



**Multi-scale variability of suspended sediment concentration in Liaodong
Bay from satellite observations (2002–2026)**

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ABSTRACT

Suspended sediment concentration (SSC) is an important indicator of coastal
15 sediment dynamics and water quality. However, discontinuous in situ observations limit
the characterization of long-term SSC variability. This study investigated the
spatiotemporal variability of SSC and its associated environmental factors in Liaodong
Bay (LDB) using MODIS satellite data from 2002 to 2026 and hourly GOCI-II
observations. Spatially, a fan-shaped high-turbidity water body is observed, with SSC
20 decreasing from nearshore to offshore areas. A distinct suspended sediment front occurs
near the 10–16 m isobaths, while the boundary of the high-turbidity water body exhibits
pronounced seasonal variations. Published in situ observations further reveal vertical
variations in SSC. Temporally, hourly SSC variations are closely associated with tidal
phases, while SSC is generally higher in winter than in summer. At the interannual scale,
25 SSC exhibits an overall declining trend with quasi-periodic fluctuations of
approximately 5–6 years. Topography plays a key role in shaping the spatial distribution
of SSC, whereas the relative influence of environmental factors varies across timescales.
At the monthly scale, sea surface temperature (SST), serving as an indicator of
stratification and vertical mixing, and current velocity are the leading factors, with
30 estimated relative contributions of 53.3% and 31.4%, respectively. At the interannual
scale, wind speed (39.0%) and river sediment discharge (33.3%) become dominant.
These findings provide insights into the multi-scale variability of SSC and its associated
environmental controls, contributing to a better understanding of coastal sediment
dynamics and supporting coastal management in semi-enclosed bays.



35 **Keywords:** suspended sediment concentration, Liaodong Bay, spatiotemporal
characteristics, remote sensing inversion, multiple linear regression analysis

1 Introduction

Estuaries are where rivers meet the sea, characterized by complex hydrodynamics and abundant sediment sources (Milliman and Syvitski, 1992). Sediment dynamics
40 within estuarine and adjacent coastal systems are closely governed by terrestrial sediment delivery, seabed deposition, and subsequent resuspension mechanisms (Li et al., 2015; Li et al., 2023; Guo et al., 2026). Suspended sediment is the primary carrier of terrigenous material transported seaward. Its concentration (SSC, suspended sediment concentration) exhibits significant spatiotemporal variations. These variations
45 reflect the combined effects of riverine sediment input, tidal dynamics, wave fields, and wind conditions (Song et al., 2011; Yunus et al., 2022; Ferrarin et al., 2025). SSC plays a dual role in estuarine and coastal environments. It modulates topographic evolution (Ji et al., 2024) and regulates primary productivity, water clarity, and ecosystem health (Tao et al., 2025; Wang et al., 2026).

50 Over recent decades, extensive research has been devoted to examining the spatiotemporal patterns of SSC across estuarine and coastal environments (Zhang et al., 2025; Zhao et al., 2025). To this end, diverse methodologies have been applied, encompassing in-situ observations, numerical simulations, and satellite-based remote sensing (Qiao et al., 2008; Song et al., 2017). Most investigations have concentrated on
55 deltaic regions of major world rivers, such as the Amazon and Yellow River estuaries



(Santos et al., 2023). In-situ field observations have been utilized to characterize the spatial distribution of SSC (Wang et al., 2024), whereas numerical modeling has been employed to simulate the hydrodynamic regime of the Bohai Sea (Liu et al., 2025). Such simulations contribute to clarifying the physical drivers of SSC variability. Additionally, SSC distribution has been interpreted in conjunction with surface sediment types (Zhang et al., 2023). This line of inquiry is particularly evident in the Yellow River estuary, where the linkage between sedimentary facies and SSC patterns has been explicitly examined (Meng et al., 2023; Ji et al., 2024).

