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ORIGINAL ARTICLE

The possible climate impact on the collapse of an ancient urban city in Mu Us Desert, China

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Abstract Tongwan City is one of the most famous and best-researched archaeological sites in China. By using palaeoclimatology proxy records from China over the last 2,000 years and archaeological/historical documents, we analyse the possible effect of climate on the collapse of Tongwan City, an ancient urban city of the Daxia state (AD 407–427). During Tongwan City's existence (AD 413–994), two severe cold and drought stages were recorded by both natural proxy data and the synthesis compiled from the historical documents. The first cold and drought stage occurred at about AD 420–550, with the lowest point centred at about AD 500. The second cold and drought stage occurred at about AD 780–950. These periods correspond to the times of climate deterioration, especially weak summer monsoons, which eventually resulted in the intensive desertification and collapse of Tongwan City.

Keywords Tongwan City · Climate impact · Mu Us desert · Historical documents · Proxy records · Archaeological site

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Introduction

The interaction between people and nature is evident from the analyses of their relationship in the past (Messerli et al. 2000). As a result of this interaction, more and more attention is being devoted to the role of past climatic changes as driving forces for human responses (Berglund 2003; Anderson et al. 2007), including changes in subsistence patterns and the catastrophic collapse of society (Diamond 2005). In China, the rise and fall of historical dynasties were always related to low temperatures or the weak East Asian Summer Monsoon (EASM) (Yancheva et al. 2007; Zhang 2007; Zhang et al. 2008). However, studies on the relationship between people and climate often cover large spatial and temporal scales. Results have also been questioned because of the lack of specific analysis of historical details (Zhang and Lu 2007; Fan 2010). Hence, further research is needed to understand completely the relationship between climate and culture. Here, we present a case study of the ancient Tongwan City in North Central China to contribute to improved understanding of the human-environment relationship in China. We chose Tongwan City for several reasons: First, it is the largest among the relic sites of ancient cities in the southern margin of Mu Us Desert, which is the Asian monsoon boundary zone. Therefore, the area's response to global climate change is sensitive. Second, because it was occupied by humans for years with crucial strategic, economic, and political status, there are rich historical and literary resources related to it that can be used to reconstruct regional historical details, including human activities and environmental conditions. Finally, the reason for the fall of Tongwan City has been a matter of dispute for decades (Hou 1973; Zhao 1981; Zhu and Wang 1992; Deng et al. 2001). Previous researchers have realized that climate is a dominant factor in environmental degradation (Zhao 1981, 1990; Huang et al. 2009). However, the possible driving mechanisms of climatic change that led to the collapse of Tongwan City remain poorly understood. In conclusion, Tongwan City is an ideal site for studying the complicated relationships between climatic change, desertification, and city rise or fall from a long-term perspective.

Our purpose is to review the physical evidence of environmental deterioration found in both historical documents and high-resolution proxy records and to point out potential climate implications, with respect to the decline of the ancient city of Tongwan. The finer-grained palaeoclimatic history reviewed in this study will especially aid archaeologists and historians in evaluating the likely role of climatic change, either local or regional, in the abandonment of an ancient city.

Location of Tongwan City and its evolutionary history

The Tongwan City site (108 51 14.0000E, 37 59 57.0000N) is located in the southern part of the present Ordos Plateau, close to the north bank of the Wuding River that flows through the south-eastern corner of the Mu Us Desert (Fig. 1). The river carries vast amounts of sand and clay with it, making its water turbid. The mean elevation of the city is 1,160 m, which is about 60 m above the river level. Tongwan City, with a total area of 7.7 km^2, has been buried beneath the desert sand for more than 1,000 years. The city was extended on an east–west axis and consisted of an outer city, an inner city, and a palace city. The outer city was where the ordinary people lived. Government offices and homes of the nobility were located in the inner city. The palace city was the inner sanctuary of the imperial city where Helian Bobo himself lived. The city wall was constructed in layers by ramming a mixture of cohesive white clay and sand bound together with glutinous rice gruel and slaked lime. The western section is 16–30 m thick. This type of rammed earth construction was proven to be almost as strong and resistant to erosion as stone masonry.

The Mu Us Desert is located at l07°20′E to 111°30′E and 37°27′N to 39°22′N, with an area of about 40,000 km^2 (Fig. 1). Situated in the East Asian monsoonal zone, this area has a typical continental semi-arid climate. Mean annual precipitation ranges from 150 mm in the northwest to 450 mm in the south-east, 60–80 % of which occurs from June to August. The annual average temperature is about 6.0–8.5 °C, with a monthly average temperature of 22 °C in July and −11 °C in January (Wu and Ci 2002). Spring is extremely dry, and wind speeds are very high (the average wind speed in spring reaches 3.0–3.9 m/s). Nearly, all dust storms occur during spring.

In AD 407, Helian Bobo, the leader of the Hsiung-nu, established the Daxia kingdom. During Helian Bobo's time, North China fell under the rule of a congeries of squabbling and unstable tribal statelets (Graff 2002). Aside from the Jin Dynasty, which was established by the Han nationality, 15 minor kingdoms had been set up by nomads. These minor kingdoms rose in power one after another. Helian Bobo became powerful on the Ordos Plateau. He founded a small kingdom called Daxia, which occupied the whole plateau and the surrounding grasslands. Helian Bobo once stormed Chang'an (the present Xi'an). His courtiers advised him to make it his capital, but he insisted on returning to the Ordos Plateau and personally chose a site where he would build his future capital, Tongwan. General Chigan Eli was tasked to build an extravagant set of palaces to serve as the emperor's metropolis. Historical records show that Helian Bobo recruited 100,000 men to construct this enormous city. During the construction of the city, thousands of artisans were killed for failing to achieve the desired solidity of the structures (Hou 1985). After 6 years of hard work, Tongwan City was finally built. Then, Officer Hu Yizhou, who was in charge of history and culture, wrote a famous article to describe the enormous size, construction pattern, and luxurious appearance of Tongwan City. At that time, both Tongwan City and the Daxia kingdom flourished to their peaks.

