A 228-year coral record in the Philippines reveals volcanic cooling in the nineteenth century and globally coherent warming in the late twentieth century

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Key Points:

- Coral geochemical data from Phillipines show clear volcanic cooling only during the nineteenth century.
- A warming trend found in the late twentieth century suggests that the recent warming has been globally synchronous.

Abstract

Both proxy and model studies seeking to understand anthropogenic warming have revealed historical variations of sea surface temperature (SST) since the Industrial Revolution. However, because of discrepancies between observations and models for the late nineteenth century, the timing and degree of anthropogenic warming is still unclear. Here we reconstructed a 228-year record of SST and salinity using a coral core collected at Bicol, southern Luzon, Philippines, which is at the northern edge of the western Pacific warm pool. The SST record showed clear volcanic cooling after the eruptions of Tambora and Krakatau in 1815 and 1883, respectively, but the pattern of change differed between them. Although there were discrepancies in SST variations among modeled, observed, and proxy SST data for the late nineteenth to early twentieth century, SST data from the late twentieth century show globally coherent anthropogenic warming, especially after 1975.

Plain Language Summary

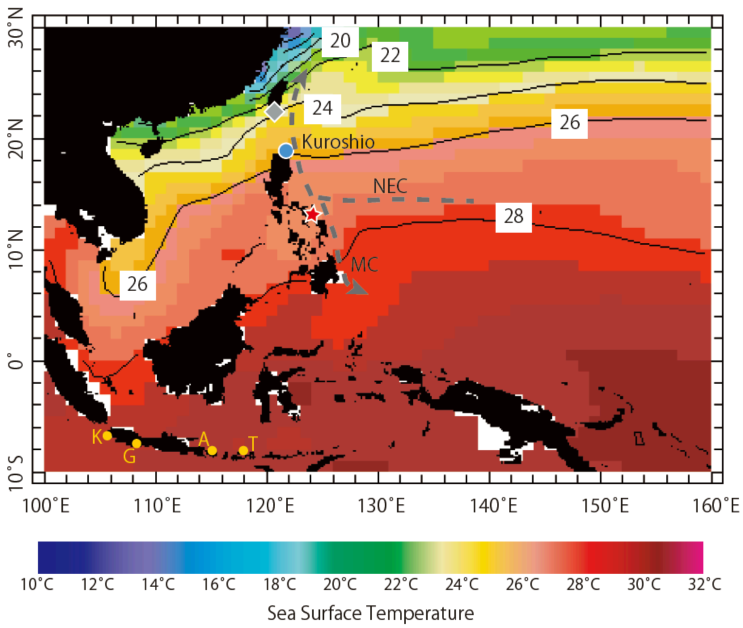
Global warming has been concerened worldwide and model studies play an important role in projecting climate change in the future. To improve accuracy of the model, comparison with observed data is critical. However continuous observed data is inadequate spacially and somtimes there is a discrepancy between the model and observed data. Then proxy data such as coral skeletons is used to understand climate valiabilities. In this study, we measured geochemical tracers in a coral skeleton collected from Bicol, southern Luzon, Philippines and reconstructed sea surface temperature (SST) and salinity for more than 200 years. The SST record showed several cooling event due to volcanic eruptions like Tambora and Krakatau in 1815 and 1883, respectively. Although there were discrepancies in SST variations among modeled, observed, and proxy SST data for the late nineteenth to early twentieth century, SST data from the late twentieth century show globally coherent anthropogenic warming, especially after 1975.