Satellite-based ocean color remote sensing constitutes an indispensable approach for large-scale and long-term SSC monitoring (Li et al., 2024; Luan et al., 2026). Retrieval of SSC from satellite reflectance data, such as MODIS and GOCI, has become a mature technique widely applied to coastal SSC monitoring (Du et al., 2021; Che and Jiang, 2026). Using multi-source satellite data, Zhou et al. (2017) delineated the large-scale SSC distribution patterns across the Bohai Sea. Existing investigations into SSC dynamics within this region have predominantly been confined to Laizhou Bay and Bohai Bay, particularly in the vicinity of the Yellow River estuary (Song et al., 2017; Liu et al., 2023; Du et al., 2025). Nevertheless, as the Bohai Sea's largest bay in terms of surface area (Geng et al., 2022), Liaodong Bay (LDB) warrants a dedicated and systematic examination of its SSC spatiotemporal variability. This multi-sensor, multi-temporal approach demonstrates the feasibility of long-term SSC monitoring in turbid coastal waters using publicly available satellite data.

This study systematically retrieved the spatiotemporal patterns of SSC in LDB on



hourly, seasonal, and long-term (25-year) scales using MODIS and GOCI-II reflectance data. Building on the above, statistical examination was undertaken to establish that

80 topography exerts the dominant influence over the lateral distribution of SSC. At the same time, multiple linear regression served as a tool for numerically evaluating the respective roles of fluvial sediment input, wind, waves, and currents in driving SSC changes across monthly and interannual time frames. The outcomes of this work promise to advance current knowledge regarding sediment dispersal processes in semi-

85 enclosed shelf seas.

2 Data and methods

2.1 Study area

LDB is one of the bays with the largest number of inflowing rivers in China (Kong, 2024), including the Luanhe, Dalinghe, Xiaolinghe, and Liaohe Rivers. Among them,

90 the Liaohe River directly discharges into LDB through the Liaohe Estuary, providing a direct sediment source for the study area (Luo et al., 2023). The abundant riverine sediment inputs make LDB an ideal region for investigating the spatiotemporal variability of SSC. In this study, the sediment discharge of the Liaohe River was selected as the representative fluvial input due to its direct connection with the study

95 area.

LDB, a typical semi-enclosed shallow sea, is located northeast of the Bohai Sea (Fig. 1). The area is roughly located near 121–122°E and 40–41°N. To better understand the spatial variation of SSC, three points (P1, P2, and P3) located in different positions



were selected for SSC analysis (Fig. 1b). Furthermore, to investigate the relationship
 100 between SSC distribution and topography, two representative transects were selected,
 namely Section A situated in the area of greatest water depth variation and Section B
 crossing the suspended sediment front. The area delineated by the black box (Fig. 1b)
 was selected for a more detailed examination of the relationship between SSC and
 topography.

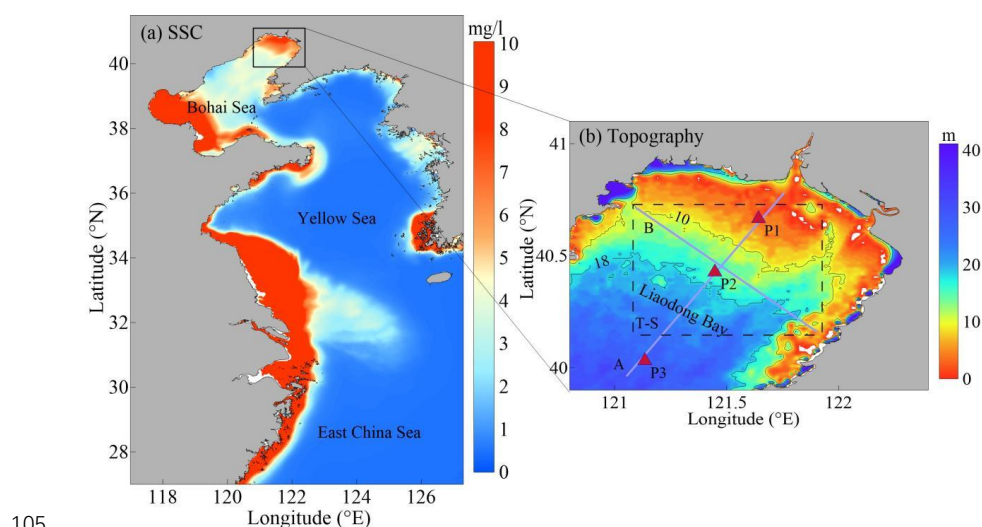


Figure 1. (a) Overview of SSC across China's coastal seas and the geographical position of the study domain. (b) Bathymetric topography of Liaodong Bay (LDB). Points P1, P2, and P3 denote representative sampling locations across different water depth zones, while the black dashed rectangle marks the region of steep bathymetric gradient.

