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Coral record reveals terrestrial controls on zinc in the northern South China Sea

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Abstract

Zinc (Zn), an essential trace nutrient in marine ecosystems, exhibits a nutrient-type vertical distribution. Increasing anthropogenic inputs have significantly modified the Zn fluxes in coastal surface waters, disrupting the natural biogeochemical cycling of Zn. Although the spatial distributions of Zn in seawater and sediments have been extensively investigated, the lack of long-term, high-resolution records restricts our understanding of the behavior of Zn in marine systems. Here, we present annually resolved Zn/Ca ratios obtained from a continuously growing *Porites lutea* coral in Xiaodonghai Bay, Sanya, northern South China Sea, to reconstruct the variability of surface seawater Zn from 1870 to 2006. Our results suggest that the trends of surface seawater Zn are influenced by submarine groundwater discharge, and the extreme values are mainly related to local military activities and infrastructure construction. This study offers novel perspectives on the Zn biogeochemistry in coastal seawater and emphasizes the key role of terrestrial input in coastal Zn budgets.

Key words South China Sea, *Porites* coral, Hainan Island, zinc, submarine groundwater discharge

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1 Introduction

Zinc (Zn), an essential trace element in the ocean, acts as a critical cofactor for numerous phytoplankton enzymes, supporting fundamental processes, including dissolved inorganic carbon assimilation and organic phosphorus utilization (Twining and Baines, 2013). By regulating these biochemical functions, Zn plays a pivotal role in controlling marine primary productivity and shaping the community structure of ecosystems (Morel and Price, 2003). The distribution of Zn in the water column typically follows a classic nutrient-type profile, with concentrations increasing with depth (Vance et al., 2014). While Zn deficiency can limit phytoplankton growth at the ocean surface (Price and Morel, 1990), elevated Zn concentrations constitute a potential threat, as Zn is toxic at high concentrations, while it has the capacity for bioaccumulation through marine food webs, ultimately reaching humans and posing health risks (Schoofs et al., 2024). Therefore, monitoring the dynamic changes of dissolved Zn, along with investigating its sources and controlling factors, is essential for advancing our understanding of its marine biogeochemical cycling, accurately assessing its ecological and environmental impacts, and providing scientifically sound marine protection strategies.

In the ocean, dissolved Zn exists primarily in the form of organic and inorganic complexes, with free Zn^{2+} ions constituting only a minor fraction. Its oceanic residence

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time is relatively short (about 11 000 years), with concentrations ranging from <0.1 nmol/kg to 10.0 nmol/kg (Sinoir et al., 2012) and the total oceanic mass estimated at about 1.35×10^{21} kg (Little et al., 2014). The marine Zn cycle is primarily sustained by inputs from natural sources; nevertheless, the influence of anthropogenic emissions has been increasing. Mediation occurs through three principal pathways: terrestrial runoff (water), atmospheric deposition (air), and sediment remobilization (sediments). Owing to the technological advancement and consequent amplified human influence on this cycle, in industrialized regions, substantial quantities of Zn-bearing aerosols from industrial emissions and fossil fuel combustion are delivered to the ocean via atmospheric deposition (Luo et al., 2022). Furthermore, land-use changes can result in increased weathering rates, releasing previously sequestered Zn, which can be subsequently transported to coastal and open oceans through terrestrial and atmospheric fluxes (Liu et al., 2023). The current understanding of seawater Zn dynamics largely relies on discrete sediment (Nisha and Achyuthan, 2014; Ochieng et al., 2009; Sun et al., 2013; Yu et al., 2022) or water column samples (Conway and John, 2014; Lemaitre et al., 2020); hence, the temporal and spatial resolution is often limited. This lack of continuous, high-resolution records hinders the mechanistic understanding of the biogeochemical behavior of Zn and its responses to environmental changes on relevant timescales.

Shallow-water reef-building corals, thriving in tropical and subtropical oceans, have been established as natural archives for reconstructing historical marine environmental conditions owing to their environmental sensitivity, continuous growth with clear annual banding, and broad spatial coverage (Kinzie III and Buddemeier, 1996). A key mechanism is the incorporation of Zn^{2+} into the aragonite skeleton, where it substitutes for Ca^{2+} proportionally to its ambient seawater concentration, allowing coral skeletons to record the variations of surface seawater Zn on a monthly to annual timescale (Xiao et al., 2020). This proxy has been applied to investigate anthropogenic influences on coastal Zn cycles over decadal scales (Wang et al., 2011a), examine the inhibitory effect of ocean acidification on Zn uptake under controlled experimental conditions (Houlbrèque et al., 2012), and explore the application of Zn isotopes ($\delta^{66}Zn$) in corals (Liu et al., 2022; Xiao et al., 2020). However, existing studies present notable gaps: long-term reconstructions often lack an integrated analysis of concurrent natural processes, experimental findings require validation with long-term, *in-situ* records, and isotopic studies that suggest major biological overprinting may limit their direct paleoenvironmental application (Xiao et al., 2020). Importantly, only few studies have systematically deconvolved the sources and drivers of the variability of coastal seawater Zn using high-resolution, temporally extended coral proxy records.

This study presents an annually resolved record of Zn/Ca ratios from a *Porites lutea* coral in Xiaodonghai Bay, northern South China Sea. We reconstructed a multi-decadal time series of surface seawater Zn concentrations in the Sanya coastal region. By analyzing the temporal variability of this record and examining the correlations it with key environmental and climatic parameters, we aimed to disentangle and evaluate the relative impacts of natural processes and anthropogenic activities on the changing Zn content in these coastal surface waters.

2 Study area, materials and methods

2.1 *Study area*

Xiaodonghai Bay is located in southeastern Sanya at the southern tip of Hainan Island. The bay exhibits a crescent-shaped morphology, with the terrain sloping from north to south, involving low hills in the northern part and gentle sandy beaches in the south. This area is highly sensitive to variations in environmental conditions, such as sea surface temperature, salinity, and water turbidity (Wang et al., 2011b); it experiences a tropical maritime monsoon climate, with prevailing southwesterly winds during summer. The coastal dynamics are influenced by tides and wind waves, featuring a small tidal range and pronounced diurnal tidal inequality. The annual average temperature is 25.5℃, and the mean annual precipitation is about 1 400 mm. The rainy season spans from May to October and accounts for about 90% of the total annual rainfall. The bay maintains good water quality and high light penetration (suspended sediment concentrations: about 17.28 mg/L; chlorophyll *a*: about 1.93 mg/m^3), thereby supporting extensive coral reef communities (Yao et al., 2025). In 1990, Xiaodonghai Bay was designated a national nature reserve—the first area in China to be recognized for its importance in relation to coral reef protection. Research has indicated the presence of groundwater discharge and upwelling in the coastal coral reef areas of Sanya (Guo et al., 2023; Lu et al., 2024; Wang et al., 2014).

