Coral Ba/Ca reflected the past earthquake and tsunami on Kikai Island in 1911

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Abstract

Natural disasters like earthquakes and tsunamis significantly affect coral reefs and marine ecosystems. The Ryukyu Islands, including Kikai Island and the surrounding coral reefs, face the potential risk of experiencing a large earthquake with $M_w > 8$. While historical records offer insights into past tsunami occurrences, there is scarce observation or quantitative data on the impacts of seismic events on the reef ecosystems. Here, we show the environmental impact of the 1911 Kikai Island Earthquake and Tsunami on coral reef ecosystems using coral skeletal geochemical proxies with weekly-to-bi-weekly temporal resolution, particularly focusing on the coral barium/calcium ratios (Ba/Ca). Analysis of a sub-fossil *Porites* coral specimen collected from Shiomichi Bay, eastern Kikai Island, revealed an anomalous peak in Ba/Ca ratios following the earthquake and tsunami event, indicating increased sediment load in seawater. This anomaly persisted for approximately two months post-earthquake, highlighting the prolonged effect of the tsunami on coral reef environments. Other coral geochemical proxies, such as coral strontium/calcium ratios (Sr/Ca), magnesium/calcium ratios (Mg/Ca), oxygen ($\delta^{18}O_{coral}$), carbon stable isotopes ($\delta^{13}C_{coral}$) and oxygen isotopes in seawater ($\delta^{18}O_{sw}$) showed no anomalous change corresponding to the event. Despite the disturbance, the coral growth rate did not show an exceptionally low value, suggesting that the event may not have been catastrophic enough to have a severe impact. Our findings underscore the utility of coral Ba/Ca ratios in assessing historical variations in sediment concentrations associated with paleo-earthquake and tsunami events and provide valuable insights into the environmental impacts of tsunamis on coastal ecosystems.

Introduction

Enormous tsunamis triggered by giant subduction zone earthquakes significantly impact the deposition of land-based material and resuspension of seafloor sediments, resulting in severe damage to shallow marine ecosystems, particularly coral reefs (e.g., Bahuguna et al., 2008). In Japan, coral reefs located near the Ryukyu Trench, such as those around the Ryukyu Islands or Amami Islands, face the potential risk of experiencing a major earthquake with a magnitude greater than 8 ($M_w > 8$) (Ando et al., 2009; Goto, 2013). Historically, these regions have encountered significant earthquakes, such as the 1771 Great Yaeyama Earthquake/Tsunami and the 1911 Kikai Island Earthquake/Tsunami. While there is scarce observation data on the impacts of these seismic events on the reef ecosystems, previous studies have focused on tsunami deposits like tsunami boulders, which provide insights into the size and distribution of these deposits (e.g., Goto et al., 2013). Massive coral-made tsunami boulders are valuable sources of historical and geological information regarding past tsunami occurrences. However, they do not offer insights into the environmental changes in coral habitat and the environment following an earthquake, as they died when drifting ashore during a tsunami. In contrast, reef-building corals (e.g., *Porites* sp.) that have experienced and survived an earthquake and tsunami event would record habitat changes through the chemical compositions of their aragonite ($CaCO_3$) skeleton (Ito et al., 2020a). Among various indicators, the coral skeletal barium/calcium ratio (Ba/Ca) serves as a long-term record of sediment influx in seawater triggered by factors like heavy rainfall, river discharge and coastal development and land use (e.g., McCulloch et al., 2003; Ito et al., 2020b). Additionally, sedimentation, indicated by high water turbidity, would disrupt coral growth and calcification (e.g., Ito et al., 2020b). Hence, coral skeletal archives, including Ba/Ca ratios and growth patterns, can potentially help detect and evaluate the impact of sediment load from tsunamis on coral habitat.

Our study site is Kikai Island, in the Amami Islands, Japan. The 1911 Kikai Island Earthquake (on 15th June, M_w 8.1 and 60 km depth, 28.7°E, 130.6°N, Fig. S1, estimated by Goto, 2013) triggered a large tsunami. Historical records of tsunamis in the Amami Islands are scarce, mainly relying on anecdotal or interview-based reports and ancient documents (e.g., Tsuji, 1997). According to these limited archives, the tsunami elevations were estimated to reach 10 m in Nakazato, 8 m in Akaren and 5.5 m in Araki, located southwest of Kikai Island (Fig. S1). Due to the absence of geological or geochemical evidence related to the 1911 Kikai Earthquake, the effects of the tsunami on the coral reefs surrounding Kikai Island are still unknown.

