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Baseline temperature amplifies warming-induced shifts in sediment metal(loid) lability across element-specific response regimes

Yang-Guang Gu [a,e,*], Yanpeng Gao [b], Hong-Hui Huang [a,e], Richard W. Jordan [c], Shi-Jun Jiang [d]

[a] South China Sea Fisheries Research Institute, Chinese Academy of Fishery Sciences, Guangzhou, 510300, China
[b] Institute of Environmental Health and Pollution Control, Guangdong University of Technology, Guangzhou, 510006, China
[c] Faculty of Science, Yamagata University, Yamagata, 990-8560, Japan
[d] State Key Laboratory of Marine Resource Utilization in South China Sea, Hainan University, Haikou, 570228, China
[e] Key Laboratory of Open-Sea Fishery Development, Ministry of Agriculture and Rural Affairs, Guangzhou, 510300, China

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ABSTRACT

Climate warming is expected to reshape sediment-associated metal behavior, yet whether warming responses of sediment metal(loid) lability are systematically regulated by baseline thermal conditions remains unresolved. Here, we combined diffusive gradients in thin films (DGT) measurements with controlled sediment incubations across 0–40 °C to quantify temperature-dependent lability responses of multiple metal(loid)s in coastal sediments. Distinct element-specific response regimes emerged. Redox-sensitive elements (Mn, V, and As) exhibited nonlinear increases in DGT-labile concentrations with warming, cobalt showed transitional non-monotonic behavior, whereas most particle-associated metal(loid)s displayed monotonic declines. These contrasting responses indicate that warming does not uniformly enhance sediment metal(loid) lability but reorganizes reactive metal behavior in patterns consistent with element-specific differences in solid-phase resupply and retention. Despite divergent element-specific trends, identical warming perturbations consistently induced larger relative lability changes at lower baseline temperatures. Model-based sensitivity analysis further showed that proportional warming responses were amplified under cold baseline conditions, identifying baseline temperature as a first-order regulator of sediment metal(loid) responsiveness to warming. This baseline-temperature control implies that climate warming may redistribute sediment contaminant sensitivity across thermal regimes, with cold coastal sediments exhibiting disproportionate geochemical responses. Our results provide a process-based framework linking warming, element-specific resupply kinetics, and sediment metal(loid) lability, and highlight baseline temperature as a critical but previously underrecognized control on contaminant dynamics at the sediment–water interface.

Environmental Implication

Sediment-contaminant monitoring commonly treats temperature as a contemporaneous variable, but our results show that baseline thermal conditions also shape warming-induced changes in DGT-labile metal(loid)s. Among otherwise comparable sediments, lower-baseline sites may therefore deserve greater monitoring attention even when total metal concentrations are not exceptional. Climate-sensitive assessments should integrate baseline temperature records with element-specific measurements of labile fractions rather than assume uniform responses across metals or regions. This approach can help identify geochemically sensitive sediments, prioritize monitoring sites and target elements, and detect warming-driven changes in sediment–water exchange and benthic exposure pathways.

* Corresponding author. Key Laboratory of Open-Sea Fishery Development, Ministry of Agriculture and Rural Affairs, Guangzhou, 510300, China.
E-mail addresses: sunshinegu@scsfri.ac.cn, hydrobio@163.com (Y.-G. Gu).

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1. Introduction

Temperature is a primary regulator of sediment biogeochemical processes, influencing microbial metabolism, redox transformations, diffusion kinetics, and mineral–solution equilibria (Tan et al., 2020; Peiffer et al., 2021; Jiao et al., 2024; Rose et al., 2024; Gu et al., 2026a). These processes collectively control the resupply of sediment-associated metals to porewaters and thus regulate their environmentally reactive fractions (Morford and Emerson, 1999; Li et al., 2021; Liao et al., 2023). With accelerating climate warming, understanding how temperature alters sediment metal lability has become essential for predicting benthic ecosystem responses and secondary release pathways (Obrist et al., 2018; Zitoun et al., 2024; Gu et al., 2026b).

Existing studies have shown that warming can stimulate redox cycling and enhance the release of redox-sensitive elements, while simultaneously strengthening mineral binding and complexation for other metals (Paufler et al., 2018; Chari et al., 2021; Liao et al., 2023; Gu et al., 2026b). However, most investigations have focused on individual elements or narrow temperature ranges, limiting the development of a unified understanding of temperature-driven metal lability across chemically diverse elements (Bennett and Canfield, 2020; Li et al., 2023). Furthermore, climate warming is inherently relative to baseline environmental conditions. Cold sediments may experience disproportionately large proportional changes in biogeochemical reaction rates despite small absolute temperature increases (Tan et al., 2020; Tian et al., 2023). Whether such baseline temperature effects systematically regulate sediment metal lability across climate zones remains poorly resolved.

Diffusive gradients in thin films (DGT) provide a powerful tool for quantifying kinetically labile metal fractions by integrating diffusion and solid-phase resupply (Davison and Zhang, 1994; Zhang and Davison, 1995; Li et al., 2021; Gu et al., 2025a; Gu, 2026). By coupling DGT measurements with controlled temperature manipulation, it becomes possible to isolate temperature-driven resupply dynamics and identify generalized response patterns across elements.

