A composite sea surface temperature record of the northern South China Sea for the past 2500 years: A unique look into seasonality and seasonal climate changes during warm and cold periods

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Abstract

High-resolution late Holocene climate records that can resolve seasonality are essential for confirming past climatic dynamics, understanding the late 20th century global warming and predicting future climate. Here a new composite record of the sea surface temperature, SST, variation in the northern South China Sea (SCS) during the late Holocene is constructed by combining seven seasonally-resolved coral and Tridacna gigas Sr/Ca-based SST time-windows with the instrumental SST record from modern interval between 1990 and 2000. This composite multi-proxy marine record, together with the reconstructions from mainland China and tropical Western Pacific, indicates that the late Holocene warm periods, the Roman Warm Period (RWP) and Medieval Warm Period (MWP), were prominently imprinted and documented in the climatic and environmental history of the East Asia–Western Pacific region. Meanwhile, substantial and significant SST seasonality variations during the late Holocene were observed in the composite record. The observed increase in seasonality (or amplitude of seasonal cycles) during the cold periods around our study area was probably caused by the different amplitudes between winter versus summer SST variations in northern SCS, with much larger SST variation during winters than during summers for the late Holocene. In addition, the distinctive warm, cold and neutral climatic episodes identified in our northern SCS composite SST record correspond well with other paleo reconstructions from mainland China and especially well with the Northern Hemisphere-wide composites by Moberg et al. (2005) and Ljungqvist (2010). The overall agreement however also calls for more information and insights on how seasonal temperatures and their ranges vary on decadal–centennial timescales.
1. Introduction

High-resolution climate reconstructions during the late Holocene, especially during the past 2000 years, can provide a timely opportunity to place the current global warming in a long-term context and help understand the importance of natural and anthropogenic forcings on past and future climate changes. Many recent works have focused on the climatic changes during this time period, but the complete characteristic of the seasonal climate during the late Holocene, as well as the historical status of the late 20th century global warming, remain debated (IPCC, 2001; Esper et al., 2002; Ge et al., 2003; Soon et al., 2003; IPCC, 2007; Wang et al., 2007). The insufficiencies of the currently available proxy data for the late Holocene are the major cause of ongoing debates and controversies. For example, although more than 1200 proxy reconstructions were used in the compilation of Mann et al. (2008), only 25 records cover the last 2000 years. Meanwhile, most of the proxy records are derived from the mid and high latitudes of the Northern Hemisphere, and the temperature reconstructions from the Southern Hemisphere and tropics are less common (IPCC, 2007; Mann et al., 2008, 2009). Furthermore, while tree-ring-proxy records during the late Holocene have been built for the vast terrestrial area over the last 20 years, high-resolution proxy ocean temperature records of the late Holocene are still very limited. Thus a more concerted study on proxy records of the late Holocene for the past 2000–3000 years, in particular high-resolution, seasonally-resolved, ocean temperature records from Southern Hemisphere and tropics, are needed.

In addition to the variations of mean climatic state [see e.g., two early papers for discussion on the inadequacy of the current definition and framework basing on the statistical 30-yr averages (Landsberg, 1972; Guttman, 1989)], the seasonal and sub-seasonal changes of climatic conditions are the primary component and physical descriptor of Earth’s climate system (Kukla and Gavin, 2004; Denton et al., 2005; Soon, 2009). The information of past seasonal and sub-seasonal changes in different weather regimes and climatic states is the key for a comprehensive understanding of past climatic dynamics and for predicting future climate. However, except the coral records in tropical area, most of proxy-based climate records have temporal resolution insufficient for quantifying temperature seasonality.

The fast-growing marine biogenic carbonates, such as corals and mollusks, are sensitive to surrounding environmental changes in most aquatic settings, and they have the potential to sample the full seasonal range of past sea surface temperature (SST) and were used extensively to provide high-resolution seasonal/monthly climate records from tropics to high latitudes for the past 30 years [Williams et al., 1982; Cole et al., 1993; Gagan et al., 1994; McCulloch et al., 1994; Schöne et al., 2004a,b; Watanabe et al., 2004; Schöne et al., 2005; Wanamaker et al., 2008; Aubert et al., 2009; Elliot et al., 2009; Maier and Tittschack, 2010; Batenburg et al., 2011; Wanamaker et al., 2011]. These seasonal and sub-seasonal proxy-climate records, together with lower resolution marine sediment records, have greatly improved our understanding of the past climate changes in global ocean during the late Holocene. However, the time spans of the marine biogenic carbonate records, typically less than 200 years for most of the reported records, are too short to cover the whole late Holocene, and thus limiting the use of high resolution marine carbonate records to reconstruct the climatic history of late Holocene and assess the past climatic dynamics.

