Geo-Marine Letters (2021) 41: 39
https://doi.org/10.1007/s00367-021-00712-9

ORIGINAL

Low-latitude control on sea surface temperatures in the middle Okinawa Trough over the last 3.6 kyr

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Received: 13 June 2020 / Accepted: 15 July 2021 / Published online: 4 August 2021

Abstract

Core OKI-152 is one of the best-dated late Holocene cores from the middle Okinawa Trough. The chronological framework and high resolution of this core can help better interpret the paleoclimatology and paleoceanography at centennial-millennial timescales. This core has been analyzed using the alkenone unsaturation index ($U^{K'}_{37}$) to determine the sea surface temperatures over the last 3.6 kyr. Temperatures obtained from the core-top sample and the 3.6-kyr-averaged temperatures correspond well to the mean annual sea surface temperature (SST) at this location. The SSTs were lower during three periods in 3.6–2.7, 2.0–1.0, and 0.6–0 cal kyr BP, which corresponded to the Neoglacial Period, Dark Age Cold Period, and Little Ice Age, respectively. The variations in the $U^{K'}_{37}$-derived SSTs in core OKI-152 were not correlated with the high-latitude North Atlantic climate but were synchronous with those of the western Pacific and the El Niño Southern Oscillation (ENSO) variability at low latitudes. When compared with SST signals from the southern Okinawa Trough, the differences in the SST (ΔSST) between the southern and middle Okinawa Trough over the past 3.6 kyr were mainly controlled by the input of freshwater from Taiwan. This result indicates that the East Asian monsoon could influence the SSTs in the Okinawa Trough by modulating precipitation. Modern observations, paleoceanographic proxies, and modeling studies are needed to further understand the interactions among the Okinawa Trough, Pacific Ocean, and East Asian monsoon system.

Introduction

Located between the Northwest Pacific Ocean and East Asian continent, the Okinawa Trough is highly impacted by land-sea interactions, sea-level changes, the East Asian monsoon (EAM), the El Niño Southern Oscillation (ENSO), and other processes (Jian et al. 2000; Kubota et al. 2010, 2015; Ruan et al. 2015). The ocean circulation near the Okinawa Trough is impacted by the Kuroshio Current, which is one of the most important western boundary currents sourced from the western Pacific warm pool (Hu et al. 2015). Because this area experiences the strongest air-sea heat exchange in the Northwest Pacific Ocean (Jian et al. 2000), the Okinawa Trough has become an important research area for investigating climate and oceanography changes during the late Quaternary.

In recent decades, many studies of sea surface temperature (SST) have been undertaken in the Okinawa Trough. Jian et al. (2000) indicated that the Holocene cold events recorded in the Okinawa Trough responded to millennial-scale climate changes in the North Atlantic. Sun et al. (2005) suggested that the tropical Pacific has played a key role in

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millennial-scale SST variations in the Okinawa Trough during the Holocene. High-resolution records during the late Holocene indicated a coupled evolution among SST, the EAM, and ENSO in the Okinawa Trough (Wu et al. 2012). Ruan et al. (2015) reported that the SST in the southern Okinawa Trough has decreased since the mid-Holocene, following the declining trend in Northern Hemisphere summer solar insolation. A recent study showed that the Holocene SST variations in the southern Okinawa Trough have been predominantly controlled by SST variations in the western tropical Pacific Ocean (Xu et al. 2018). Thus, there are scientific debates regarding the climatic forcing mechanisms, i.e., high- or low-latitude forcing, in this region.

The alkenone unsaturation index ($U^{K'}_{37}$) is a reliable and efficient parameter that cannot be altered by terrigenous material inputs (Villanueva et al. 1997), water salinity (Sonzogni et al. 1997), or early diagenesis (Conte et al. 1992). The $U^{K'}_{37}$ index has been widely used for quantitative SST reconstructions in global ocean regions (e.g., Prahl and Wakeham 1987; Müller et al. 1998; Kim et al. 2010), including the Okinawa Trough (e.g., Zhao et al. 2005, 2015; Xu et al. 2018). These studies have mainly focused on the glacial-interglacial scale (Zhao et al. 2005; Zhou et al. 2007), the last deglaciation (Ruan et al. 2015; Zhao et al. 2015), and the Holocene period (Meng et al. 2003; Xu et al. 2018). However, high-resolution studies on the variations in $U^{K'}_{37}$-derived SST in the Okinawa Trough during the late Holocene remain very limited due to the relatively low sedimentation rate. In this new study, a 415-cm-long core spanning the past 3.6 kyr from the middle Okinawa Trough is selected to quantify the high-resolution SST variations. To the best of our knowledge, this core is one of the best-dated late Holocene cores from the middle Okinawa Trough and has one of the highest temporal resolutions. Furthermore, the responses of SST in the study region to high- and low-latitude climate changes and the EAM are discussed.