Here, we investigated the temperature dependence of DGT-labile metal(loid) lability in coastal sediments across a broad thermal gradient (0–40 °C) using controlled laboratory incubations. We aimed to determine whether warming responses follow consistent element-specific patterns and whether baseline temperature systematically regulates the relative sensitivity of sediment metal(loid) lability to warming. By integrating experimentally constrained temperature–response relationships with process-based interpretation, we identify distinct response regimes associated with redox-sensitive release, transitional behavior, and solid-phase-controlled suppression. We further show that identical warming perturbations generate amplified relative responses under colder baseline conditions, revealing baseline temperature as an important regulator control on warming-driven changes in sediment metal(loid) lability. This work provides a framework for understanding how climate warming may reorganize contaminant responsiveness at the sediment–water interface and supports improved prediction of climate-sensitive metal(loid) dynamics in coastal and estuarine environments.

2. Materials and methods

2.1. Study area and sediment sampling

Daya Bay is a shallow semi-enclosed drowned-valley embayment located in the northern South China Sea, covering approximately 516 km^2 with water depths ranging from 5 to 18 m (Gu et al., 2026a). The region experiences a subtropical marine climate with a mean annual temperature of 21.7 °C, annual precipitation of approximately 1984 mm, and relative humidity of about 82% (Gu et al., 2026a). Freshwater input is limited to three small rivers, while seawater exchange with the South China Sea dominates hydrodynamic circulation (Gu et al., 2026a).

Over recent decades, Daya Bay has experienced increasing anthropogenic influence associated with rapid urbanization in the Shenzhen region and industrial activities within the Huizhou Daya Bay petrochemical complex (Gu et al., 2025b; Man et al., 2025). These activities contribute trace metals through wastewater discharge, surface runoff, and atmospheric deposition (Man et al., 2022; Gu et al., 2023). In addition, thermal discharge from the Daya Bay Nuclear Power Plant locally modifies seawater temperatures, making the bay a suitable system for investigating temperature-driven sediment biogeochemical processes.

Surface sediments (0–5 cm) were collected from 24 sampling sites distributed across the bay (Fig. S1). Sediment physicochemical characteristics including total organic carbon (TOC), sulfide concentrations, and grain size distribution have been reported previously and are summarized here to characterize sediment heterogeneity. TOC contents ranged from 0.17% to 1.58%, while sulfide concentrations reflected typical redox variability in coastal sediments (Gu et al., 2022). Median grain sizes ranged from 3.34 to 6.97 Φ, indicating predominantly silt-dominated sediments (Gu et al., 2022; Gu et al., 2026a).

To minimize site-specific heterogeneity and isolate temperature-driven effects, equal masses of surface sediment from the 24 sites were homogenized to produce a composite sediment sample for laboratory incubation experiments. This composite sediment represents typical nearshore coastal sediment conditions while avoiding disproportionate influence from individual sampling locations. The homogenized sediment was gently mixed under anoxic conditions prior to incubation in order to preserve redox-sensitive phases.

2.2. DGT incubation experiment and analytical procedures

Homogenized sediments were transferred into light-proof 2 L polyvinyl chloride (PVC) containers. Each container received 500 mL of pre-collected Daya Bay seawater that had been stored at low temperature prior to use. Sediment–water systems were incubated at five controlled temperatures (0, 10, 20, 30, and 40 °C) to examine temperature-dependent changes in metal lability. This broad and evenly spaced thermal gradient was selected to resolve the shapes of element-specific temperature responses, including potential nonlinear, threshold-like, and non-monotonic behavior. The 0 and 40 °C treatments served as lower and upper experimental boundary conditions for constraining the response relationships and were not intended to represent the present-day seasonal temperature range of Daya Bay or direct near-term warming at a single coastal site. Three independent replicate incubations were prepared for each temperature treatment.

Following a 96h pre-equilibration period at the target temperature, flat-type diffusive gradients in thin films (DGT) devices equipped with ZrO–Chelex mixed binding gels were vertically inserted into the sediments. The target analytes—Mn, Co, Ni, Cu, Zn, Cd, Pb, V, Cr, As, Se, Mo, Sb, and W—were selected to encompass environmentally relevant metal (loid)s with contrasting sediment geochemical behaviors, including differences in mineral association, sorption, complexation, sulfide affinity, and solid-phase resupply. All selected analytes can be simultaneously accumulated by the ZrO–Chelex mixed binding phase and quantified by ICP-MS, enabling direct cross-element comparison under identical experimental conditions. DGT devices were deployed for 48 h to quantify labile metal fluxes under each temperature condition. After retrieval, devices were gently rinsed with ultrapure water to remove adhering sediment particles.

The binding gels were removed from the devices and sectioned into 5 mm slices using a ceramic blade to facilitate complete elution of accumulated metals from the resin layer. Each gel slice was eluted with 2 mL of elution solution. Eluates were subsequently diluted with 3% (v/v) HNO_3 prior to analysis.

Metal(loid) concentrations were determined using inductively coupled plasma mass spectrometry (ICP-MS; Agilent 7700). Instrumental drift was corrected using Rh and Ge (5 μg/L) as internal

standards. Analytical accuracy was evaluated using six measurements of a multielement verification standard distributed throughout the analytical sequence (n = 6). Element-specific mean recoveries ranged from 95 ± 2.9% for Ni and 95 ± 2.7% for W to 102 ± 1.9% for Cr, corresponding to mean relative errors of −5% to +2%. The limits of detection for ICP-MS determination ranged from 0.03 to 0.55 μg/L. Detailed element-specific recoveries and detection limits are provided in Table S3. Experimental reproducibility was independently evaluated using three replicate sediment incubations and DGT deployments for each temperature treatment, and the resulting DGT-labile concentrations are reported as mean ± standard deviation (n = 3).

