Climate warming intensifies coastal hypoxia response to extreme river discharge in the Ariake Sea

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1. Introduction

Coastal hypoxia (dissolved oxygen, DO < 3 mg L^{-1}) is an increasingly widespread environmental problem in semi-enclosed coastal seas and regions of freshwater influence (ROFIs), threatening marine ecosystems, fisheries, and aquaculture[1]. Climate change is expected to increase the frequency and intensity of extreme precipitation events, potentially exacerbating hypoxia through enhanced freshwater stratification and nutrient loading. Strong stratification suppresses vertical oxygen transport, while increased nutrient inputs stimulate oxygen consumption, together promoting bottom-water oxygen depletion[2].

The Ariake Sea, a semi-enclosed bay in southwest Japan, is particularly vulnerable to hypoxia. Previous studies have shown that large river discharge events can expand hypoxic areas and negatively affect benthic ecosystems[3]. However, the impacts of low-probability, high-impact extreme discharge events remain poorly understood. This study investigates how climate warming alters hypoxia duration, intensity, and frequency in response to extreme river discharge events in the Ariake Sea using event-based hydrodynamic–ecological simulations driven by a large-ensemble, high-resolution climate dataset.

2. Method

2.1 Data sources

Climate forcing data were obtained from the 20-km regional climate model of the Database for Policy Decision-Making for Future Climate Change (d4PDF) large-ensemble dataset, including the historical climate simulation (HPB) and future warming scenarios (F2K and F4K). Hourly river discharge was first estimated using the 1-km Distributed Hydrological Model (1K-DHM)[4]. The top 100 extreme discharge events in each climate scenario were then identified based on annual 48-hour maximum discharge for upper-tail analysis. To account for reservoir operations and floodplain inundation, the selected events were further simulated using the Rainfall–Runoff–Inundation (RRI) model for eight Class-A rivers flowing into the Ariake and Yatsushiro Seas[5]. The resulting discharge time series were used to force the hydrodynamic–ecological model and evaluate hypoxia responses under present and future climate conditions.

2.2 Numerical models

This study employed the open-source numerical simulation software package Delft3D, which integrates the FLOW and WAQ modules. Horizontal grid is structured as rectangular in a Cartesian frame of reference, while the vertical grid is based on a σ-coordinate system. The vertical grid consists of 10 layers with varying thicknesses. Open boundaries are situated beyond the mouth of the Ariake Sea and along the line linking Kabashima and Akune. Harmonic constants for the major tidal components (M2, S2, K1, and O1) were applied at these open boundaries. The Murakami model was used to simulate surface heat flux. Freshwater inflows were considered from eight A-class rivers and nine B-class rivers (**Fig.1**).

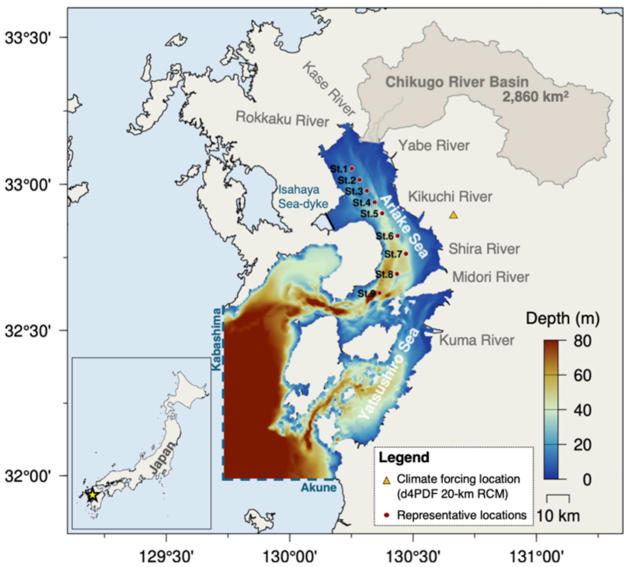

Figure 1. Calculation domain.

