Multi—Proxy Reconstructions of Climate Change and Human Impacts Over the Past 7000 Years From an Archive of Continental Shelf Sediments off Eastern Hainan Island, China

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Abrupt climatic events and the history of human activities on Hainan Island are poorly understood, due to the lack of high-resolution records. We present high-resolution multiproxy records from the coastal shelf off eastern Hainan Island in China to investigate abrupt climate change and regional human–environment interaction over the last 7,000 years. A prominent climatic anomaly occurred during 5,400–4,900 cal yr BP. This abrupt monsoon failure has been detected in various paleoclimatic records from monsoonal regions. Anomalous summer monsoon intensity during 5,400–4,900 cal yr BP is probably driven by solar variability, ENSO activity and ice-rafting events in the North Atlantic. Over the past 1,500 years, with the growing population and progress in production technology, human activity has increasingly become the dominant factor controlling the natural environment of Hainan Island.

Keywords: Asian summer monsoon, holocene, human activity, abrupt climate change, chemical weathering, terrigenous influx

INTRODUCTION

Extreme weather events are becoming more frequent owing to global warming, and people are increasingly concerned about climate change and its impacts on their lives. Over recent Earth history, several abrupt global climatic anomalies occurred during the Holocene (Bond et al., 2001; Mayewski et al., 2004; Wanner et al., 2011). For example, the 4200 BP climate event and the Little Ice Age, these events had disastrous consequences for humans, and seriously influenced the development of agriculture and the prehistoric advancement of human society (Cullen et al., 2000; DeMenocal, 2001; Douglas et al., 2016; Sinha et al., 2019). Climatic anomaly around 5,500 cal yr BP have recently received attention as a result of the close linkage between climate change and the evolution of prehistoric culture (Shuman, 2012; Bai et al., 2017; Wu et al., 2018; Hou and Wu, 2021; Tan et al., 2020). A detailed understanding of abrupt climatic events in the past is therefore critical for exploring their underlying forcing mechanisms and dealing with abrupt changes in the climate system in the future.
In recent years, studies have suggested that human activities play an important role in controlling ecosystems and soil erosion in monsoonal China. Increases in $\chi_{lf}$ and $\chi_{fd}$ over the last 2000 years in sediments from the Yangtze delta in eastern China, Lake Xiaolongwan in northeast China, and lakes Erhai and Xingyun in southwest China reflect an increase in soil erosion attributed to enhanced human activity (Dearing et al., 2008; Wang et al., 2010; Su et al., 2015; Wu et al., 2015). Numerous studies likewise found that increasing contents of various metals, including Cu, Pb, and Zn, could be closely linked to mining and metalworking activities, reflecting a progressive intensification of human activities (Zong et al., 2010; Hu et al., 2013; Hillman et al., 2014; Wan et al., 2015; Xu et al., 2017; Huang et al., 2018). Additionally, pollen and black carbon results indicate significantly accelerated deforestation in monsoonal China since 2000 cal yr BP (Zhao et al., 2010; Ma et al., 2016a; Cheng et al., 2018; Lu et al., 2019; Pei et al., 2020).

As human populations grew and progress in production technology increased, human influences on the natural environment became increasingly important during the late Holocene, and often obscure the detection of climatic fluctuations in the archives investigated. Human activities can mediate the terrestrial ecosystems and soil erosion, generating unavailability of the relevant proxy indicators to reconstruct climate change. It is therefore essential to understand climate and human activities, as well as their impacts upon terrestrial ecosystems on longer timescales, in order to reconstruct each of them accurately. However, previous studies to determine human—environment interactions were mainly dependent on sediment cores from lakes (Dearing et al., 2008; Hillman et al., 2014; Su et al., 2015) and river deltas (Wang et al., 2010; Zong et al., 2010; Strong et al., 2013). High-resolution records from continental shelves are relatively scarce. Well dated and high-resolution data of various geologic archives from wide regions are crucial for better understanding the complex interplays between humans and the Earth. Sediment cores from continental shelves would therefore provide an excellent opportunity to understand human—environment interactions at regional scales.