2.2 *Coral core collection and preparation*

The *Porites* coral sample used in this study was collected in May 2006 from Xiaodonghai Bay (18°12′N, 109°30′E) and labeled as XL1 (Fig. 1). After transportation to the laboratory, the sample was rinsed with clean water to remove surface impurities and air-dried. A DJ-800 rock cutting saw was then used to slice the core along its major growth axis into 8 mm thick slabs. Medical X-ray radiography was subsequently employed to obtain X-ray images (Fig. 1), revealing clear and regular annual density bands that guided subsequent sampling. To eliminate surface organic matter and contaminants, the prepared slabs were soaked in 10% H_2O_2 for 48 h, followed by ultrasonic cleaning with ultrapure water (repeated three times). Finally, the slabs were dried in an oven at 60℃ for

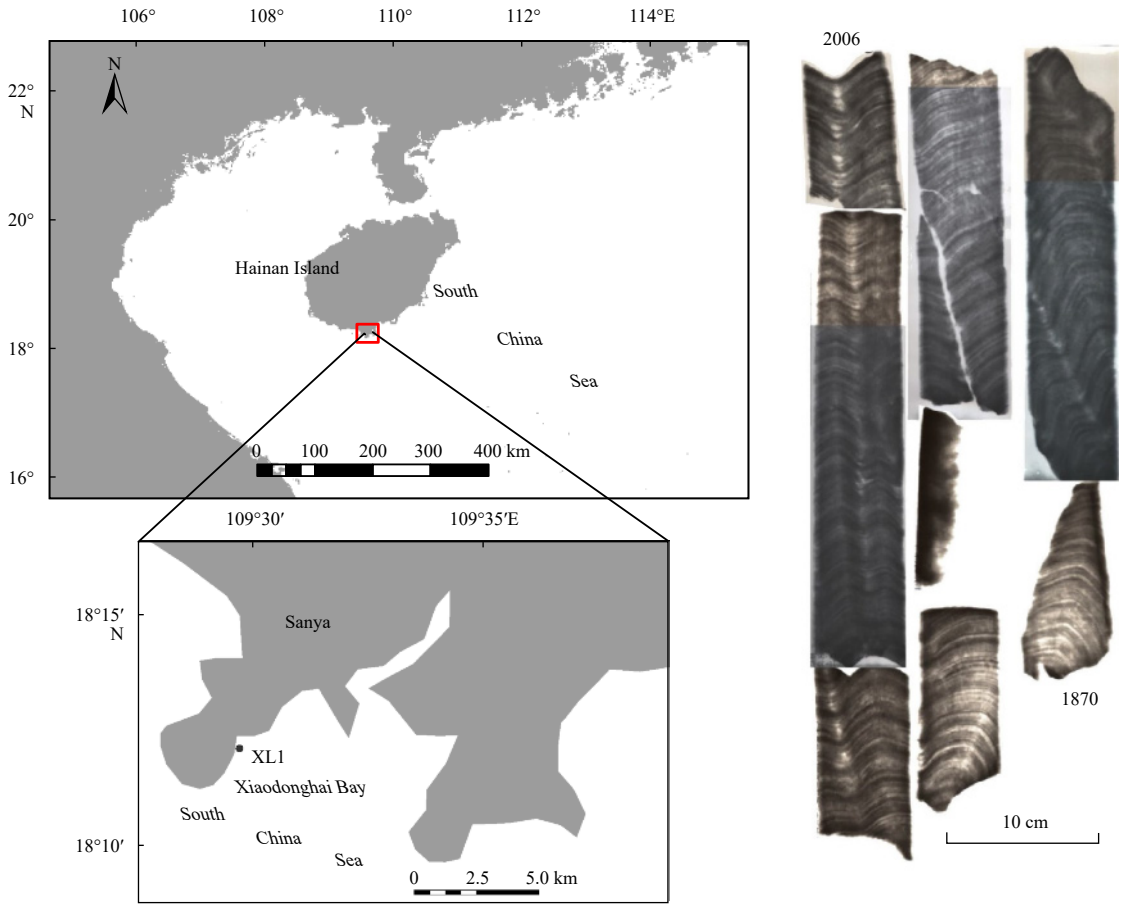


Fig. 1. Location map of the sampling site and the X-ray image of the coral specimen XL1.

48 h. After pretreatment, 137 subsamples were continuously scraped along the growth bands of the coral slab using a ceramic knife and ground into powder with an agate mortar and pestle for measurement. The chronological framework of the coral was established based on the annual growth bands. Sample XL1 includes skeletal material spanning from 1870 to 2006, providing a 137-year geochemical record (Guo et al., 2023).

2.3 *Geochemical analysis*

Sample analysis was conducted using a Thermo X-Series Ⅱ inductively coupled plasma mass spectrometer at the Radiogenic Isotope Facility of the University of Queensland. All plastic containers used in the experiment were pre-cleaned following a strict acid-cleaning procedure to ensure contamination-free processing. Certified geochemical reference materials, i.e., W-2 and BIR-1 from the United States Geological Survey and JCp-1 from the Geological Survey of Japan, were prepared from premade stock solutions and diluted with 2% HNO_3 to 6 ng/mL for use as external calibration standards. Approximately 2.5–3.0 mg of homogenized sample powder was weighed with precision and dissolved in 10 mL of 2% HNO_3 spiked with internal standards (^{6}Li, ^{61}Ni, ^{103}Rh, ^{115}In, and ^{187}Re) in low-density polyethylene tubes. Each sample was measured four times, with relative standard deviations <5% for all runs. For more details on the analytical procedures, we refer to Nguyen et al. (2013) and Song et al. (2014).

2.4 *Climate and environmental data*

Submarine groundwater discharge (SGD) rates were reconstructed using rare earth element (REE) data from the coral core used also in Jiang et al. (2018). Rainfall, air temperature, and wind speed data were obtained from the Sanya Meteorological Station. Upwelling intensity data were derived from Liu et al. (2009).