1 Introduction

Historical variations of sea surface temperature (SST) in relation to anthropogenic warming since the Industrial Revolution have been extensively investigated by both proxy and model studies to understand and explain changes in the contemporary climate and to estimate future impacts of climate change (e.g., Neukom et al., 2019; Abram et al., 2020; Hegerl et al., 2011; Ramos et al., 2020; Knutson et al., 2006; Papalexiou et al., 2020). Although recently developed models simulate well the observed long-term warming trend from 1880 to 2014 (Papalexiou et al., 2020), they show pronounced and fairly prolonged cooling during the 1880s. A likely strong contributor to this relatively prolonged cooling behavior is the occurrence of multiple significant volcanic eruptions during this period, such as the 1883 Krakatau eruption, but the discrepancies between models and observations during this period remain unresolved (Knutson et al., 2006). One possible cause may be insufficient observational data, because before 1910, observed data were available from less than 20% of the total ocean area (https://icoads.noaa.gov/index_fig3.html). In contrast, global paleoclimate reconstructions of the past 2,000 years have revealed globally coherent warming only during the twentieth century. Thus, within the past 2,000 years, anthropogenic global warming is not only unparalleled in terms of absolute temperature but also unprecedented in spatial consistency (Neukom et al., 2019). In this regard, paleoclimate records from after 1500 CE show that sustained industrial-era warming of the tropical oceans first occurred during the mid-nineteenth century and was nearly synchronous with Northern Hemisphere continental warming (Abram et al., 2016). However, few proxy data from the subtropical northwestern Pacific, which includes the northern edge of the western Pacific warm pool (WPWP), are available, though this region is of critical importance for determining anthropogenic impacts on the warm pool.

The warm pool of the western tropical Pacific contains some of the warmest seawater globally, with SSTs exceeding 28 °C. Because high SSTs favor deep convection (Roxy, 2014; Zhang, 1993), warm pool variations strongly modulate the atmospheric circulation (Lindzen & Nigam, 1987; Numaguti, 1995), monsoon rainfall (Cai et al., 2010; Dado & Takahashi, 2017), and tropical cyclone intensity (DeMaria & Kaplan, 1994; Emanuel, 2005). The WPWP, which together with the Indian Ocean warm pool is referred to as the Indo-Pacific warm pool (IPWP), plays a key role in climate and monsoon variability, which not only affects many developing countries throughout Asia and Africa (Zhou et al., 2009; Annamalai et al., 2013; Williams & Funk, 2011) but also influences remote regions and large-scale modes of climate variability (Hoerling & Kumar, 2003; Hoerling et al., 2012; Han et al., 2014). Hayashi et al. (2021) reported that record northwestern Pacific warming occurred in August 2020 under anthropogenic forcing, and expansion of the IPWP due to human-induced global warming has also been reported (Weller et al., 2016; Cravatte et al., 2009; Roxy et al., 2019). To elucidate how anthropogenic forcing has historically affected the warm pool, the long-term variability of SST and sea surface salinity (SSS) in the warm pool must be examined. Recently, Ramos et al. (2019, 2020), who reconstructed long-term SST and SSS records using *Porites* coral from off southern Taiwan and the northeastern tip of Luzon, Philippines, reported that temperature variations seemed to differ between these sites, especially in the early twentieth century. Even including these records, however, few high-resolution coral data for both water temperature and salinity from the northwestern Pacific are available in the PAGES Ocean2k dataset (Abram et al., 2016).

In this study, we conducted Sr/Ca and ^{18}O analyses of a *Porites* coral collected from Bicol, southern Luzon, to reconstruct SST and SSS records over 228 years with a monthly time resolution. These records can be used to investigate the influence of volcanic cooling in the Bicol region because they include years in which large volcanic eruptions occurred, such as Tambora in 1815 and Krakatau in 1883. The WPWP, defined by SSTs of 28.5 °C or more, extends in a band along the equator that reaches 10°N in boreal winter and 30°N in boreal summer (Cravatte et al., 2009). Thus, our sampling site, which is located at the northwestern edge of the persistent warm pool (Figure 1), is positioned suitably for studying the evolution of the warm pool.



2 Materials and Methods

The Bicol sampling site (13°03 N, 124°01 E) is off southeastern Luzon Island (Figure 1), near where the westward flowing North Equatorial Current (NEC) bifurcates into northward and southward flowing branches. The northward flowing branch is the Kuroshio, which transports a large amount of heat northward, and the southward branch, which has approximately the same volume transport ratio as the Kuroshio, is the Mindanao Current (Nitani, 1972; Toole et al., 1988). At the sea surface, the bifurcation occurs at 13–14°N near a salinity front (Toole et al., 1990; Qu et al., 1998). In the western equatorial Pacific, salinity minima of less than 34.3 due to dilution by precipitation are located at 6–8°N (Donguy & Henin, 1975; Delcroix & Hénin, 1991) and spread into the NEC region (Kimura et al., 1994). The surface water of the NEC, therefore, is composed of both this low-salinity water and high-salinity water (>34.8) due to excess evaporation. A shift of bifurcation latitude may be related to intensity of upwelling (Amedo et al., 2002).