2.3. Calculation of DGT-labile concentrations

DGT-labile metal(loid)s diffuse through the diffusive gel layer in accordance with Fick's first law of diffusion. The mass of metal accumulated in the resin gel (M) was calculated using Eq. (1):

$$M = \frac{C_e(V_e + V_g)}{f_e} \quad (1)$$

where C_e is the concentration measured in the elution solution, V_e is the elution volume, V_g is the resin gel volume, and f_e is the element-specific elution factor.

The time-averaged DGT-labile concentration (C_{DGT}) was then calculated as Eq. (2):

$$C_{DGT} = \frac{M\triangle g}{DAt} \quad (2)$$

where $\triangle g$ represents the total thickness of the diffusion layer (diffusive gel plus filter membrane), D is the temperature-corrected diffusion coefficient in the gel, A is the exposure area of the DGT device, and t is the deployment time (48 h). Diffusion coefficients were corrected for experimental temperature using manufacturer-provided values.

2.4. Temperature–response modeling and conceptual visualization

To characterize temperature–lability relationships, empirical regression models were fitted to the DGT-labile concentrations measured across the experimental temperature gradient (0–40 °C). Depending on the observed response pattern, either quadratic regression models or weighted linear regressions were applied.

To facilitate comparison of temperature responses among elements with different concentration ranges, normalized response curves were generated. A continuous temperature gradient (0–40 °C) was discretized into 200 points, and modeled DGT concentrations were normalized using Eq. (3):

$$C_{rel}(T) = \frac{C_{DGT}(T) - \min(C_{DGT})}{\max(C_{DGT}) - \min(C_{DGT})} \quad (3)$$

where $C_{rel}(T)$ the normalized relative DGT-labile concentration at temperature T, $C_{DGT}(T)$ is the modeled DGT-labile concentration at temperature T, and $\max(C_{DGT})$ and $\min(C_{DGT})$ are the maximum and minimum modeled concentrations, respectively, across the 0–40 °C temperature range. The resulting dimensionless values range from 0 to 1, preserving the qualitative shape of each temperature response while removing concentration-scale differences among elements. These normalized response curves were used to compare generalized response regimes and support mechanistic interpretation, rather than to predict absolute metal concentrations.

2.5. Warming scenario projection

To explore the implications of climate warming for sediment metal lability, model-based projections were conducted using the fitted temperature–response relationships described above. Representative baseline sediment temperatures were defined for four climate zones: Polar (0–5 °C), Temperate (5–15 °C), Subtropical (15–25 °C), and Tropical (25–35 °C).

For each climate zone, the midpoint temperature was used as the baseline condition. These temperature ranges were used as illustrative baseline-temperature scenarios rather than as direct representations of the physicochemical properties of sediments from the respective climatic regions. In the scenario analysis, sediment composition and the fitted temperature–response relationships were held constant, and only baseline temperature was varied. The resulting estimates therefore isolate baseline-temperature dependence within the experimental sediment system and should not be interpreted as site-specific or region-specific predictions of metal(loid) release. A uniform warming perturbation of +1.1 °C was applied to represent the observed increase in global mean surface temperature since the Industrial Revolution. Relative changes in DGT-labile concentrations were calculated as Eq. (4):

$$\Delta\% = \frac{C_{T+1.1} - C_T}{C_T} \times 100 \quad (4)$$

where C_T and $C_{T+1.1}$ represent modeled concentrations before and after warming.

2.6. Baseline temperature–dependent sensitivity analysis

To further interpret the amplification patterns observed across climate zones, a baseline temperature–dependent sensitivity analysis was performed. The proportional warming sensitivity $S(T)$ of each element was defined as Eq. (5):

$$S(T) = \frac{1}{C(T)} \frac{dC(T)}{dT} \quad (5)$$

where $C(T)$ represents the modeled DGT-labile concentration at baseline temperature T, and dC/dT is the slope of the fitted temperature–response relationship.

This formulation represents the logarithmic temperature responsiveness of labile metal concentrations and allows comparison of warming sensitivity independent of absolute concentration magnitude. Analytical derivatives of quadratic regression functions were used for nonlinear responses, whereas normalized slopes from weighted linear regressions were used for monotonic responses. Conceptual sensitivity curves were generated to illustrate the inverse relationship between baseline temperature and proportional warming sensitivity.

2.7. Statistical analysis

All statistical analyses and graphical visualizations were conducted using R software (version 4.4.3). Temperature–lability relationships were fitted using the lm(.) function in the base stats package. Weighted regressions were applied where appropriate using weights defined as the inverse of the squared standard deviation of replicate measurements.

All figures were generated using the ggplot2 package within the *tidyverse* framework.