3 Results

3.1 *Temporal variability of coral Zn/Ca ratios*

The skeletal material of sample XL1 provide a continuous 137-year geochemical record spanning 1870 to 2006. As shown in Fig. 2, the annual Zn/Ca ratios in sample XL1 range from 0.59 μmol/mol to 60.18 μmol/mol, with a mean value of (6.34 ± 8.44) μmol/mol. This range is consistent with the Zn levels reported for *Porites* corals from the relatively pristine Xisha Islands (Zhou et al., 2007). To assess the anthropogenic influence, the record was subdivided into three phases based on the intensity of local human activity: P1 (1870–1894, low activity), P2 (1895–1977, wartime periods), and P3 (1978–2006, rapid industrialization) (Liu et al., 2023).

In P1, the Zn/Ca ratios exhibit low-amplitude variabil-

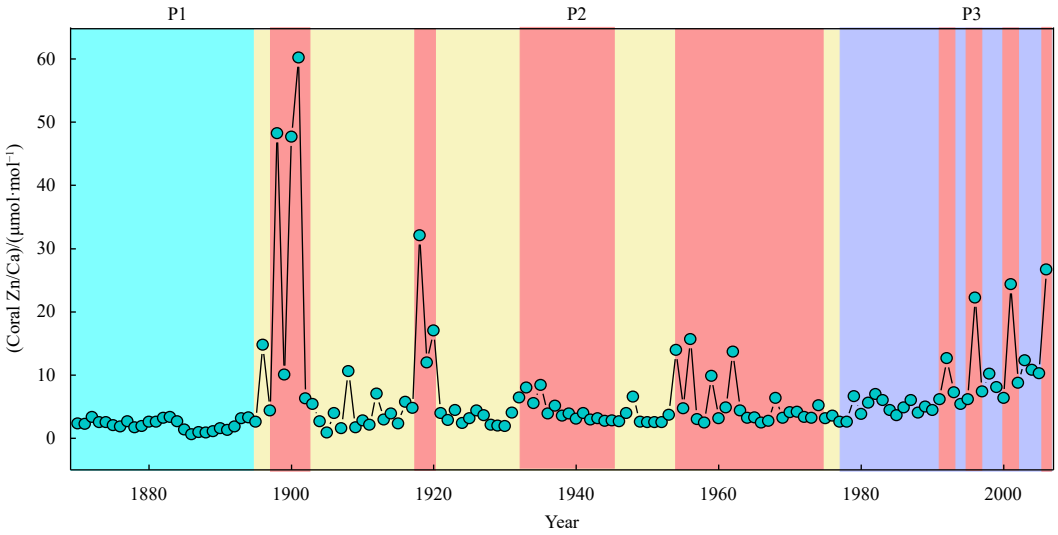


Fig. 2. Zn/Ca ratios in coral XL1 from 1870 to 2006. The blue background corresponds to Phase P1, the yellow background corresponds to Phase P2, and the purple background corresponds to Phase P3. The red background emphasizes the years when major human-related events took place: the Spanish-American War in the Philippines (1898), the Guangdong-Guangxi War (1920–1921), the Second Sino-Japanese War (1931–1945) and the Vietnam War (1955–1975), the construction of Sanya Phoenix Airport (1991–1994), the commissioning of the Yalong Bay Wastewater Treatment Plant (1996), the construction of Sanya International Passenger Port (2001), and the construction of Nanshan Cargo Port (2005).

ity without pronounced peaks. In contrast, three distinct high-value intervals are evident in P2: 1895–1905, 1913–1921, and 1959–1975. These periods correspond to major regional conflicts, including the Spanish-American War in the Philippines, the Guangdong-Guangxi War, the Second Sino-Japanese War and the Vietnam War. During the Spanish-American War in the Philippines around 1898, the primary operational area of the US Navy was the region that included the Philippines and southern China. Thus, it is hypothesized that this war activity could have had an influence on the corals of Hainan Island. During the Guangdong-Guangxi War (1920–1921), military operations were carried out directly on Hainan Island, which might be the cause of the peaks around 1920. The Vietnam War (1955–1975) took place in the vicinity of Hainan Island. Starting from 1964, the main battlefield shifted to southern Vietnam relatively far from Hainan Island, and the impacts of military operations on the Zn/Ca ratios of coral might decrease. It is worth noting that during the Second Sino-Japanese War (1931–1945), coral Zn/Ca ratios showed relatively high values in some individual years. This phenomenon could be related to the limited military operations of the Japanese forces during this period. The reason may be that for most of this period, Hainan Island was under Japanese occupation, and only sporadic battles took place. During other wars, there were no clearly distinguishable extreme points in the time series of coral Zn/Ca ratios. This might be related to the fact that the areas affected by the wars were relatively far from Hainan Island. Such elevated values have previously been linked to potential trace metal releases from military activities, including naval operations and ordnance disposal (Sanderson et al., 2010; Song et al., 2014; Wang et al., 2011a). P3 exhibits the highest mean Zn/Ca ratio [(8.59 ± 5.95) μmol/mol; range: 2.63–26.70 μmol/mol], with several sharp peaks coinciding with phases of large-scale infrastructure construction on Hainan Island. The rapid increase after 1990 might be related to the acceleration of chemical weathering caused by human activities, which is supported by the Zn data from Liu et al. (2023).

3.2 *Zn concentration in surface seawater*

Our study employs the Zn/Ca ratio, which offers a more accurate representation of seawater content than the direct use of Zn content by Song et al. (2014). To quantitatively reconstruct seawater Zn concentrations from the record of coral Zn/Ca ratios, we applied the partition coefficient expression (Shen and Boyle, 1987), i.e., K_D = [Metal (Me)/Ca]$_{coral}$ / (Me/Ca)$_{seawater}$, assuming a constant seawater Ca concentration of 10.3 mmol/kg (Kelly et al., 2009; Quinby-Hunt and Turehian, 1983). For the specific Zn partition coefficient, we adopted the value of 1.76 determined for *P. lutea* from the northern South China Sea (Jiang et al., 2020). Based on this coefficient, the calculated average surface seawater Zn concentration in Xiaodonghai Bay is about 37.07 nmol/L. This value is below the reported global average of 76.5 nmol/L (Abdel-Salam, 1989) and according to Table 1 significantly lower than most values occurring in other anthropogenically impacted coastal waters worldwide. Within the South China Sea, the concentration is comparable to or slightly higher than the levels reported in the relatively undisturbed area of Xisha Islands, which is consistent with the national nature reserve status of the site.