In order to overcome the short time-duration limit of the bio-carbonate records, several recent studies have tried to concatenate some short bio-carbonate archives together in order to produce longer composite climate records (Cobb et al., 2003; Yu et al., 2005; Patterson et al., 2010; Wanamaker et al., 2011; Giry et al., 2013). For example, Cobb et al. (2003) reconstructed the El Niño-Southern Oscillation (ENSO) variability covering the past millennium using several coral δ18O time windows from mid-Pacific (Cobb et al., 2003); Yu et al. (2005) discussed the mid-to-late Holocene monsoonal climate in South China Sea based on the Sr/Ca chemical ratio and δ18O of several coral records. Recently, the North Atlantic seawater temperature seasonality variations during the past two millennia, concatenated from about 26 time windows, were investigated using some bivalve shell archives (Patterson et al., 2010; Wanamaker et al., 2011). These studies highlighted the potential of compositing bio-carbonate records in order to reconstruct high-resolution climate history of the world ocean and for providing the most important historical and geological context for judging the current climatic changes. We followed similar approach in producing our composite SST record for northern SCS covering the past 2500 years.

South China Sea, SCS, is the largest marginal sea of the western tropical Pacific (Fig. 1). The seasonal climate variation in the SCS is largely controlled by the East Asian Monsoon; but on inter-annual timescales, it is probably dominated by tropical Pacific ENSO conditions (Yan et al., 2010, 2011). Climate records from SCS are thus important for investigating the interactions between tropical climate and the Northern Hemisphere high latitudes. However, climate characteristics of the SCS during the late Holocene are still somewhat unclear because there are insufficient numbers and types of paleoclimate proxies available.

The coral Sr/Ca-based SST reconstructions in SCS have been systematically developed in recent decades and a series of paleo-SST records is reported to reflect high-time-resolution Holocene climate history (Wei et al., 2004a,b; Yu et al., 2004, 2005; Wei et al., 2007; Deng et al., 2009). In addition to the coral records, Tridacna gigas, the biggest marine bivalves in the SCS region, was also used to reconstruct the high resolution climate history in the South China Sea. T. gigas shell is the largest bivalve species in global ocean; it can grow to over 1 m in length and live up to 100 years (Rosewater, 1965). T. gigas has hard and dense aragonite shells with daily growth lines and its growth rate is usually higher than 1 mm per year. The microdrill sampling method can provide monthly resolution δ18O and Sr/Ca profiles easily (Watanabe and Oba, 1999; Watanabe et al., 2004; Elliot et al., 2009; Yan et al., 2013, 2014a, b,c). The calibrations between modern T. gigas Sr/Ca and instrumental SST confirmed that the T. gigas Sr/Ca can be used as a high resolution (resolution time changes, at least, on a month-to-month basis) SST proxy comparable to the coral Sr/Ca measure (Yan et al., 2013, 2014a) and indeed several T. gigas Sr/Ca-based Holocene proxy-SST records were recently reported (Yan et al., 2014b). These high resolution bicarbonate SST records, although each covering only specific time intervals for certain warm and cold periods, offer a new opportunity in gaining a broader overall knowledge and detailed insight by coming up with a high-resolution composite SST series in the South China Sea during the late Holocene.

In this study, we will combine seven high-resolution, seasonally-resolved, coral and T. gigas proxy-SST records together with the instrumental SST record from 1990 to 2000 interval to provide a 2500-year long documentation and view of the climatic variations in the northern SCS during the late Holocene. The changes of temperature seasonality and the climatic dynamics in the northern SCS during the warm and cold periods of the late Holocene will also be highlighted.

2. Material and methods

2.1. Regional setting

The SCS is located in the far western tropical Pacific, it is a semi-enclosed marginal sea with an area of ~3.6 million km2 (Fig. 1). SCS consists of hundreds of islands, coral reefs, atolls, and shoals. The largest island is Hainan Island. Most of the others are much smaller and divided into four archipelagos: Nansha Islands (Sprattly Islands), Xisha Islands (Paracel Islands), Zhongsha Islands (Macclesfield Islands), and Dongsha Islands (Pratas Islands).

The coral and T. gigas records used in this study are from the Leizhou Peninsula (20°15′N, 109°56′E), Yongxing Island (16°50′N, 112°20′E), Shidao Island (16°50′, 112°20′) and Dongdao Island (16°40′N, 112°44′E). The Leizhou Peninsula is located in the north of Hainan Island and
the coral reef in Leizhou Peninsula is the only developed and well-preserved coral fringing reef on the Mainland China (Yu et al., 2005) (Fig. 1). The Yongxing Island, Shidao Island and Dongdao Island are located in the Xisha Islands, and they are elliptical tropic reef islands with a land area of 2.13 km², 0.8 km² and 1.55 km², respectively.