China's history has been shaped by war. Shortly after AD 300, barbarian invaders from Inner Asia toppled China's Western Jin Dynasty, leaving the country divided and at war for several centuries (Graff 2002). In the year AD 427, Tongwan City was sacked by the army of the Northern Wei Dynasty. In AD 431, the kingdom of Daxia was conquered by the Northern Wei Dynasty. In AD 427, Tongwan City, the glorious capital of the Daxia kingdom, was degraded into a town used for grazing animals because of its bountiful water and lush grass. The Northern Wei Dynasty made Tongwan City its local administrative centre until AD 487. According to the description in *Shuijingzhu* (a well-known historical geography book written during the Northern Wei period), Tongwan City still maintained its original configuration during the reign of the Northern Wei Dynasty. During the Sui Dynasty, Tongwan City was governed by the Shuofang County, which served as the local centre at the time. In AD 617 (the end of the Sui Dynasty), Liangshidu, the general of Shuofang County, rebelled and built up a small regime with Tongwan City as his capital. The domination of Liangshidu was ended by the army of the Tang Dynasty in AD 628. The land occupied by Liang was recovered by the Xiazhou (a regional administrative agency of Tang Dynasty), which made Tongwan City as its political centre. Since this event, Tongwan City became an important regional centre along the northern frontier that connected the Han people with

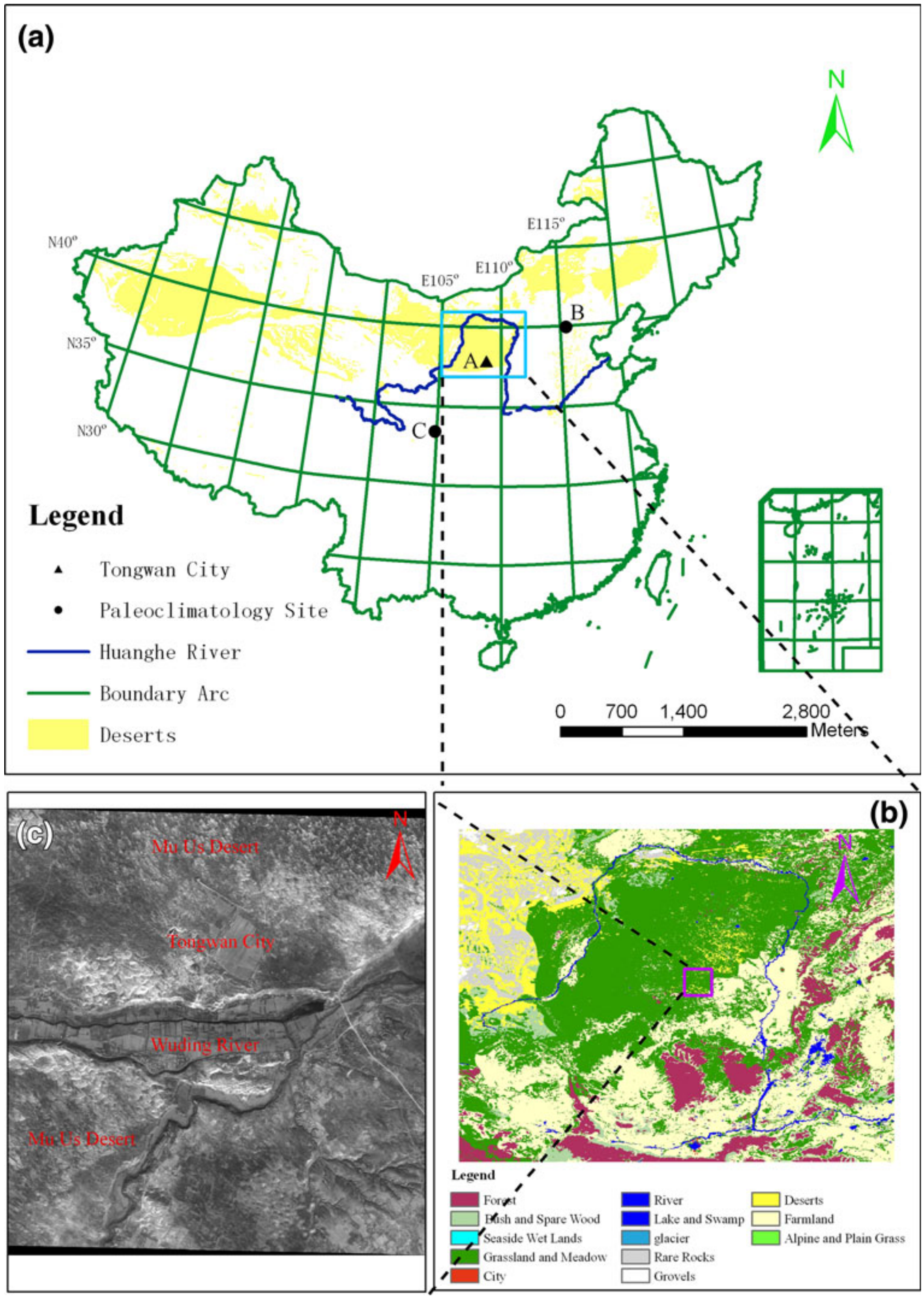

Fig. 1 Geographic setting of Tongwan City. Map **a** is a general map of China and the locations of Tongwan City and palaeoclimate sites of China mentioned in this study were shown; *A* Tongwan City, *B* Shihua Cave (Tan et al. 2003), *C* Wanxiang Cave (Zhang et al. 2008). Map **b** is the sketch map of the Ordos Plateau. Map **c** is the detailed remote-sensing image information of the Tongwan City region (data source: Worldview-1; spatial resolution 0.5 m). The *blue rectangle* shows the location of the Ordos Plateau in China and the *purple rectangle* shows the location of Tongwan City relative to the Ordos Plateau (colour figure online)

the nomadic people. Five Dynasties and Ten States was another era of disunity. It was during this period that Tongwan City became the focus for fight among those separatist regimes. But most of the time, it was controlled by the force of the Dangxiang army (nomadic people).