Table 1. Zn concentrations in surface seawater collected from the published references

Study sides	Zn concentration/ (nmol·L^{-1})	References
Xiaodonghai Bay	37.07	This study
Daya Bay	56.1−211.4	Yang et al. (2017)
Luhuitou Bay	60.7−224.4	Yang et al. (2017)
Xisha Islands	10.1 (average)	Zhou et al. (2007)
Northern Hainan Island	548.6 (average)	Zeng et al. (2023)
Beibu Gulf	63.2−484.9	Lao et al. (2019)
Southern Yellow Sea	95.0	He et al. (2008)
Al Lith Bay	101.2	Alharbi et al. (2024)
Jeddah Bay	12.59	Al-Farawati et al. (2011)
Northern Nile Delta	40.8−336.5	Okbah and Nasr (2006)
Amazon Basin	0.45−148.78	Seyler and Boaventura (2003)
Bohai Gulf	24.9−281.4	Lin et al. (2020)

4 Discussion

4.1 *Sources of surface seawater Zn*

The ocean serves as a major sink for most trace metals (Sabarathinam et al., 2019). According to previous research (Liu et al., 2023), the surface seawater Zn concentration is influenced by runoff input, upwelling, and human activities. Elevated Zn levels are typically associated with historical natural events (such as volcanic eruptions, typhoons, and upwelling) and pollutant inputs. Song et al. (2014) utilized principal component analysis and correlation analysis in mathematical statistics to focus on 10 elements in coral from Xiaodonghai Bay. They concluded that Zn was associated with war and military activities based on the extreme value of Zn. To investigate the factors influencing the temporal variations of Zn/Ca ratios in coral skeletons from Xiaodonghai Bay and analyze the sources and main controlling factors of surface seawater Zn in the northern South China Sea, the following potential drivers were discussed: (1) terrestrial input, (2) upwelling, and (3) human activities such as shipping.

4.1.1 *Terrestrial input*

We evaluated the potential influence of terrestrial input—a major pathway allowing trace metals to enter the ocean via surface runoff and SGD (Wang et al., 2010)—on the Zn record from Xiaodonghai Bay. Rainfall is a primary driver of runoff flux; hence, we used local precipitation as a proxy for the terrestrial Zn supply. Correlation analysis between the 3-year smoothed record of coral Zn/Ca ratios (1959–2006) and the precipitation data revealed no statistically significant relationship (r = 0.266, p > 0.05). This lack of correlation is consistent with the specific geomorphic setting of the site. The XL1 coral site is distant from major river systems of Hainan Island (i.e., Nandu River, Changhua River and Wanquan River). The nearest river, namely the Sanya River, has limited discharge and is hydrologically isolated from the bay by the Luhuitou Peninsula. Consequently, the study site is effectively non-estuarine, and fluvial Zn inputs are likely negligible, with surface runoff exerting an insignificant influence on the observed temporal variations of dissolved Zn in the surface seawater in Xiaodonghai Bay during the study period.

SGD is a well-documented pathway allowing the transport of terrestrial materials, including nutrients and trace metals, to coastal oceans (Moore, 1996; Li and Wang, 2015). Given the substantial SGD flux reported in the adjacent Sanya Bay (Guo et al., 2023; Lu et al., 2024), we evaluated their potential influence on the surface seawater Zn in Xiaodonghai Bay. The geological setting of Hainan Island, comprising metamorphic, volcanic, and carbonate rocks (Liang, 2018; Chao et al., 2016), constitutes a source of Zn. The oxidative weathering of Zn-bearing sulfide minerals in these lithologies can release soluble Zn into groundwater (Kim et al., 2020), which is then facilitated by active water-rock interactions within the local karst and fissured aquifers (Liang, 2018; Lu et al., 2024).

To assess this linkage, we compared the record of coral Zn/Ca ratios with a long-term reconstruction of the SGD flux for the Sanya coast based on coral REE/Ca ratios (Jiang et al., 2018). Pearson's correlation analysis revealed a significant positive relationship between the two-time series (r = 0.46, p < 0.01; Fig. 3). This correlation indicates that SGD contributes to the Zn levels in the surface waters in Xiaodonghai Bay and partially explains the temporal pattern preserved in the coral skeleton, which is consistent with findings from other coastal systems (Tovar-Sánchez et al., 2014). However, a notable divergence in the trends of the Zn/Ca ratios and SGD flux is evident after about 1990. This decoupling likely reflects the increasing overprint of anthropogenic inputs since the 1990s driven by rapid economic development, coastal construction, aquaculture, and intensified maritime activities on Hainan Island (Luo et al., 2014; Yang et al., 2017). Further analysis of the SGD–Zn relationship in relation to anthropogenic perturbations is presented in Section 4.1.3.

4.1.2 *Upwelling*

Coastal upwelling is a key mesoscale oceanographic process capable of altering surface water chemistry by transporting deeper waters rich in nutrients and trace metals to the photic zone. Given that dissolved Zn exhibits a nutrient-type vertical profile, its surface concentration can potentially be modulated by upwelling intensity. Upwelling has been identified as a persistent feature in this study region, with records indicating significant intensification over the past century (Liu et al., 2009). Therefore, we investigated the potential link between upwelling and the record of coral Zn/Ca ratios. Pearson's correlation analysis between the 3-year smoothed coral Zn/Ca ratios (1906–1991) and a regional upwelling index showed no statistically significant relationship (Fig. 4). Hence, up-