Oceanographic setting

The Kuroshio Current, which originates from the North Equatorial Current, enters the East China Sea along the east side of Taiwan Island and flows northward over the western slope of the Okinawa Trough. The Kuroshio Current not only controls the physical oceanography and sedimentary environment of the region but also imports information from the open ocean (Li and Chang 2009). This current is one of the most important factors controlling the marine environment and hydrological characteristics in the Okinawa Trough. When the sea level reached its highstand at 7 cal kyr BP, the SST in the Okinawa Trough was mainly controlled by the intensity of the Kuroshio Current and was less affected by Chinese coastal cold waters which was related to the intensification of the East Asian winter monsoon (Jian et al. 2000; Xu et al. 2018).

Taiwan Island is located southwest of the Okinawa Trough. The climate of Taiwan Island is mainly influenced by the EAM and has relatively cool winters and warm summers (15–18 °C in January and February, 24–28 °C in July and August; Li et al. 2012). Taiwan is primarily influenced by the summer monsoon superimposed by episodic tropical cyclones (typhoons), which bring abundant rainfall from the western tropical Pacific (greater than 90×10^9 m^3/yr; Li et al. 2012). The southern Okinawa Trough is heavily influenced by abundant freshwater from small mountainous rivers draining Taiwan Island; for example, the runoff of the Lanyang River is 2.8×10^9 m^3/yr (Li et al. 2012), while such water has a limited effect on the middle Okinawa Trough because of the limited amount of water discharge to the ocean and its far distance from land.

Materials and methods

Core OKI-152 (127.35° E, 28.41° N, water depth 1145 m, Fig. 1) was collected from the middle Okinawa Trough using a gravity corer by the R/V Haidahao in 2015. The 415 cm long core was subsampled at 2 cm intervals. The core mainly consisted of gray silty clay, with no apparent bioturbation, tephra, or turbidite layers.

Nine AMS ^{14}C dating samples of the planktonic foraminifer *G. ruber* were analyzed at Beta Analytic Inc., USA. The raw AMS ^{14}C dates were converted to calendar ages (yr BP) by applying the Marine13 curve using CALIB 7.0.2 software (Reimer et al. 2013). The ΔR value of 40 ± 31 yr (the local difference in reservoir age from 400 yr in the Okinawa Trough) was adopted according to a previous study (Xu et al. 2018). A total of 89 samples were collected for alkenone analysis in a laboratory at Zhejiang University, following the methods described in He et al. (2014). The $U^{K'}_{37}$ values and corresponding temperatures were calculated according to Prahl et al. (1988).

Results

Age model

As shown in Table 1, the AMS ^{14}C and calibrated ages showed no reversed dates, and the errors in the calibrated ages were mostly less than ± 100 yr. However, the calendar age for the depth of 120 cm was only slightly older than the upper overlying age at the depth of 80 cm (368 and 353 cal yr BP, respectively). For the depth of 120 cm, the $\delta^{18}O$ and $\delta^{13}C$ values (0.2 and 0.4, respectively) are obviously different from those of the other layers (Table 1) and