2.2 Data sources

2.2.1 Remote sensing data

This study uses MODIS-Aqua Level 3 remote sensing reflectance (R_{rs}) products from the polar-orbiting Aqua satellite, provided by the National Aeronautics and Space Administration (NASA). The data cover July 2002 to May 2026. The annual mean data



115 for 2002 and 2026 include only selected months and are therefore used for reference
only. The spatial resolution of the downloaded product is 4 km; the temporal resolution
is daily.

The GOCI-II reflectance data from the geostationary satellite were obtained
through the Korea Ocean Satellite Center (KOSC). Level-2 reflectance products
120 acquired on 5–6 July 2025 (UTC) were used, with a temporal interval of 1 h and a
spatial resolution of 250 m. The 555 nm reflectance was used to retrieve SSC and to
examine hourly SSC distribution patterns across the study area. As with other ocean-
color retrievals, the quality of the results may be affected by atmospheric correction and
cloud screening, particularly in turbid coastal waters.

125 Additionally, a Landsat-8 scene captured on 15 December 2021, was sourced from
the United States Geological Survey (USGS). A preprocessing workflow was executed
in ENVI, encompassing radiometric calibration, atmospheric correction, and subsetting,
which ultimately generated a true-color composite image for visualizing the
morphological features of high-turbidity water bodies in the region.

130 2.2.2 Hydrodynamic and sediment transport data

Wind, wave, and sea surface temperature (SST) data were obtained from the ERA5
reanalysis dataset, which is maintained by the European Centre for Medium-Range
Weather Forecasts (ECMWF). Monthly data with a spatial resolution of $0.25^\circ \times 0.25^\circ$
were selected. The extracted variables include 10 m wind components, SST, and
135 significant wave height. Monthly ocean current velocity data, with a spatial resolution
of approximately 0.083° , were derived from the Copernicus Marine Environment



Monitoring Service (CMEMS) global ocean reanalysis product.

The tidal data were obtained from the Ocean Knowledge Professional Service System, operated by the National Marine Data and Information Service (NMDIS).

140 Hourly tidal-level observations at the Yingkou tidal gauge station in Liaoning Province, corresponding to the GOCI-II observation period (5–6 July 2025, UTC), were used to analyse the hourly variations in SSC. Although actual tidal levels within Liaodong Bay are unavailable, observations from Yingkou, the nearest tide gauge station, can be used to characterize the flood–ebb tidal patterns in the bay.

145 River sediment discharge data were obtained from the *China River Sediment Bulletin*, published by the Ministry of Water Resources of China. Annual sediment discharge records for 2002–2025 were collected from the Tieling and Xinmin hydrological stations on the Liaohe River, and the two station records were summed for each year. Because the Liaohe River directly discharges into the study area, its sediment
150 discharge was used as the representative fluvial input for assessing the contribution of fluvial forcing to SSC variability. Sediment supplied by smaller rivers and material transported into Liaodong Bay from other areas was not included in this representative riverine series.

2.2.3 SSC data

155 SSC is defined as the mass of suspended particles per unit volume of water (mg/l) and is commonly measured in situ using the filtration–gravimetric method. In this study, published in situ SSC observations from three studies were compiled to characterize the vertical distribution of SSC in Liaodong Bay. The observations were collected



within the bay in spring, summer, and autumn, and the sampling stations and depth
 160 levels are summarized in Table 1. The sampling positions are shown in Fig. S1. These
 measurements provide independent information on the vertical structure of SSC and are
 used to support the interpretation of satellite-derived surface SSC. Differences in
 sampling time, location, and water depth may introduce uncertainties; therefore, these
 observations are presented only to illustrate the vertical variability of SSC.