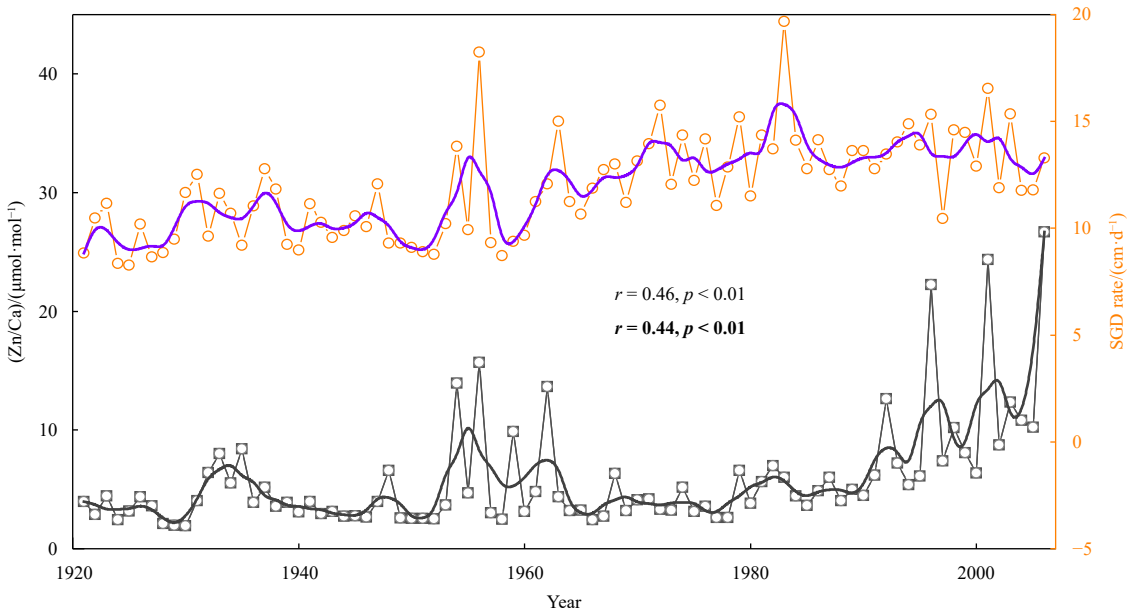


Fig. 3. Comparison between Zn/Ca ratios in coral and reconstructed SGD flux from 1921 to 2006 (the thick lines represent the 3-year moving average data, the bold characters represent the correlation coefficients after a 3-year moving average).

welling may not be the primary influencing factor surface seawater Zn because of the relatively shallow depth in the study area or the masking of its signal by terrestrial input.

4.1.3 *Possible anthropogenic sources*

Anthropogenic emissions have dramatically altered the global Zn cycle, with their current estimated level exceeding that of natural fluxes by approximately one order of magnitude (Kalisinska, 2019; Rauch and Pacyna, 2009). In the study region, the rapid economic development of Hainan Island has been accompanied by increased coastal construction, fossil fuel combustion, transportation, and tourism, all of which are potential contributors of heavy metals to the marine environment. Globally, such activities increase metal inputs via riverine transport and atmospheric deposition of aerosols (Duce et al., 1991; Guo et al., 2012; Chester and Jickells, 2012; Nriagu and Pacyna, 1988; Pacyna and Pacyna, 2001). Elevated Zn levels in modern coral skeletons are widely interpreted as anthropogenic signature (Al-Rousan et al., 2007; Esslemont, 2000; Guzmán and Jiménez, 1992; Hanna and Muir, 1990; Ramos et al., 2004; Runnalls and Coleman, 2003). The fluctuating increase in our record of coral Zn/Ca ratios during the late 20th century aligns with the period of accelerated industrialization and urbanization in Sanya. Atmospheric deposition from fossil fuel combustion and transportation, including vehicle wear, ship antifouling paints, and fuel emissions, constitutes a major pathway (Yang et al., 2011). Additional local sources include untreated wastewater, port operations, and maritime activities (Yang et al., 2011).

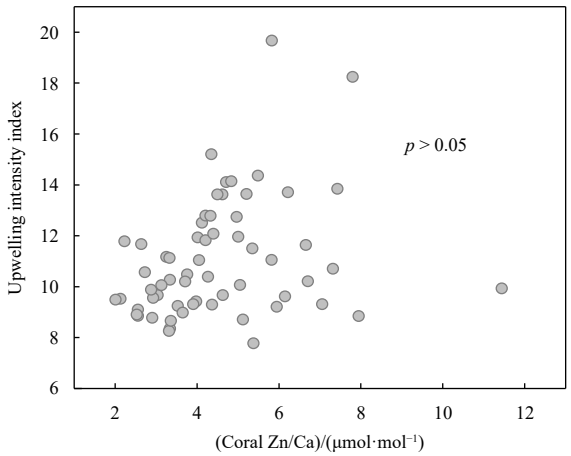


Fig. 4. Correlation between 3-year moving average of coral Zn/Ca ratios and a regional upwelling index derived from Liu et al. (2009) from 1906 to 1991.

To quantify key anthropogenic drivers, we correlated the record of coral Zn/Ca ratios with proxies for local industrial and economic activities (Fig. 5). The analysis revealed significant positive correlations with provincial coal (r = 0.67, p < 0.01) and petroleum (r = 0.62, p < 0.01) consumption. In contrast, no significant correlation was found with cargo throughput at Sanya port (r = 0.15, p > 0.05). These results strongly suggest regional fossil fuel combustion, rather than general maritime trade volume, as the primary anthropogenic source influencing dissolved Zn concentrations in the surface waters in Xiaodonghai Bay during the study period.

5 Conclusions

Our record of coral Zn/Ca ratios indicates that the regional anthropogenic forcing in Xiaodonghai Bay has be-