Hainan Island, the second largest island in the northern South China Sea (SCS), is sensitive to climatic fluctuations. Previous studies have confirmed that continental shelf sediments off eastern Hainan provide valuable information on paleoclimate variation and human activity (Liu et al., 2013; Wu et al., 2017; Xu et al., 2017; Ji et al., 2020). However, most previous studies have focused on short timescales during the past 200 years (Liu et al., 2013; Wu et al., 2017). Accurate timing and intensity of human activity have not been well constrained. This study presents a high-resolution multi-proxy record with a robust chronology spanning the last 7,000 years collected from the continental shelf off eastern Hainan. The main aims are to investigate the interaction between Holocene climate variability, human activity and environmental changes, and to determine the timing and intensity of human activity on Hainan Island during the last 1,500 years.

**MATERIALS AND METHODS**

**Materials**

Hainan Island is the second largest island in the northern SCS and has an area of $\sim 33.9 \times 10^3$ km$^2$ (Figure 1). The Wanquan River is the third largest river on the island and originates from the Wuzhishan Mountains. It drains southeast Hainan and eventually discharges into the northwestern SCS at Boao Township in Qionghai City. The river’s total length is $\sim 157$ km and its drainage area covers 3,693 km$^2$ (Yang et al., 2013). The study region is dominated by a tropical monsoon climate (Zeng and Zeng, 1989). The annual mean temperature is 22.8–25.8°C. Annual precipitation ranges 961–2,439 mm yr$^{-1}$, with about 80% occurring during the wet season from April to September (Zhang et al., 2013).

The GH6 core (19°06′N, 110°42.85′E; 2.4 m in length) was collected using a gravity corer from approximately 50 m water
depth on the continental shelf off eastern Hainan Island (Figure 1). The sediment core was cut longitudinally and samples were stored at 4°C prior to analysis. As shown in Figure 2, GH6 core can be divided into three lithological units: Unit 1 (0–20 cm) consists of yellow-brown clayey silt; Unit 2 (20–176 cm) consists of grey silt containing occasional shells; and Unit 3 (176–240 cm) consists of grey clayey silt.

Age Model
The chronology for the GH6 core was based on six AMS 14C dates from mixed species of planktonic foraminifera (Table 1; Figure 2). 10 mg of complete and clean planktonic foraminifera were selected hand-picked under a binocular dissecting microscope at 40× magnification and cleaned by sonication in deionized water in order to remove surface adhesions. AMS 14C dates were measured at the BETA Laboratory in the United States. All radiocarbon dates were calibrated to calendar ages with Calib 8.1.0 software using the marine20 program (Reimer et al., 2020). The age models of each sample are established by Polynomial (n = 2) fitting between these calibrated ages. The average temporal resolution is ~58 years, and the average sedimentation rate is 0.03 cm/yr. For further details of the dating method and modelling approach, see Kong et al. (2021).

Major and Trace Element Compositions
Bulk sediment samples were freeze-dried and ground, then heated at 650°C for 4 h to remove organic matter. The samples were digested in an HNO3 + HF acid mixture and the solutions were heated at 650°C for 4 h to remove organic matter. The samples then have a significant effect on the results because only relative variations in chemical weathering are considered (Arnaud et al., 2012).

Environmental Magnetic Measurements
Magnetic susceptibility was determined at about 1–6 cm intervals. The low-field magnetic susceptibility (χlf) for all discrete samples was measured using a Kappabridge MKF1-FA (AGICO) magnetic susceptibility meter at low (976 Hz) and high (15,616 Hz) frequencies (defined as χlf and χhf respectively). Frequency-dependent magnetic susceptibility (χdf%) was calculated using the formula χdf% = 100 × (χhf−χlf)/χlf.