3. Results

3.1. Divergent temperature–lability responses across sediment metal(loid)s

Temperature manipulation revealed strongly divergent responses in DGT-measured metal lability (Fig. 1). Redox-sensitive elements (Mn, V, and As) exhibited model-fitted nonlinear responses, with pronounced increases in lability at higher temperatures. In contrast, most particle-associated metals (Ni, Cu, Zn, Cd, Pb, Cr, Se, Mo, Sb, and W) displayed generally decreasing trends across the temperature gradient,

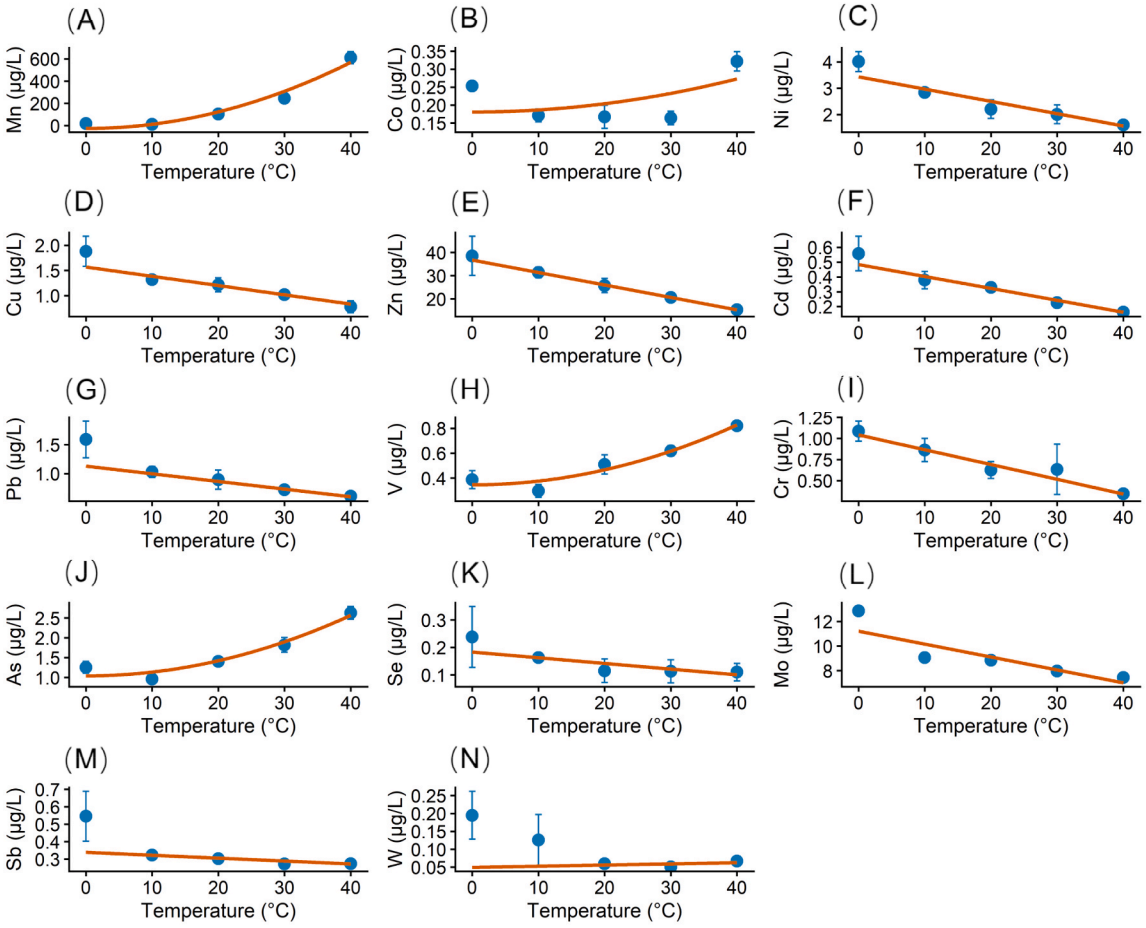


Fig. 1. Element-specific temperature–lability responses of sediment metal(loid)s measured using DGT across a 0–40 °C gradient. Redox-sensitive elements (Mn, V, As) exhibit nonlinear increases in lability with warming, cobalt shows transitional behavior, and most particle-associated metals display monotonic decreases. These contrasting responses demonstrate that temperature reorganizes sediment metal lability patterns rather than uniformly enhancing mobility. Symbols represent mean values with standard deviations, and lines denote best-fit regression relationships.

with some element-specific variation, which is consistent with strengthened retention or suppressed solid-phase resupply under elevated temperature. Cobalt exhibited an apparent transitional, non-monotonic response, potentially reflecting competing resupply mechanisms. These contrasting responses demonstrate that warming does not exert a uniform control on sediment metal lability but instead reorganizes lability patterns in an element-specific manner.

3.2. *Emergence of temperature–lability response regimes*

Normalization of temperature-dependent trends revealed three distinct response regimes (Fig. 2): nonlinear mobilization for redox-sensitive elements, transitional behavior reflecting competing processes, and monotonic suppression for particle-associated metals. The emergence of these regimes across chemically diverse elements indicates that the observed temperature-driven changes cannot be explained solely by diffusion enhancement and are consistent with element-specific differences in resupply and retention processes. This regime structure provides a unifying framework linking diverse elemental behaviors to underlying resupply controls.