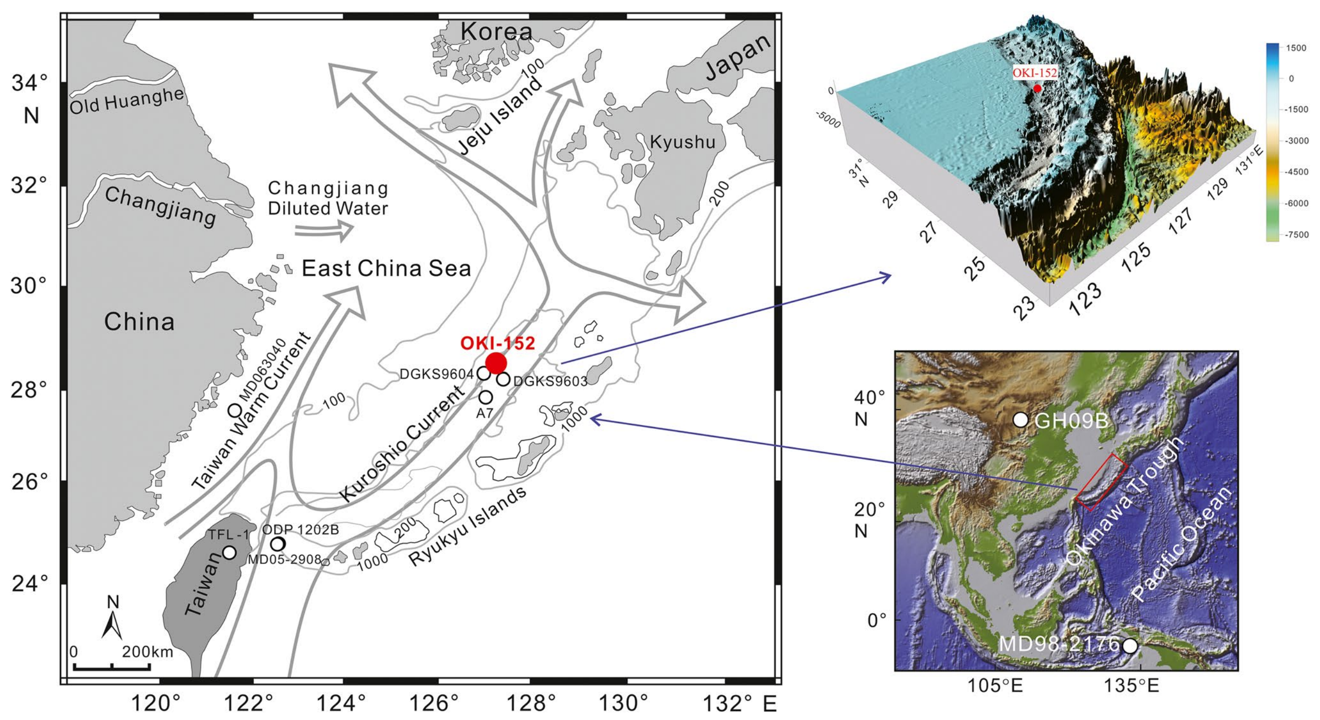

Fig. 1 A schematic map showing the study area and topography of the Okinawa Trough. Locations of core OKI-152 (red dot) and other paleoenvironmental settings, including cores DGKS9603 (Liu et al. 1999), DGKS9604 (Dou et al. 2012), and A7 (Sun et al. 2005) in the middle Okinawa Trough; cores MD05-2908 (Chen et al. 2019) and ODP 1202B (Ruan et al. 2015) in the southern Okinawa Trough; core MD98-2176 in the western Pacific (Stott et al. 2004); core TFL-1 from Tsuifong Lake in northeastern Taiwan (Wang et al. 2015); core MD063040 in the inner shelf of the East China Sea (Kajita et al. 2018); and core GH09B from Gonghai Lake, North China (Chen et al. 2015). The ocean current patterns were modified from Xu et al. (2018)

Table 1 AMS ^{14}C and calendar ages for core OKI-152

Depth (cm)	Beta lab code	δ^{13}C (‰)	δ^{18}O (‰)	Conventional age ± error (yr BP)	2 σ Range of calendar age (cal yr BP)	Calendar age (cal yr BP)
80	Beta-434817	1.6	− 1.7	740 ± 30	265–440	353
120	Beta-434818	0.4	0.2	760 ± 30	280–455	368
200	Beta-434819	1.0	− 1.2	1610 ± 30	1040–1230	1135
240	Beta-434820	1.1	− 1.3	2350 ± 30	1825–2025	1925
280	Beta-434821	1.6	− 0.8	2800 ± 30	2340–2665	2503
320	Beta-434822	1.6	− 1.2	3180 ± 30	2815–3040	2928
360	Beta-434823	1.4	− 0.9	3300 ± 30	2955–3200	3078
400	Beta-434824	1.5	− 1.1	3680 ± 30	3440–3635	3538
412	Beta-434825	1.1	− 1.0	3750 ± 30	3535–3725	3630