Here, we present the first coral archive documenting a paleo-tsunami event using skeletal Ba/Ca. The coral-based paleo-tsunami archive sheds light on environmental changes resulting from tsunami sediment accumulation on coral reefs, particularly palaeo-tsunami events with limited historical records. We further investigate local conditions at the study site, such as water temperature, salinity change and light availability, by examining coral strontium/calcium ratio (Sr/Ca, e.g., Mitsuguchi et al., 2003), magnesium/calcium ratio (Mg/Ca. e.g., Mitsuguchi et al., 2003), oxygen ($\delta^{18}O_{coral}$, e.g., Cahyarini et al., 2008) and carbon stable isotopes ($\delta^{13}C_{coral}$, e.g., Grottoli and Wellington, 1999). Furthermore, we evaluate the impact of the 1911 Kikai Earthquake/Tsunami event on the coral skeleton and reef habitats.

Materials and Methods

Sample collection and preparation

We used a sub-fossil *Porites* coral collected in Shiomichi Bay on the northeastern coast of Kikai Island (Fig. S1). This coral specimen is part of the 217-year skeletal Sr/Ca record from 1798 to 2015, first reported by Ito et al. (2024). The coral specimens collected in Shiomichi Bay would not be affected by freshwater input because there is no river or freshwater source. The coral core covering 1908 to 1917 (dated according to Ito et al., 2024) was washed with distilled water in an ultrasonic bath several times and dried at 50°C for 24 hours. Skeletal powder samples for geochemical analysis were obtained using a micro drill and a PC-controlled XY stage. Microsampling intervals were 0.3 mm, equivalent to weekly or bi-weekly resolution. The sampling area was cleaned with high-pressure air after each microsampling to prevent cross-contamination.

Coral geochemical analysis

Skeletal Sr/Ca, Mg/Ca and Ba/Ca analyses were performed by inductively coupled plasma optical emission spectrometry (ICP-OES, iCAP 6200 ICP Spectrometer, Thermo Scientific) with an autosampler (ASX-260, Teledyne CETAC Technologies) and an ultrasonic nebuliser (U-5000AT, Teledyne CETAC Technologies) installed at Hokkaido University, following the method described by Watanabe et al. (2021). The analytical uncertainties (1σ; relative standard deviations) were 0.17% for Sr/Ca, 0.73% for Mg/Ca and 2.24% for Ba/Ca.

The skeletal $\delta^{18}O_{coral}$ and $\delta^{13}C_{coral}$ analyses were performed using a mass spectrometer (Finnigan MAT 253, Thermo Scientific) coupled to a carbonate reaction device (Kiel IV Carbonate Device, Thermo Scientific) installed at Hokkaido University, following the method described by Ito et al. (2020b). The standard deviations (2σ; 95% confidence) were 0.04‰ and 0.03‰ for $\delta^{18}O_{coral}$ and $\delta^{13}C_{coral}$, respectively.

Chronology, skeletal extension rate and statistical analysis

Our coral record has a weekly to bi-weekly resolution from 1910 to 1912 and a monthly resolution for other periods. Following Ito et al. (2024), we used tie points to connect the values of skeletal highest

Sr/Ca and coolest water temperature month (the 15th of February) records to establish each year. The annual extension rates (AER) of the coral skeleton were determined by measuring distances between Sr/Ca maxima (water temperature minima).

We converted our coral Sr/Ca values into temperature units (ºC) following Ito et al. (2024). Besides, we calculated oxygen isotopes in seawater ($\delta^{18}O_{sw}$) by removing the temperature component of $\delta^{18}O_{coral}$ using coral Sr/Ca-inferred temperature. The Monte-Carlo technique was employed to estimate temperature and $\delta^{18}O_{sw}$ and their uncertainties (Watanabe and Pfeiffer, 2022).