The seasonal climate of SCS is dominated by East Asia Monsoon (EAM). EAM is characterized by southwesterly winds (warm and wet) in boreal summer and northeasterly winds (cool and dry) in boreal winter. The monthly SST of the Leizhou Peninsula and Xisha Islands are shown in Fig. 2 and the average annual-mean SST (AD 1982–2011) are 25.41 and 27.59 °C, respectively. The monthly time series of SST and SST anomalies in Leizhou Peninsula and Xisha Islands are shown in Fig. 3. As seen in Figs. 2 and 3, the summer SSTs in Leizhou Peninsula and Xisha Islands are similar, but the winter SSTs in Leizhou Peninsula are substantially colder than those in Xisha Islands, leading to a larger seasonality of SST in Leizhou Peninsula than in Xisha Islands. The SST data are obtained from the NOAA-NCEP-EMC-CMB GLOBAL Reyn_SmithOlav2 database (a global weekly SST data starting from 1982 with a spatial resolution of 1° × 1°); the grid cells of the NOAA SST data used were selected to include Leizhou Peninsula and Xisha Islands, respectively.

2.2. Data sources

The Sr/Ca ratios of coral skeletons have long been known to robustly yield a high-resolution SST proxy and have been extensively utilized in high-resolution paleo-temperature reconstructions in the tropical oceans (Beck et al., 1992; McCulloch et al., 1994, 1996; Alibert and McCulloch, 1997). The coral Sr/Ca-based SST reconstructions in the SCS have also been developed and reported in recent decades. For example, three high-resolution late Holocene paleo-SST records, around ~535 BC, ~495 AD and ~1464 AD, were reported in northern SCS from Leizhou Peninsula, Hainan Island and Xisha Islands, respectively (Wei et al., 2004a,b). Yu et al. (2005) reported five mid-late Holocene monthly resolution Porites corals Sr/Ca based SST records from Leizhou Peninsula and Xisha Islands are shown in Fig. 3. As seen in Figs. 2 and 3, the summer SSTs in Leizhou Peninsula and Xisha Islands are similar, but the winter SSTs in Leizhou Peninsula are substantially colder than those in Xisha Islands, leading to a larger seasonality of SST in Leizhou Peninsula than in Xisha Islands. The SST data are obtained from the NOAA-NCEP-EMC-CMB GLOBAL Reyn_SmithOlav2 database (a global weekly SST data starting from 1982 with a spatial resolution of 1° × 1°); the grid cells of the NOAA SST data used were selected to include Leizhou Peninsula and Xisha Islands, respectively.

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assembled here to produce a proxy-SST record over the last 2500 years. Coral and T. gigas records meeting the following conditions were included in this assembly work. First, the coral and T. gigas records are from the northern SCS. Second, the time windows of coral and T. gigas records must cover the late Holocene of the last 3000 years or so. Third, the time resolutions of the coral and T. gigas records are higher than one month. Based on these three stringent conditions, one coral record from Xisha Islands (Wei et al., 2004a), four coral records from the Leizhou Peninsula (Wei et al., 2004a,b; Yu et al., 2005), and two T. gigas Sr/Ca based SST time series from Xisha Islands (Yan et al., 2014b) were selected (see all the individual records in Fig. 4). The details and statistics of the coral and T. gigas proxy-SST for the seven time windows of the late Holocene and

Fig. 3. SST and SST anomaly series from 1982 to 2012 in Xisha Islands (red curve) and Leizhou Peninsula (purple curve). A significant correlation between SST anomalies in Xisha Islands and Leizhou Peninsula is observed (r = 0.54, p < 0.001). The source of the SST data is the NOAA NCDC ERST ver.2 data, a global monthly SST data from January 1854 with a spatial resolution of 2° × 2°. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 4. All seven coral and T. gigas Sr/Ca-based SST time series used in this study. One coral record from Xisha Islands (Wei et al., 2004a), four coral records from the Leizhou Peninsula (Wei et al., 2004a,b; Yu et al., 2005), and two T. gigas records from Xisha Islands (Yan et al., 2014b) were selected for our study.
2.3. The method of compositing

so there can be no doubt that our coral and bivalve samples actually studied here. We believe that this assumption is reasonable since the representative of the major climatic warm, cold and neutral periods relatively short in the full extent of their actual time coverages, can be compositing explicitly assumed that each of the time window, though presented. Please see Section 2.3 for the methodology for the assembly of our composite SST record combining the seven coral and T. gigas records with the instrumental SST records.

Table 1

<table>
<thead>
<tr>
<th>Locations</th>
<th>Materials</th>
<th>References</th>
<th>Dating (BC/AD)</th>
<th>Length (years)</th>
<th>SST anomalies</th>
<th>SST relative change rates</th>
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<td></td>
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<td>Winter SST (°C)</td>
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<td>Instrumental data</td>
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<td>0 ± 0.56</td>
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<td>Coral</td>
<td>T. gigas</td>
<td>AD 1990–2000</td>
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<td>1.39 ± 0.64</td>
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<td></td>
<td></td>
<td>Leizhou Peninsula</td>
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<td>−2.9 ± 2.46</td>
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<tr>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>T. gigas</td>
<td>AD 50 ± 40</td>
<td>15</td>
<td>1.55 ± 0.64</td>
<td>1.88 ± 0.73</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Leizhou Peninsula</td>
<td>BC 535 ± 24</td>
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<td>0.1 ± 1.53</td>
<td>0.4 ± 2.48</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Coral</td>
<td>BC 541 ± 24</td>
<td>11</td>
<td>−0.4 ± 1.54</td>
<td>−0.8 ± 2.49</td>
</tr>
</tbody>
</table>

the instrumental SST data are summarized in Table 1. Our method of compositing explicitly assumed that each of the time window, though relatively short in the full extent of their actual time coverages, can be representative of the major climatic warm, cold and neutral periods studied here. We believe that this assumption is reasonable since the dating accuracy of the coral and T. gigas samples is relatively accurate so there can be no doubt that our coral and bivalve samples actually sampled and recorded the SST conditions during the historical time windows when they were alive.