those of other cores in the Okinawa Trough. The planktonic foraminiferal δ^{18}O value is mainly controlled by the global ice volume, regional SST, and salinity (Li et al. 2007). The δ^{13}C value is affected by the surface water in the open area of the Northwest Pacific and the terrigenous dilute water (Sun et al. 2007). The δ^{18}O values of *G. ruber* and *N. dutertrei* in core DGKS9603 (Li et al. 2001), *G. ruber* in core A7 (Sun et al. 2005), *N. dutertrei* in core ODP 1202B (Wei et al. 2005), and *G. sacculifer* in core DGKS9604 (Yu et al. 2009) were all negative during the Holocene. The δ^{13}C values of *G. ruber* and *N. dutertrei* in core DGKS9603 (Li et al. 2002), *N. dutertrei* in core ODP 1202B (Wei et al. 2005) and core DGKS9604 (Yu et al. 2009) are all > 1.0 since 6 cal kyr BP. Compared with the δ^{18}O values of *G. ruber* in the adjacent core DGKS9603 (Li et al. 2001), our δ^{18}O values are higher, indicating that the SST was much lower than the period of the last glacial maximum and the Heinrich events. Compared with the δ^{13}C values of *G. ruber* in core DGKS9603 (Li et al. 2002), our $\delta^{13}C$ values are lower, indicating that our study area was more influenced by the surface water of the tropical Pacific. However, this is not the case. It is widely known that the climate is warmer during the Holocene than during the period of the last glacial maximum and the Heinrich events, and there are no significant strengthened impacts of tropical Pacific water during this period (Li et al. 2001, 2002). Our records also reveal no significant SST variations during this period (see below). These results should indicate that some impurities might have been mixed with the dating samples. Thus, the 368 cal yr BP age at 120 cm was rejected in the final age model in this study. The timescale was constructed using linear interpolation and extrapolation between the eight remaining dates (Fig. 2). Since sediment from core OKI-152 was retrieved in 2015, the core-top age was considered – 65 cal yr BP, which was similar to the extrapolated age of – 168 yr and within the analytical error of the AMS ^{14}C method. The AMS ^{14}C dates suggest that core OKI-152 represents a complete high-resolution sediment record of the last 3.6 kyr. The linear sedimentation rates of core OKI-152 ranged from 51 to 267 cm/kyr, with an average of 114 cm/kyr. The average temporal resolution of the samples was approximately 41 yr.

Xiong et al. (2005) found that the Holocene linear sedimentation rates in the Okinawa Trough generally ranged from 6.3 to 38.8 cm/kyr, with an average of 20.2 cm/kyr. The sedimentation rates for the past 4–5 kyr in several cores collected near OKI-152 (Fig. 1), e.g., DGKS9603 (~ 6 cm/kyr, 1 AMS ^{14}C data, Liu et al. 1999), A7 (~ 14 cm/kyr, 2 AMS ^{14}C data, Sun et al. 2005), and DGKS9604 (~ 20 cm/kyr, 2 AMS ^{14}C data, Dou et al. 2012), were much lower than those of the results in this study. To the best of our knowledge, OKI-152 is one of the best-dated cores from the middle Okinawa Trough with the highest temporal resolution. Thus, the chronological framework and higher resolution of this core can help better interpret the paleoclimatology and paleoceanography at centennial-millennial timescales.

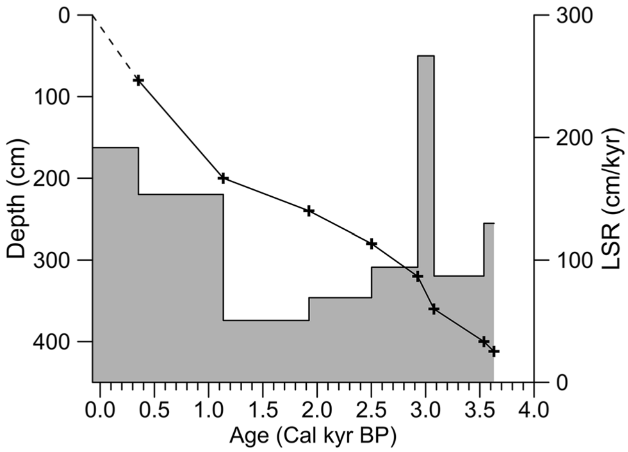

Fig. 2 Age model and sedimentation rate of core OKI-152 in the middle Okinawa Trough. LSR, linear sedimentation rates

$U^{K'}_{37}$-derived temperatures in core OKI-152

Over the past 3.6 kyr, the $U^{K'}_{37}$ index in core OKI-152 has ranged from 0.88 to 0.94, which corresponds to temperatures ranging from 24.8 to 26.6 °C (Fig. 3a). The $U^{K'}_{37}$-derived temperature obtained from the core-top sample of core OKI-152 is 25.3 °C, while the 3.6-kyr-averaged temperature is 25.6 °C. These values are comparable to the mean annual SST at this location (25.31 ± 0.27 °C, 1955–2012, https://odv.awi.de/data/ocean/world-ocean-atlas-2013/). Multiple studies have found that the alkenone temperature is a reliable