During the early years of the Song Dynasty, Tongwan City was occupied by the Xixia people (a minority group from the northern steppe). Thereafter, the city was alternately governed by the Song Dynasty and the Xixia people. In AD 994, the Song Dynasty army gained control over Tongwan City and Song Emperor Taizong ordered his troops to destroy the city. The city's inhabitants immigrated to other places. Since then, Tongwan City was abandoned and never used again as a major regional centre. Why did Song Emperor Taizong make such a decision? What caused the collapse of this ancient urban city? According to Sima Guang's *Comprehensive Mirror for Aid in Government* (*Zizhitongjian*), the Xia state, where

Tongwan City was located, had been surrounded by deserts, indicating that the environment was no longer favourable for human settlement.

Materials and methods

Descriptive historical data on the environmental information around Tongwan City

Much documentary data were used in this study to provide additional information about specific episodes of climatic change. The data are divided into two types. One group is composed of original historical documents that describe extreme climates and weather phenomena in history. The other group is made up of reconstruction results based on original documents. The former denotes extreme weather events with accurate time and location. Thus, we can obtain an intuitive cognition of historical extreme weather events. Extreme cold weather events or dust events around Tongwan City were cited to reflect the environmental background during that specific time period. To understand the detailed information on environmental changes around Tongwan City, we examined historical sources about Tongwan City and its surrounding areas (Table 1). Although the scattered description is discrete, it can provide climatic information for extreme climate events. The main literary sources are *Twenty-Four Histories* (including *Songshu, Weishu, Nanshu*, *Suishu*, and *Tangshu*), Tang Dynasty Poetry, and other literature.

Hypothesis: weakening EASM effect on the fall of Tongwan City

Based on the previously mentioned information (Table 1), we found that the ecological environment around Tongwan City changed as time went by. During its existence, several severe cold events had been recorded by historical documents. Companied with the cold events, the desertification of this region had become very serious. However, desertification was only an external manifestation of climatic deterioration that had played a key role in the dynamic evolution of Chinese history. Several scholars concluded that changes in EASM cycles and prolonged drought contributed to the decline of historical dynasties (Yancheva et al. 2007; Zhang et al. 2008). The historical documents and the conclusion of previous studies impelled us to present the following hypothesis: when the EASM strengthens, its rain belt moves northward and stays longer in the north. This movement brings more rain to North Central China. Thus, desertification was reversed in the Mu Us Desert. In contrast, when the EASM weakens, the rain belt reaches more southward than normal and rapidly retreats, resulting a decrease in rainfall and the intensified desertification of arid and semiarid China. A recent research demonstrates that warm-humid/cool-dry has been the main climate pattern in North Central China in the past 1,800 years (Tan et al. 2011). Therefore, we can conclude that weakening EASM corresponds to lower temperature, less precipitation, intensified desertification, and vice versa. Thus, the cold/dry climatic events and the desertification caused by the weakening EASM all contributed to the environmental deterioration and the ultimate fall of Tongwan City.

Testing the hypothesis based on proxy records

The descriptive historical documents recorded the extreme weather conditions, the process of intensified desertification around Tongwan City, and the city's abandonment. However, how can environmental deterioration and Tongwan City's collapse be related to the weakening EASM? To verify the hypothesis mentioned above, a multidisciplinary integrated research, including the composite historical documents and the high-resolution palaeoclimatology records, is required. An important contribution for physical proxy record is the accurate reconstruction of a detailed record of EASM variability for the past two millennia. Compared with descriptive historical documents, the present composite historical proxy records cover a larger spatial scale and enable us to study the long-term climatic fluctuations that were sensed by the ancient people. This paper attempts to integrate documentary and physical evidence on the abandonment of Tongwan City. The time of Tongwan City's fall was almost simultaneous with the collapse of the Maya culture in Mesoamerica. What drove these concurrent cultural declines in northern China and Mesoamerica? In this paper, we explore the possible effect of climate on large-scale cultural decline and the potential climatic driven mechanisms.

Physical proxy records

Proxy data are our main sources of information on temperature variability during a period prior to instrumental temperature measurements (Ljungqvist 2009). In recent years, a number of efforts have been made to reconstruct the mean temperatures during the last one to two millennia in China and in the world. Two well-dated and high-resolution proxy records based on speleothem methods were selected. Several criteria were applied to select the proxy records. First, a proxy data series must have a very robust chronology. Dating uncertainties should be as small as possible. Second, study sites must be located in regions influenced by the Eastern Asian monsoon. Consequently,

