamal Days and Modern Coral Proxy Data from the Gulf of Oman

Today, winter shamals strongly influence aridity in western Asia and impact societies in various ways. An increase in the frequency of winter shamals is also a potential candidate for causing the disruption of agriculture in ancient Mesopotamia, as shamals negatively impact winter precipitation in the headlands of the Euphrates and Tigris Rivers that feed the arid to semiarid Mesopotamian plains (Rao et al., 2001; Notaro et al., 2015).

We assess the frequency of shamals from the in situ wind-speed data from the Port Sultan Qaboos. The number of winter shamal days correlates significantly with mean winter coral proxy data measured in the modern Omani coral (Fig. 4; $\delta^{18}O_{coral}$: $r = 0.71$, $P < 0.01$, $n = 13$, versus Sr/Ca: $r = 0.78$, $P < 0.01$, $n = 13$). Significant positive (negative) correlations between the winter SST proxies ($\delta^{18}O_{sw}$) from the modern Omani coral and the winter shamal frequency suggest that the fossil Omani corals can be used to infer past winter shamal frequency (Fig. 4; Table DR5). The modern Omani *Porites* records frequent occurrences of winter shamals via decreases in SST (i.e., increases of $\delta^{18}O_{coral}$ and Sr/Ca) and $\delta^{18}O_{sw}$ in winter. A typical winter shamal develops after the passage of a cold frontal trough from the eastern Mediterranean Sea into Arabia and disturbs weather conditions (Fig. 1). A winter shamal transports cold and dry air to western Asia and creates large dust storms (Perrone, 1979; Rao et al., 2001; Parolari et al., 2016). In the Gulf of Oman, winter shamals bring cold air from Mesopotamia, cooling SSTs due to the southward migration

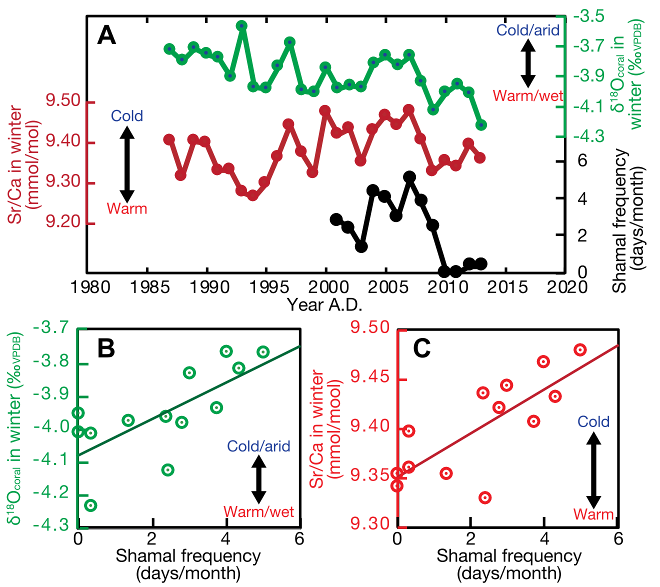

Figure 4. (A) Mean winter $\delta^{18}O_{coral}$ (green) and Sr/Ca (red) of modern coral records compared with shamal frequency, Oman (black; wind data are from the meteorological station at Port Sultan Qaboos, 23°37′N, 58°34′E, accessed from the U.S. Geological Survey website: https://www7.ncdc.noaa.gov/CDO/cdo). Note that coral proxies are plotted with more positive values (i.e., colder temperatures) up, for easy comparison with winter shamal frequency. (B) Cross-plot of shamal frequency and winter $\delta^{18}O_{coral}$ (winter Sr/Ca) (shamal frequency versus $\delta^{18}O_{coral}$: $r = 0.71$, $P < 0.01$, $n = 13$; shamal frequency versus Sr/Ca: $r = 0.78$, $P < 0.01$, $n = 13$). Regression lines between winter shamal frequency and winter $\delta^{18}O_{coral}$ (winter Sr/Ca) are shown. VPDB—Vienna Peedee belemnite.

of cold fronts. The latter also cause wet conditions in the Gulf of Oman (i.e., low $\delta^{18}O_{sw}$). Low winter SSTs indicated by positive $\delta^{18}O_{coral}$ and Sr/Ca anomalies from A.D. 2004 to 2008 coincide with frequent winter shamals. This caused a prolonged drought in Syria, with widespread crop failures and loss of agricultural livelihoods, followed by massive rural-to-urban migration (Gleick, 2014; Kelley et al., 2015; Khaniabadi et al., 2017; Ide, 2018). The drought in the late 2000s resulted in the displacement of 1.5 million Syrians (10% of the Syrian population), and a majority of studies find that this contributed to social unrest in Syria (Kelley et al., 2015; Selby et al., 2017), although this issue is the subject of debate (Ide, 2018).