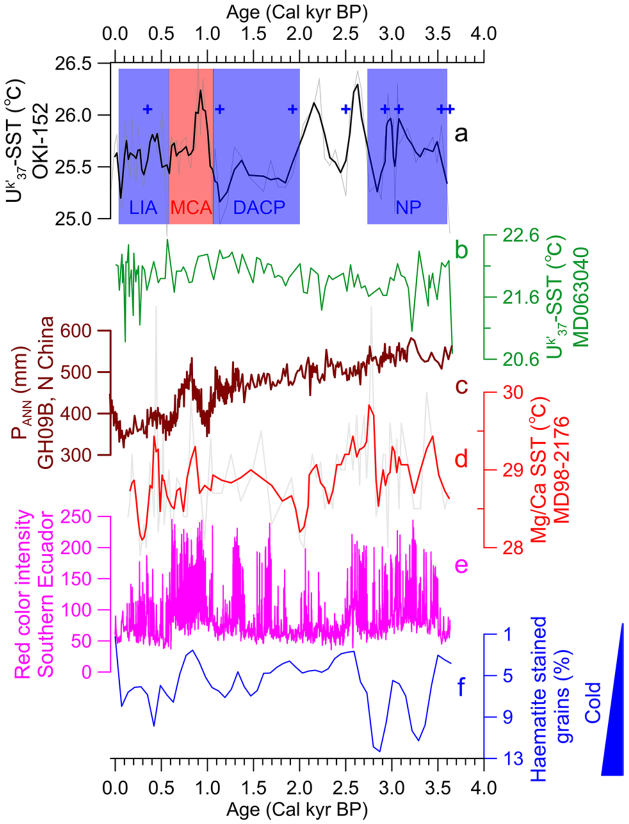

Fig. 3 Comparison of $U^{K'}_{37}$-derived SSTs from core OKI-152 in the middle Okinawa Trough (a, this study) with the $U^{K'}_{37}$-derived SSTs from core MD063040 in the inner shelf of the East China Sea (b, Kajita et al. 2018), the reconstructed annual precipitation (P_{ANN}) from core GH09B sediments in Gonghai Lake, North China (c, Chen et al. 2015), and Mg/Ca-based SSTs from core MD98-2176 in the western tropical Pacific (d, Stott et al. 2004). The red color intensity of the sediments from Laguna Pallcacocha, southern Ecuador, shows ENSO variability (e, Moy et al. 2002), and the stacked hematite-stained grains of sediments are from the North Atlantic (f, Bond et al. 2001). The black and red solid curves were smoothed with 3-point running averages. Blue crosses show the age control points. LIA, Little Ice Age; MCA, Mediaeval Climate Anomaly; DACP, Dark Age Cold Period; and NP, Neoglacial Period

and effective indicator of early summer coccolith blooming and is roughly equivalent to the annual mean temperature (D'Andrea et al. 2011; Longo et al. 2018; Łącka et al. 2019). The Okinawa Trough region is also one of the most rapidly warming regions due to anthropogenic forcing. The summer SST has already warmed by 0.65 ± 0.21 °C compared with the preindustrial background level (Seki et al. 2012). Although core OKI-152 is one of the best-dated cores from the middle Okinawa Trough with the highest temporal resolution, there are still ± 100 yr errors in the calibrated ages. Thus, the instrumental temperature records can still be roughly compared with the core-top $U^{K'}_{37}$-derived SST data. Our results indicated that the $U^{K'}_{37}$-derived temperature can be reliably used to represent the annual mean SST, which is consistent with previous studies (e.g.Nakanishi et al. 2012; Kim et al. 2015; Ruan et al. 2015; Xu et al. 2018). The SST fluctuated over time, with a relatively cold period from 3.6 to 2.7 cal kyr BP (average 25.6 ± 0.4 °C), a warm period from 2.7 to 2.0 cal kyr BP (average 25.9 ± 0.4 °C), and long-term cold conditions from 2.0 to 1.0 cal kyr BP (average 25.4 ± 0.3 °C). The SST fluctuated moderately at the centennial timescale from 1.0–0 cal kyr BP, with a relatively warm period from 1.0 to 0.6 cal kyr BP (average 25.8 ± 0.3 °C) and a cold period from 0.6 to 0 cal kyr BP (average 25.6 ± 0.3 °C) (Fig. 3). The amplitude of the SST variation in core OKI-152 was ~ 1.7 °C.

Discussion

SST evolution and low-latitude climatic forcing

The SST fluctuated sharply with a relatively cold period from 3.6 to 2.7 cal kyr BP (average 25.6 ± 0.4 °C). Between 4.0 and 2.5 cal kyr BP, an increase in cold-water planktonic foraminiferal species and a remarkable decrease in the Kuroshio water species (*Pulleniatina obliquiloculata*) occurred in the northern East China Sea (Kim and Lim 2014). Similar records of the so-called *Pulleniatina* minimum event, which suggests a weakened Kuroshio Current influence, have been widely found in the Okinawa Trough (4–2 cal kyr BP, Jian et al. 1996; Li et al. 1997). This cold period coincides with a series of glacier advances during the late Holocene (~3.5–2.5 cal kyr BP), which is defined as the Neoglacial Period (Porter and Denton 1967; Solomina et al. 2015; Denton and Karlén 2017), although this is not widely recognized in the community (Kullman 1989).