Table 1 Environment information around Tongwan City

Year (AD)	Description records including environmental information	Literature source
407	Emperor Helianbobo ever said: "I went through so many places, never seen such a beautiful place like Tongwan City which is close to the great lakes and the clear river"	*Shiliuguochunqiu*
407	Ministers suggested Helianbobo to construct the imperial capital in Chang'an. But Helianbobo said: "I know that Chang'an was the imperial capital city for a long time, with fertile soil and advantageous terrain. Jin, however, it is far away from us, will not be our worry. But Wei has the same customs with us, to which is only 100-li from Tongwan City. If we lived in Chang'an, Tongwan City will be threatened. On the contrary, if Tongwan City as the capital, Wei certainly will not across the river to attack here. You do not take this factor into account"	*Zizhitongjian*
426	Drought, locusts	*Weishu*
426	The emperor of Wei marched to the Junzi crossing, when the weather was very cold, and the river was frozen. He led 20,000 cavalry across the frozen river to attack Tongwan City	*Weishu*
426	The emperor of Daxia kingdom (at that time, Emperor Helianbobo has died and his son Helianchang set the throne) out of the city at war with Wei, was defeated and fled into the city. But it had no time to close the city gate when the enemies breakthrough the west palace and burned the west gate	*Weishu*
426	Wei's army stationed at the north of the Tongwan City, soon after, they attacked, killed and captured tens of thousands of people, and grabbed ten thousands cattle and horses. The emperor of Wei said to the soldiers: "Now we still can not break the Tongwan City, but sooner or later we will occupy it". Thus, they migrated more than 10 thousands people here to the other places, then the army returned to their home territory	*Zizhitongjian*
427	Wei army marched to Tongwan City. The arm forces of Daxia kingdom scheduled on both side of it, beat drums and chasing. After walking for about 5–6-li, they encountered dust storm blowing from the south-east and raised sand diffused in the sky	*Zizhitongjian*
428	Emperor of Daxia kingdom rushed to the battlefield in person, and the enemy soldiers recognized him, so everyone was eager to catch him. Just at this time, a fierce storm suddenly blew up and the sky was as dark as the night	*Dushifangyujiyao*
433	The Northern Wei state set up Tongwan town, because in lush, used as pasture	*Dushifangyujiyao*
487	The Northern Wei state set up Xiazhou, and Tongwan City served as its political centre	*Weishu*
500	In April, the serious frost occurred and the grass was all frozen to death	*Weishu*
500–503	Since AD 500–503, the northern region's drought continued for a few years, and large tracts of land on the plateau is not hospitable for planting any crops, only a small part of the paddy fields can be cultivated	*Weishu*
520–524	"The river run across the sand dunes of the southwestern Sheyan county (where Tongwan City located) and flow to northeast"	*Shuijingzhu*
520–524	"Although the Tongwan City has now been established for some time, the walls looked still like the new one." This shows that desertification surrounding Tongwan City was not serious	*Shuijingzhu*
524	"Ethnic minority rebels took place in northern part of the Northern Wei dynasty and the enemies surrounded Tongwan City. At this time, the food is eaten up, and people had to eat horses, but the soldiers did not shake their faith. The regional government's top executive would like to go out to look for food personally, leaving his son guarding Tongwan City." This shows that Tongwan City still being treated as a very important military frontier town	*Zizhitongjian*
534	The first emperor of Northern Zhou dynasty came to Xiazhou, gave birth in his son in Tongwan City, and gave him a name of "Tongwan". This shows that Tongwan City was used as an important frontier city for both military and livelihood purposes	*Zhoushu*
536	Lunar January 22, East Wei prime minister Gao Huan personally led ten thousand horsemen attacking on the Xiazhou of Western Wei. After force March for 4 days without cooking, they arrived at the destination. They broke through the city the night and caught the commissioner. Then, Gao Huan left Gao Qiong guarding Xiazhou and migrated five thousands local people to his territory	*Zizhitongjian*
622	The general Duan Decao of Sui dynasty fought with Liang Shidu who occupied the Xiazhou and took Tongwan City as his capital. In this war, Liang Shidu was defeated	*Zizhitongjian*
775	"December, when thousands of northern minorities (Uighur) attacked Xiazhou, general of Xiazhou Liang Rongzong fought with them in the black water, and defeated them. At this time, Guo Ziyi sent 3,000 soldiers to rescue; the men had to run away." This shows that Tongwan City was an important military city during the Tang dynasty	*Zizhitongjian*
786	"Tubo violated Xiazhou again; provincial governor of Xiazhou took all the men to leave there, So Tongwan City was occupied by the Tubo tribes." This shows that Tongwan City was an important frontier city which was occupied by the Han peoples and the nomadic peoples alternatively	*Zizhitongjian*

Table 1 continued

Year (AD)	Description records including environmental information	Literature source
789	Han Quanyi was sent to Xiazhou as defender. People in his army said to him: "Xiazhou is desert land; there is no way to engage in agricultural production. And we do not adapt to climate conditions there". That evening, the soldiers guarding the Xiazhou rebelled and Han Quanyi turned over the wall and ran away. This shows that environmental conditions of Xiazhou where Tongwan City located had been much harsh at the time and their land were considered barren and uninhabitable, so that soldiers were reluctant to stay there. During this period, the desertification has become rather serious	*Jiutangshu*
822–824	"One day in lunar January of AD 822, the sky was filled with sand; in lunar October of this year, The wind was in a rage and the windblown sand deposited to the top of Tongwan City's wall. Then another day in lunar January of the next year, The sky was dark all day long with sand rising up through the air. In lunar June of AD 824, the strong wind destroyed two of Chang'an City's palace gates." All these show that dust storm events during this time was very frequent, attended with deep degree desertification around Tongwan City	*XinTangshu*
862	In AD 862, when the poet Xu Tang came to the Tongwan City, what he has seen was a big desert landscape, which was recorded in his poem. This shows that the densification around Tongwan City has been very serious	*Quantangshi*
994	The emperor of Song considered that the Tongwan City, which was occupied by the Dangxiang ethnic group for a long time, has been deep in the desert. Therefore, he ordered to destroy the city	*Xuzizhitongjian*