Results

As shown in Figs. 1a and 1b, the coral Sr/Ca and Mg/Ca records revealed clear annual cycles reflecting water temperature seasonality. The mean seasonal cycle of Sr/Ca was 0.58 mmol/mol, equivalent to 9.0 ºC (Fig. 2a). The $\delta^{18}O_{coral}$ record also showed clear seasonal cycles, and it significantly correlated with coral Sr/Ca at the 95% confidence level (r = 0.98, n = 12, Figs. 2-a and 2-e). It suggests that the $\delta^{18}O_{coral}$ record was strongly controlled by water temperature and potentially affected by $\delta^{18}O$ changes in seawater. The $\delta^{13}C_{coral}$ record displayed seasonality from 1910 to 1912 (weekly- or bi-weekly-resolved record) but was less clear in other years (monthly-resolved record) (Fig. 1-d). The coral Ba/Ca demonstrated seasonality with peak values in March and April (Fig. 2-c).

After the 1911 Kikai Island Earthquake (which occurred on 15th June), the water temperature proxies, coral Sr/Ca and Mg/Ca records did not show any anomalous change (Figs. 1a and 1b). In contrast, the coral Ba/Ca increased throughout1.5 to 2 months post-earthquake, peaking at 6.89 µmmol/mol (Fig. 1c). Both the $\delta^{13}C_{coral}$ and $\delta^{18}O_{sw}$ showed a slight upward shift during or after the earthquake event (Figs. 1d and 1e), but it seems to be part of the seasonal change of these proxies (see "Coral Ba/Ca signals of the 1911 Kikai Earthquake and Tsunami").

Discussion

Coral Ba/Ca signals of the 1911 Kikai Earthquake and Tsunami

Coral Ba/Ca record showed a clear seasonal cycle with an anomalously high peak in the 1911 summer (value: 6.89 µmol/mol) compared to the mean seasonal cycle (Fig. 2-c). Coral Ba/Ca is potentially influenced by water temperature changes (Lea et al., 1989). Nevertheless, our coral record does not support it, as the mean seasonal cycle of our coral Ba/Ca was out-of-phase with temperature proxies, and they did not significantly correlate (r = 0.40, n = 12 for Sr/Ca; r = –0.38, n = 12 for Mg/Ca; r = 0.51, n = 12 for $\delta^{18}O_{coral}$, Fig. 2). Hence, the influence of temperature changes on coral Ba/Ca was overprinted by other factors.

Coral Ba/Ca also reflects seawater Ba/Ca changes, as its distribution coefficient ($Ba/Ca_{coral}/Ba/Ca_{seawater}$) is mostly constant (Saha et al., 2016). The desorbed Ba^{2+} from the particulate matter is readily substituted for Ca^{2+} in the coral aragonite lattice in proportion to the aqueous Ba/Ca ratio (Lea et al., 1989). The increase in coral Ba/Ca values can also be attributed to the uptake of high concentrations of seawater Ba. Since Ba is enriched in the deep sea or river more than in the sea surface, seawater Ba and coral Ba/Ca increase due to upwelling or vertical water mixing (e.g., Lea et al., 1989), as well as sediment runoff from rivers (i.e., freshwater/flood plumes) (e.g., McCulloh et al., 2003; Ito et al., 2020b). Basically, the effect of upwelling or vertical water mass mixing at our sampling location should be minimal because it is situated within a semi-closed bay. The Ryukyu Current System flows northeastwards to the southeast of the Ryukyu Islands (Thoppil et al., 2016), with higher volume transport from winter to spring around Amami-Oshima Island (i.e., from November to April; Thoppil et al., 2016, data from 1993 to 2012). This suggests that the increased coral Ba/Ca from winter to spring may be linked to vertical mixing associated with the Ryukyu Current System. Moreover, the seasonal influence of Ba-containing sediments running to the bay through freshwater/plumes is negligible because no rivers or freshwater sources are close to our study site. Besides, from June to August in the year of the Kikai Island Earthquake (1911), the water temperature was significantly warm compared to other years. The higher $\delta^{18}O_{sw}$ was also recorded, suggesting a drier or more saline environment. It aligns with the higher $\delta^{13}C_{coral}$ indicating increased insolation (i.e., less cloud cover or rainfall). It is supported by the *in situ* precipitation dataset (observed at Nase, Amami-Oshima Island), which indicates no heavy rainfall or deviated precipitation from June to August 1911 (Fig S2). Therefore, the increased Ba/Ca values in 1911 are not influenced by Ba-enriched water related to vertical water mass mixing and cool freshwater input resulting from rainfall.