165 **Table 1.** Summary of published SSC observations used to describe the vertical distribution of SSC
 in Liaodong Bay.

Sampling stations	Sampling date	n	Sampling depths	Reference
V1, V3, V5	November, 2009	3	0, 0.2, 0.4, 0.6, 0.8, 1.0	(Wang and Kang, 2015)
S2, S3, S4, S5, S6	April, 2019	5	0, 1.0	(Li et al., 2025)
Average	April, June and November 2021	76	0, 0.25, 0.5, 0.75, 1.0	(Zhao et al., 2023)

Note: Sampling depths are expressed as relative water depths, ranging from 0 (surface) to 1 (bottom), with intermediate levels at 0.2, 0.4, 0.6, and 0.8.

In addition, a satellite-derived SSC product entitled “Satellite Derived Total
 170 Suspended Sediment in China Sea 2020” was obtained from the National Marine Data
 and Information Service (NMDIS). The product covers Liaodong Bay, provides daily
 and monthly gridded data, and has a maximum spatial resolution of 500 m. Monthly
 mean SSC fields for 2020 were used as the reference satellite product for comparison
 with the monthly mean SSC retrieved from MODIS.

175 2.2.4 Topography data

Topography data were obtained from the NMDIS. The spatial resolution is 1 arc-
 minute. Shoreline boundaries were primarily extracted from the vector coastline
 embedded in this bathymetric product, supplemented by the Global Self-consistent,



Hierarchical, High-resolution Geography Database (GSHHS) for large-scale spatial
180 validation and positional correction. These data were used to analyze the influence of
topography on SSC distribution.

2.3 Methods

2.3.1 Suspended sediment concentration retrieval

Retrieval of SSC was accomplished using the model formulated by Liu et al.
185 (2020), which exploits the empirical correlation between surface reflectance and in-situ
SSC data. The model is suitable for coastal waters in China. The model expression is:

$$SSC = 1.556 \times \exp(94.03 \times Rrs(555)) \quad (1)$$

where SSC denotes the suspended sediment concentration (mg/l), and Rrs(555)
represents the reflectance at 555 nm. The retrieval model was constructed using in-situ
190 SSC data covering the Bohai Sea and Yellow Sea. In this study, the retrieved SSC
represents surface SSC because the satellite reflectance primarily characterizes the
optical properties of the upper water layer.

The retrieval SSC was evaluated (Fig. 2) by comparing the monthly mean MODIS-
derived SSC with the monthly mean NMDIS satellite-derived SSC product in 2020.
195 Before comparison, the two datasets were spatially averaged over several subregions of
Liaodong Bay and matched to the same monthly time scale. The results yielded an R^2
of 0.96 and an RMSE of 0.63 mg/l, indicating good consistency between the two
satellite products at the matched spatiotemporal scale. Differences may partly reflect
sensor characteristics, atmospheric correction, spatial averaging, and retrieval



200 algorithms.

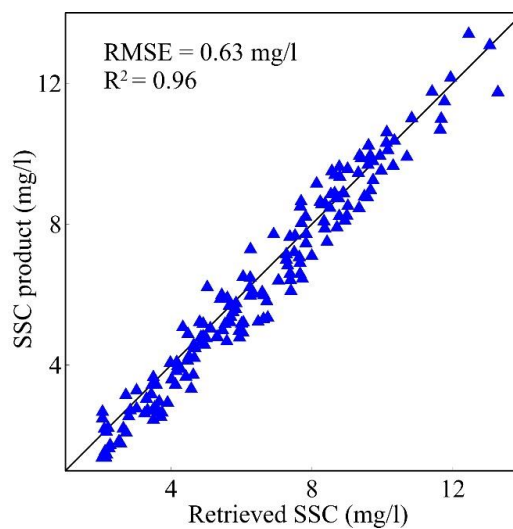


Figure 2. Comparison between the monthly mean MODIS-derived SSC and the NMDIS satellite-derived SSC product in Liaodong Bay in 2020. The two datasets were spatially averaged over several subregions and matched at the monthly scale. The retrieved SSC represents surface SSC.