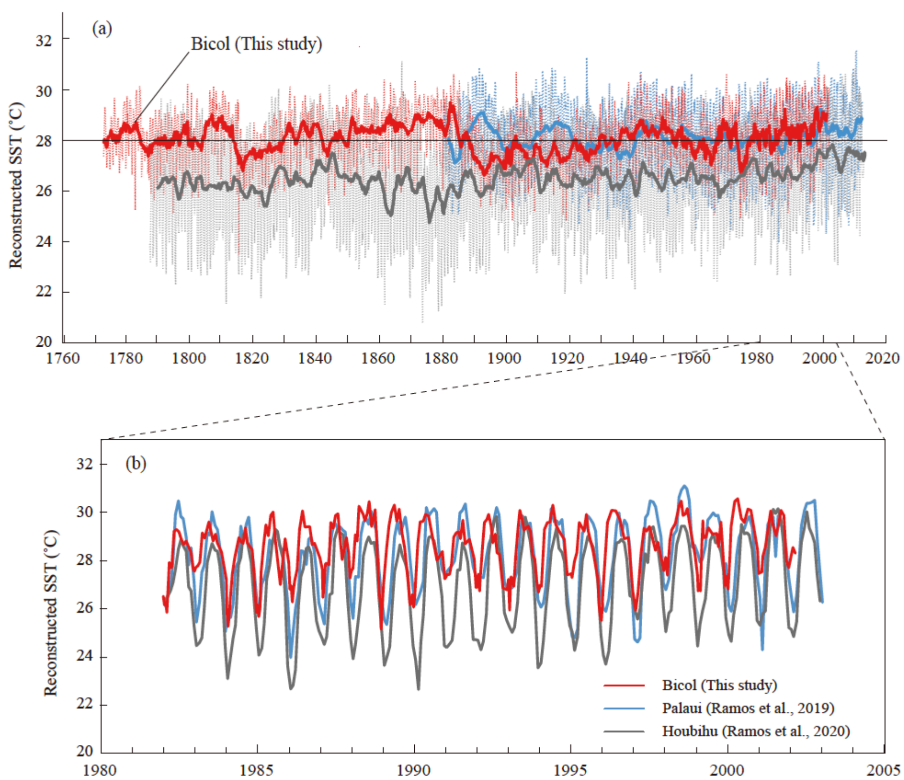
Bicol is also on the northwestern edge of the WPWP (SST > 28 °C), which greatly impacts the global climate through ocean–atmosphere interactions. According to SST records (1° × 1° grid) of the ship- and satellite-derived Integrated Global Ocean Services System Products Bulletin (IGOSS, available from November 1981 to the present), the mean annual SST (12.5°N, 124.5°E) at Bicol was 28.6 °C during 1982–2002. Mean maximum and minimum SSTs were 29.8 °C (mostly in June) and 26.9 °C (in January or February), respectively. SSS also varies seasonally, reaching a maximum (~34.3) in boreal winter and a minimum (around 34) in boreal summer (August to September), based on the

SODA database.

A 2.5-m-long core (SWGM01–01) was collected from a *Porites* sp. colony at 6 m below mean sea level on 16 March 2002. The core was drilled vertically from the top of the colony and then cut into 7-mm-thick slabs in the laboratory. Counting the annual density bands on X-radiographs of these slabs revealed mostly continuous growth and provided an estimated age of around 230 years (Figure S1). Coral ^{18}O and Sr/Ca were analyzed using an online system comprising an IsoPrime Isotope-ratio mass spectrometer (GV Instruments Ltd.) and inductively coupled plasma optical emission spectrometry, respectively. Detailed analytical methods including age model and calibrations to reconstruct SST and SSS are presented in supplementaly information.

