[POC-P3] [ECOP-award]

Season- and depth-dependent steric contributions to rapid sea level rise in the southwestern East Sea (Japan Sea) from 1993 to 2023

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Introduction

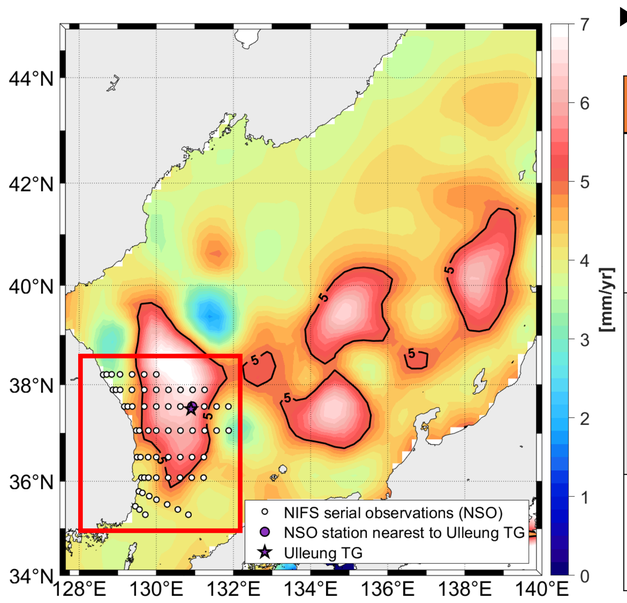
Background: Regional SLR rates reach 5–7 mm/yr, but seasonal and depth-dependent steric contributions remain uncertain

Objective: Quantify upper-500-m thermosteric and halosteric contributions to regional and seasonal SLR differences

Key Findings

- Upper-500-m steric effects explain **2.22 mm/yr** of the regional SLR-rate difference
- Steric contributions account for **47.9%** of tide-gauge SLR annually; thermosteric expansion contributes **98.3%** of the annual steric rate
- **Density layers (σ in kg/m³): Layer 1 (24.6 ≤ σ < 26.1):** spring halosteric contraction and autumn expansion; **Layer 2 (26.1 ≤ σ < 28.2):** largest annual steric contribution, with thermosteric expansion partly reduced by halosteric contraction; **Layer 3 (28.2 ≤ σ ≤ 29.7):** similar thermosteric and halosteric SLR rates

Data and Methods



▶ **Fig. 1**. Satellite-derived sea-level rise (SLR) rates in the East Sea (Japan Sea) during 1993–2023. Symbols mark the Ulleung Island tide gauge (TG) and NIFS serial observations (NSO) stations; black contours indicate 5.0 mm/yr. Red box outlines the area shown in Fig. 2.

▶ **Table 1.** Datasets used to estimate long-term sea-level rise (SLR) rates during 1993–2023.

Variable	Data source	Data interval	Data characteristics
Tide-gauge sea level [m]	Korea Hydrographic and Oceanographic Agency (KHOA)	1 hour	Quality-controlled records; gaps filled and datum shifts adjusted*
Satellite sea-level anomaly [m]	Copernicus Climate Change Service (C3S)	1 month	Monthly means; two-satellite merged grid; 0.25° × 0.25°**
Temperature and salinity profiles	National Institute of Fisheries Science (NIFS)	10 days	14 standard depths within 0–500 m***

*Tide-gauge product: KHOA Level-2 records after quality control, gap filling, and datum adjustment
**Satellite product: delayed-time (DT) reprocessed data, version DT2024
***NIFS profiles: observations approximately every 2 months, processed into 10-day time series (Dasgupta et al., 2026)

Upper-500-m steric sea-level change

$$\eta_c(t) \approx \rho \Sigma_i [\delta_c(t, zi) - \delta_{ref}(z_i)] \omega_i$$

c: total, thermosteric, or halosteric component; η_c: steric sea-level change [m];
δ: specific volume anomaly [m³/kg]; $\rho = 1025\ kg/m^3$: seawater density;
ω_i: layer thickness represented by depth z_i, with $\Sigma_i \omega_i = 500\ m$

- **Reference state:** 1993–2023 mean profiles of Conservative Temperature (CT) and Absolute Salinity (SA)
- **Thermosteric component:** CT variations with SA fixed at reference values
- **Halosteric component:** SA variations with CT fixed at reference values
  - Specific volume anomalies from the Thermodynamic Equation of Seawater–2010 (TEOS-10)

- **Spatial comparison:** Stations with satellite-derived SLR rates **≥5.0 mm/yr (23 stations)** and **<5.0 mm/yr (40 stations)**
- **Seasonal averaging:** Monthly tide-gauge means and 10-day steric estimates averaged over **winter (December–February), spring (March–May), summer (June–August), and autumn (September–November)**
- Trend estimation: Least-squares linear regression of annual and seasonal means; SLR rates in mm/yr, with ± values denoting 95% confidence intervals