205 2.3.2. Contribution rate calculation

Multiple linear regression was used to quantify the relative contributions of key environmental factors to interannual SSC variability in Liaodong Bay. The analysis used annual mean SSC and corresponding annual environmental variables, yielding one observation per year over the 25-year study period. Five explanatory variables were selected based on their roles in sediment dynamics and long-term data availability. River sediment discharge represents the external sediment supply, while wind speed and significant wave height characterize wind and wave induced sediment resuspension. Current velocity reflects sediment transport and redistribution, whereas SST serves as an indirect indicator of water-column stratification and vertical mixing. Tidal forcing was excluded from the monthly and interannual analyses because its periodic



fluctuations are largely smoothed by temporal averaging. The regression model is expressed as:

$$SSC(t) = \beta_0 + \beta_1 Q_s(t) + \beta_2 U_{10}(t) + \beta_3 H_s(t) + \beta_4 SST(t) + \beta_5 U_{cur}(t) \quad (2)$$

Where SSC is the suspended sediment concentration, Q_s is river sediment discharge, U_{10} is wind speed, H_s is significant wave height, SST is sea surface temperature, and U_{cur} is current velocity. β_0 is the constant term, and β_1 , β_2 , β_3 , β_4 and β_5 are the regression coefficients for the respective variables. The relative contribution of each factor was calculated using standardized regression coefficients.

2.3.3. Data preprocessing

All data were projected to the WGS-84 geographic coordinate system. ERA5 and CMEMS data were read and cropped using functions in MATLAB. To match the spatial resolutions of different data sources, all data were resampled to a $0.05^\circ \times 0.05^\circ$ grid. The resampling was used to establish a common analysis grid and did not increase the effective spatial resolution of the original datasets.

3 Results

3.1 Spatial distribution characteristics of SSC in LDB

The Landsat 8 true-color image reveals a fan-shaped distribution of turbid waters extending seaward from the estuary (Fig. 3a). To quantify this spatial pattern, SSC was retrieved from MODIS reflectance, and its mean distribution during 2002–2026 is presented in Fig. 3b. The spatial distribution of SSC closely follows the bathymetry (Fig. 1b), with SSC contours generally parallel to the coastline and concentrations



decreasing offshore with increasing water depth. A pronounced horizontal SSC gradient occurs along the submarine slope at depths of approximately 10–16 m, where SSC decreases sharply from 7.5 to approximately 6 mg/l, forming a distinct suspended
 240 sediment front (Du et al., 2025). This front may restrict offshore particulate transport (Maihamuti et al., 2026). Accordingly, the spatial distribution of SSC can be divided into three zones: a high-SSC nearshore zone (<10 m), a transitional zone (10–16 m) characterized by the pronounced SSC gradient and sediment front, and a low-SSC offshore zone (>16 m). Overall, SSC exhibits a clear bathymetry-related decline from
 245 nearshore to offshore waters, with a distinct frontal zone separating the high and low SSC regions.

