Accelerating Interannual Variability of Summer Stratification in the Southeastern Yellow Sea

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1 Introduction

The interannual variability of summer stratification in the southeastern Yellow Sea has been increasing, with a rapid acceleration observed. Understanding stratification variability is crucial for predicting water mass dynamics, marine ecosystem, and fisheries resources. This study analyzes the physical mechanisms driving this acceleration based on the monitoring data provided by the National Institute of Fisheries Science (NIFS).

2 Study area

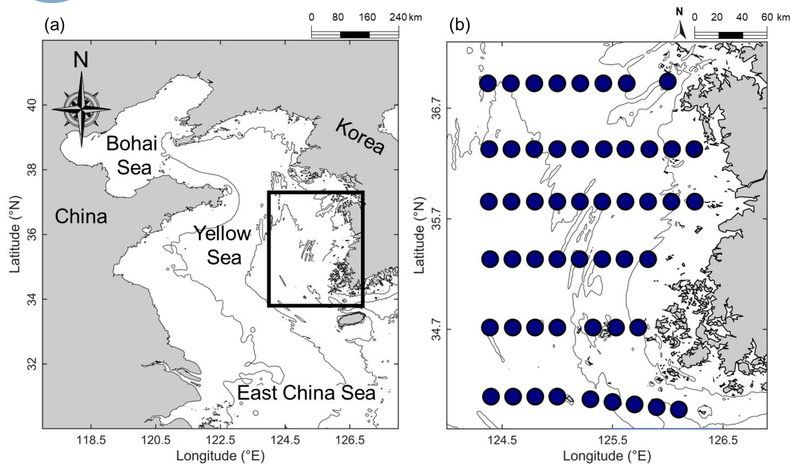


Figure 1. (a) Bathymetric map of the Yellow Sea and surrounding regions. The black box outlines the southeastern Yellow Sea, which is the primary study area of this research. (b) Detailed bathymetry of the southeastern Yellow Sea showing transect observation stations (blue circles) conducted by the National Institute of Fisheries Science (NIFS).

Table 1. Study area and analysis period

Latitude range	30°N–41°N
Longitude range	124.1°E–126.9°E
Analysis period	2013.08–2024.08

3 Methodology

Stratification intensity was quantified using the squared Brunt–Väisälä frequency (N^2). The depth-averaged stratification index $\langle N^2 \rangle$ was calculated at each station by vertically averaging $N^2(z)$ from the surface to the maximum observed depth (H).

$$N^2(z) = -\frac{g}{\rho_0}\frac{\partial \rho}{\partial z} \qquad \langle N^2 \rangle = \frac{1}{H}\int_0^H N^2(z)dz$$

The total stratification index $\langle N^2_S \rangle$ was decomposed into thermal ($\langle N^2_T \rangle$) and haline ($\langle N^2_S \rangle$) components. $\langle N^2_T \rangle$ was derived using the observed temperature profile and a depth-averaged salinity, while $\langle N^2_S \rangle$ was derived using the observed salinity profile and a depth-averaged temperature. The N^2 is approximated as the sum of these two components.

$$N^2_T(z) = -\frac{g}{\rho_0}\frac{\partial \rho(T(z), \overline{S(z)})}{\partial z} \qquad N^2_S(z) = -\frac{g}{\rho_0}\frac{\partial \rho(\overline{T(z)}, S(z))}{\partial z} \qquad \langle N^2 \rangle \approx \langle N^2_T \rangle + \langle N^2_S \rangle$$