sites in regions influenced by other circulations (e.g. the westerlies and the southwest monsoon) were excluded. Third, proxy records should be indicative of changes in the EASM with no ambiguous meaning. Finally, the resolution of the proxy records must be sufficient to observe climatic events that occurred over 50–100 years. Laminated stalagmites have been used as high-resolution climatic indicators because their growth layers have been verified to be annual by ^{14}C and TIMS-230Th methods. Here, we refer to the warm season temperature reconstruction results during the last 2,650 years based on the Beijing Shihua Cave stalagmite layer thickness. Correlation analysis shows that warm season temperature may play an crucial role in layer thickness variations (Tan et al. 2003). A record from Wanxiang Cave, China, which characterized EASM precipitation history over the past 1,810 years, was also cited (Zhang et al. 2008). These records indicate that warm season temperature and precipitation are directly related to the strength of the EASM. For a more convenient global comparison, a sediment record from Lake Chichancanab and a stalagmite δ^{18}O record from the northwest Yucatán Peninsula were cited as supplementary materials (Ljungqvist 2009; Medina-Elizalde et al. 2010).

To facilitate the comparison between different proxy records, each single-temperature proxy record was first standardized according to the temperature anomaly index. The Wanxiang Cave and Tzabnah Cave speleothem records were established with δ^{18}O analyses with an average resolution of 2.5 and 2.3 years, respectively. However, temple resolutions of Shihua Cave speleothem and lacustrine sedimentary records were annual. To keep the same resolution in different records, the data of Shihua Cave and Lake Chichancanab were filtered by an 11-point moving average and the other two records by a 5-point moving average.

Historical proxy records

The record in the historical documents is descriptive and discrete. To indicate the variability and the periods of historical climatic change, a continuous time series based on the original historical documents is required. Much effort has been spent in the last few decades in reconstructing the climate of China using a variety of historical documents (Ge et al. 2008). An important source is Ge et al. (2003), which provides a valuable temperature synthesis of the last 2,000 years. The summaries of Zhang (1983), Wang (2001), and Liu and Wang (2006), which describe the most important dust records during the last 2,000 years, were also used. Extreme cold climate and weather events during the Tang Dynasty (AD 642–907) are reported by Man (1998) and Fei et al. (2004).

Results

Proxy records of temperature/precipitation anomaly (weak EASM)

Previous debates on the cause of Tongwan City's abandonment were mainly based on documents records. High-resolution palaeoclimatology records were not used as strong evidence in previous studies. Through the integration of published high-resolution palaeoclimatology records, we provide straightforward proof on climate evolution during the last two millennia in China. The palaeotemperature and precipitation comparison between the stalagmite records from Shihua Cave, Wanxiang Cave, Tzabnah Cave, and Lake Chichancanab are shown in Fig. 2. The starting and ending time of the cold/dry intervals and the duration at the curves are different. This discrepancy can be partly