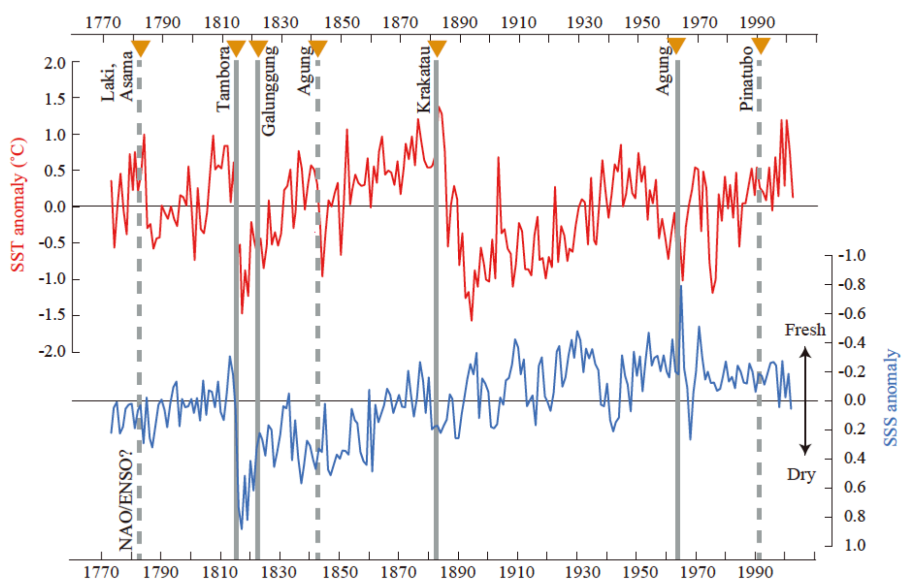
3. Results and Discussion

3.1., Influences of volcanic eruptions on SST and SSS at Bicol



The high-resolution time series from Bicol shows that SST varied dynamically during the 228 years of the coral record, with a prominent cooling episode around 1890 (Figure 2a). Other periods of cooling were associated with volcanic eruptions. Among the volcanic eruptions that occurred in Indonesia and the Philippines since the late eighteenth century (Newhall & Self, 1982), we selected four large eruptions, Tambora (1815), Galunggung (1822), Krakatau (1883), and Agung (1963), that satisfied the following three conditions: (1) Volcanic Explosivity Index (VEI) 5 according to de Maisonneuve and Bergal-Kuvikas (2020); (2) VEI 4 according to Newhall and Self (1982); and (3) Scaled Amplitude 1 in more than one ice core reference as described in Crowley et al. (1997). According to de Maisonneuve and Bergal-Kuvikas (2020), the eruptions of Agung in 1843 and Pinatubo in 1991 also had VEI 5, but, although the reconstructed SST dropped after these eruptions, the magnitude of the SST decrease did not correspond to the VEI (Figure 3).

Another famous volcanic eruption that affected global or regional climate is the 1783 eruption of Laki, Iceland. Although these previous studies did not include the Laki eruption among large eruptions, its impacts on climatic conditions in the Northern Hemisphere and globally have been widely reported in contemporary sources (Thordarson & Self, 2003). However, D'Arrigo et al. (2011) suggested that the dominant cause of the anomalous 1783/1784 winter was a negative NAO combined with an ENSO warm phase, both of which likely resulted from natural variability unconnected to the Laki eruption. It is difficult to determine whether



Bicol

experiences cooler or warmer conditions during an ENSO warm phase that cannot be explained by absolute cool conditions as in the western equatorial Pacific. Thus, the SST decrease at Bicol that began in 1785 and lasted for a decade cannot be definitively attributed to an ENSO warm phase (Figure 3). It is also difficult to conclude that the cause of this cooling event at Bicol was the Laki eruption alone, because its VEI was not large and associated volcanic cooling was reported mainly in high-latitude regions of the Northern Hemisphere such as Europe and North America. Moreover, Mt. Asama in

Japan erupted at the same time, so the cooling might reflect the combined impact of the two eruptions. Although the cause and mechanism of this late eighteenth century cooling is uncertain, this climate change event probably contributed to the Great Tenmei famine in Japan; this Edo period famine is considered to have begun in 1782 and lasted until 1788.