4 Results

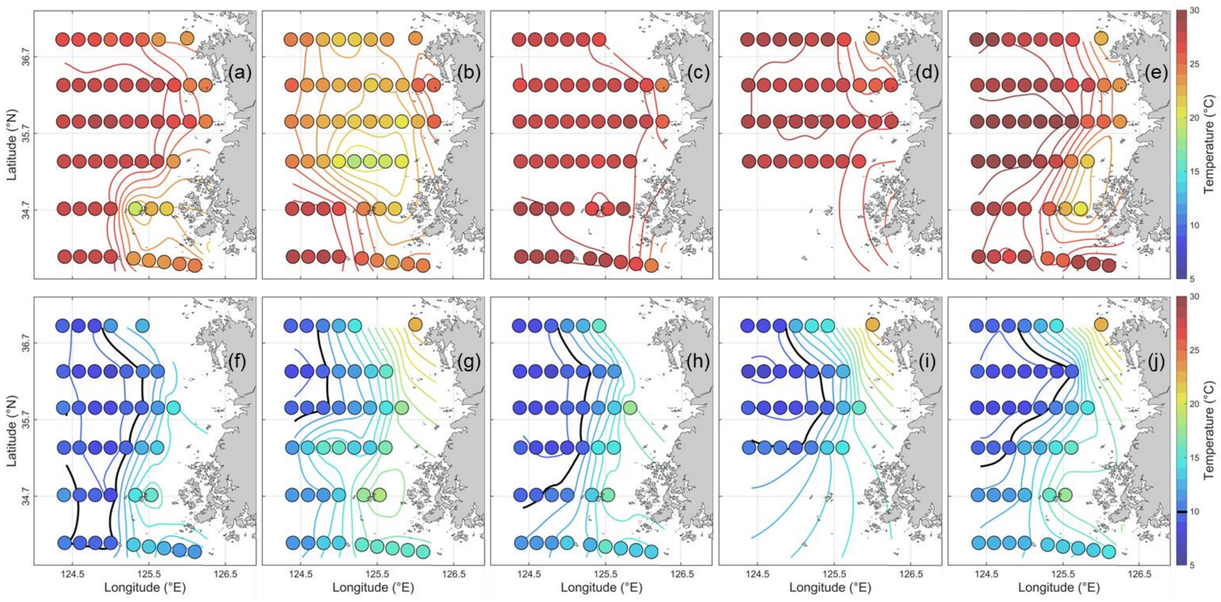


Figure 2. Spatial distributions of (a-e) sea surface temperature and (f-j) temperature at 50 m depth, based on transect observations in the southeastern Yellow Sea in August from 2019 to 2023. From left to right, panels represent the results for 2019 (a, f), 2020 (b, g), 2021 (c, h), 2022 (d, i), and 2023 (e, j). The bold black contour in panels (f-j) indicates the 10°C isotherm.