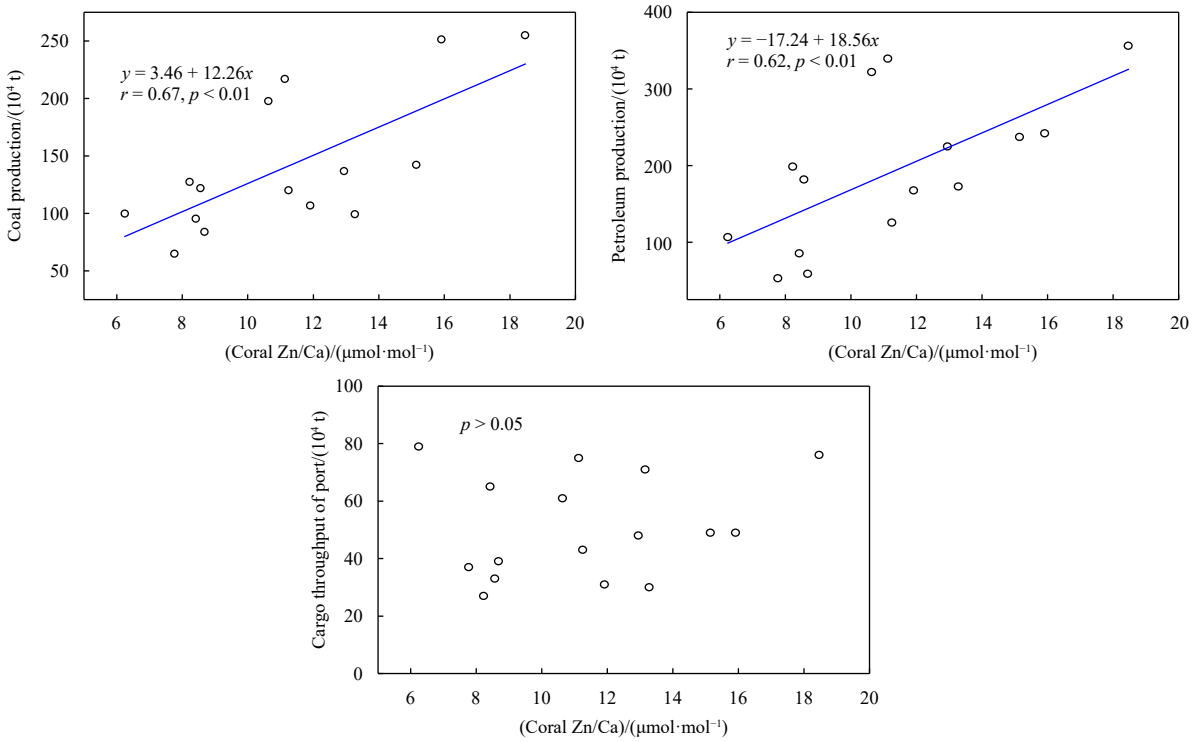


Fig. 5. Correlation between 3-year moving average of coral Zn/Ca ratios and coal consumption, petroleum consumption, and cargo throughput from 1991 to 2006.

come increasingly significant since the 1990s. Research has suggested that human-induced soil and rock weathering associated with large-scale construction may release dissolved Zn at magnitudes that surpass previous estimates. In our record of coral Zn/Ca ratios, distinct peaks coincide with major infrastructure developments in Sanya. This synchronicity suggests that the unprecedented economic and population growth on Hainan Island has enhanced weathering fluxes, contributing to elevated Zn levels in coastal waters. To assess the robustness of the coral Zn/Ca ratios as a proxy against sporadic anthropogenic inputs, we re-evaluated their relationship with SGD after excluding data from major wartime periods and phases of infrastructure construction. The correlation with the reconstructed SGD flux remained significantly positive, with no substantial change in the correlation coefficient, whereas the correlation with precipitation remained insignificant. Hence, the primary long-term trend in the record of coral Zn/Ca ratios reliably reflects the SGD variability, while isolated anthropogenic pulses do not dominate the multidecadal signal. Consequently, anthropogenic Zn inputs to this coastal system —albeit detectable— have remained relatively limited within the context of the recorded long-term natural flux.

References

Abdel-Salam H M. 1989. The physiological effects of environmental stress on Atlantic reef corals [dissertation]. Georgia: University of Georgia

Al-Farawati R K, Gazzaz M O, El Sayed M A, et al. 2011. Temporal and spatial distribution of dissolved Cu, Ni and Zn in the coastal waters of Jeddah, eastern Red Sea. Arabian Journal of Geosciences, 4(7–8): 1229–1238, doi: 10.1007/s12517-010-0137-y

Alharbi T, El-Sorogy A S, Al-Kahtany K. 2024. Distribution and comprehensive risk evaluation of Cr, Cd, Fe, Zn, and Pb from Al lith coastal seawater, Saudi Arabia. Water, 16(13): 1923, doi: 10.3390/w16131923

Al-Rousan S A, Al-Shloul R N, Al-Horani F A, et al. 2007. Heavy metal contents in growth bands of *Porites* corals: record of anthropogenic and human developments from the Jordanian Gulf of Aqaba. Marine Pollution Bulletin, 54(12): 1912–1922, doi: 10.1016/j.marpolbul.2007.08.014

Chao Huixia, Han Xiaohui, Yang Zhihua, et al. 2016. New exploration of geotectonic characteristics of Hainan Island. Earth Science Frontiers (in Chinese), 23(4): 200–211

Chester R, Jickells T. 2012. Marine Geochemistry. Hoboken: John Wiley & Sons, Ltd

Conway T M, John S G. 2014. The biogeochemical cycling of zinc and zinc isotopes in the north Atlantic Ocean. Global Biogeochemical Cycles, 28(10): 1111–1128, doi: 10.1002/2014GB004862

Duce R A, Liss P S, Merrill J T, et al. 1991. The atmospheric input of trace species to the world ocean. Global Biogeochemical Cycles, 5(3): 193–259, doi: 10.1029/91GB01778

Esslemont G. 2000. Heavy metals in seawater, marine sediments and corals from the Townsville section, Great Barrier Reef Marine Park, Queensland. Marine Chemistry, 71(3–4): 215–231, doi: 10.1016/S0304-4203(00)00050-5

Guo Ning, Jiang Wei, Yu Kefu, et al. 2023. Coral reveals a transition in sources of seawater vanadium from submarine

groundwater discharge to upwelling in the northern South China Sea. Journal of Geophysical Research: Oceans, 128(11): e2023JC020104, doi: 10.1029/2023JC020104

Guo Cui, Yu Jianzhen, Ho T Y, et al. 2012. Dynamics of phytoplankton community structure in the South China Sea in response to the east Asian aerosol input. Biogeosciences, 9(4): 1519–1536., doi: 10.5194/bg-9-1519-2012

Guzmán H M, Jiménez C E. 1992. Contamination of coral reefs by heavy metals along the Caribbean coast of central America (Costa Rica and Panama). Marine Pollution Bulletin, 24(11): 554–561, doi: 10.1016/0025-326X(92)90708-E

Hanna R G, Muir G L. 1990. Red sea corals as biomonitors of trace metal pollution. Environmental Monitoring and Assessment, 14(2–3): 211–222, doi: 10.1007/BF00677917

He Zhipeng, Song Jinming, Zhang Naixing, et al. 2008. Variation characteristics and controlling factors of heavy metals in the south Yellow Sea surface seawaters. Environmental Science (in Chinese), 29(5): 1153–1162, doi: 10.1007/s10661-008-0552-7

Houlbrèque F, Rodolfo-Metalpa R, Jeffree R, et al. 2012. Effects of increased pCO_2 on zinc uptake and calcification in the tropical coral *Stylophora pistillata*. Coral Reefs, 31(1): 101–109, doi: 10.1007/s00338-011-0819-2

Jiang Wei, Yu Kefu, Song Yinxian, et al. 2018. Coral geochemical record of submarine groundwater discharge back to 1870 in the northern South China Sea. Palaeogeography, Palaeoclimatology, Palaeoecology, 507: 30–38