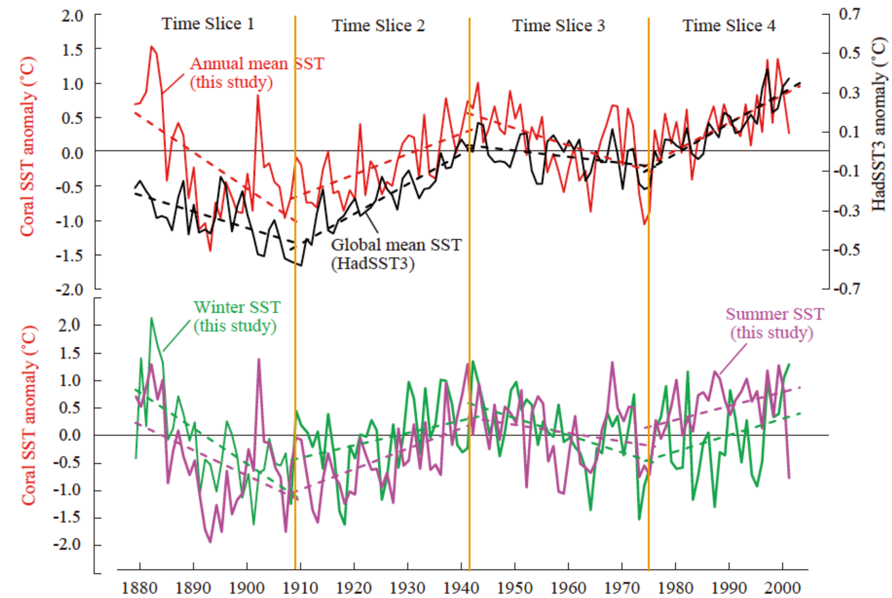
In contrast to the situation after the Laki eruption, the pronounced cooling around Bicol after the Tambora (1815) and Krakatau (1883) eruptions was certainly due to the volcanic eruptions. However, each eruption seemed to affect marine conditions differently. SST cooled relatively sharply by ~2.0 °C just after the Tambora eruption, which was associated with a substantial drought (Figure 3), whereas SST cooling by ~2.5 °C after the Krakatau eruption began only after a delay of 2–3 years and persisted for a decade with little change in salinity. However, because our age model for the period before 1885 includes an error of 1–3 years (see Section 2), this might be only an apparent time lag; nevertheless, marine conditions were certainly fairly different between these two historically large eruptions. In 1816, the coldest summer in two centuries was observed in both northeastern North America and western Europe and has been widely attributed to the 1815 Tambora eruption (e.g., Luterbacher and Pfister, 2015). In southeast Asia, a hydroclimate reconstruction shows that a strong drought struck regions of India, Indonesia, and southeast Asia that year (Cook et al., 2010). A simulation of the climatic response to the volcanic forcing of the Tambora eruption showed a particularly pronounced surface ocean cooling response in the subtropics (Fasullo et al., 2017). The occurrence of severe drought in southeast Asia and ocean cooling in the subtropics after the Tambora eruption are consistent with our SST and SSS records.

Climate model simulations show that the Krakatau eruption also affected oceanic conditions (Gleckler et al., 2006a). Volcanically induced cooling of the ocean surface penetrated the deep ocean, where it persisted for decades after the event. Multiple models have simulated surface ocean cooling that lasted until around 1900 to 1920, depending on the model, even though the eruption occurred in 1883. This remarkable effect on the oceanic thermal structure, which appears to be longer lasting than previously suspected, is sufficient to offset a large fraction of the ocean warming caused by anthropogenic influences (Gleckler et al., 2006b). Unfortunately, Gleckler et al. (2006a) did not directly compare the climatic impacts of the Tambora and Krakatau eruptions. However, the simulated heat content recovery was much more rapid following eruptions in the late twentieth century, such as the Pinatubo eruption, than it was following the Krakatau eruption, although Pinatubo was comparable to Krakatau in terms of its radiative forcing (Gleckler et al., 2006a). Gleckler et al. (2006a) attributed this difference to the fact that the response to Pinatubo was superimposed on a non-stationary background of a large and increasing anthropogenically forced ocean warming. Alongside the possible impact of prolonged cooling after the Krakatau eruption, coral studies from Ishigaki Island suggest an abrupt shift toward cooler conditions in the earliest part of the twentieth century (Mishima et al., 2010). Mishima et al.