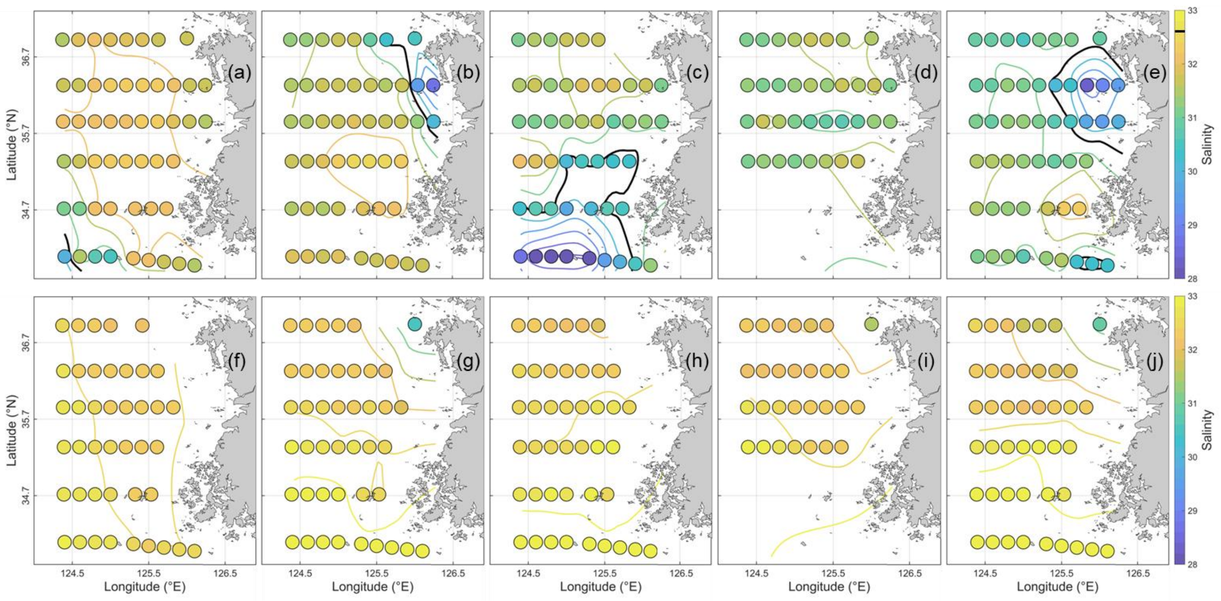


Figure 3. Spatial distributions of (a-e) sea surface salinity and (f-j) salinity at 50 m depth, based on transect observations in the southeastern Yellow Sea in August from 2019 to 2023. From left to right, panels represent the results for 2019 (a, f), 2020 (b, g), 2021 (c, h), 2022 (d, i), and 2023 (e, j). The bold black contour in panels (a-e) indicates the 30.5 isohaline.