Prolonged effect of tsunami event on coral reefs

A tsunami event will lead to the resuspension of bottom sediments and terrestrial input by the backwash. This natural process will lead to an increase in the concentration of Ba in seawater as sediments containing Ba flow into the ocean (Saha et al., 2016). Based on these theories, the high peak in our coral Ba/Ca recorded in 1911 suggests an increase in Ba concentration in seawater caused by the 1911 Kikai Earthquake/Tsunami event. Our coral Ba/Ca record demonstrates that the tsunami effect, such as terrestrial input by the backwash and sediment resuspension on Shiomichi Bay, persisted for approximately two months after the tsunami. This finding agrees with Murakami-Sugihara et al. (2019), which indicated a high peak in the manganese/calcium ratio (Mn/Ca) in mussel shell skeletons resulting from prolonged tsunami disturbances.

The impact of Earthquake/Tsunami event on coral in the east Kikai Island

Numerous previous reports have shown the impacts of reef disturbance due to sediment load on coral growth (e.g., Ito et al., 2020a; 2020b). For the earthquake/tsunami-related reef disturbance, Ito et al. (2020a) found the coral skeletal growth response linked to tsunami elevations of 4 to 13 meters during the 2004 Indian Ocean Earthquake/Tsunami. They presented a significant decrease in the annual extension rate corresponding to temporal-low water visibility caused by the tsunami-related resuspension of the seafloor sediments and coastal runoff. Previous studies have estimated the tsunami elevation and damage from the 1911 Kikai Earthquake/Tsunami (e.g., Tsuji, 1997); however, there is no detailed estimation on our study area, the eastern part of Kikai Island. Its impact on reef environments is also unknown.

To evaluate the impact of the 1911 Kikai Island Earthquake/Tsunami in the eastern area of the island, we analysed coral AERs from 1909 to 1916. Then we compared them with the records from the 19th, 20th and 21st centuries (1800~1825, 1900~1925, 1990~2014, data based on Ito et al., 2024 and this study). The mean value of the skeletal AER from 1909 to 1916 was 12.2 mm/year (Fig. 3a). For comparison, the AER values for the 19th, 20th and 21st centuries were 12.9, 13.5 and 16.0 mm/year, respectively (Fig. 3b). There was no significant relationship between AER and coral Sr/Ca over the entire period at the 95% confidence level (r = 0.18, n = 75); therefore, water temperature change did not directly affect to the skeletal growth of our specimens. The AER for the year of the 1911 Kikai Island Earthquake/Tsunami was 9.3 mm/year (Fig. 3a), and this value was the minimum extension rate between 1909 and 1916. Although this value was low, it did not deviate exceptionally from the 20th-century record. Despite the approximately two-month duration of the tsunami effect, the 1911 Kikai Island earthquake would not significantly impact coral skeletal growth. An irregular density band or green colour band can also be observed on the coral skeleton when being exposed to extreme stress, for example, thermal stress, terrestrial runoff and bloom of endolithic algae (e.g., Fine and Loya, 2002; Ito et al., 2020a; 2020b). However, our coral specimen showed neither a stress band nor a green band. The disagreement may be explained by the geographical or reef conditions and the difference in the level of reef disturbance. We, therefore, concluded that the 1911 Kikai Island Earthquake/Tsunami event led to the prolonged Ba-enrich sedimentation load on the eastern coast of Kikai Island; however, it would not be extreme stress for our specimen, *Porites* corals.

Conclusion

Coral Ba/Ca has long been used as a proxy for assessing historical variations in sediment concentrations in seawater linked to factors such as precipitation, river discharge and coastal land use. We reconstructed the 1911 Kikai Island Earthquake/Tsunami event using coral skeletal geochemical proxies, including coral Ba/Ca. We found a tsunami signal as a coral Ba/Ca peak lasting approximately two months in the semi-closed bay, which cannot be explained by other potential control factors of this proxy and is far beyond its mean seasonal cycle. In contrast, the other coral proxies (Sr/Ca, Mg/Ca, $\delta^{13}C_{coral}$, $\delta^{18}O_{coral}$ and $\delta^{18}O_{sw}$) showed no anomalous changes during and following the tsunami event. Although the 1911 Kikai Island Earthquake/Tsunami event marks the geochemical signal as a coral Ba/Ca peak, it might not be catastrophic enough to influence *Porites* coral growth. Our coral Ba/Ca and coral growth data provided new evidence that the tsunami reached the east coast of Kikai Island, with no report associated with the 1911 Kikai Island Earthquake/Tsunami.