3. Results and discussion

3.1. A composite proxy-SST record in the northern SCS during the late Holocene

Both SST anomalies and relative change rates of the composite SST record, including winter, summer and annual-mean SSTs, in northern SCS during the late Holocene are plotted in Fig. 5. Both plots cover a total of 8 time windows (see summary in Table 1 and Fig. 5), including 5 coral-based time windows around BC 541, BC 535, AD 487, AD 495 and AD 1464, two T. gigas-based time windows around AD 50 and AD 990, and the instrumental SST time window covering AD 1990–2000.

The annual-mean SST anomalies for the 8 time windows are ranging from −2.2 °C (−8.6%) to 1.55 °C (5.6%) during the last 3000 years (Fig. 5). The SSTs of warm period–time windows around AD 990 ± 40, AD 50 ± 40 and BC 535 ± 24 are 0.89 °C (3.2%), 1.55 °C (5.6%) and 0.1 °C (0.4%), higher than that during modern instrumental period of AD 1990–2000 (Fig. 5). The SSTs of cold period–time windows around AD 1464 ± 51, AD 495 ± 22, AD 487 ± 22 and BC 541 ± 24 are 1.08 °C (−3.9%), 2 °C (−7.8%) and 2.2 °C (−8.6%) and 0.4 °C (−1.6%), lower than that of the modern instrumental SST decade (Fig. 5). It is worthwhile to note that the warmer SSTs in northern SCS around AD 990 ± 40 (3.2%) and AD 50 ± 40 (5.6%) occurred within the notable warm episodes of Medieval Warm Period (MWP, ≈ AD 800–1300) and Roman Warm Period (RWP, ≈ BC 400–AD 200), respectively. Conversely, the cooler SSTs around AD 1464 ± 51, AD 495 ± 22 and AD 487 ± 22 are consistent with the European cold periods of Little Ice Age (LIA, ≈ AD 1400–1850) and Dark Age Cold Period (DACP, ≈ AD 400–800).

3.2. Intercomparison with other SST proxies from tropical Western Pacific

Although the high resolution temperature reconstructions in northern SCS are scarce, the nearby low resolution marine sediment SST anomaly is 0.89 °C (28.54–27.65 = 0.89), and the relative change rate is thus calculated to be 3.2% (0.89/27.65 = 0.032). All relative change rates are also given in Table 1.

1 Please see pp. 235–239 of Soon et al. (2003) for a detailed discussion on the appropriate use of the terminology “Medieval Warm Period”. We also propose here that the timing of 1300 AD for the transition between MWP and LIA may be not entirely arbitrary nor accidental but instead has a physical root and link to the timing of 1246 AD being the last time in which the perihelion of the Sun–earth orbit coincided with Northern Hemisphere winter solstice (see e.g., Kukla and Gavin, 2004).
to our composite 8 time windows SST record (Fig. 6). First to note is the variation pattern with our composite SST record, provide some support TEX86 (Wu et al., 2012) also showed similar time variation pattern Shintani et al., 2011). The SST reconstruction of Indonesia derived different proxies and methodologies in Fig. 6 serve as a very good inde-
agreement of our Sr/Ca-based SST proxies with the SST deduced from 
largely supported the reliability of our composite SST record in northern marine sediment SST records that are more continuous in time coverage.

3.3. Distribution of RWP and MWP in the Asia-Paci
c region with a compar-
other regions

The composite proxy-SST record gives us an important overview and scientific context for the climate changes in northern SCS during the late Holocene (Fig. 5). As seen in Fig. 5, the reconstructed SST record revealed six climatically recognizable periods: two warm periods around AD 990 and AD 50 corresponding to the MWP and RWP, two cold periods around AD 1464 ± 51, AD 495 ± 22 and AD 487 ± 22 corresponding to the LIA and DACP, and two “normal” periods around BC 541 ± 24, BC 530 ± 24 and AD 1990–2000.