Discussion

- **Spatial consistency:** Steric SLR rate difference of **2.22 mm/yr**, similar to regional differences in combined steric and circulation contributions (**2.21–2.61 mm/yr**; Cha et al., 2024); **~2 mm/yr differences** also retained for 1993–2018
- **Eddy-related interpretation:** Upper-500-m thermosteric SLR rate (**2.95 mm/yr**) close to the reported eddy-warming contribution (**2.66 mm/yr**; Lee et al., 2024); **eddy warming and deepening** as possible contributors to **Layer 2 thermosteric expansion**
- **Autumn SLR budget:** Circulation-related temperature, salinity, and layer-thickness changes already reflected in upper-500-m steric estimates; **steric contributions below 500 m and ocean mass contributions** still unquantified
- **Water-mass interpretation: Layer 3 freshening** qualitatively consistent with reported **intermediate-water freshening** (Park, 2022); further quantitative assessment of links between layer-specific SLR contributions and **eddy, current, and water-mass changes**

References

- Cha, H., Jo, S., & Moon, J.-H. (2024). A Process-based Relative Sea-level Budget Along the Coast of Korean Peninsula Over 1993–2018. *Ocean and Polar Research*, 46(1), 31–42.
- Copernicus Climate Change Service (2018). Sea level gridded data from satellite observations for the global ocean from 1993 to present. *C3S Climate Data Store*.
- Dasgupta, P., et al. (2026). Continuous gridded time series of temperature and salinity in the seas around the Korean Peninsula using the DIVA method (Version 1). *SEANOE*.
- Lee, K. J., Park, J.-H., & Park, Y.-G. (2024). Eddy-driven sea-level rise near the frontal region off the east coast of the Korean Peninsula during 1993–2020. *Frontiers in Marine Science, 11, 1283076.*
- McDougall, T. J., & Barker, P. M. (2011). Getting started with TEOS-10 and the Gibbs Seawater (GSW) oceanographic toolbox. *Scor/iapso WG, 127(532)*, 1-28.
- Park, J. J. (2022). Long-Term Variability of the East Sea Intermediate Water Thickness: Regime Shift of Intermediate Layer in the Mid-1990s. *Frontiers in Marine Science,* 9, 923093.

Results

Spatial differences in SLR rates

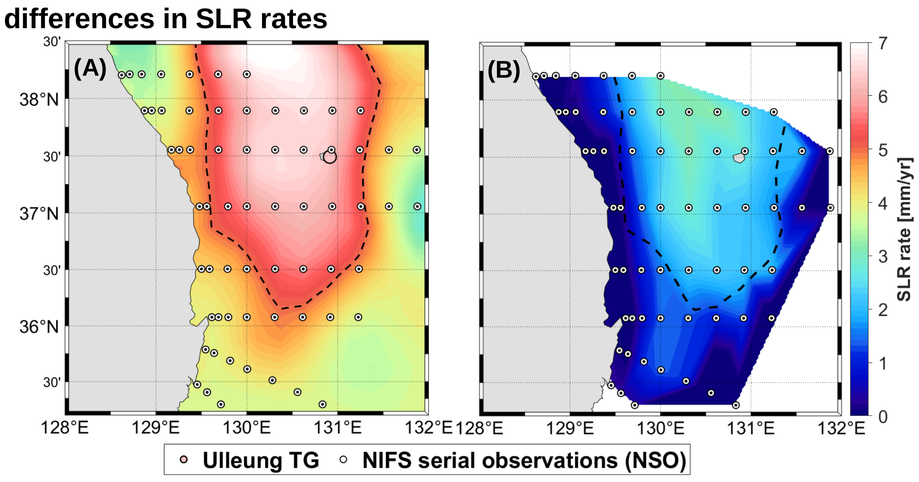


Fig. 2. Spatial distributions of long-term sea-level rise (SLR) rates during 1993–2023: (A) satellite altimetry and (B) upper-500-m steric estimates. Open circles: NSO stations; filled circle in (A): Ulleung Island TG. Dashed lines: satellite-derived 5.0 mm/yr contours in both panels. SLR rates for inner (≥5.0) and outer (<5.0) groups, respectively: **5.90±1.20 and 4.13±0.67** in (A); **2.68±1.00 and 0.46±0.53** in (B). **Inner − outer differences** 1.77 mm/yr (altimetry); 2.22 mm/yr (steric)