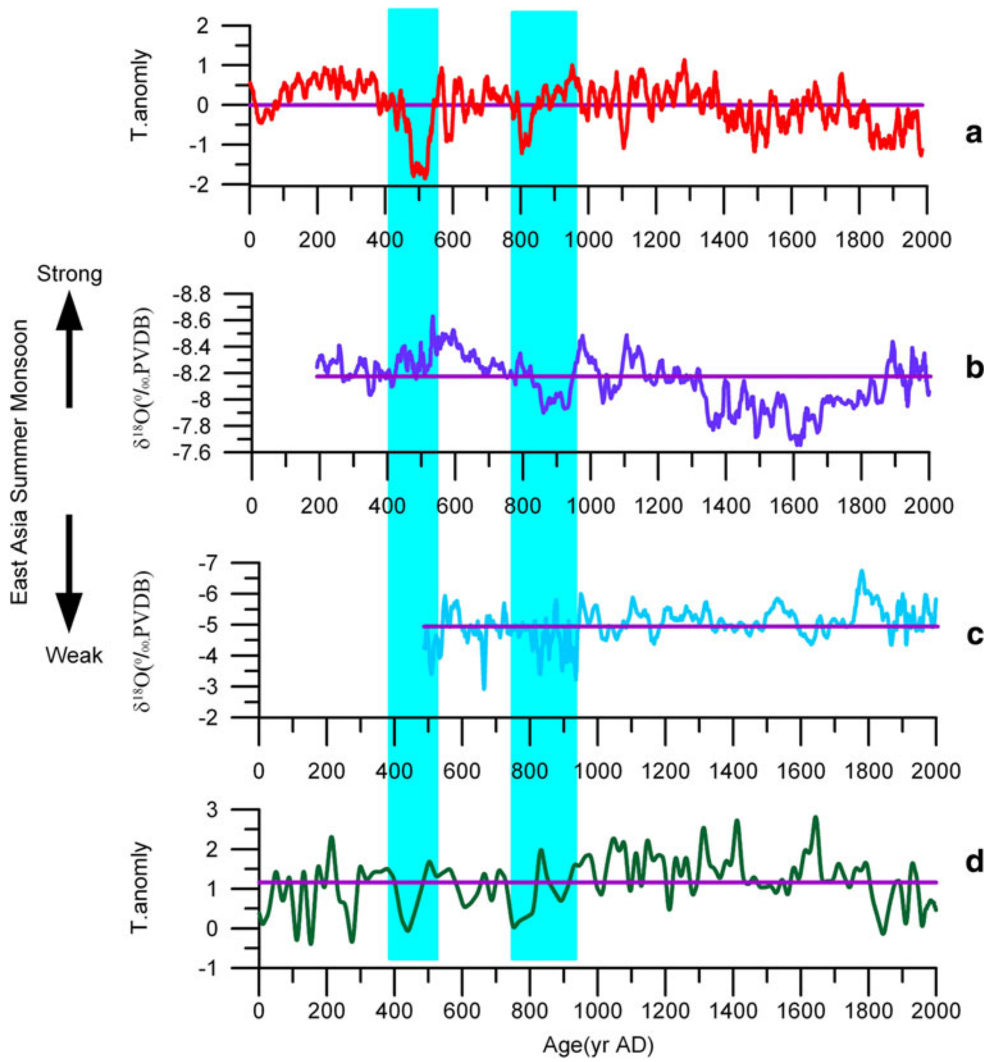

Fig. 2 Temperature anomalies and precipitation proxy records reconstructed by Shihua Cave Speleothem, Wanxiang Cave Speleothem, Lake Chichancanab, and Tzabnah Cave Speleothem. The *lines* show the results at a 10-year resolution. Two *vertical blue bars* denote the timing of the two weak EASM events. These trends were estimated based on published data (Tan et al. 2003; Zhang et al. 2008; Ljungqvist 2009; Buckley et al. 2010)

explained by different climatic conditions and resolutions in different records. Despite this discrepancy, the whole trends of variation are similar, particularly in the prominent peaks and troughs (Fig. 2). During this period, two abrupt cold/drought climate events (or weakening EASM events) can be identified in the climate curves.

The first cold and drought stage dates to about AD 420–550, with the lowest point centred in AD 500. Many studies have linked the cold/drought stage to disunity and disorder—a time of chaos in Chinese history. Graff (2002) described the situation in that period as follows: "A rump Jin government in the south survived the debacle of the early fourth century and lasted until AD 420. It was replaced by a succession of short-lived southern regimes, the Liu Song, Qi, Liang, and Chen. In the north, the Wei rulers found it necessary to deploy strong forces to the northern border to guard against nomadic newcomers, and in the 520s their empire was thrown into chaos by a rebellion of the garrison forces, who were in part protesting the increasing sinicization of the Wei court and its lack of solicitude for the frontier warriors. In the wake of the Wei collapse, the north was divided between two rival successor states, Western Wei (later Northern Zhou) and Eastern Wei (later Northern Qi)". From a global point of view, this cold stage can be compared with the Dark Age Cold Period (DACP). The DACP has been detected in palaeoclimatic data throughout the northern hemisphere (Esper et al. 2002; Moberg et al. 2005). Climatically, both tree-ring data and sea-surface temperature reconstruction data indicate abrupt cooling events during this period. These events correspond with Bond's event 1 in North Atlantic sediments. In Europe, similar to Asia, evidence shows that the DACP was not a good time for human societies in the northern parts of the continent. Based on pollen data, Berglund (2003) reported the "retreat of agriculture" that occurred in AD 500. The Roman Empire collapsed in AD 480 and the Justinian plague (ca. AD 540) also took place during this period (Berglund 2003). The worst of this cold period was associated with the so-called "dry fog" event of AD 536–541, as recorded in historical documents (Gunn 2000).

Another cold/dry interval occurred in AD 780–950. Desertification took place during this period in Northern China. This event was followed by decreasing biological productivity that exacerbated the decline of the Tang Dynasty (Yancheva et al. 2007; Huang et al. 2009; Wang et al. 2010). In Mesoamerica, the proxy record of Lake Chinchancan and the stalagmite $\delta^{18}O$ record from the northwest Yucatán Peninsula also suggest an intensive cold/dry interval at almost the same time (Fig. 2). Long-term drought appeared to have lasted from AD 760–930 in the Cariaco Basin. This drought was coincident with the four phases of city abandonment at around AD 760, 810, 860, and 910 (Gill et al. 2007). Climatic anomalies of the ninth century were not limited to China, as they occurred throughout the Northern Hemisphere. The climate of the ninth century was as cold as that during the Little Ice Age (Gill 2000).

Weak EASM in synthesis history documents

In China, dust events tend to be associated with cooling and drought events (Zhang 1983). Palaeotemperature data and dust records were both reconstructed based on historical documents (Fig. 3). Climatic reconstruction by Ge et al. (2003) demonstrates a dramatic decrease in temperature from AD 450–530, which was followed by a sustained rise after AD 530. In AD 490, the lowest temperature of this cold interval was reached. This temperature is about 1 °C lower than the temperature in 1951–1980 (Ge et al. 2003). The aforementioned cold interval is also reflected in other dust records (Wang 2001; Liu and Wang 2006). This cold interval is related to the first cold/dry interval shown in the nature proxy data. Another cold period that took place from AD 795–915 can be identified from the reconstructed winter half-year temperature departure for the past 2,000 years with a 30-year resolution. However, there are no marked responses to this cold event in the dust records. In contrast, both dust records remain at a relatively lower level. Nevertheless, Liu and Wang (2006) identified two extreme dust periods (which exceeded the mean level during the last two millennia) in the result with a 10-year resolution. These dust periods occurred in AD 820–829 and AD 900–909. These data are consistent with the two lowest points in the winter temperature curve during that time interval. A more detailed palaeotemperature series from AD 618–959 (including the Tang Dynasty and the Five Dynasties Period in Chinese history) based on historical documents was reconstructed by Fei et al. (2004). The quantified temperature index curve indicates a strong cold stage lasting from AD 794–844. This result can be compared with the stalagmite record from the Shihua Cave (Beijing). Based on historical documents, Man (1998) also reported the cold climate during the mid-later period of the Tang Dynasty, especially the sea ice events that took place in AD 821, 822, and 903, indicating extreme cold events.