The physical conditions simulated by the FLOW module were coupled with the WAQ module to simulate the transport and transformation of water quality parameters, as depicted in **Fig.2**. In this study, we simplified the general ecological model and considered only one phytoplankton species (green algae). The model variables include living organic matter (algae), dissolved organic matter (DOM), particulate organic matter (POM), dissolved inorganic nutrients (NH4-N, NO3-N, and PO4-P), and dissolved oxygen (DO) concentration.

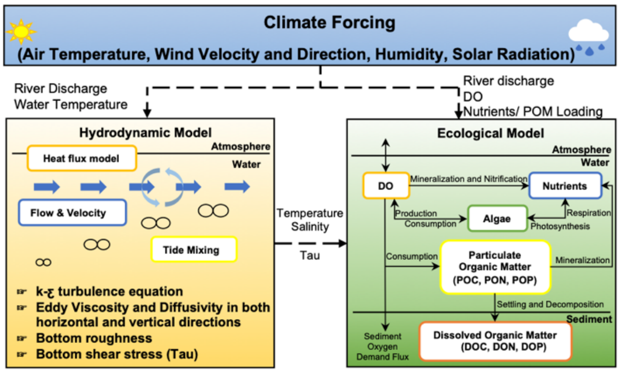

Figure 2. Conceptual diagram of the numerical model.

3. Results and Discussion

Climate warming amplified hypoxia responses to extreme river discharge events in the Ariake Sea. At the nearshore station (St.1), hypoxia duration increased systematically under future warming scenarios, accompanied by a shift of the DO distribution toward lower concentrations (**Fig.3a**). As a result, the cumulative probability of hypoxia increased from 40% in the historical climate to 50% under future warming conditions (**Fig.3b**).

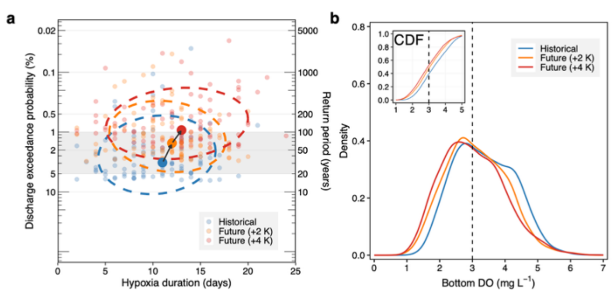

Figure 3. (a) Relationship between hypoxia duration and discharge exceedance probability. Filled circles indicate median conditions. (b) Probability density distributions of bottom DO concentrations.

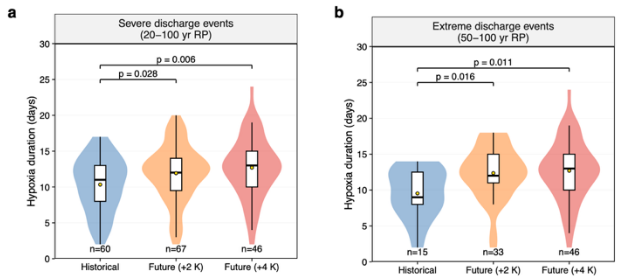

Figure 4. Comparison of hypoxia duration. Yellow markers denote mean hypoxia duration, and sample sizes (n) are provided below each group.

The enhancement of hypoxia was particularly evident for severe and extreme discharge events. The frequency of prolonged hypoxia episodes (>20 days) increased substantially under warming, reflecting both stronger freshwater forcing and longer recovery times (**Fig.4**). Under the +4 K scenario, 50- and 100-year return period discharges increased by 6.9% and 10.0%, respectively, relative to the historical climate, leading to a 33.2% increase in mean hypoxia duration for events within the 50–100-year return period range.

4. Conclusion

Climate warming increases the duration and frequency of hypoxia following extreme river discharge events through enhanced stratification, nutrient loading, and warming. The resulting intensification of hypoxia may increase ecological stress and vulnerability in the Ariake Sea. These findings highlight the need to incorporate low-probability, high-impact extreme events into future coastal risk assessments and adaptation planning.

Reference

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