Acknowledgments

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Figure captions

Fig. 1. Coral geochemical records from 1917 to 1908

The time series of coral skeletal (a) Sr/Ca and Sr/Ca-inferred temperature (Sr/Ca-inferred temperature is shown in centred values based on Watanabe and Pfeiffer (2022), (b) Mg/Ca, (c) Ba/Ca, (d) $\delta^{13}C_{coral}$, (e) $\delta^{18}O_{coral}$ and (f) $\delta^{18}O_{sw}$. In panel (f), the grey hatch envelopes the 95% confidence interval. The red hatch in the chronology indicates the timing of the 1911 Kikai Island earthquake. All records from 1910 to 1912 have a higher temporal resolution (weekly to bi-weekly) than those other than periods (monthly).

Fig. 2. Seasonality of coral geochemical records

The mean seasonal cycle of (a) Sr/Ca, (b) Mg/Ca, (c) Ba/Ca, (d) $\delta^{13}C_{coral}$, (e) $\delta^{18}O_{coral}$ and (f) $\delta^{18}O_{sw}$ is shown by a solid black line and standard error (grey shading) in each panel. Each coloured solid line indicates the year 1911 for the respective record. The records for other years are shown by thin grey lines.

Fig. 3. Skeletal annual extension rate

The annual extension rates (AER) from 1909 to 1916 were determined by measuring the distance between Sr/Ca maxima (SST minima). For comparison, the data distributions of the skeletal annual extension rate in the 19th (1800~1824, $n = 25$), 20th (1900~1924, $n = 25$), and 21st centuries (1990~2014, $n = 25$) are shown as histograms. The comparison dataset is based on Ito et al. (2024) and this study. The red line on each histogram indicates the AER of the year 1911 Kikai Island earthquake (9.3 mm/year).