3.3. *Discovery of baseline temperature–controlled sensitivity*

Under the illustrative scenario analysis, identical absolute warming perturbations produced different modeled relative lability responses depending on the assigned baseline sediment temperature (Fig. 3). Cold sediments showed disproportionately large proportional changes,

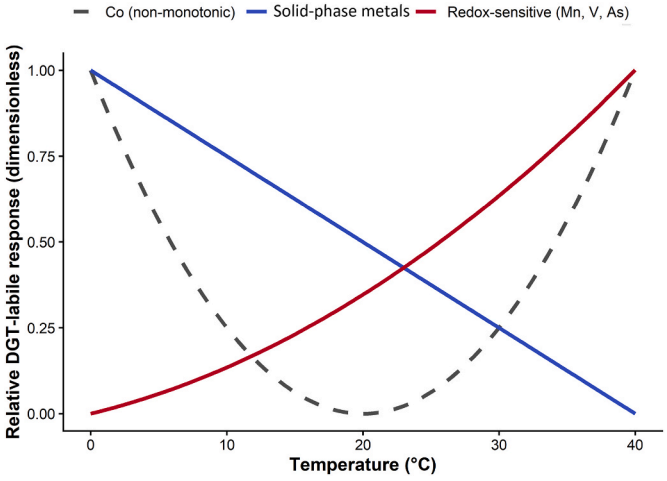


Fig. 2. Temperature–lability response regimes derived from normalized experimental trends. Conceptualized normalized trends illustrate three generalized response types: nonlinear mobilization for redox-sensitive elements, transitional behavior reflecting competing resupply processes, and monotonic suppression for particle-associated metals. These regimes provide a process-informed framework linking element-specific lability responses to temperature-dependent resupply dynamics.

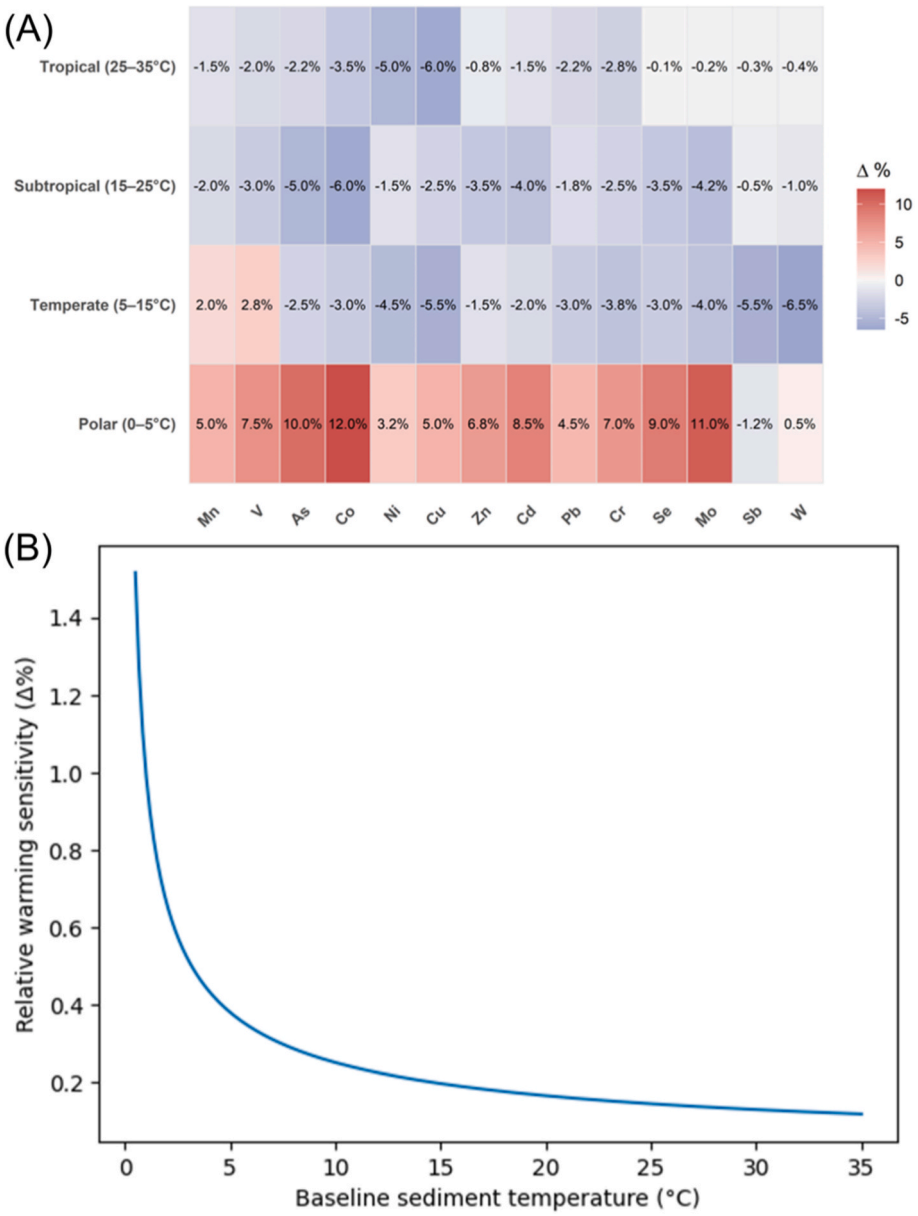


Fig. 3. Baseline temperature controls warming-induced sensitivity of sediment metal lability across climate zones. (A) Heatmap showing modeled relative changes (Δ%) in DGT-labile metal(loid) concentrations under a +1.1 °C warming scenario across four climate zones: Polar (0–5 °C), Temperate (5–15 °C), Subtropical (15–25 °C), and Tropical (25–35 °C). Relative changes were derived from fitted temperature–response relationships using representative baseline temperatures for each climate zone. Redox-sensitive elements (Mn, V, As) exhibit pronounced positive responses in cold environments, whereas most particle-associated metals show moderate declines with warming. (B) Conceptual relationship between baseline sediment temperature and proportional warming sensitivity, illustrating amplified relative responses at low baseline temperature.