The RWP has been proposed as a period of unusually warm weather in Europe and the North Atlantic (Lamb, 1977). The time span for RWP is generally considered to cover broadly between 2500 and 1600 BP, although the exact time period varies in different regions and stated to be so by different authors: 2700–1600 BP in southwest Greenland (Seidenkranz et al., 2007), 2400–1600 BP in the North Sea (Hass, 1996) and 2600–1600 BP in southern Spain (Martín-Puertas et al., 2009). It is still unclear if the warm climate during the Roman times occurred globally but it is clear from the literatures, even within dating imprecision, the warm period probably did not occur or initiated synchronously all across the globe. From the perspective of multi-century scale variation of glacier mass fluctuations, Joerin et al. (2006), for example, through the accurate dating of wood and peat fragments, suggested a warm and major glacier recession in the Swiss Alps centered around the 300-year long period from 2150 to 1850 BP. Although many paleoclimate reconstructions from the Eurasia-Atlantic regions revealed an obvious warm climate around AD 0, there were also some temperature records from the Northern and Southern Hemispheres (Cook et al., 2000; Hantemirov and Shiyatov, 2002) as well as Antarctica (Masson et al., 2000), that showed no significant warm condition during the RWP 2000 years ago. Similarly, there were some efforts to synthesize various records from different regions to produce a wider area, if not hemispheric, averages, but the results were also controversial. For example, one early multi-proxy compilation of Northern Hemisphere did not find the obvious warm period during the Roman times (Moberg et al., 2005), but a more recent synthesis of extratropical Northern Hemisphere temperature showed the obvious warm climate around AD 0 (Ljungqvist, 2010) (see Fig. 7).

The annual-mean proxy-SST for the time window during the RWP (around AD 50 ± 40) is the warmest one among the eight time windows of our northern SCS composite record, with 1.55 °C warmer than that of recent decades (Fig. 4). The warm climate in northern SCS during the RWP is consistent with the nearby SST reconstruction surrounding the marine-continental region of Indonesia (Fig. 6) (Oppo et al., 2009) and in China (Fig. 7a) (Yang et al., 2002), however, the warm RWP does not seem to be uniformly warm for the whole East Asian Monsoon affected domain. The historical documentary and stalagmite reconstructions from the mid-east (Fig. 7b) and north China (Fig. 7c) suggested a relatively warm period (Ge et al., 2003; Tan et al., 2003), but the tree ring (Fig. 7d) and lake sediment records (Fig. 7e) from the northwest China indicated either neutral or even a cold period during the Roman times (Liu et al., 2009; He et al., 2013). The regional difference, the errors of age models and nonlinear proxy transfer functions or relative insensitivity of certain proxies could all provide some explanations for the discrepancy. Overall, we find that although the presence of warm climate in northwest China during the Roman times remains to be substantiated, the relatively prominent and geographically wide distribution of the Roman warm period in the Eastern margin of China and the western tropical Pacific region is well established.

In contrast to RWP, there are more comprehensive proxy records that support the MWP, a warm period during AD 800–1300, and the existence of MWP is demonstrated by climate data from not only in northern SCS and northern Europe but also in many parts of the world (Hughes and Diaz, 1994; Soon et al., 2003; Mann et al., 2008, 2009; Esper and Frank, 2009; Ljungqvist, 2010; Graham et al., 2011). The averaged SST of the time window during the MWP (around AD 990 ± 40) was higher than that during the DACP and the LIA (Fig. 5 and Table 1), confirming the existence of a warm period during the MWP in the northern SCS. The warm medieval times was also found in the Indonesian record, as well as some records from China (Figs. 6 and 7). Although there are also some difference in the timing and the temperature change amplitude in these diverse types of proxy records, but a warm climate during the MWP seems to be certain in Asia-Pacific region, covering broad geographical areas from Northwest China to the Western Pacific.

Our composite proxy-SST record also reveals two cold periods, one is between RWP and MWP corresponding to the European DACP well noted in historical documents and the other is between MWP and current warm period corresponding to the relatively better-studied LIA interval (Matthes, 1939, 1940; Grove, 1988). The cold climate during the
Dark Age was pointed out specifically by Hubert Lamb (Lamb, 1977). Later studies further confirmed a cold and wet period in Europe during the DACP. The cold climate during the DACP was also clearly recorded in various proxies from the Western Pacific to the Northwestern China (Figs. 6 and 7), such as the marine sediment record (Oppo et al., 2009), the ancient Chinese literature record (Ge et al., 2003), the cave stalagmite record (Tan et al., 2003) and the lake sediment record (He et al., 2013), confirming that the cold climate during the DACP was indeed widely distributed all over the East Asia–Western Pacific region. Despite the relatively more stringent requirements for persistency of meteorological and climatic forcings and finite time for the growth of glacier ice mass, the clear imprints of the DACP can also be found in the glacial record of Sheridan Glacier, around the Copper River Delta, coastal South–Central Alaska which has its peaked phase of advance centered at around 530 to 640 AD (Barclay et al., 2013). In addition, the recent syntheses work of Northern Hemisphere temperature variations also demonstrated an obvious cold climate during the DACP (Fig. 7) (Moberg et al., 2005; Ljungqvist, 2010). The anomalous weather regimes and climatic conditions during the LIA have been heavily studied in recent decades and the results suggested a cold climate with a substantial accumulation of land ice covering most high-elevation areas of the Earth. The relatively low temperature anomaly of 1.08 °C during the LIA in our composite proxy–SST record was clearly consistent with the other reconstructions from the East Asia–Western Pacific region (Figs. 6 and 7).