(2010) attributed this cold event to a contemporaneous intensified East Asian winter monsoon (EAWM), which was associated with active heat convection in the tropics and weak westerlies. They suggested that several phenomena in the northwestern subtropical Pacific, including the SST cooling at Ishigaki Island and surface ocean freshening around the Ogasawara Islands, were uniquely coupled during the first few years of the twentieth century (Mishima et al., 2010). Thus, it might be possible to explain the pronounced late nineteenth to early twentieth century cooling at Bicol by the combination of the prolonged impact of the Krakatau eruption and the intensified EAWM. The negligible or only slight ocean surface cooling caused by volcanic eruptions in the late twentieth century, attributed by Gleckler et al. (2006a) to the background of increasing greenhouse-gas forcing, is also consistent with the findings of this study (Figure 3). Overall, reconstructed SSTs at Bicol appear to reflect volcanic cooling events that occurred during the past 228 years, but it is unclear whether the magnitude of cooling (up to ~2 °C) at this site is plausible.

3.2., Long-term SST and SSS variations in the northwestern subtropical Pacific

We compared our long-term SST record at Bicol to those reported by Ramos et al. (2019, 2020), who studied corals collected at Houbihu, southern Taiwan, and Palaui, northeastern Luzon (Figure 2a). The seasonality of SST is well reconstructed in the records of the three individual corals: reconstructed SSTs in boreal winter during 1982–2002 were coolest in at Houbihu, and slightly cooler at Palaui than at Bicol (Figure 2b). In contrast, the long-term records from the late nineteenth to early twentieth century showed little consistency among the three corals. In particular, reconstructed SSTs were ~2 °C warmer at Palaui than at Bicol for a period of about four decades. The large cooling seen at Bicol after the Krakatau eruption is absent in both the Palaui and Houbihu records, although Ramos et al. (2020) suggested that volcanic activities contributed to the SST variability at Houbihu. Knutson et al. (2006) reported discrepancies between modeled and observed SSTs during the corresponding time period, and the pattern of SST variation differed among the three individual coral records; these results suggest that climate conditions during this period may have been variable, or very sensitive to different forcings, at least in the northwestern Pacific. The SST time series and the SSS variations reconstructed using the Palaui and Houbihu corals have been explained mainly by regional phenomena such as the EAWM and the Pacific Decadal Oscillation (PDO) (Ramos et al., 2019, 2020). In contrast, the decadal trend in the SST record at Bicol from 1880 to 2002 corresponded well to the global mean SST record (HadSST3) for that period.



Statistical analyses have been used to divide the time series of global surface air temperature anomalies from 1860 to 2014 into stages defined by warming and cooling phases and hiatus periods (Zhu et al., 2018). Following Zhu et al. (2018), Papalexiou et al. (2020) divided the historical time period into four time slices: (1) a cooling phase during 1880–1909; (2) a warming phase during 1909–1942; (3) a hiatus from 1942 to 1975; and (4) a warming phase during 1975–2014. In each time slice, the trend of the SST anomalies at Bicol is similar to that of global mean SST anomalies (Figure 4). In addition, the overall warming of the global SST by 0.59 °C from 1880 to 2002 is similar to that of 0.72 °C for the Bicol SST. Moreover, in Time Slice 4 (1975–2002), even the annual variation is mostly consistent between the observed and reconstructed SST anomalies, which are significantly correlated (r = 0.74), although the absolute values of the SST anomalies, and hence the magnitude of warming, differ between them. When we divided the time series of Bicol SST anomalies into winter and summer values, the trend during each time slice was similar (Figure 4), but the absolute values of the SST anomalies differed slightly among time slices; in particular, summer SSTs were warmer than winter SSTs during the most recent warming phase (Time Slice 4). At Palaui, Ramos et al. (2019) reported a summertime Sr/Ca-SST increase, but suggested that anthropogenic warming in the wintertime Sr/Ca and SST trends is masked by interannual to multidecadal scale changes driven by the EAWM and the PDO. However, given that Palaui is far to the north of the warm pool in winter (Figure 1), it is also possible that the impact of anthropogenic warming might differ between the warm pool and its outer region. Kosaka and Xie (2016), who conducted simulations with a global coupled ocean-atmosphere model in which the tropical Pacific SST was forced to follow the observed temperature evolution, identified the tropical

Pacific as a key determinant of the global mean surface warming rate. The similarity between the global and Bicol SST trends appears to support their hypothesis.