Particle Size Analysis
The samples used for the particle-size analysis were collected at about 1–7 cm intervals. All samples were pre-treated with 10% H2O2, followed by treatment with 10% HCl, to remove organic matter and carbonates, respectively. They were then rinsed with deionized water and dispersed with 10 ml of 0.05 mol L−1 (NaPO3)6 on an ultrasonic vibrator for 10 min. The grain-size distribution was measured using a Malvern 3,000 laser diffraction instrument. Mean grain size was calculated according to Folk and Ward (1957).

RESULTS
As shown in Figure 3, the Al/K, CIA, Al, Fe, Ti, Cu and Pb values share very similar trends through time. Generally, the variations in multi-proxy of GH6 core can be divided into four stages. During the interval 7,000–5,400 cal yr BP, CIA values and Al/K ratios are relatively high, and contents of Al, Fe, Ti, Cu, and Pb are also relatively high; both χlf and χfd values remain relatively high, but the mean grain size has relatively low values. During the interval 5,400–4,900 cal yr BP, all of proxies in GH6 core show an abrupt shift; a sharp decrease in CIA and Al/K ratios is observed, and contents of Al, Fe, Ti, Cu, and Pb exhibit clear decreasing trends; both χlf and χfd values show a rapid decrease, but the mean grain size exhibits a rapid increase. During the interval 4,900–1,500 cal yr BP, CIA and Al/K ratios are relatively low, and contents of Al, Fe, Ti, Cu, and Pb remain fairly constant and relatively low values; both χlf and χfd values are relatively low except the period of 4,000–3,200 cal yr BP, and prominent peaks

| Sample Code | Beta Lab Code | Depth (cm) | Material | Conventional age (years, BP) | Error (2σ) | Calibrated Age (years, BP) | Error (2σ) |
|-------------|---------------|------------|----------|-------------------------------|------------|---------------------------|------------|
| GH6-F10     | 530613        | 8          | Foraminifera | 460                          | 30         | 20                        | 30         |
| GH6-F17     | 530614        | 37         | Foraminifera | 1,760                        | 30         | 1,655.5                   | 60         |
| GH6-F84     | 530615        | 84         | Foraminifera | 2,240                        | 30         | 1,656.5                   | 65         |
| GH6-F114    | 545408        | 114        | Foraminifera | 2,980                        | 30         | 3,085                     | 84.5       |
| GH6-F148    | 532199        | 148        | Foraminifera | 4,230                        | 30         | 4,142                     | 81.5       |
| GH6-F198    | 532200        | 198        | Foraminifera | 5,420                        | 30         | 5,599.5                   | 96.5       |

Table 1: Details of 6 AMS 14C dates from the GH6 core (after Kong et al., 2021).
of them would be attributed the pedogenic process; the mean grain size show a rapid increase. After 1,500 cal yr BP, CIA, and Al/K exhibit clear increasing trends, and contents of Al, Fe, Ti, Cu, and Pb show an overall increasing trend; both χlf and χfd values show an overall increase, and the mean grain size exhibits an overall decreasing trend.

DISCUSSION

Palaeoclimatic Significance of Proxy Indicators

Different elements behave differently during chemical weathering processes. Elemental ratios can therefore be applied to indicate variations in chemical weathering intensity. K tends to be enriched in weathering products after moderate chemical weathering, but depleted after extreme chemical weathering (Nesbitt et al., 1980; Condie et al., 1995), whereas Al tends to be retained and enriched in weathering products (Nesbitt and Markovics, 1997; Nesbitt et al., 1980). Thus, Al/K ratios can be used to reflect the intensity of chemical weathering, with higher Al/K ratios indicating stronger chemical weathering. In our core GH6, Al/K ratios exhibit similar variations to CIA values (Figures 3A,B). The latter have been widely used to trace the intensity of chemical weathering; e.g., core KNG5 from the northern SCS slope (Huang et al., 2015), core YJ from the northern SCS inner shelf (Huang et al., 2018), and core 337 PC from the Qiongdongnan Basin (Wan et al., 2015). In addition, Al/K ratios have been successfully used to indicate variations in chemical weathering intensity in the northern SCS and the Pearl River delta (Wei et al., 2006; Hu et al., 2012; Hu et al., 2013; Clift et al., 2014). This provides further evidence that Al/K ratios can be employed as an indicator of chemical weathering intensity.