Figures

Fig. 1

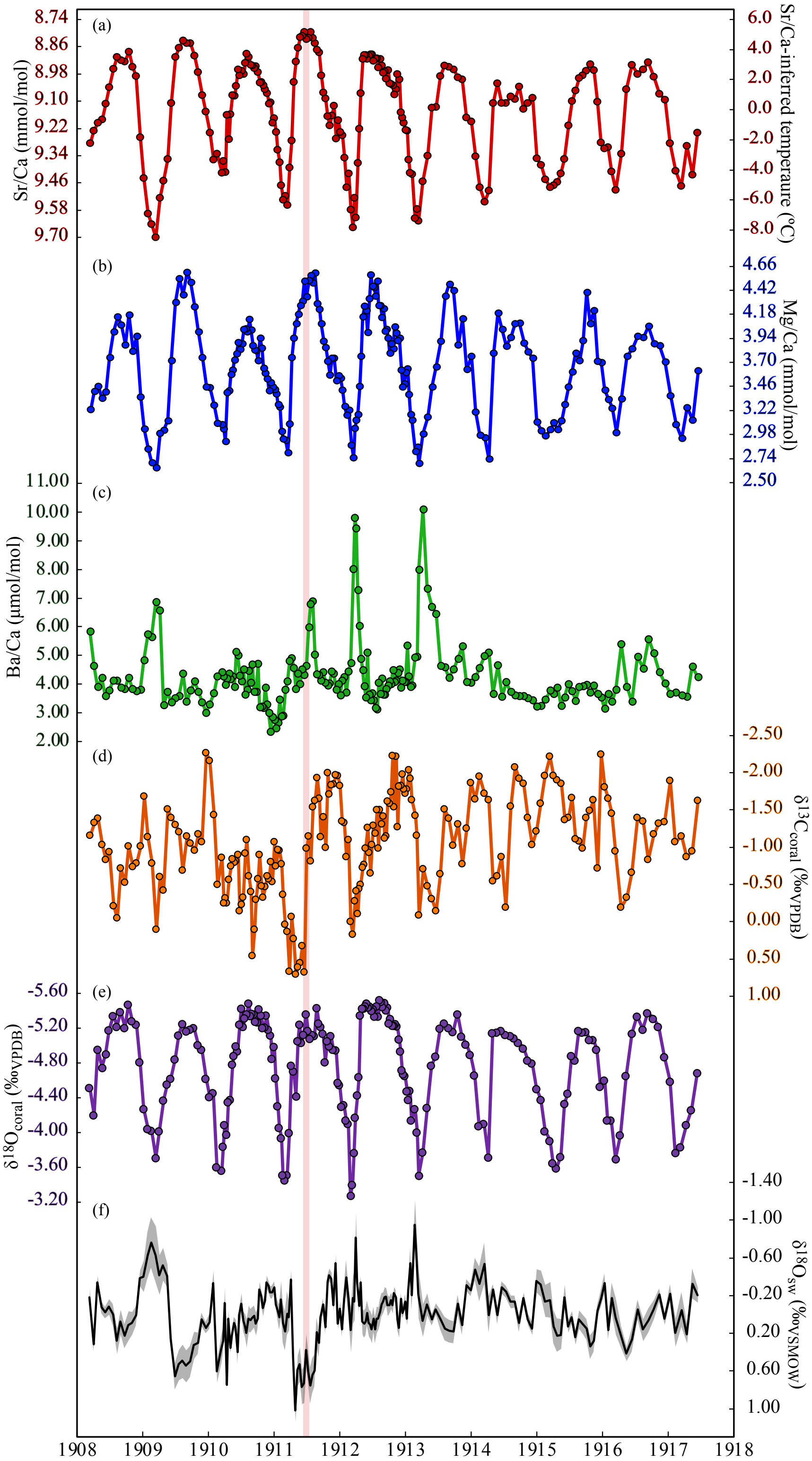


Fig. 2

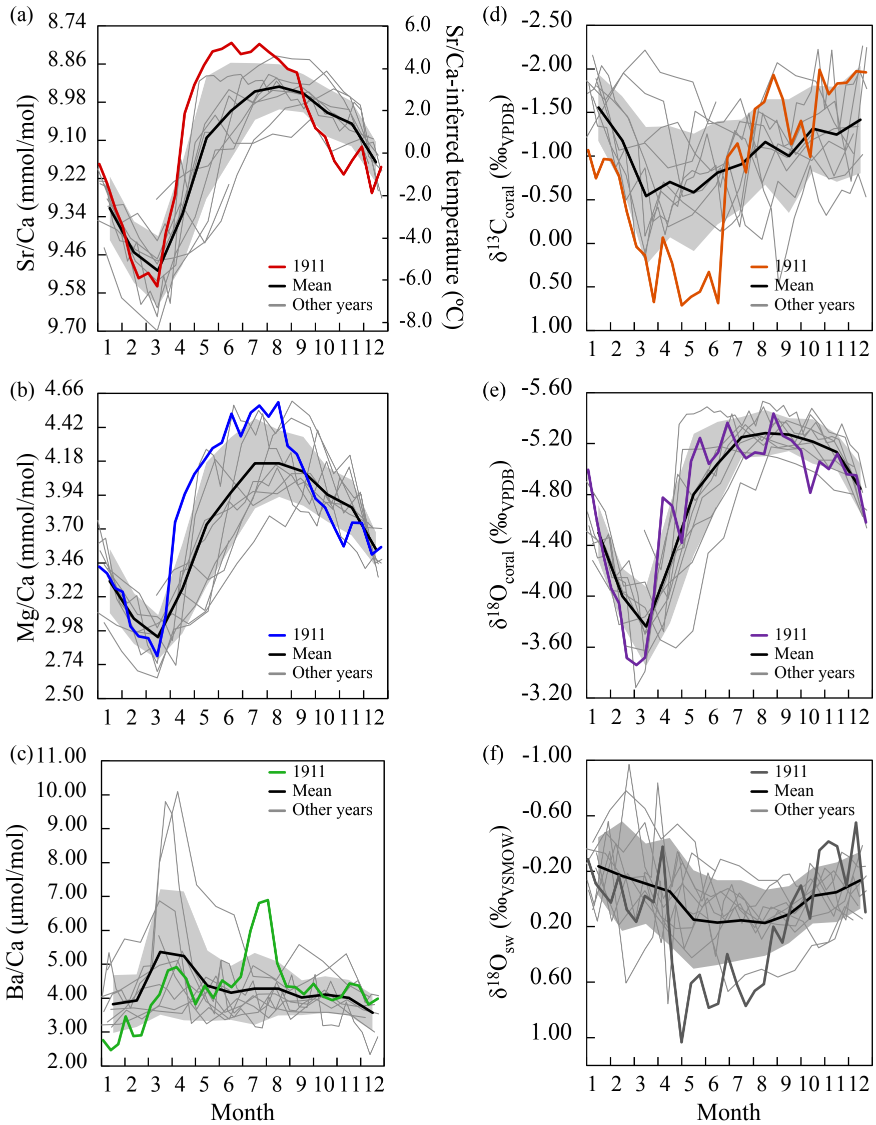
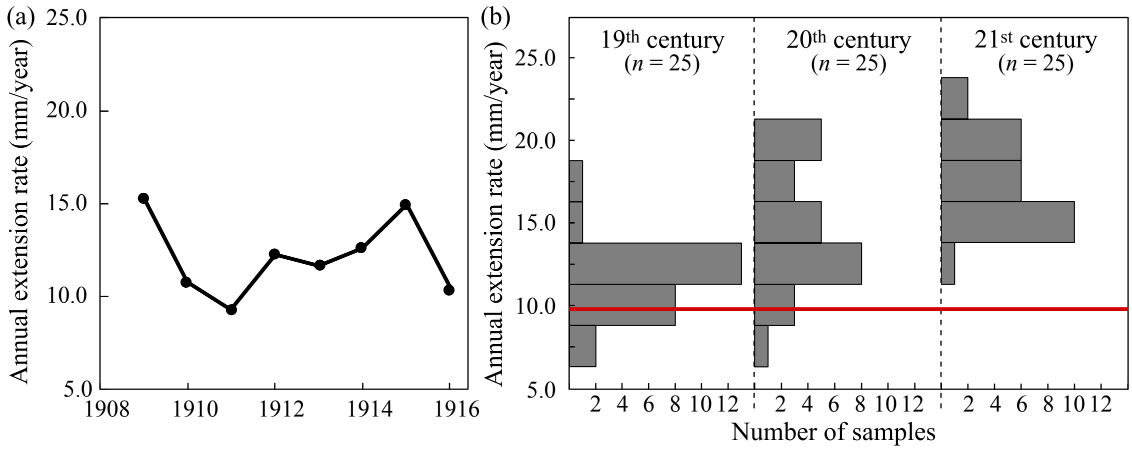

(a)
Sr/Ca (mmol/mol)
Sr/Ca-inferred temperature (°C)
1911
Mean
Other years
(b)
Mg/Ca (mmol/mol)
(c)
Ba/Ca (μmol/mol)
Month
(d)
δ13Ccoral (‰VPDB)
(e)
δ18Ocoral (‰VPDB)
(f)
δ18Osw (‰VSMOW)
Month

Fig. 3


(a)
Annual extension rate (mm/year)
25.0
20.0
15.0
10.0
5.0
1908
1910
1912
1914
1916
(b)
19th century
(n = 25)
20th century
(n = 25)
21st century
(n = 25)
Annual extension rate (mm/year)
25.0
20.0
15.0
10.0
5.0
2 4 6 8 10 12
Number of samples

Supplementary Figure captions

Fig. S1 Regional map and coral sampling site

On the left panel, the red line shows the Ryukyu Trench and the blue star shows the hypocentre of the 1911 Kikai Island earthquake (28.7 E, 130.6 N; M_w 8.1, reported by Goto, 2013). On the right panel (figure modified from Figure S1 of Watanabe et al., 2020), the coral sampling site of this study is marked with a red circle. Three blue circles indicate the places where the estimated tsunami elevations were reported (e.g., Tsuji, 1997).