Annual and seasonal steric contributions

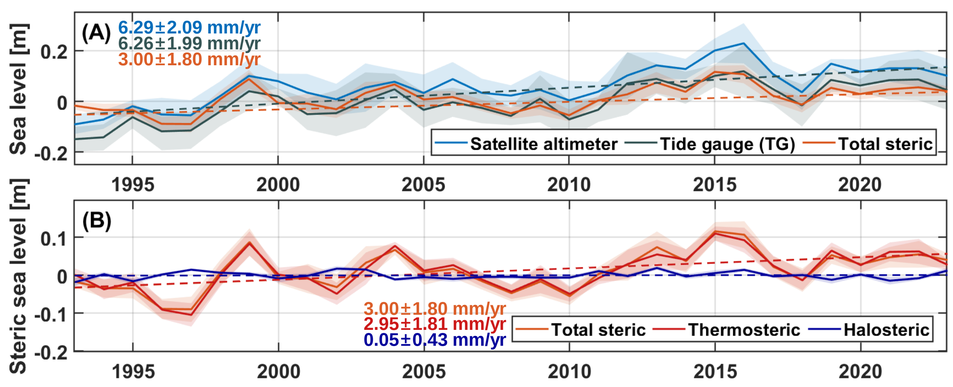


Fig. 3. Annual-mean sea-level anomalies near Ulleung Island during 1993–2023. (A) Satellite altimetry, tide-gauge (TG) observations, and upper-500-m total steric sea level at their nearest locations. (B) Total steric sea level and thermosteric and halosteric components at the nearest NSO station. Solid and dashed lines indicate annual means and linear trends, respectively. Shading indicates 95% confidence intervals of the annual means.

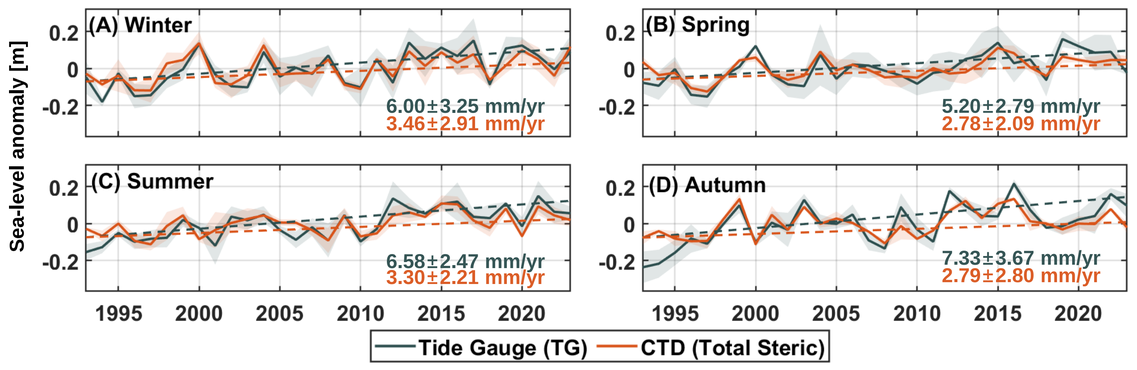


Fig. 4. Seasonal sea-level anomalies from the Ulleung Island tide gauge (TG, dark teal) and upper-500-m total steric estimates (orange) at the nearest NSO station during 1993–2023: (A) Winter, (B) Spring, (C) Summer, and (D) Autumn. Solid and dashed lines denote seasonal means and linear trends, respectively. Shading denotes ±1 standard deviation of the monthly TG means and steric estimates within each season.

Density-layer contributions

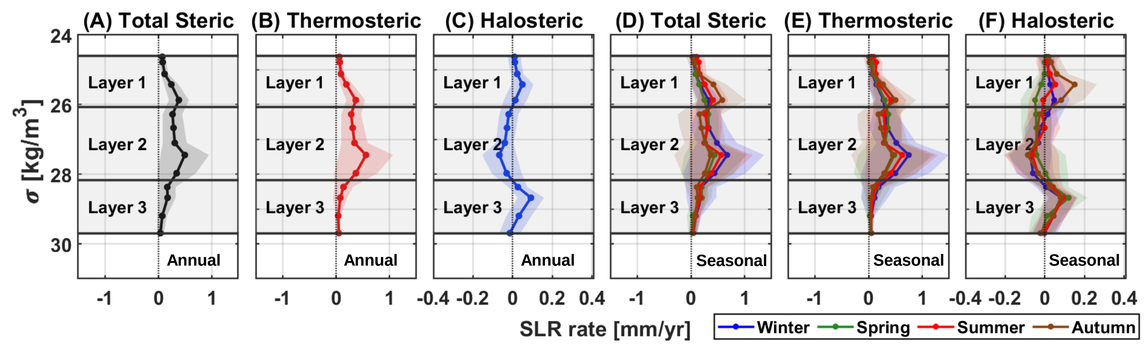


Fig. 5. Annual-mean (A–C) and seasonal (D–F) contributions to SLR rates from total steric (A, D), thermosteric (B, E), and halosteric (C, F) changes in the upper 500 m at the NSO station nearest Ulleung Island during 1993–2023. The contribution from each depth interval (circles) is plotted at its 1993–2023 reference density (σ). Horizontal solid lines mark density-layer boundaries. Shading denotes 95% confidence intervals.