Overall, the variation pattern of our northern SCS SST record was similar to that of other temperature reconstructions from East Asia–Western Pacific regions and two syntheses of the Northern Hemisphere-wide temperature records during the late Holocene with some divergences in details especially for the RWP (Fig. 7). These results demonstrated convincingly that the climate oscillations in northern SCS were in step with other regional and perhaps even the global climate changes during the late Holocene.

3.4. Variation of the SST seasonality in the SCS during the late Holocene and its relationship with the mean climate state

Temperature seasonality, the difference between summer and winter temperatures, is an important aspect of Earth’s climate and has significant influences on local, regional and global terrestrial and marine
environments and ecosystems. However, most of the current proxy-based climate records are not sufficient to quantify the temperature seasonality due to the limits of the temporal resolution inherent in those individual paleoclimate proxies. In this study, our high-resolution SST record gives us an exciting opportunity to examine the seasonality variation in northern SCS during the late Holocene that are known to cover several warm and cold weather regimes and climatic periods. We emphasize that the current climate understanding and theory are still
simply not mature enough (Essex, 2011, 2013) to answer such a direct question, so we will have to rely on empirical knowledge systematically built from such a paleoclimatic study.

The changes in SST seasonality derived from the differences between winter and summer SST anomalies were shown in Fig. 8. Both the constant nature of and the large variation in the amplitude of seasonality for locations like Northern SCS are the major findings in this study. The SST seasonality anomalies of eight time windows during the late Holocene varied substantially from $-1.09$ to $3.1^\circ$ C and the relative change rates of SST seasonality varied from $-22.2\%$ to $34.5\%$ (Table 1 and Fig. 8).

We compare the annual-mean SST anomalies with the SST seasonality anomalies and find a strong and statistically significant negative correlation ($r^2 = 0.69, p < 0.001$, Fig. 8). The seasonality decreased when the mean SSTs were warmer, such as the time windows centered at around RWP (SST seasonality anomaly was $-0.75^\circ$ C) and MWP (SST seasonality anomaly was $-1.09^\circ$ C). The result of decreased seasonality under warmer climate is consistent with the previous composite bivalve shell records (i.e., also concatenated from several time windows) from the Gulf of Maine, North Atlantic, which revealed increased seasonality with climatic cooling (Wanamaker et al., 2011). This empirical fact concerning the inverse relation between amplitude of seasonality and mean climatic condition is also supported by some marine sediment records. For example, the nearby marine sediment core SCS90-36 (17°59.70′N, 111°29.64′E) record presents an obvious decrease of seasonality in northern SCS during the Holocene than during the last glacial period (Huang et al., 1997). The new and independent results, both in terms of area of study and methodology, from western Arabian Sea also found, from analyses of $^18$O in individual shells of planktic foraminifera samples from their Ocean Drilling Program Site 723A, that the seasonality amplitude of SST around western Arabian Sea for the relatively colder time during LIA (ca. 0.5 ka for their samples) is about four times larger than the seasonal SST amplitude during the warmer period around RWP (ca. 2.07 ka) (Naidu et al., 2014). Our result can further directly verify such an observation for northern SCS where the largest amplitude variation for the seasonality occurs during the cold period of DACP. We have also checked the relationship between the SST seasonality and the SST anomalies in winter and summer, respectively. The results suggested that the SST seasonality anomalies were highly correlated with the winter SST anomalies ($r^2 = 0.86, p < 0.001$, Fig. 8), but not with the summer SST anomalies ($r^2 = 0.19, p = 0.29$, Fig. 8), probably indicating that the changes of SST seasonality in northern SCS mainly depend on the variations of winter climate which is suggestive of the more prevalent effects on seasonality by the land–sea contrast of the monsoon-controlled climate regions like East Asia (Ding et al., 2014).

Similar statistical correlations and physical tendencies can also be found in instrumental SST data for modern period from 1982 to 2012. Both the observations from Xisha Island and Leizhou Peninsula revealed stronger correlations between SST seasonality and winter SST, and weak ones between SST seasonality and summer SST (Fig. 9). The coefficients of the correlations between SST seasonality and annual-mean, summer and winter SST in Xisha Islands were $-0.5$ ($r^2 = 0.25, p < 0.01$), $0.1$ ($r^2 = 0.01, p = 0.58$) and $-0.82$ ($r^2 = 0.68, p < 0.001$), respectively (Fig. 9 top panels). The coefficients of the correlations between SST seasonality and annual-mean, summer and winter SST in Leizhou Peninsula were $-0.58$ ($r^2 = 0.34, p < 0.001$), $0.45$ ($r^2 = 0.21, p = 0.01$) and $-0.92$ ($r^2 = 0.85, p < 0.001$), respectively (Fig. 9 bottom panels). Such an observed reality from instrumental data clearly provides a good physical grounding for our interpretation of the paleo-SST results.