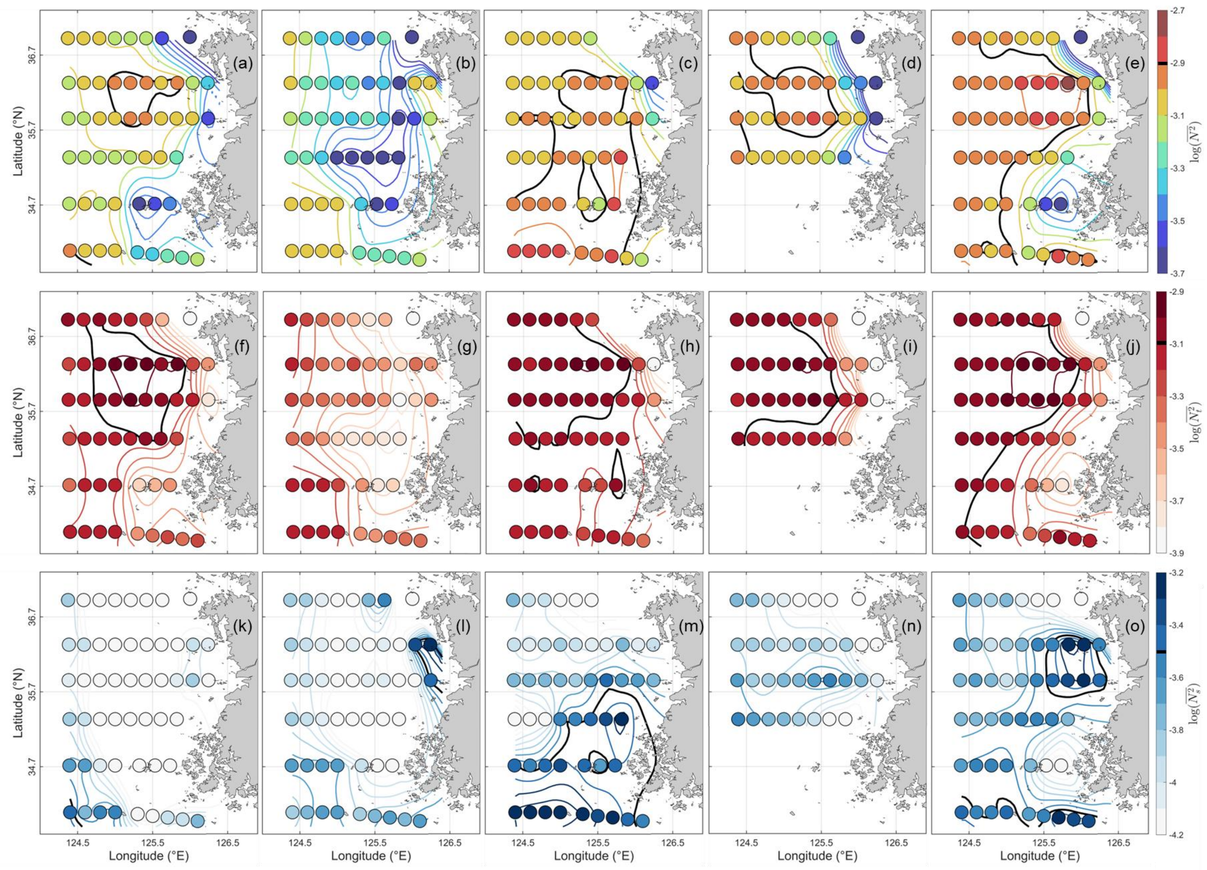


Figure 4. Spatial distributions of (a–e) total stratification, (f–j) thermal stratification, and (k–o) haline stratification in the southeastern Yellow Sea, based on August transect observations conducted by the NIFS from 2019 to 2023. Panels represent each year from left to right: 2019 (a, f, k), 2020 (b, g, l), 2021 (c, h, m), 2022 (d, i, n), and 2023 (e, j, o). All panels show $\log_{10}$-transformed values of the squared Brunt-Väisälä frequency ($\log_{10}N^2$), with contour intervals of 0.1. Bold black contours indicate the -2.9 isoline in panels (a–e), the -3.1 isoline in panels (f–j), and the -3.5 isoline in panels (k–o).