Comparison of weakening EASM and Tongwan City history

In summary, the natural proxy records, the proxy records from old documents, and the original description in historical literature show an extremely comparable inclination. As the resolution and application of multiple environmental proxy studies increased and combined with the application of historical documents, it is possible to identify the large number of climatic shifts and the corresponding human responses.

Throughout Tongwan City's existence (AD 413–994), two severe cold and drought (weak EASM) stages were recognized by both the natural proxy data and the synthesis compiled from the historical documents. The first cold and drought stage occurred at about AD 420–550 and its lowest point was centred at about AD 500. Compared with the original descriptive historical documents, proxy data (based on both natural evidence and historical documents) are successive and can indicate large-scale and long-time climate oscillation. However, short-time extreme events can be evened out if these are not intensive enough. Conversely, the scattered descriptive historical literature can provide detailed information about short-time extreme climatic events such as the severe cold/drought events that occurred in AD 426–427, AD 500–503, and AD 822–824 (Table 1).

Altogether, the proxy data and the descriptive records (Table 1) show that when Tongwan City was constructed, the climate remained mild but not optimum as mentioned by some researchers. Temperature reconstruction based on tree-ring indicates an intensive "Dongjin warm period" corresponding to the time Tongwan City was being built (Liu et al. 2009). Nonetheless, more high-resolution proxy records and literature are required to support these findings. Most previous studies consider the earliest evidence of desertification around Tongwan City to occur during the period of the Northern Wei Dynasty (AD 520–524), when the famous historical geography book *Shuijingzhu* was written. In this book, author Li Daoyuan described in detail the desertification taking place in the environment surrounding Tongwan City. In fact, the Mu Us Desert had already been in existence when Tongwan City was built (Dong et al. 1983; Wu 1991). Under mild climate conditions, deserts, wetlands, and lakes can coexist (Deng et al. 2001). To date, many lakes and wetlands are distributed in the hinterland of the Mu Us Desert. Soon after it was

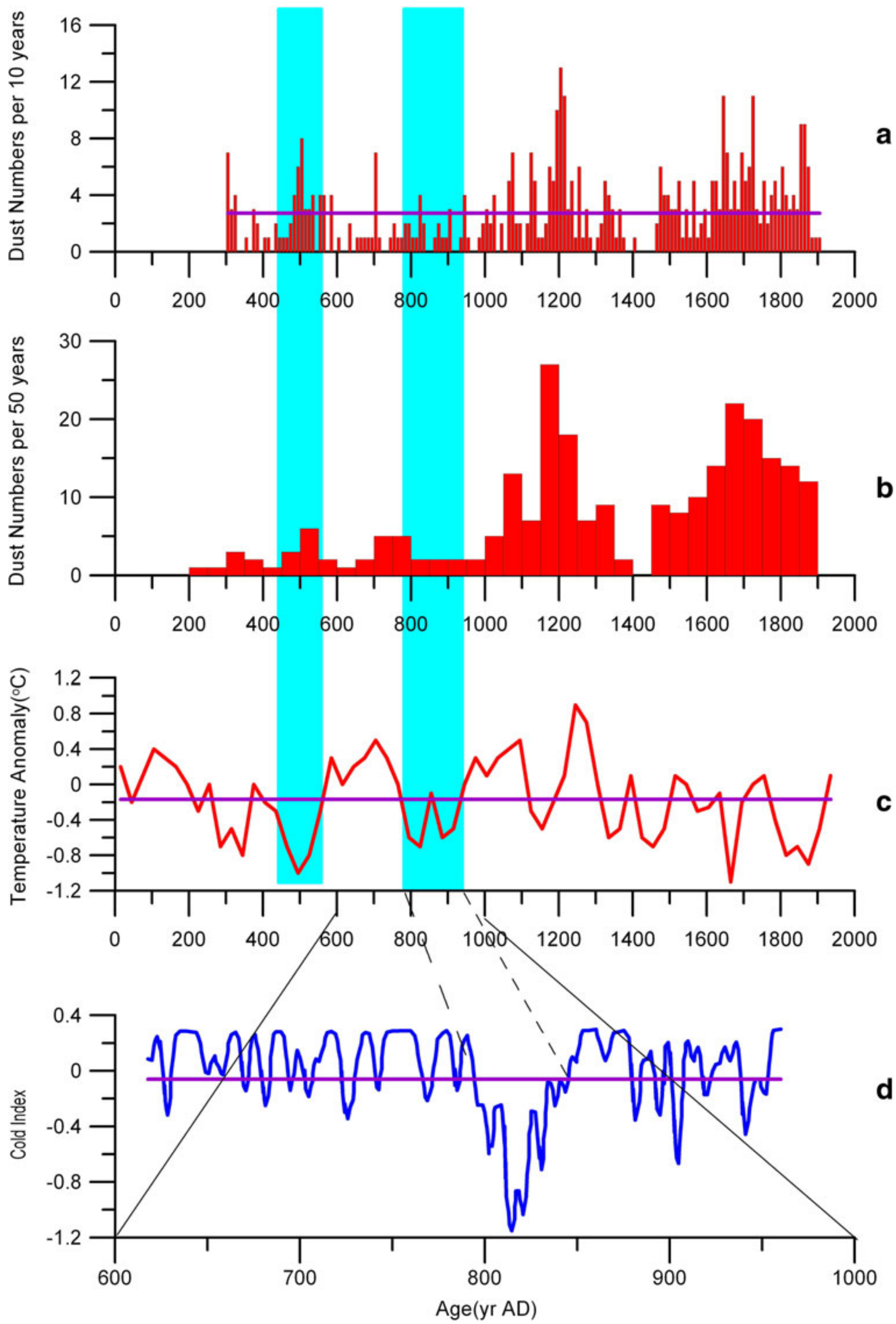

Fig. 3 Temperature and dust frequency records based on historical documents. **a** dust frequency during the last 2,000 years at a 10-year resolution (Liu and Wang 2006); **b** dust frequency during the last 2,000 years at a 50-year resolution (Wang 2001); **c** winter half-year temperature reconstruction during the past 2,000 years in East Central China (Ge et al. 2003); **d** temperature records in China from AD 618–959 (Fei et al. 2004); Two *horizontal blue bars* denote the timing of the two cold events