### 3.5. Different amplitudes of summer and winter SST variations during the late Holocene

Meanwhile, the variation of the winter SST anomaly amplitude in our composite record was much larger than that of summer SST anomaly during the late Holocene (Fig. 5). The winter SST anomalies for the eight-time windows changed from $-3.8^\circ$ C to $1.88^\circ$ C and the summer values varied from $-1.45^\circ$ C to $1.13^\circ$ C. The regression between annual-mean SST anomalies and winter SST anomalies of eight time windows yielded the equation (Fig. 10): winter-SST ($^\circ$ C) = $1.45 \times$ annual-

![Fig. 8](image-url) The SST seasonality in northern SCS during the late Holocene (a). The linear regressions of SST seasonality versus annual-mean SST anomaly (b), SST seasonality versus summer SST anomaly (c) and SST seasonality versus winter SST anomaly (d) are also shown.
SST has also been detected in two previously published coral. An increase of only 0.52 °C (Fig. 10). SST of 1 °C corresponds to a winter SST increase of 1.45 °C and a summer SST (°C) = 0.52 × annual-mean-SST (°C)

This large difference in the variability of the winter SST and summer SST has also been detected in two previously published coral δ18O time series from northern SCS (Peng et al., 2003; Sun et al., 2005). For example, Sun et al. (2005) found that the interannual variability of winter coral δ18O in Hainan Island of northern SCS was dominated by the interannual variation of the winter SST, but the interannual variability of summer coral δ18O was primary controlled by the summer rainfall with little impact from the summer SST variation. This independent result and interpretation confirm the small interannual variability of summer SST relative to winter SST variability. Peng et al. (2003) reported a significant correlation between the interannual variation of coral δ18O from Hainan Island and the winter monsoon index/winter SST, also implying a larger variability of winter SST.

The large difference in the variability of the winter SST and summer SST in northern SCS was also observed in the instrumental SST record (Fig. 11). The direct instrumental SST data for the most recent 50 years in northern SCS suggest that an annual-mean-SST increase of 1 °C corresponds to a winter SST increase of 1.64 °C and a summer SST increase of 0.62 °C (Fig. 11), similar to the calculated results from the paleo–SST records during the late Holocene even in a quantitative sense. This fact adds confidence to our paleoclimate study of seasonality contrasting the sharp differences between climate warm and cold periods of the past 2500 years.

Thus, we conclude that the larger amplitude in SST variation during winters than during summers in northern SCS during the late Holocene and instrumental era could explain the negative correlation between the SST seasonality and the mean climate state in Figs. 8 and 9. When northern SCS climate turned warm, the summer SST increased less and the winter SST increased disproportionately more, resulting in a reduction of the amplitude of seasonality. When northern SCS climate was undergoing cooling tendencies, the summer SST decreased less and winter SST decreased more, resulting in a larger seasonality. The stronger correlation between the winter SST and seasonality than that between summer SST and seasonality could be similarly explained by the relative dominance of the winter season for northern SCS monsoon-climate region.

3.6. Mechanism for the different variation amplitudes of the summer and winter SST during the late Holocene

Seasonal and sub-seasonal changes are important components of Earth’s multi-scale and multi-component climate system. The mechanism for the different variation amplitudes in winter and summer SST is, therefore, essential both for clarifying and understanding the climatic dynamics in the northern SCS. The SST maps in the tropical Western Pacific (including SCS) for the winter (i.e., January, 2000) and summer (i.e., July, 2000), respectively, are shown in Fig. 12. The SCS was covered by the West Pacific Warm–Fresh Pool (WPWFP; consider isothermal temperature zones with SST > 28.5 °C (Cravatte et al., 2009)) during
summer when the WPWFP migrated north (right panel in Fig. 12). The summer SST in northern SCS was, therefore, consistent with the SST of WPWFP. As a result, the changes of summer SST in northern SCS were closely controlled by and connected to the climate conditions of the WPWFP. However, the situation was quite different during winter when the WPWFP migrated south (left panel in Fig. 12). The SCS now seemed to be free from the predominance of the WPWFP and an obvious “cold tongue” lied on the northern SCS (Fig. 12). The “cold tongue” was formed by the southward migration of the cold water along the northwest coast of the northern SCS driven by the strong East Asian Winter Monsoonal circulation (EAWM). The “cold tongue” makes the SST in northern SCS about 3–5 °C lower than the SST in the eastern part of the Philippines under the same latitude.