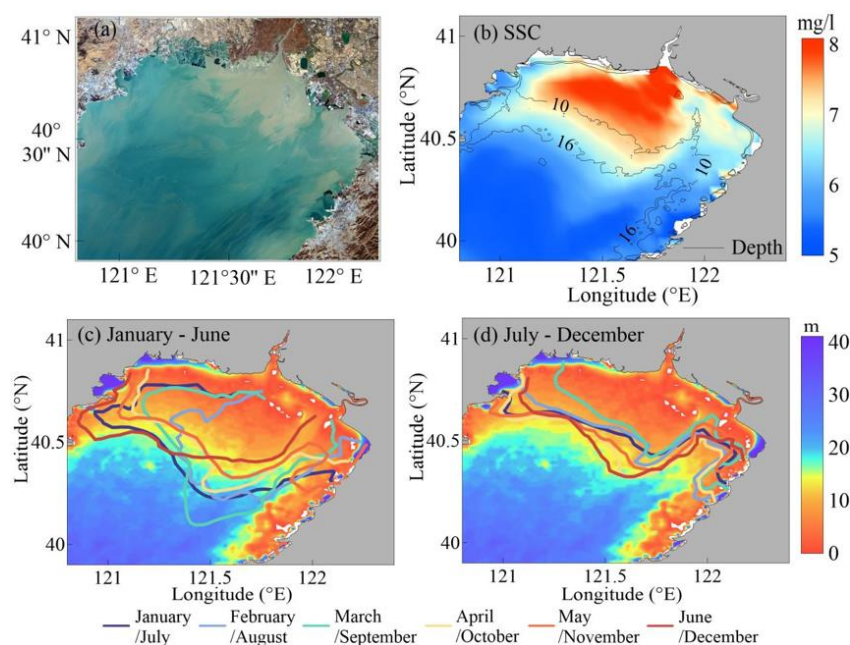


Figure 3. The spatial distribution of high turbidity water bodies in the LDB. (a) Original Landsat image acquired on December 15, 2021. (b) The long-term average SSC in the LDB. (c) and (d) Morphological characteristics of high-turbidity water bodies in different months. The different colored lines represent the SSC in different months, and the filled color represent the water depth. The SSC were derived from MODIS satellite data.



The 7 mg/l SSC contour was used to delineate the high-turbidity water body, and its monthly morphological variations were examined (Fig. 3c, d). The boundary exhibited substantial seasonal variability (Fig. S2). During January–June, its morphology and spatial extent varied considerably, whereas during July–December, the boundary remained relatively stable and closely followed the local bathymetry. This seasonal contrast suggests that hydrodynamic forcing may exert a stronger influence on the boundary during the first half of the year, while topographic constraints become more prominent during the second half.

To further characterize the vertical distribution of SSC, published in situ measurements were compiled and normalized to their corresponding surface concentrations (Fig. 4). Near the estuary, observations by Zhao et al. show a pronounced increase in SSC with depth, with bottom concentrations exceeding 1.5 times the surface values. At stations V1 and V5, SSC varies little with depth, whereas V3 exhibits a marked near-bottom increase. Stations S2–S6 span the three SSC zones identified above. In the high-SSC zone, S2 and S4 exhibit relatively weak vertical gradients, whereas S3 and S5 in the transitional zone show more pronounced variations, particularly at S5, where bottom SSC exceeds 1.5 times the surface concentration. At S6 in the low-SSC zone, bottom SSC remains approximately 1.3 times the surface value. Overall, these observations reveal spatial variations in vertical SSC gradients, with notable bottom enrichment at several locations.

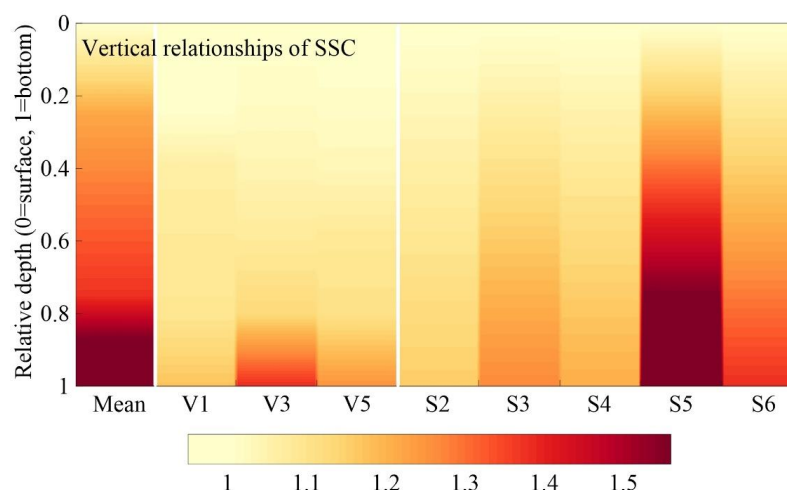


Figure 4. Vertical relationships of SSC in LDB. SSC values were normalized by the corresponding surface concentrations using published in situ measurements. Relative depth ranges from 0 (surface) to 1 (bottom). The locations of stations with published in situ SSC data are shown in Fig. S1.