The $U^{K'}_{37}$-derived SST in core OKI-152 reflects long-term cold conditions from 2.0 to 1.0 cal kyr BP (average 25.4 ± 0.3 °C). Lamb (1982) found that a generally cold climate occurred from 1.55 to 1.05 cal kyr BP in Europe and defined this period as the Dark Age Cold Period. However, the starting and ending dates of the Dark Age Cold Period varied greatly among different areas (Helama et al. 2017, and references therein). In East Asia, the Dark Age Cold Period has also been reported in the Wanxiang record from Gansu Province (~ 1.75–1.0 cal kyr BP, Zhang et al. 2008), the western Nanling Mountains, South China (1.7–1.0 cal kyr BP, Zhong et al. 2014), Lake Qinghai, China (1.5–1.1 cal kyr BP, Liu et al. 2006), and other regions. Thus, the long-term cold period from 2.0 to 1.0 cal kyr BP may correspond to the Dark Age Cold Period.

The SST fluctuated moderately at the centennial timescale from 1.0 to 0 cal kyr BP, with a relatively warm period from 1.0 to 0.6 cal kyr BP (average 25.8 ± 0.3 °C) and a cold period from 0.6 to 0 cal kyr BP (average 25.6 ± 0.3 °C), corresponding to the widely known Medieval Warm Period (also known as the Mediaeval Climate Anomaly, MCA) and the Little Ice Age (LIA), respectively (Mann and Jones 2003; IPCC 2007; Mann et al. 2009; Liu et al. 2011; Wang et al. 2013b; Zhu et al. 2017; Neukom et al. 2019; Nakatsuka et al. 2020). The MCA and LIA are commonly associated with warm and cold temperatures during 1.15–0.75 cal kyr BP (800–1200 AD) and 0.65–0.1 cal kyr BP (1300–1850 AD), respectively, with different regional patterns (Mann et al. 2009; Cook et al. 2013; PAGES 2k Consortium 2013; Neukom et al. 2019). As shown in Fig. 3a, the coldest temperature of the last millennium occurred during the nineteenth century. This result is consistent with the global paleoclimate reconstructions for the past 2 kyr (Neukom et al. 2019).

The SST variations in the Okinawa Trough have been ascribed to sea-level variations (Zhao et al. 2015) and changes in the EAM and Kuroshio Current related to climatic changes in the high-latitude North Atlantic (Jian et al. 2000; Sun et al. 2005; Kubota et al. 2010; Ruan et al. 2015; Zhao et al. 2015) and/or low-latitude western tropical Pacific Ocean (Xu et al. 2018). The sea level was relatively stable during the late Holocene (Liu et al. 2004; Xue 2014). Thus, sea-level changes had minimal effects on the SST variations in core OKI-152. The variations in the $U^{K'}_{37}$-derived SST from core OKI-152 over the past 3.6 kyr (Fig. 3a) are inconsistent with the $U^{K'}_{37}$-derived SSTs from core MD063040 recovered from the inner shelf of the East China Sea, which were strongly affected by the terrestrial climate because of its proximity to land (Fig. 3b, Kajita et al. 2018). The variations in the $U^{K'}_{37}$-derived SST from core OKI-152 are also inconsistent with the variations in pollen-based EAM precipitation (Fig. 3c, Chen et al. 2015). Our records are similar to the variations in the Mg/Ca-based SST in the low-latitude western Pacific (Fig. 3d, Stott et al. 2004) and roughly the ENSO variability (Fig. 3e, Moy et al. 2002). However, these SST variations do not resemble the variations in the stacked hematite-stained grains of sediments from the North Atlantic (Fig. 3f, Bond et al. 2001), although some cold periods might be tentatively correlated with the North Atlantic ice-rafted debris events.