The summer and winter SSTs in northern SCS are controlled by oceanographic conditions of the WPWFP and the strength of the EAWM atmospheric circulation, respectively. In modern meteorological observation, the impacts of EAWM on the northern SCS are manifested through the pulse type of cold waves. The winter temperature around the region could drop significantly by more than five degrees rather abruptly when a cold wave sets in from the Siberian High, and the sea surface temperature also could recover quickly after the cold waves dissipated (Ding et al., 2014). In contrast, the WPWFP oceanographic

![Fig. 11. The variation trends of annual-mean (a), summer (b) and winter (c) SST in Xisha Islands from 1958 to 2005. The linear regressions of summer SST versus annual-mean SST (d) and winter SST versus annual-mean SST (e) from 1958 to 2005 are also shown.](image)

![Fig. 12. The spatial distributions of SST in SCS in January 2000 (left) and July 2000 (right). The source of the SST data is the NOAA NCDC ERSST ver.2 data, a global monthly SST data from January 1854 with a spatial resolution of 2° × 2°.](image)
conditioning during summers is usually kept more stable with less variability. That is why the instrumental SST has a relatively larger variation amplitude during winters than during summers (see Fig. 11).

From a broader and even hemispheric view, the pulse-type cold wave is likely one major cause for the larger variability of winter temperatures (Ding et al., 2014). For example, in regions like East Asia and the east coast of North America, which are strongly influenced by the winter pulse-type cold waves, hence winter temperature variability was much larger than summer one (Fig. 13). Ding et al. (2014) recently provided a comprehensive description and summary of the multi-scale and multi-modal natures of the EAWM. These authors explained that EAWM is modulated on timescale of several decades while being represented by at least three major meteorological modes that are concurrently operating and competing. On the prominent multidecadal timescale, Ding et al. (2014)’s illuminating discussion of physical processes covered not only ENSO but also the co-workings of AO, PDO and AMO phenomena that are not necessarily local to East Asia or South China Sea.

The modern instrumental data could provide us some additional clues about the seasonal variations of our composite SST record during the late Holocene. The similar patterns of winter and summer SST variations in northern SCS probably hinted at a close inverse relation between the EAWM and WPWFP conditions during the late Holocene, with a weak EAWM corresponding to a warm WPWFP. This coupling between EAWM and tropical Pacific has also been reported by many previous studies using instrumental data and observations (Lau and Li, 1984; Masumoto and Yamagata, 1991; Li and Mu, 2000; Wang et al., 2000).

The larger variability of atmosphere-controlled EAWM than ocean-controlled WPWFP conditions derived from the instrumental data explains the relatively larger variation amplitude of winter SST than that of summer SST in northern SCS during the late Holocene. We compare our composite record with the SST reconstruction from the Indonesian region of WPWFP. The variability of the winter proxy-SST in our composite record was much larger than that of the proxy-SST record from the Indonesia region of WPWFP, but the amplitude of the summer SST variations in both our northern SCS and Indonesian WPWFP records were comparable. This fact suggests the existence of different mechanisms for the summer and winter SST variations in northern SCS during the late Holocene.

The large differences in the amplitude of summer and winter SST variations found in our study imply a potentially serious problem for other synthses of multi-proxy paleoclimate records. In many of the current synthesis works (IPCC, 2001, 2007; Mann et al., 2008, 2009), most of the proxy records considered and adopted have a time-resolution too low to take seasonal effect into consideration and these proxy records tend to reflect the climate of a particular season. For example, most tree ring growth and increment in Northern Hemisphere occur during boreal springs and summers and the tree ring width index is basically recording summer-climate information (Briffa et al., 1990; Büntgen et al., 2005). The climate information derived from the phenological records and historical winter snow-day records in East Asia region mainly reflect the early-spring and winter temperatures, respectively (Ge et al., 2003; Aono and Kazui, 2008). Another example is recently pointed out by Ekaykin et al. (2014) where these authors convincingly demonstrated that their stacked δD isotopic proxy record for the past three centuries from Vostok station in East Antarctica best represented summer temperature variations and that summer-sensitive proxy behavior is distinctly different from variations in annual-mean temperature (Ekaykin et al., 2014). The synthesis of these climate records may result in substantial uncertainty if the seasonal cycle amplitude is large (i.e., especially over mid-to-high latitude regions; including even highly sensitive tropical regions like northern SCS described above) and that seasonal bias is a significant factor for the proxies.

4. Conclusions

In this study, a composite multi-proxy record of the SST variation in the northern SCS during the late Holocene is constructed by the combination of seven high-resolution coral and T. gigas Sr/Ca-based SST time windows and the instrumental SST from 1990 to 2000 interval. The
variation pattern and characteristic of the composite SST record is consistent with other reconstructions from Eastern to Northwestern China and tropical Western Pacific; they all indicate a prominent high-amplitude and geographically wide distribution of the warm climate during the RWP and MWP in the East Asian–Western Pacific region. Meanwhile, we also observe the substantial difference in seasonal SST variations in northern SCS during the late Holocene, with much larger SST amplitude during winters than during summers, and the climatic seasonality of northern SCS over the last 2500 years appears to be significantly impacted by East Asian Winter Monsoon. The importance of seasonality for past climate states and climatic variations highlights the potential uncertainty in other current synthesis works that adopted climate proxies that cannot resolve seasonal SST.

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