Long-term SSS variations can be decoupled from the SST variations; SSS anomalies show persistent freshening starting around 1820, after the extreme drought following the Tambora eruption (Figure 3). This long-term SSS trend is similar to that reported from Vanuatu in the southwestern Pacific (Gorman et al., 2012). In the northwestern Pacific, the low-salinity front moved northward from 13°N to 17°N during 1970–2000 (Kimura et al., 2001), a finding that suggests that the salinity front can move like the warm pool (Qiu & Lukas, 1996). A shift of the salinity front may thus be responsible for the observed freshening after 1820. In particular, because both warming and freshening trends were found from 1820 to 1880, a northward shift of the warm pool might have been accompanied by northward migration of the salinity front. SSTs at Bicol before 1880 were comparable to those around 2000; most of the time before 1880, SSTs were greater than 28 °C, except during periods of volcanic cooling (Figure 2). These warm SSTs might reflect a northward shift or an expansion of the warm pool, or simply local variations.

Abram et al. (2016), who studied industrial-era warming in both paleoclimate records and model simulations, revealed that the greenhouse forcing causing industrial-era warming commenced around 1830 in the western Pacific and included an enhanced response in the equatorial ocean. This enhanced equatorial response might account for the warming after the Tambora eruption at Bicol, although the warming was largely suspended around 1880, probably as a result of both the Krakatau eruption and an intensified EAWM, which were not considered by Abram et al. (2016).

3.3., Coherent warming trend in the late twentieth century

Although SST behaviors from the late nineteenth to the early twentieth century differed among Bicol, Palaui, and Houbihu, the records of SST anomalies from these three sites were consistent in the late twentieth century, approximately corresponding to Time Slice 4. The warming trend during this period, calculated using high-resolution (biweekly) data, was 0.21 °C per decade at Houbihu and 0.17 °C per decade at Palaui, whereas trends calculated using annual mean data at Bicol, global mean SSTs (HadSST3), and multi-model mean data were 0.40, 0.15, and 0.24 °C per decade, respectively (Papalexiou et al., 2020). At Bicol, excluding the first two years (1975 and 1976, when the mean annual SSTs were very low), the warming trend is 0.25 °C per decade. Although the magnitude of the warming trend differs a little among the sites and the global and modeled mean SSTs, the trends in all records are similar in the late twentieth century, unlike those in the late nineteenth and early twentieth centuries. Neukom et al. (2019) suggested that more than 98% of the globe experienced the warmest temperatures of the past two millennia during the twentieth century. The results of coral studies from the northwestern Pacific show more specifically this coherent anthropogenic warming reported by Neukom et al. (2019) since at least 1975

(Time Slice 4). As Neukom et al. (2019) have suggested, past climates showed extensive spatial variations, reflecting complicated interactions among diverse climatic responses. However, the recent warming has been globally synchronous, showing reduced climatic diversity. The similar warming trends seen at all three coral sites in the northwestern Pacific (Figure 2) support the recent finding that anthropogenic forcing has caused expansion of the IPWP (Weller et al., 2016). The size and intensity of the warm pool in the western Pacific affects both the East Asian monsoon and western Pacific tropical cyclones (Wang et al., 2013; Ueda et al., 2015), and precise long-term SST and SSS records are important for improving our understanding of the evolution of the IPWP.

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Open Research

Our original data of coral Sr/Ca and ^{18}O are presented as a supporting material (Original Data_Inoue et al.pdf). If my article is accepted, I will submit our data in PANGEA (https://www.pangaea.de) that is member of the World Data System.

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