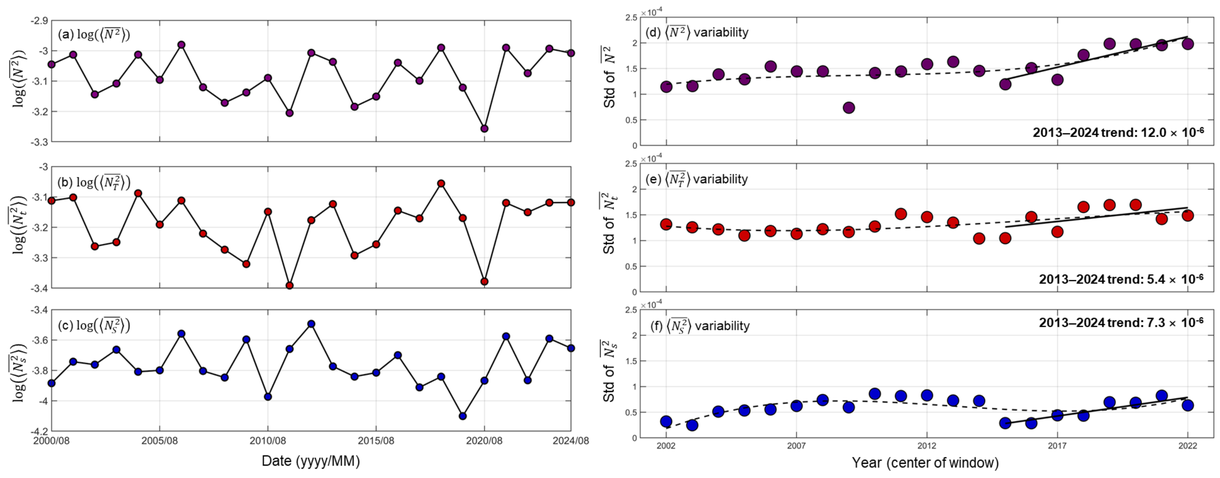


Figure 5. Time series and variability of depth-averaged buoyancy frequency in the southeastern Yellow Sea in August from 2000 to 2024. (a–c) Time series of $\log_{10}$-transformed depth-averaged total ($\log(\langle N^2 \rangle)$), thermal ($\log(\langle N^2_T \rangle)$), and haline ($\log(\langle N^2_S \rangle)$) buoyancy frequency, respectively. (d–f) Standard deviations of $\langle N^2 \rangle$, $\langle N^2_T \rangle$, and $\langle N^2_S \rangle$ calculated using a 5-year sliding window, respectively. In panels (d–f), the solid black lines represent linear regression trends for the period 2013–2024, and the black dashed curves represent third-order polynomial regression trends for the full period 2000–2024. The 2013–2024 linear regression trend value is indicated in each panel.

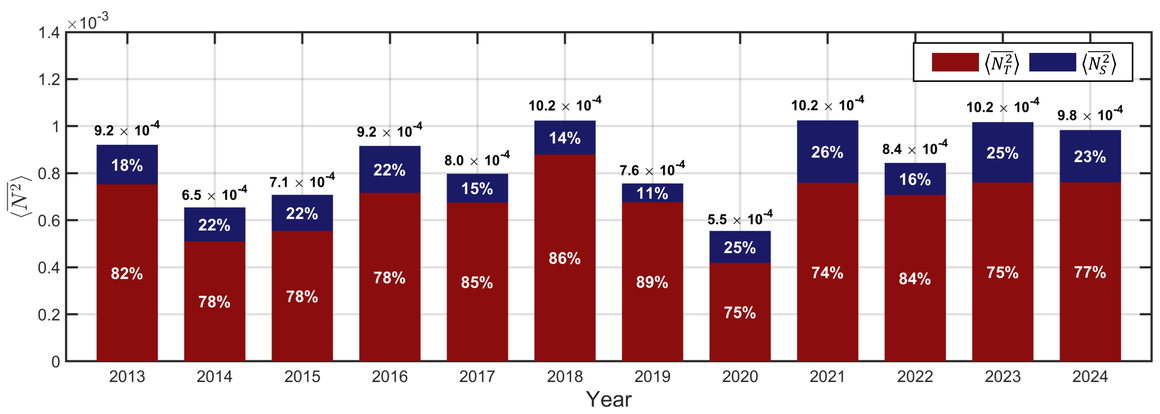


Figure 6. Thermal and haline contributions to stratification in the southeastern Yellow Sea in August from 2013 to 2024. (a) Averaged stratification intensity $\langle N^2 \rangle$ for each year, with red and blue segments indicating thermal and haline contributions, respectively. The values above each bar represent the total $\langle N^2 \rangle$ for each year, and the percentages within each segment represent the relative contributions of thermal and haline components to the total stratification.

- **The distribution and intensity of stratification** in the southeastern Yellow Sea in August are **influenced by the combined effects** of the Yellow Sea Bottom Cold Water, river discharge from the Korean west coast, and the Changjiang Diluted Water.
- **The Interannual variability of August Stratification** in the southeastern Yellow Sea has shown an **increasing trend since 2013.**
- **Haline stratification exhibiting greater spatial variability** than thermal stratification.

5 Conclusions

- Interannual variability of stratification in the southeastern Yellow Sea in August shows an increasing trend from 2013 to 2024.
- The increase in stratification variability is attributed to the growing influence of salinity over temperature.
- The haline contribution to stratification in the southeastern Yellow Sea averaged 19.9%

- 이 논문은 해양수산부 재원으로 해양수산과학기술진흥원의 지원을 받아 수행된 연구임 (RS-2023-00256330, 쿠로시오 해류로 인한 한반도 해양위기 대응기술 개발).
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- 이 성과는 정부(과학기술정보통신부)의 재원으로 한국연구재단의 지원을 받아 수행된 연구임(RS-2025-24683148).