particularly for redox-sensitive elements, whereas warmer sediments exhibited attenuated responses. This amplification persisted across multiple elements and response regimes. The consistent amplification observed under low baseline temperatures indicates that sediment metal lability sensitivity is governed primarily by baseline thermal conditions rather than warming magnitude alone. Within the experimental sediment system and fitted response relationships, this pattern identifies baseline temperature as an important determinant of modeled relative geochemical sensitivity to warming.

4. Discussion

4.1. Temperature reorganizes sediment metal lability rather than uniformly enhancing mobility

The divergent response regimes observed in this study indicate that warming acts as a reorganizing force on sediment metal lability rather than a universal mobility enhancer. As shown in Fig. 1, redox-sensitive elements (Mn, V, and As) exhibited nonlinear increases in DGT-labile concentrations with warming, whereas most particle-associated metals displayed consistent monotonic decreases across the temperature gradient. Cobalt exhibited a transitional, non-monotonic response, which is consistent with, but does not directly demonstrate, the coexistence of competing geochemical processes. DGT quantifies an integrated kinetically labile fraction sustained by porewater diffusion and

solid-phase resupply; it does not independently resolve metal speciation, mineral host phases, or the individual reaction pathways responsible for the observed responses.

Here, "redox-sensitive" is used as a functional geochemical term rather than to imply a single shared mechanism. Mn lability is directly affected by redox transformations of Mn-bearing phases, whereas the behavior of V and As can be influenced by changes in their oxidation states, sorption affinities, and associations with redox-active Fe- and Mn-bearing minerals (Morford and Emerson, 1999; Gorny et al., 2015; Shaheen et al., 2019). Thus, the responses of Mn, V, and As may all be sensitive to sediment redox conditions, although the underlying pathways differ among elements. Other analyzed elements may also respond indirectly to redox changes through sulfide formation, mineral transformation, or changes in organic complexation.

Temperature may also influence metal(loid) lability indirectly by modifying the physicochemical conditions of the sediment–water system. Increasing temperature can reduce oxygen solubility and accelerate oxygen consumption, potentially promoting lower dissolved-oxygen and redox conditions within sediments. Concurrent changes in pH, carbonate equilibria, mineral dissolution–precipitation, ionic activity, and electrical conductivity may further affect metal complexation, sorption, desorption, and solid-phase resupply. Such indirect effects could have contributed to the contrasting responses observed among elements. For example, the enhanced lability of Mn, V, and As at higher temperatures is consistent with changes in redox conditions and associated mineral–sorption environments, whereas the generally decreasing responses of several other metals may partly reflect strengthened sorption, precipitation, complexation, or reduced release from their dominant solid-phase pools. Because pH, dissolved oxygen, redox potential, and conductivity were not continuously measured during the incubations, their individual contributions cannot be quantitatively separated from the direct kinetic effects of temperature. The observed responses should therefore be interpreted as integrated temperature-induced changes in the sediment–water system rather than as exclusively direct thermal effects.

The classification of these responses into three generalized regimes (Fig. 2) indicates that the observed temperature-dependent changes cannot be explained solely by enhanced molecular diffusion. Instead, they are consistent with element-specific differences in release, retention, and solid-phase resupply, potentially involving mineral dissolution–precipitation, sorption–desorption, complexation, and redox-dependent transformations (Brown et al., 1999; Knight et al., 2024). However, because element speciation and the associated solid-phase transformations were not directly characterized, the relative contributions of these processes cannot be quantitatively resolved from the present data.

Microbial processes provide a plausible link between temperature and the contrasting element-specific responses observed in this study. Warming can accelerate microbial respiration and alter sediment redox conditions, potentially promoting microbially mediated transformations of Fe- and Mn-bearing mineral phases. Such processes may enhance the release or resupply of redox-associated elements, which is consistent with the increased DGT-labile concentrations of Mn, V, and As at elevated temperatures. Microbial degradation of organic matter may also modify pH, dissolved organic ligands, and sorption environments, thereby influencing metal(loid) partitioning between porewater and sediment particles.

Conversely, warming-induced changes in microbial sulfur cycling and organic-matter processing may promote metal retention through sulfide precipitation, complexation, or enhanced sorption within solid phases. These processes could partly explain why many particle-associated metals exhibited decreasing DGT-labile concentrations despite the expected enhancement of molecular diffusion at higher temperatures. Therefore, the net response of each element may reflect the balance among microbial redox processes, mineral reactions, sorption–desorption, organic complexation, and solid-phase resupply kinetics. Because metal speciation, mineral-phase transformations, microbial community composition, and process rates were not directly measured, these pathways should be regarded as process-consistent interpretations rather than experimentally demonstrated mechanisms (Tan et al., 2020; Chari et al., 2021; Peiffer et al., 2021).