Jiang Wei, Yu Kefu, Wang Ning, et al. 2020. Distribution coefficients of trace metals between modern coral-lattices and seawater in the northern South China Sea: species and SST dependencies. Journal of Asian Earth Sciences, 187: 104082, doi: 10.1016/j.jseaes.2019.104082

Kalisinska E. 2019. Mammals and Birds as Bioindicators of Trace Element Contaminations in Terrestrial Environments: An Ecotoxicological Assessment of the Northern Hemisphere. Cham: Springer, 363–412

Kelly A E, Reuer M K, Goodkin N F, et al. 2009. Lead concentrations and isotopes in corals and water near Bermuda, 1780–2000. Earth and Planetary Science Letters, 283(1–4): 93–100, doi: 10.1016/j.epsl.2009.03.045

Kim D M, Oh Y S, Lee J S. 2020. $\delta^{34}S$ and $\delta^{18}O$ of sulfates and Zn/Cd ratios reveal the cause of soil and groundwater contamination in metalliferous mining areas. Journal of Geochemical Exploration, 209: 106437, doi: 10.1016/j.gexplo.2019.106437

Kinzie III R A, Buddemeier R W. 1996. Reefs happen. Global Change Biology, 2(6): 479–494, doi: 10.1111/j.1365-2486.1996.tb00062.x

Lao Qibin, Su Qizhong, Liu Guoqiang, et al. 2019. Spatial distribution of and historical changes in heavy metals in the surface seawater and sediments of the Beibu Gulf, China. Marine Pollution Bulletin, 146: 427–434, doi: 10.1016/j.marpolbul.2019.06.080

Lemaitre N, de Souza G F, Archer C, et al. 2020. Pervasive sources of isotopically light zinc in the north Atlantic Ocean. Earth and Planetary Science Letters, 539: 116216, doi: 10.1016/j.epsl.2020.116216

Li Hailong, Wang Xuejing. 2015. Submarine groundwater discharge: a review. Advances in Earth Science (in Chinese), 30(6): 636–646, doi: 10.5194/hess-2017-142-rc1

Liang Guanghe. 2018. A study of the genesis of Hainan Island. Geology in China (in Chinese), 45(4): 693–705

Lin Heshan, Li Hongjun, Yang Xiaolong, et al. 2020. Comprehensive investigation and assessment of nutrient and heavy metal contamination in the surface water of coastal Bohai Sea in China. Journal of Ocean University of China, 19(4): 843–852, doi: 10.1007/s11802-020-4283-x

Little S H, Vance D, Walker-Brown C, et al. 2014. The oceanic mass balance of copper and zinc isotopes, investigated by analysis of their inputs, and outputs to ferromanganese oxide sediments. Geochimica et Cosmochimica Acta, 125: 673–693, doi: 10.1016/j.gca.2013.07.046

Liu Yi, Chen Maoqing, Zhang Ting, et al. 2023. Isotope compositions of century-long corals reveal significant dissolved Cu, Zn fluxes from human-accelerated weathering into the ocean. Geophysical Research Letters, 50(7): e2022GL102482, doi: 10.1029/2022GL102482

Liu Yang, Kuang Weiming, Xu Jing, et al. 2022. Distribution, source and risk assessment of heavy metals in the seawater, sediments, and organisms of the Daya Bay, China. Marine Pollution Bulletin, 174: 113297, doi: 10.1016/j.marpolbul.2021.113297

Liu Yi, Peng Zicheng, Wei Gangjian, et al. 2009. Variation of summer coastal upwelling at northern South China Sea during the last 100 years. Geochimica (in Chinese), 38(4): 317–322

Lu Li, Fan Lianjie, Pei Lixin, et al. 2024. Groundwater resources and environmental geologic problems on Hainan Island. Geology in China (in Chinese), 51(2): 499–510

Luo Wanci, Su Bo, Liu Xiong, et al. 2014. Spatial and temporal distributions and influence factors of the dissolved heavy metals in surface water in the mangrove reserve at the Beilun River estuary in Guangxi. Marine Science Bulletin (in Chinese), 33(6): 668–675

Luo Manhua, Zhang Yan, Li Hailong, et al. 2022. Pollution assessment and sources of dissolved heavy metals in coastal water of a highly urbanized coastal area: the role of groundwater discharge. Science of the Total Environment, 807: 151070, doi: 10.1016/j.scitotenv.2021.151070

Moore W S. 1996. Large groundwater inputs to coastal waters revealed by ^{226}Ra enrichments. Nature, 380(6575): 612–614, doi: 10.1038/380612a0

Morel F M M, Price N M. 2003. The biogeochemical cycles of trace metals in the oceans. Science, 300(5621): 944–947, doi: 10.1126/science.1083545

Nguyen A D, Zhao Jianxin, Feng Yuexing, et al. 2013. Impact of recent coastal development and human activities on Nha Trang Bay, Vietnam: evidence from a *Porites lutea* geochemical record. Coral Reefs, 32(1): 181–193, doi: 10.1007/s00338-012-0962-4

Nisha V, Achyuthan H. 2014. Geochemical evaluation of sea

surface sediments along the continental shelf, south east coast of India. Indian Journal of Geo-Marine Sciences, 43(2): 241–251

Nriagu J O, Pacyna J M. 1988. Quantitative assessment of worldwide contamination of air, water and soils by trace metals. Nature, 333(6169): 134–139, doi: 10.1038/333134a0

Ochieng E Z, Lalah J O, Wandiga S O. 2009. Anthropogenic sources of heavy metals in the Indian Ocean coast of Kenya. Bulletin of Environmental Contamination and Toxicology, 83(4): 600–607, doi: 10.1007/s00128-009-9807-4

Okbah M A, Nasr S M. 2006. Dissolved trace-metal concentrations along the Mediterranean Sea, to the north of the Nile Delta Region, Egypt. Chemistry and Ecology, 22(2): 125–135, doi: 10.1080/02757540600579268

Pacyna J M, Pacyna E G. 2001. An assessment of global and regional emissions of trace metals to the atmosphere from anthropogenic sources worldwide. Environmental Reviews, 9(4): 269–298, doi: 10.1139/a01-012

Price N M, Morel F M M. 1990. Cadmium and cobalt substitution for zinc in a marine diatom. Nature, 344(6267): 658–660, doi: 10.1038/344658a0

Quinby-Hunt M S, Turehian K K. 1983. Distribution of elements in sea water. Eos, Transactions American Geophysical Union, 64(4): 130