Climate is believed to be the dominant factor controlling the degree of chemical weathering under specific environmental conditions (White and Blum, 1995). Warm and humid conditions favour intense chemical weathering, with humidity playing the more important role (White and Blum, 1995; West et al., 2005; Gabet et al., 2006). Previous studies have confirmed that sediments on the continental shelf off Hainan in the northern SCS were primarily derived from the island itself (Tian et al., 2013; Hu et al., 2014; Yan et al., 2016; Xu et al., 2017). Hainan currently experiences a humid tropical climate that is strongly influenced by the Asian summer monsoon (Liu et al., 1999). The proxies for chemical weathering (CIA and Al/K) in core GH6 can therefore be used to trace the strength of the summer monsoon.

In marine sediments, concentrations of Al, Ti, and Fe are primarily derived from terrigenous detrital materials (Latimer and Filippelli, 2001; Ishfaq et al., 2013). Thus, these elements are widely employed as a tracer of terrigenous flux in marine sediments (Haug et al., 2001; Peterson and Haug, 2006; Revel et al., 2010). Al, Ti, and Fe variations in core YJ from the northern inner shelf of the SCS have been successfully used to indicate changes in terrigenous influx (Huang et al., 2019). This provides further evidence that Al, Ti, and Fe concentrations in our GH6 core can be used to trace changes in terrigenous sediment input. In southern China, numerous studies have confirmed that continental erosion is primarily associated with monsoon precipitation, with heavier monsoon precipitation causing...
FIGURE 4 | Comparisons between related records: (A) Al/K ratios from our GH6 core; (B) K/Al record from the northern South China Sea slope (Huang et al., 2016); (C) compound-specific δ¹³C record from the Pearl River Estuary (Strong et al., 2013); (D) δ¹³Corg record from the Pearl River Estuary (Yu et al., 2012); (E) Al/K ratios from the northern inner shelf of the South China Sea (Huang et al., 2019); (F) chlorophyll-a record from Huguangyan Maar Lake (Wu et al., 2012); (G) Ti/Ca record from Huguangyan Maar Lake (Shen et al., 2013); (H) stalagmite δ¹⁸O record from Dongge Cave (Dykoski et al., 2005); and (I) TOC data from Retreat Lake in northeastern Taiwan (Selvaraj et al., 2007).
greater terrigenous influx (Hu et al., 2012; Clift et al., 2014; Wan et al., 2015; Huang et al., 2019). Furthermore, Al, Ti, and Fe variations in our GH6 core, as proxies for terrigenous influx, show similar temporal patterns to CIA and Al/K ratios throughout the core. Consequently, we can reasonably speculate that stronger monsoon precipitation generates greater chemical weathering and associated volumes of terrigenous inputs.

**Abrupt Changes in Summer Monsoon Strength 5,400–4,900 cal yr BP and Forcing Mechanisms**

During the period 5,400–4,900 cal yr BP, the intensity of chemical weathering decreased rapidly, as inferred from the profiles of CIA and Al/K in our GH6 core. The terrigenous influx decreased rapidly during the same interval, as indicated by concentrations of Al, Ti, and Fe. Simultaneously, the mean sediment grain size increased sharply. The distinct variations in these records suggest a rapid climatic deterioration, which was likely associated with abrupt changes in the Asian summer monsoon. This abrupt climatic event generally coincides with a dramatic weakening of the summer monsoon at 5,400–4,900 cal yr BP, as inferred from various paleoclimate records from monsoonal regions elsewhere (Dykoski et al., 2005; Strong et al., 2013; Huang et al., 2019; Shah et al., 2020).