4.2. Baseline temperature as a key regulator of geochemical sensitivity

Beyond element-specific response patterns, a central finding of this study is the identification of baseline sediment temperature as a key regulator of relative lability sensitivity. Despite identical absolute warming perturbations, modeled relative changes in DGT-labile metal concentrations varied systematically across baseline temperature conditions (Fig. 3A). Cold sediments showed disproportionately large proportional responses to warming, whereas warmer sediments exhibited attenuated sensitivity.

This pattern arises from the nonlinear temperature dependence of diffusion and reaction kinetics governing sediment metal resupply (Liu et al., 2018; Peiffer et al., 2021). At low baseline temperatures, biogeochemical reaction rates are strongly temperature-limited, meaning that small increases in temperature can induce relatively large proportional increases in reaction rates and metal release (Tan et al., 2020; Tian et al., 2023). Consequently, identical warming perturbations can generate substantially larger relative changes in labile metal fractions in cold sediments.

The conceptual relationship between baseline sediment temperature and proportional warming sensitivity (Fig. 3B) illustrates this inverse sensitivity pattern. This finding highlights an important but previously underrecognized mechanism governing the climate sensitivity of sediment geochemical processes. Our results therefore suggest that the relative magnitude of warming perturbations, rather than absolute temperature change alone, controls the responsiveness of sediment metal lability to climate warming (Zitoun et al., 2024).

The baseline-temperature analysis should be interpreted within the controlled framework of the present experiment. Because the same composite sediment and fitted temperature–response functions were applied across all baseline scenarios, the analysis isolates the influence of baseline temperature while holding mineralogy, organic matter, grain size, contamination level, salinity, and microbial characteristics constant. It therefore does not imply that natural sediments from polar, temperate, subtropical, and tropical coasts will exhibit identical response functions.

4.3. Low-baseline-temperature amplification within the experimental response framework

The baseline-temperature dependence observed in the scenario analysis suggests that lower starting temperatures may amplify proportional changes within the fitted response framework. However, this modeled behavior should not be equated directly with geographical or polar amplification because the analysis does not incorporate the contrasting sediment properties of different climatic regions. As illustrated in Fig. 3, sediments with low baseline temperatures exhibit amplified relative changes in metal lability compared with warmer systems.

This pattern parallels the well-established phenomenon of polar amplification observed in climate dynamics and other biogeochemical processes (Liao et al., 2023; Pan et al., 2023; Zeng et al., 2024). However, while polar amplification is typically discussed in the context of atmospheric and cryospheric systems, our results indicate that similar amplification behavior may occur within sediment geochemical processes.

Such amplification suggests that high-latitude coastal sediments may experience stronger perturbations in metal lability and sediment–water exchange under future warming. Systems that currently exhibit relatively stable geochemical conditions may therefore transition toward regimes of heightened responsiveness as warming progresses. This

previously overlooked amplification mechanism highlights sediment metal lability as an additional dimension of climate-driven vulnerability in coastal ecosystems.

4.4. Climate-driven redistribution of sediment metal sensitivity

The baseline temperature–controlled sensitivity identified here further implies that climate warming may redistribute sediment metal vulnerability across geographic gradients rather than uniformly increasing risk. As illustrated conceptually in Fig. 4, warming-driven changes in metal lability are expected to vary systematically across climate zones.

Regions characterized by low baseline sediment temperatures, such as polar and subpolar coastal environments, may become hotspots of geochemical responsiveness under future warming. In contrast, warmer subtropical and tropical sediments may exhibit comparatively smaller relative shifts in metal lability. This spatial redistribution of sensitivity could alter benthic exposure pathways, sediment–water metal fluxes, and the ecological consequences of metal contamination in coastal environments.

Incorporating baseline temperature sensitivity into environmental risk assessment frameworks may therefore improve predictions of climate-driven contaminant dynamics in marine sediments. Recognizing how warming redistributes geochemical sensitivity across regions represents an important step toward understanding the broader environmental consequences of climate change for coastal contaminant cycling.

4.5. Boundary conditions and uncertainty of baseline temperature–controlled sensitivity

Several uncertainties should be considered when interpreting the baseline temperature–controlled sensitivity identified in this study. First, the temperature–lability relationships were derived from controlled incubations using a single composite sediment from a subtropical coastal embayment. This design reduced site-specific variability and allowed the temperature effect to be examined under standardized sediment conditions. However, natural sediments across climatic regions differ in mineralogy, grain size, organic matter, redox state, salinity, microbial communities, contamination histories, and metal host phases. The climate-zone scenarios therefore represent baseline-temperature sensitivity within the present experimental sediment system rather than direct predictions for polar, temperate, subtropical, or tropical coastal sediments. Future validation using sediments collected across contrasting climatic and geochemical settings is necessary before geographical generalization (Li et al., 2023; Gu et al., 2026a; Gu et al., 2026b).

Second, metal speciation, pH, dissolved oxygen, redox potential, microbial community composition, and microbial process rates were not directly quantified during the incubations. Temperature-induced changes in these physicochemical and biological variables may have affected mineral transformation, sorption, dissolution, precipitation, complexation, and solid-phase resupply. Consequently, the mechanisms discussed here are inferred from the observed DGT-labile response patterns and established sediment biogeochemical principles rather than directly demonstrated by speciation or microbial measurements. Future studies combining DGT with sequential extraction or spectroscopic speciation, high-resolution pH and redox profiling, porewater chemistry, and microbial functional analyses would help distinguish the individual processes responsible for the observed responses.