Ramos A A, Inoue Y, Ohde S. 2004. Metal contents in *Porites* corals: anthropogenic input of river run-off into a coral reef from an urbanized area, Okinawa. Marine Pollution Bulletin, 48(3–4): 281–294, doi: 10.1016/j.marpolbul.2003.08.003

Rauch J N, Pacyna J M. 2009. Earth's global Ag, Al, Cr, Cu, Fe, Ni, Pb, and Zn cycles. Global Biogeochemical Cycles, 23(2): GB2001, doi: 10.1029/2008gb003376

Runnalls L A, Coleman M L. 2003. Record of natural and anthropogenic changes in reef environments (Barbados West Indies) using laser ablation ICP-MS and sclerochronology on coral cores. Coral Reefs, 22(4): 416–426, doi: 10.1007/s00338-003-0349-7

Sabarathinam C, Bhandary H, Al-Khalid A. 2019. A geochemical analogy between the metal sources in Kuwait Bay and territorial sea water of Kuwait. Environmental Monitoring and Assessment, 191(3): 142, doi: 10.1007/s10661-019-7219-4

Sanderson H, Fauser P, Thomsen M, et al. 2010. Environmental hazards of sea-dumped chemical weapons. Environmental Science & Technology, 44(12): 4389–4394, doi: 10.1021/es903472a

Schoofs H, Schmit J, Rink L. 2024. Zinc toxicity: understanding the limits. Molecules, 29(13): 3130, doi: 10.3390/molecules29133130

Seyler P T, Boaventura G R. 2003. Distribution and partition of trace metals in the Amazon Basin. Hydrological Processes, 17(7): 1345–1361, doi: 10.1002/hyp.1288

Shen G T, Boyle E A. 1987. Lead in corals: reconstruction of historical industrial fluxes to the surface ocean. Earth and Planetary Science Letters, 82(3–4): 289–304, doi: 10.1016/0012-821X(87)90203-2

Sinoir M, Butler E C V, Bowie A R, et al. 2012. Zinc marine biogeochemistry in seawater: a review. Marine and Freshwater Research, 63(7): 644–657, doi: 10.1071/MF11286

Song Yinxian, Yu Kefu, Zhao Jianxin, et al. 2014. Past 140-year environmental record in the northern South China Sea: evidence from coral skeletal trace metal variations. Environmental Pollution, 185: 97–106, doi: 10.1016/j.envpol.2013.10.024

Sun Weiping, Hu Chuanyu, Weng Huanxin, et al. 2013. Sources and geographic heterogeneity of trace metals in the sediments of Prydz Bay, east Antarctica. Polar Research, 32: 20049, doi: 10.3402/polar.v32i0.20049

Tovar-Sánchez A, Basterretxea G, Rodellas V, et al. 2014. Contribution of groundwater discharge to the coastal dissolved nutrients and trace metal concentrations in Majorca Island: karstic vs detrital systems. Environmental Science & Technology, 48(20): 11819–11827, doi: 10.1021/es502958t

Twining B S, Baines S B. 2013. The trace metal composition of marine phytoplankton. Annual Review of Marine Science, 5: 191–215, doi: 10.1146/annurev-marine-121211-172322

Vance D, Zhao Ye, Abouchami W, et al. 2014. Corrigendum to "Biogeochemical cycling of zinc and its isotopes in the Southern Ocean" [Geochim. Cosmochim. Acta 125 (2014) 653–672]. Geochimica et Cosmochimica Acta, 134: 342

Wang B S, Goodkin N F, Angeline N, et al. 2011a. Temporal distributions of anthropogenic Al, Zn and Pb in Hong Kong *Porites* coral during the last two centuries. Marine Pollution Bulletin, 63(5–12): 508–515, doi: 10.1016/j.marpolbul.2011.02.011

Wang Guizhi, Jing Wenping, Wang Shuling, et al. 2014. Coastal acidification induced by tidal-driven submarine groundwater discharge in a coastal coral reef system. Environmental Science & Technology, 48(22): 13069–13075., doi: 10.1021/es5026867

Wang Yue, Shen Jianwei, Wang Xu, et al. 2011b. Ree distribution pattern in the xiaodonghai fringing reef-flat sediments off sanya, hainan island and its environmental implications. Marine Geology & Quaternary Geology (in Chinese), 31(5): 59–66, doi: 10.3724/SP.J.1140.2011.05059

Wang Changyou, Wang Xiulin, Li Keqiang, et al. 2010. The estimation of copper, lead, zinc and cadmium fluxes into the sea area of the East China Sea interferenced by terrigenous matter and their environmental capacities. Haiyang Xuebao (in Chinese), 32(4): 62–76

Xiao Hangfang, Deng Wenfeng, Wei Gangjian, et al. 2020. A pilot study on zinc isotopic compositions in shallow-water coral skeletons. Geochemistry, Geophysics, Geosystems, 21(11): e2020GC009430

Yang Zhongping, Lu Wenxi, Long Yuqiao, et al. 2011. Assessment of heavy metals contamination in urban topsoil from Changchun City, China. Journal of Geochemical Exploration, 108(1): 27–38, doi: 10.1016/j.gexplo.2010.09.006

Yang Hua, Wang Shaopeng, Yu Kefu, et al. 2017. Pollution characteristics of heavy metals in seawater of coral growing regions in the northern South China Sea. Ecology and Environmental Sciences (in Chinese), 26(2): 253–260

Yao Yukun, Li Yingxin, Zhou Weihua, et al. 2025. Chlorophyll *a* and photosynthetic carbon fixation in a tropical coral reef bay (Sanya Bay) of the northern South China Sea, with special reference to the effects of solar ultraviolet radiation B. Marine Pollution Bulletin, 220: 118473, doi: 10.1016/j.marpolbul.2025.118473

Yu Xiaodong, Sun Lianpeng, Zhu Xinzhe, et al. 2022. Distribution characteristics and risk assessment of heavy metals in seawater, sediment and shellfish in the inner and outer Daya Bay, Guangdong. Frontiers in Marine Science, 9: 1064287, doi: 10.3389/fmars.2022.1064287

Zeng Weite, Zhang Dongqiang, Liu Bing, et al. 2023. Distribution, main controlling factors and pollution assessment of heavy metals in surface seawater of the northern bay of Hainan Island, South China. Journal of Tropical Oceanography (in Chinese), 42(6): 156–167

Zhou Jing, Yang Dong, Peng Zicheng, et al. 2007. The concentrations of dissolved heavy metals in Xisha waters and their influential factors. Journal of University of Science and Technology of China (in Chinese), 37(8): 1036–1042