Chemical weathering interpreted from core KNG5, retrieved from the northern SCS slope, shows an abrupt decrease, reflecting reduced monsoon rainfall (Figure 4B; Huang et al., 2016). In the Pearl River estuary, abrupt summer monsoon failure can be detected in bulk-sedimentary δ¹³Corg and compound-specific δ¹³C records (Figures 4C,D; Yu et al., 2012; Strong et al., 2013). In the northern inner shelf of the SCS, Al/K ratios, used as an indicator of chemical weathering, exhibit a rapid decrease in response to the weakening monsoon (Figure 4E; Huang et al., 2019). This sudden climate shift is also documented in terrestrial sediment records in southern China. In Huguangyan Maar Lake, the weak summer monsoon during this period is detected from multiple climatic indices, including records of chlorophyll a and TOC (Figure 4F; Wu et al., 2012), Ti/Ca ratios (Figure 4G; Shen et al., 2013), and magnetic properties (Duan et al., 2014). Similarly, a positive shift in the stalagmite δ¹⁸O record from Dongge Cave implies a weakening of the summer monsoon (Figure 4H; Dykoski et al., 2005). The development of stagnant swampy environments in the northern Wuyi Mountains is also attributed to a decline in the summer monsoon (Ma et al., 2016b). Within age uncertainty, the subalpine Retreat Lake in Taiwan also experienced an abrupt weak monsoon event, as indicated by low TOC (Figure 4I; Selvaraj et al., 2007). Taken together, these multiple proxy records from various geological archives in southern China capture this abrupt climatic shift (Figure 4).

In addition, solar activity may influence variability in the summer monsoon indirectly, perhaps amplified by North Atlantic teleconnection and El Niño-Southern Oscillation (ENSO) activity (Wang et al., 2005; 2016; Marchitto et al., 2010). During the period 5,400–4,900 cal yr BP, the weaker monsoon inferred from our GH6 core coincides with higher percentages of hematite-stained grains in the North Atlantic, which can be taken as an indication of ice-rafted debris (IRD) (Figure 5D; Bond et al., 2001). Reduced solar activity may trigger IRD events in the North Atlantic (Bond et al., 2001) and a slowdown of North Atlantic meridional overturning circulation (AMOC) (Oppo et al., 2003), eventually weakening the summer monsoon. Likewise, the abrupt summer monsoon failure during this period is also consistent with strong ENSO activity, indicated by sea surface temperature (SST) records from the Western Pacific Warm Pool (Figure 5E; Stott et al., 2004). Previous studies have confirmed that ENSO may act as a mediator between solar energy input and the Asian summer monsoon (Asmerom et al., 2007; Emile-Geay et al., 2007; Marchitto et al., 2010). These results suggest a link between East Asia, the tropical Pacific and the North Atlantic: a potential forcing mechanism for abrupt climate change is that solar variability can affect the Asian summer monsoon via the North Atlantic and the ENSO system.

**Human Disturbance Over the Past 1,500 Years**

As shown in Figure 6, some decoupling have been observed between records of climate, chemical weathering and fluvial discharge over the past 1,500 years. Temperature reconstructions for the Northern hemisphere and the whole of China exhibit an overall cooling trend (Figures 6A,B; Yang et al., 2002; PAGES 2k Consortium, 2013). There is a general decrease in the intensity of monsoonal precipitation during this period, as inferred from pollen-reconstructed annual rainfall from Gonghai Lake and annual mean precipitation reconstructions in northern China (Figures 6C,D; Chen et al., 2015; Li et al., 2017b). Similarly, a long-term decrease in monsoon precipitation can be found in high-resolution stalagmite δ¹⁸O records from Dongge and Heshang caves in southern China (Wang et al., 2005; Hu et al., 2008).