Third, the warming sensitivity analysis employs representative baseline temperatures to illustrate general response patterns rather than to predict site-specific changes. Consequently, the amplification patterns

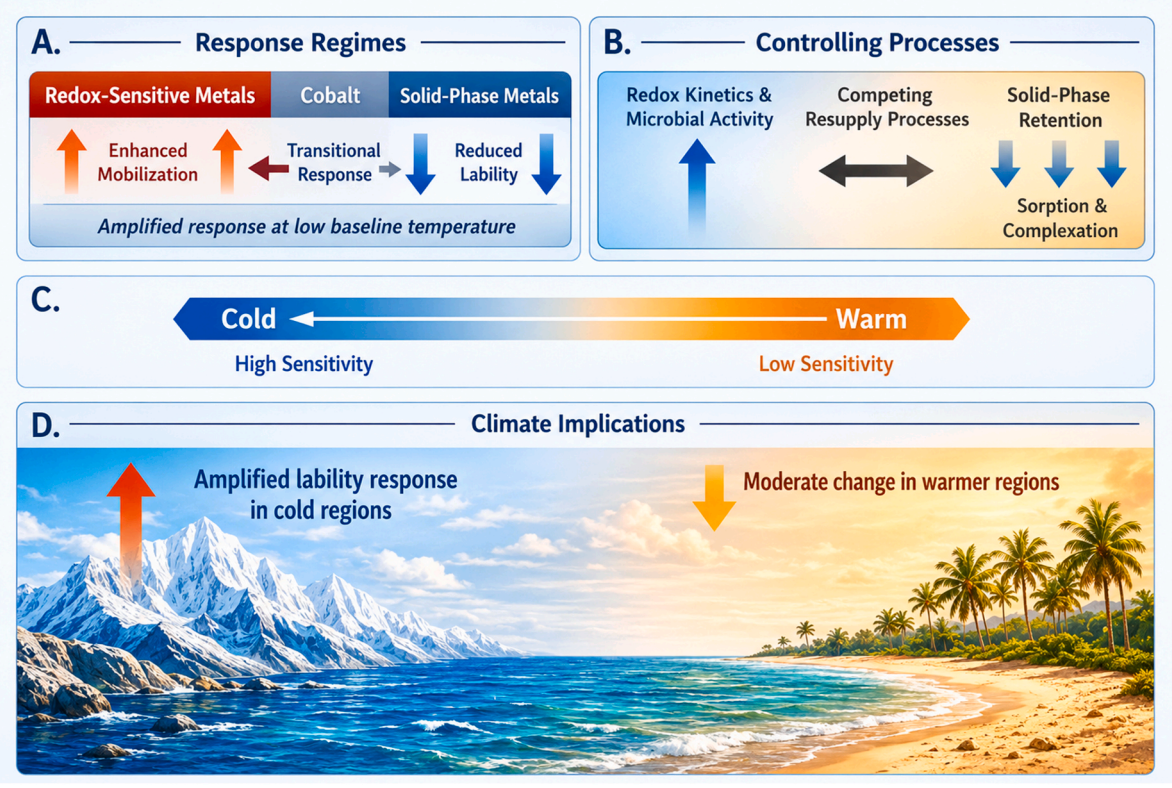


Fig. 4. Conceptual synthesis linking temperature–lability response regimes with baseline temperature–controlled amplification of sediment metal sensitivity. (A) Normalized response regimes illustrating divergent temperature–lability behaviors among element groups. (B) Conceptual processes consistent with the observed response regimes, highlighting the roles of redox transformations, competing resupply processes, and solid-phase retention. (C) Baseline sediment temperature regulates proportional lability sensitivity to warming, producing amplified responses under low-temperature conditions. (D) Conceptual redistribution of sediment metal sensitivity across climate zones under warming, highlighting cold-region amplification.

presented here should be interpreted as reflecting generalized sensitivity behavior rather than precise quantitative projections for individual environments.

Despite these uncertainties, the consistent emergence of baseline temperature–dependent amplification across multiple elements and response regimes suggests that the identified sensitivity represents a consistent feature property of sediment metal lability dynamics under warming.

5. Conclusion

This study reveals that climate warming does not uniformly enhance sediment metal mobility but instead reorganizes sediment metal lability through element-specific resupply dynamics. Controlled temperature experiments combined with DGT measurements demonstrate three distinct temperature–lability response regimes among metal(loid)s, including nonlinear mobilization of redox-sensitive elements, monotonic suppression of particle-associated metals, and transitional behavior for cobalt. More importantly, our results identify baseline sediment temperature as a key regulator of proportional lability sensitivity to warming. Identical warming perturbations produce amplified relative responses under low baseline temperatures, indicating a previously underrecognized cold-region amplification effect in sediment geochemical sensitivity. Together, these findings establish a process-informed framework linking temperature-dependent resupply kinetics with spatial redistribution of sediment metal responsiveness under climate warming, improving understanding of climate impacts on coastal sediment biogeochemistry.

CRediT authorship contribution statement

Yang-Guang Gu: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Yanpeng Gao:** Validation, Investigation, Funding acquisition. **Hong-Hui Huang:** Resources. **Richard W. Jordan:** Writing – review & editing. **Shi-Jun Jiang:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2026.128923.

Data availability

Data will be made available on request.

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