In fact, the changes in SST in the western Pacific could restrict climate changes in the Asia–Pacific region and even across the world (Alexander et al. 2002; Wang et al. 2013a). In modern times, the SST variations in the Okinawa Trough have also been synchronous with those in the western Pacific (Di Lorenzo et al. 2010). Regarding this variability, previous studies have proposed two main driving mechanisms: the coupled air-sea interaction in the tropical Pacific Ocean can produce interdecadal changes and affect the mid-latitude Pacific Ocean via atmospheric teleconnection (Trenberth 1990; Graham et al. 1994; Di Lorenzo et al. 2010), and the heat transfer in ocean and atmospheric processes in the mid-latitude Pacific Ocean could be stored in the ocean and then transported to the tropics via ocean circulation, thus forming the SST variability in the Pacific Ocean (Latif and Barnett 1996; Jin et al. 2001). Xu et al. (2013) showed that over the past 40 kyr, the SSTs in the Okinawa Trough have been influenced predominantly by heat transfer from the tropical western Pacific by the Kuroshio Current. Recently, we found that the Holocene SST variations in the southern Okinawa Trough were predominantly controlled by the low-latitude western tropical Pacific and not so much by the high-latitude North Atlantic (Xu et al. 2018). Our new results indicate that the SST variations in the middle Okinawa Trough over the past 3.6 kyr are correlated with those in the low-latitude western Pacific on centennial-millennial timescales.

Our study area is also affected by the ENSO (Hu et al. 2015; Zheng et al. 2016; Chen et al. 2019; Asami et al. 2020). As shown in Fig. 3c, on centennial-millennial timescales, the variations in the $U^{K'}_{37}$-derived SSTs of core OKI-152 are roughly similar to the variations in the ENSO as determined from the red color intensity of clastic layers in lake sediments in southern Ecuador produced by moderate-to-strong El Niño events (Moy et al. 2002). Di Lorenzo et al. (2010) showed that the SST anomaly in the Okinawa Trough induced by the Central Pacific El Niño is similar to the SST anomaly in the low-latitude western Pacific. Several studies have argued that the climate of coastal East Asia has been predominantly controlled by ENSO in the late Holocene (Park 2017). As the main source of heat, the low-latitude Pacific should contribute more than the high-latitude North Atlantic to the Okinawa Trough via the Kuroshio Current and ENSO during the late Holocene. Thus, as the “firebox” of the Earth weather system (Kerr 2001), low-latitude tropical oceans, especially the tropical western Pacific, and their effect on centennial- to millennial-scale paleoceanography changes in the Okinawa Trough should be the focus of more studies in the future.

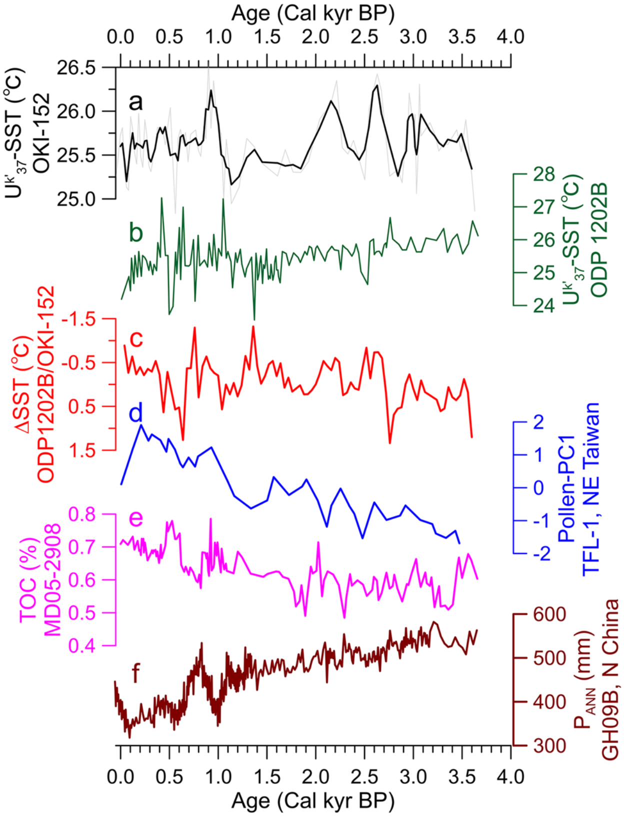

Fig. 4 Comparison of $U^{K'}_{37}$-derived SST from core OKI-152, middle Okinawa Trough (a, this study), with $U^{K'}_{37}$-derived temperatures from core ODP 1202B in the southern Okinawa Trough (b, Ruan et al. 2015); the ΔSST between the southern and middle Okinawa Trough over the past 3.6 kyr (c, this study; Ruan et al. 2015); the pollen records derived from core TFL-1 sediments from Tsuifong Lake in northeastern Taiwan (d, Wang et al. 2015); the TOC record from core MD05-2908 in the southern Okinawa Trough (e, Chen et al. 2019); and the reconstructed annual precipitation (P_{ANN}) from core GH09B sediments in Gonghai Lake, North China (f, Chen et al. 2015). The black solid curve was smoothed with 3-point running averages