Past Winter Shamal Frequency from Fossil Corals

The frequency of winter shamals is deduced by applying the linear regression model (Figs. 4B and 4C) derived from the modern Omani coral to the fossil corals (Fig. 2B) before, during, and after the collapse of the Akkadian Empire. The 4.1 kyr B.P. coral showing anomalously cold winters indicates more frequent occurrences of winter shamals than at present, i.e., more frequent cold frontal troughs passing from the eastern Mediterranean Sea into Arabia. In addition, the 4.1 kyr B.P. coral data suggest a prolonged winter season, which may have contributed to an increase in the number of winter shamal days (Fig. 3). A climate model study suggests hydrological changes during the 4.2 kyr B.P. event (wet in the northwestern Indian Ocean and aridification in Mesopotamia; Cookson et al., 2019) that are consistent with our coral data. None of the other fossil Omani corals before or after 4.1 kyr B.P. show such extreme cold and/or wet winters, both in terms of magnitude and duration (Fig. 3). Since ca. 3.6 kyr B.P., the winter shamal frequency has been more or less comparable to modern values.

Frequent Winter Shamals and the Akkadian Empire Collapse

Combined with archaeological surveys around Tell-Leilan (Fig. 2B; Ristvet and Weiss, 2005), our fossil coral records suggest that frequent winter shamals and a prolonged cold winter season would have caused a social instability in the Akkadian Empire. Social instabilities have been linked to civilization collapses (Weiss, 2017). Winter shamals have a significant impact on the region of ancient Mesopotamia today (most notably in Syria and Iraq). This impact includes severe aridification, cooling, and intense dust storms (Kelley et al., 2015; Selby et al., 2017; Ide, 2018). In the Akkadian Empire, which was based on agriculture and dependent on rainfall and river discharge from the Euphrates and Tigris, severe droughts such as these likely had an even larger impact and would have caused extreme famines. Food scarcity in 4.2 kyr B.P. is also supported by climate models, which show that crop-related grass production decreased in 4.2 kyr B.P. (Cookson et al., 2019). Frequent dust storms probably further contributed to salinization of the irrigated fields of the Akkadian Empire (Jacobsen and Adams, 1958). In the present day, they increase the risks for cardiovascular and respiratory diseases (Khaniabadi et al., 2017). The Akkadian population would have faced increased risks for health hazards as a consequence of the drought and the collapse of the agricultural systems in 4.2 kyr B.P. due to the frequent winter shamals.

Our seasonal-resolved proxy records help to explain the climatic processes behind aridification and social responses. Previous studies proposed scenarios of the Akkadian Empire collapse (e.g., limits of sustainability due to increase in urban populations: Lawrence et al., 2016; a collapse of agricultural systems: Cookson et al., 2019; Wilkinson et al., 2014; a shift to a pastoralist lifestyle: Wilkinson et al., 2014; migration to agricultural refugia: Weiss, 2016; and foreign invasions: Jacobsen, 1957). Agricultural failure due to aridification in winter would have caused high mortality and/or mass migration to southern Mesopotamia, potentially contributing to social instability in 4.2 kyr B.P. This is consistent with the abandonment of cities and villages around Tell-Leilan between 4.1 and 3.8 kyr B.P. The Akkadian Empire finally collapsed following the invasion of Mesopotamia by other populations (Jacobsen, 1957). Three-hundred (300) years later, other populations resettled again in the region of the former Akkadian Empire under again more favorable stable climatic conditions as indicated by the fossil corals since 3.8 kyr B.P.

CONCLUSIONS

Our fossil coral records provide new evidence that frequent winter shamals and a prolonged cold winter season contributed to the collapse of the Akkadian Empire. The combination of archaeological evidence with low- and high-temporal-resolution paleoclimate records helps to constrain the climatic processes that contributed to the collapse of the empire. Interdisciplinary research will help to improve our understanding of the dynamic interaction between climate changes and human societies in the past.

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