Fig. S2 Precipitation observed at Nase, Amami-Oshima Island

The time series displays a monthly anomaly (black line) with a standard deviation (grey hatch). The red hatch in the chronology indicates the timing of the 1911 Kikai Island earthquake. The dataset is available at the Japan Meteorological Agency (https://www.data.jma.go.jp/gmd/risk/obsdl/index.php).

Fig. S1

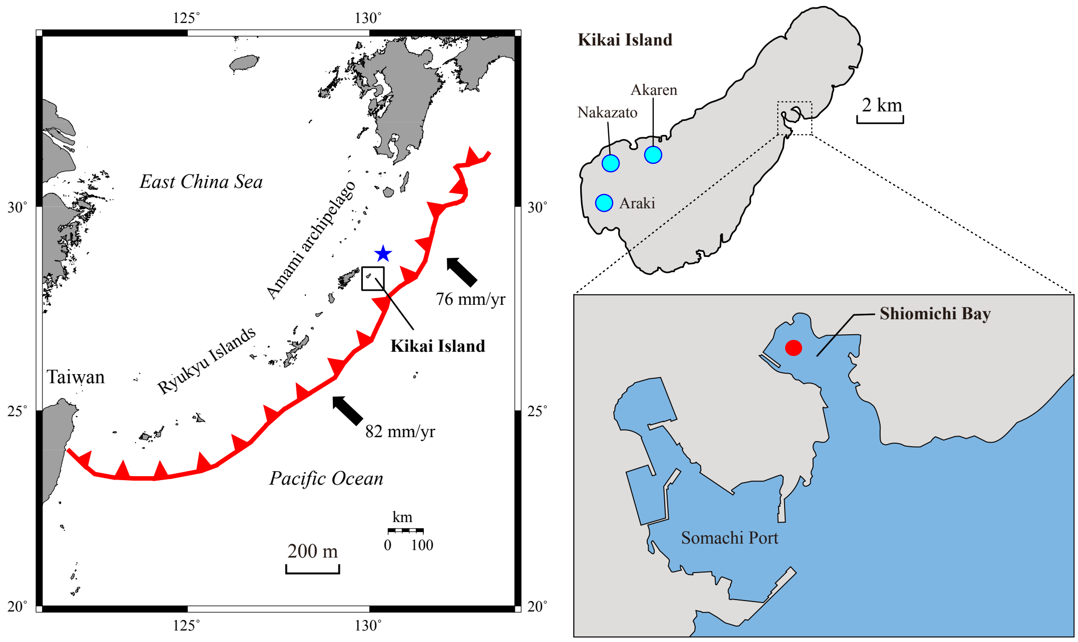
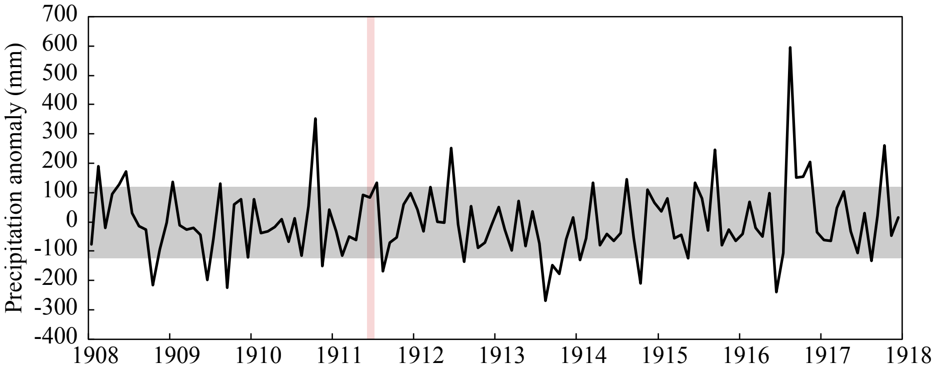

125°
130°
30°
25°
20°
East China Sea
Amami archipelago
Ryukyu Islands
Taiwan
Kikai Island
76 mm/yr
82 mm/yr
Pacific Ocean
km
0 100
200 m
Kikai Island
Akaren
Nakazato
Araki
2 km
Shiomichi Bay
Somachi Port

Fig. S2


700
600
500
400
300
200
100
0
-100
-200
-300
-400
Precipitation anomaly (mm)
1908
1909
1910
1911
1912
1913
1914
1915
1916
1917
1918