However, values of CIA and Al/K ratios in our GH6 core show an overall increasing trend during the last 1,500 years.
(Figure 6E), reflecting enhanced chemical weathering. An overall increasing trend of terrigenous supply can be also seen, as indicated by concentrations of Al, Ti, and Fe (Figure 6F). These trends suggest that climate alone cannot be responsible for changes in chemical weathering and fluvial influx. The concentrations of Cu and Pb in the GH6 core increase dramatically over the past 1,500 years (Figures 6G, H). Previous studies have confirmed that increasing metal contents (Cu, Pb, and Zn) appear to be associated with mining and smelting activities (Hu et al., 2013; Hillman et al., 2014; Wan et al., 2015; Huang et al., 2018). Moreover, $\chi_{\text{fl}}$ and $\chi_{\text{fd}}$ values in core GH6 exhibit a striking increase over the same period. Mounting evidence suggests that such increases in $\chi_{\text{fl}}$ and $\chi_{\text{fd}}$ can be attributed to human-induced soil erosion (Dearing et al., 2008; Wang et al., 2010; Wu et al., 2015; Huang et al., 2018).

More importantly, all of the proxies in our GH6 core are generally consistent with the historical exploitation of Hainan Island (Figure 7; Situ, 1987). This provides further evidence for
increasing influence of human activities over the last 1,500 years. According to historical documents, the first large-scale immigration from mainland China took place during the Sui and Tang Dynasty (581–907 AD), with the majority of migrants settling in eastern coastal areas of Hainan (Figure 7; Situ, 1987). Migrant numbers increase dramatically during the Song Dynasty.

These migrants brought advanced tools and cultivation techniques, such as metalworking and Champa rice (Situ, 1987). The advent of metal tools and metalworking activities may be responsible for the increasing concentrations of Cu and Pb in core GH6 during the past 1,500 years. Population expansion and advanced cultivation techniques would have accelerated
deforestation for farming and caused reworking of older highly-weathered materials. This probably enhanced the input of terrestrial material, sourced more deeply and from a wider area. These effects correspond to the increase of proxy indicators in our GH6 core (i.e., CIA, Al/K, χ_{lf}, χ_{fd}, Al, Ti, Fe, Cu, and Pb). Consequently, we can reasonably conclude that human activities have had a growing influence on the natural environment and landscape in eastern Hainan over the past 1,500 years.

CONCLUSION

This study presents high-resolution multi-proxy analyses incorporating chronological, environmental-magnetic, geochemical and grain-size evidence from the coastal shelf off eastern Hainan Island, China. The prominent climatic anomaly during 5,400–4,900 cal yr BP is observed, which is coincides with a dramatic weakening of the summer monsoon. This abrupt event is synchronous with a period of weak solar activity, strong El Niño-Southern Oscillation (ENSO) activity and North Atlantic ice-rafting. These results suggest a climatic link between East Asia, the tropical Pacific and the North Atlantic. The possible forcing mechanism for abrupt climate change is solar variability affecting the Asian summer monsoon via the North Atlantic and ENSO system. There are some decoupling between records of climate, chemical weathering and fluvial discharge over the past 1,500 years. Moreover, enhanced chemical weathering and terrigenous influx during the past 1,500 years are consistent with increasing metal contents (Cu and Pb), and increases in magnetic susceptibility (χ_{ld}) and frequency-dependent magnetic susceptibility (χ_{fd}). All of these proxies are generally consistent with the historical exploitation of Hainan Island. We therefore suggest that enhanced human activity (deforestation, cultivation and mining) over the past 1,500 years has overwhelmed the natural climatic controls on the environment and landscape of Hainan Island.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

FC and CH designed the study; CH, DK, JH, PW, and JL performed research; CH analyzed data and contributed to data interpretation and paper writing. All authors contributed to the discussion and interpretation of the results and to the writing of the manuscript.

FUNDING

This work was financially supported by National Natural Science Foundation of China (Nos. 42001078, U1901213, 41876058, 41876059).
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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2021.663634/full#supplementary-material
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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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