Monsoon and rainfall influence on temporal- and spatial-scale variations in SST

The SST variations in the Okinawa Trough were also influenced by changes in the EAM (Sun et al. 2005; Ruan et al. 2015; Zhao et al. 2015; Asami et al. 2020). However, whether the temperature changes vary synchronously with the EAM is debatable (Peterse et al. 2011; Wu et al. 2017). Previous studies have shown that temperature and the EAM were decoupled during the last deglaciation on Jeju Island, South Korea, which is adjacent to the Okinawa Trough (Park et al. 2014). Low-resolution records have also suggested that the SST variations in the Okinawa Trough were decoupled from the EAM system during the Holocene (Xu et al. 2018). The previously published high-resolution $U^{K'}_{37}$-derived annual mean SST record from core ODP 1202B in the southern Okinawa Trough (Ruan et al. 2015) facilitates comparisons with our records. As shown in Fig. 4a and b, these two records showed inconsistent trends. Ruan et al. (2015) suggested that the Holocene SST variations in ODP 1202B in the southern Okinawa Trough are mediated by a complex interaction via variations in the EAM and Kuroshio Current.

However, the SST variations in core OKI-152 in the middle Okinawa Trough are predominantly controlled by the western Pacific. Thus, the comparison of high-resolution SST data between ODP 1202B and OKI-152 in the southern and middle Okinawa Trough could provide information on the temporal and spatial scales of the variations in the SST.

The difference in SST (ΔSST) between the southern and middle Okinawa Trough over the past 3.6 kyr was calculated and is shown in Fig. 4c. The pollen records derived from Tsuifong Lake sediments in northeastern Taiwan (Fig. 4d, Wang et al. 2015) and the TOC record from core MD05-2908 (Fig. 4e, Chen et al. 2019) showed increased Taiwan rainfall since then. The ΔSST decreased gradually and correlated well with the increased Taiwan rainfall (Wang et al. 2015; Chen et al. 2019). The southern Okinawa Trough was influenced by freshwater from Taiwan (Ruan et al. 2015; Chen et al. 2019), while such water had a limited effect on the middle Okinawa Trough because of far distance. Thus, the ΔSST between the southern and middle Okinawa Trough over the past 3.6 kyr should be mainly controlled by the Taiwan freshwater input. When the Taiwan rainfall strengthens, the increase in the freshwater input could depress the SST in the southern Okinawa Trough. Consequently, the increase in the Taiwan rainfall intensity resulted in a more negative ΔSST. The long-term reduction in ΔSST values caused by the Taiwan rainfall is inversely related to the precipitation record from North China (Fig. 4f, Chen et al. 2015), further indicating a dipolar pattern in EAM precipitation, or the so-called northern drought – southern flood scenario (Kubota et al. 2010; Chen et al. 2018, 2019; Zhang et al. 2018).

Conclusions

High-resolution studies on the variation in SST in the Okinawa Trough during the late Holocene are scarce. The SST record of the last 3.6 kyr was reconstructed to study the paleoclimatology and paleoceanography.

1) The temperature obtained from the core-top sample and the 3.6-kyr-averaged temperature of core OKI-152 corresponded well to the modern mean annual SST at this location. The SSTs were lower during the periods of 3.6–2.7, 2.0–1.0, and 0.6–0 cal kyr BP, which corresponded with the Neoglacial Period, Dark Age Cold Period, and Little Ice Age, respectively.
2) The variations in the $U^{K'}_{37}$-derived SSTs in core OKI-152 were decoupled from the high-latitude North Atlantic climate but coupled with the SSTs in the western Pacific and the ENSO variability since 3.6 cal kyr BP. The low-latitude Pacific contributed more than the high-latitude North Atlantic to the Okinawa Trough via the Kuroshio Current and ENSO.
3) The ΔSST between the southern and middle Okinawa Trough over the past 3.6 kyr was mainly controlled by the Taiwan freshwater input. More negative ΔSST values were caused by stronger Taiwan rainfall, and the trend was inversely related to the EAM precipitation record from North China. This finding further indicated the dipolar pattern of the EAM precipitation.

Acknowledgements We would like to thank Editor Andrew Green and multiple anonymous reviewers for their constructive comments and suggestions regarding earlier versions of this paper.

Funding This work was supported by the Paleoceanography Evolution Research of the Northwestern Pacific (GASI-GEOGEO-04), the National Natural Science Foundation of China (41776077), the Shandong Provincial Natural Science Foundation of China (ZR2020MD061), and the China Scholarship Council (201906455016).

Data availability All data used in this study are presented in the manuscript and appendices.

Declarations

Competing interests The authors declare no competing interests.

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