3.2 Hourly variability of SSC in LDB

Based on GOCI-II remote sensing inversion, this study obtained hourly SSC data in LDB. A representative example is shown for July 5–6, 2025 (Fig. 5), a day on which complete satellite retrievals were obtained. Throughout the hourly variations on this day, the fan-shaped high-turbidity water body persisted. The results show significant hourly SSC variations (Fig. 5). These variations are closely related to tidal fluctuations (Hart-Davis et al., 2026). During the ebb tide (01:16–07:16, UTC), the spatial extent of the high-SSC zone gradually decreased with falling tidal level. During the flood tide (23:16–01:16 and 07:16–08:16, UTC), the extent of the high-SSC zone slightly expanded. These results indicate that the hourly SSC variations in LDB exhibit a clear tidal-phase dependence. This is consistent with the characteristics of a tide-dominated estuary (Costa and Silveira, 1998), where sediment transport and resuspension are



largely modulated by tidal currents. The detailed spatiotemporal evolution of the high-
 290 SSC zone and its underlying controlling mechanisms will be further discussed in
 Chapter 4.2.

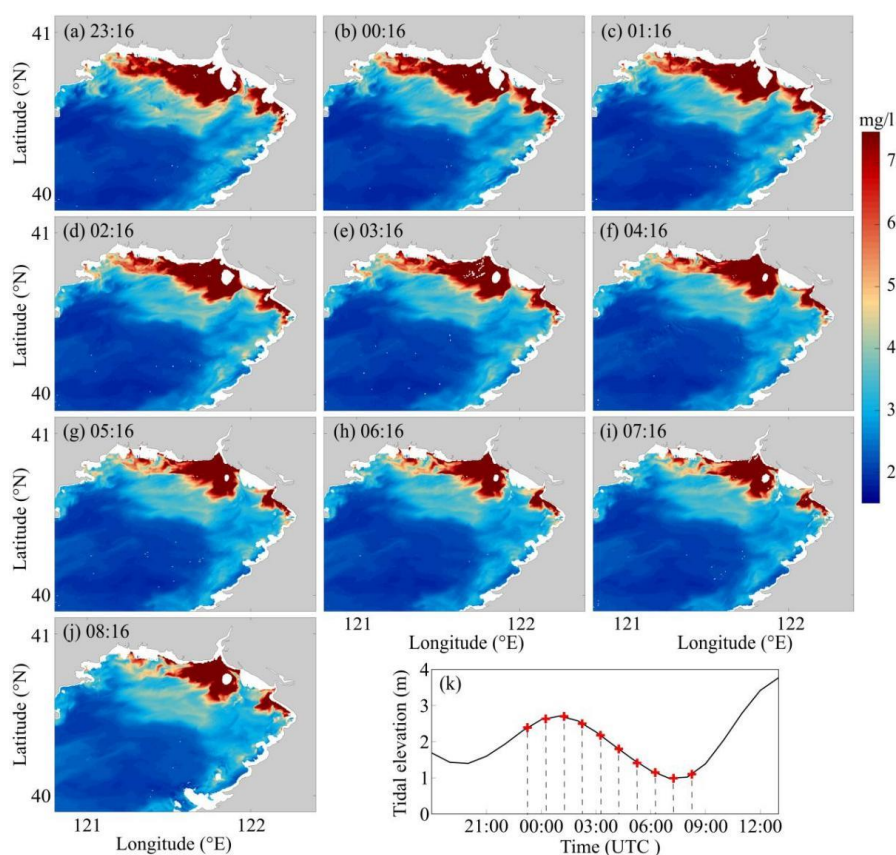


Figure 5. The distributions of SSC in different hours. (a)–(j) The hourly SSC distribution for July 6, 2025 derived by GOCI-II inversion. (k) Tidal elevation variations during July 5–6, 2025. Red
 295 crosses mark the tidal stages corresponding to subplots (a)–(j), respectively.