constructed, Tongwan City withstood a strong sand invasion caused by the weakening EASM (Table 1; Figs. 2, 3). Nonetheless, the occupation of Tongwan City was almost never intermitted. For example, in AD 432, the Northern Wei Dynasty set up Tongwan town in the area. When well-known historical geographer Li Daoyuan (about AD 520) visited the area, the city had almost maintained its original appearance. In AD 534, one of the Northern Zhou emperors was born in Tongwan City. This event suggests that the city still held vital political and military roles. Both proxy data and descriptive records indicate the weak EASM period from AD 420–550. This climate event should have aggravated the desertification process. However, at that time, the large-scale continuous desert had not yet expanded to the Tongwan City region that lies on the southern margin of the current Mu Us Desert.

Another weak EASM event can be identified based on the proxy data (Figs. 2, 3). The beginning and the end of this cold climate interval are not exactly consistent in different records because of various resolutions, reconstruction materials, and methods. To ensure no climate information was missed, we adopted the longest interval between AD 780 and 950. During this period, Tongwan City endured a desertification erosion process that finally stimulated its end. Many related records in historical books describe the great damage caused by desertification to Tongwan City (Table 1). Table 1 shows that Tongwan City remained an important frontier town before AD 789 when several wars broke out, as armies from the Tang Dynasty and a minority nationality fought for controlling over the city. In AD 789, soldiers who were tasked to guard Xiazhou and Tongwan City revolted against the government because of the rugged conditions of frontier life. According to the soldiers, “Vast areas of land have become deserts and no farmland to support the huge populations. For survive, we have to shift from place to place.” This historical event indicates that the environment around Tongwan City had degraded. Since then, descriptions about the area’s desertification rapidly increased (Table 1). According to the records in *Xintangshu*, the climate from AD 822–824 was harsh. Aeolian sand encircled the city and almost reached the top of the city wall. Strong wind and dust storm records in history appear to be consistent with the result of the proxy records (Figs. 2, 3). Therefore, the weak EASM event during the later stage of the Tang Dynasty could be largely responsible for the desertification of the Mu Us Desert and the collapse of Tongwan City. Moreover, many descriptions were made about the desertification of the landscapes of the Tongwan City region in late Tang Dynasty poetry. After the decline of the Tang Dynasty, the Song Dynasty set up the Xiazhou in Tongwan City. Almost no farmland could be used to support the army of the Han people because of the harsh environment; thus, the Song Dynasty placed no importance to this region. In fact, this region was often controlled by nomadic people at that time. In AD 994, the emperor gave the order to destroy the city. The imperial edict gave a detailed account of the abandonment cause. According to the emperor, “Xiazhou is already located in the deep of the desert and this region has been occupied by the nomadic peoples for a long time. Now, we tend to give up this city and immigrant the residents to the bordering regions”. Since then, Tongwan City was finally abandoned and never reused.

Discussion

Since the establishment of Tongwan City, two weak EASM events were identified by both natural records and historical documents. These weak EASM events were also recorded in other sites in the world, indicating regional climatic trends instead of local events. The first weak EASM event coincided with the so-called “dark ages.” The climate was cold and dry when global cultures reached a trough. In Chinese history, this period was a time of chaos. The effect of the first weak EASM event on Tongwan City was little. Physical proxy records in China indicate an obvious decrease in temperature, but precipitation fluctuation was relatively small. Therefore, the desertification strength of the Mu Us Desert was relatively low. A number of high-resolution local proxy records are required to give more solid evidence. The second weak EASM event accompanied with strong desertification processes eventually had a destructive effect on the structure of Tongwan City. Aside from this environmental consideration, the pressure of population growth in the region and the long occupation by ethnic minorities were additional factors that led the Song Dynasty to abandon the city. The last weak EASM event coincided with the final stage of the Maya’s collapse and the end of Tongwan City. Therefore, cultural responses to climatic events in China and in the world were almost coincident. A low-frequency teleconnection of drought and wetness during the past 2,000 years was revealed between the tropical Peruvian Quelccaya ice cap and the temperate Chinese Guliya ice cap (Thompson 1996). The dry periods were related to the reduced isolation in the Northern Hemisphere, the southward displacement of the Intertropical Convergence Zone (ITCZ), and the decrease in summer monsoons from the equator to 22–23N. Previous palaeoclimatic reconstructions generally agree that the Asian summer monsoon is weaker during cold phases in the Northern Hemisphere, when the ITCZ tends to move southward, as it does during El Niño periods. These results show that major circum-Pacific shifts in the ITCZ position possibly catalysed simultaneous events in civilizations on opposite sides of the Pacific Ocean. To sum up, our data provided a case study that links regional and global climate and culture.

Conclusion

In this paper, we related the evolutionary history of ancient Tongwan City and Mu Us Desert to environmental deterioration caused by the weakening monsoons and the intensified desertification of this region. Based on the descriptive historical documents about extreme weather events and the desertification process around Tongwan

City, we propose the following hypothesis: climatic changes play a crucial role in the decline and eventual fall of Tongwan City. Then, we use high-resolution proxy records to support the hypothesis of weakening monsoons accompanied by low temperature and drought. We also quote teleconnection evidence to support the findings.

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