3.3 Seasonal variability of SSC in LDB

The results in Chapter 3.1 indicate that the morphological variations of the high-
 SSC boundary differed significantly between the first and second halves of the year. On
 an annual timescale, the seasonal characteristics of hydrodynamic conditions and river



300 discharge in the Bohai Sea region are significant (Qiao et al., 2016). Based on multi-
year seasonal average MODIS data from 2002 to 2026, the SSC demonstrates a
pronounced seasonal cycle (Fig. 6). SSC peak in winter, reach minimum values in
summer, and undergo transitional changes during spring and autumn (Zhang et al.,
2026). The seasonal difference in SSC was particularly evident in the high-SSC zone
305 (near point P1), where SSC exhibited a variation of over 7 mg/l (approximately 12 mg/l
in winter versus 5 mg/l in summer). In contrast, a much smaller seasonal difference of
approximately 5 mg/l was observed in the low-SSC zone. This result confirms that the
high-SSC zone is more sensitive to changes in suspended sediment. In winter, driven
by strong monsoon winds, wave action intensifies, leading to strong resuspension of
310 bottom sediments (Wang et al., 2024; Chen et al., 2026), resulting in SSC reaching its
annual peak. In summer, wind speed weakens, and although riverine sediment input
increases, significant water column stratification inhibits vertical mixing of bottom
sediments (Kalhoro et al., 2025), causing SSC to drop to its annual minimum. This
seasonal pattern reflects the combined control of wind-wave disturbance and water
315 column stratification processes.

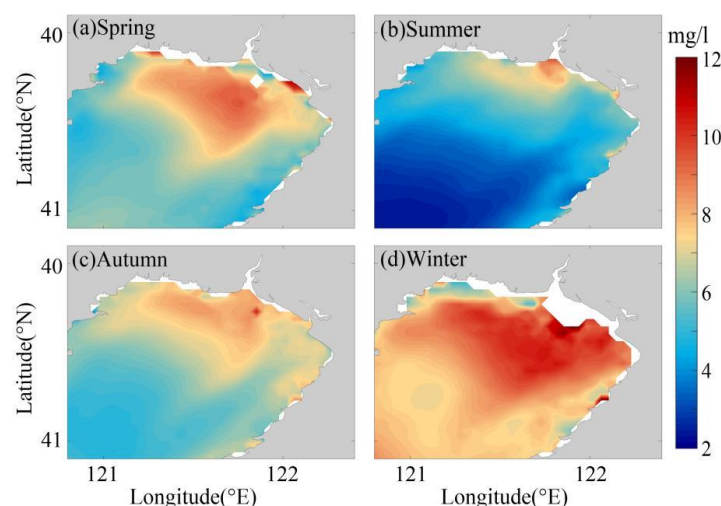


Figure 6. The distributions of SSC in different seasons. The data is derived from MODIS and represents the average values for each season over multiple years (2002–2026).

3.4 Interannual variability of SSC in LDB

320 Compared with hourly and seasonal variations, the interannual variability provides a more direct indication of the overall evolutionary trend of SSC. The interannual variation in SSC is jointly influenced by watershed sediment discharge and local hydrodynamic disturbances (Jia et al., 2025). Based on MODIS data from 2002 to 2026, the interannual variation characteristics of SSC in the LDB were analyzed. The results

325 indicate that the SSC exhibited a significant overall decreasing trend during the study period (Fig. 7). Compared with 2002, the overall SSC in 2026 decreased by approximately 2 mg/l. This long-term trend is closely related to the continuous reduction in sediment discharge from the estuary into the sea (Muzaffar et al., 2017). However, this decreasing process is non-linear, with notable interannual fluctuations:

330 the concentration in 2012 was significantly lower than that in the preceding and following years, whereas a clear rebound occurred in 2019. This variation may be



closely related to interannual changes in hydrodynamic conditions (Zhong et al., 2020).

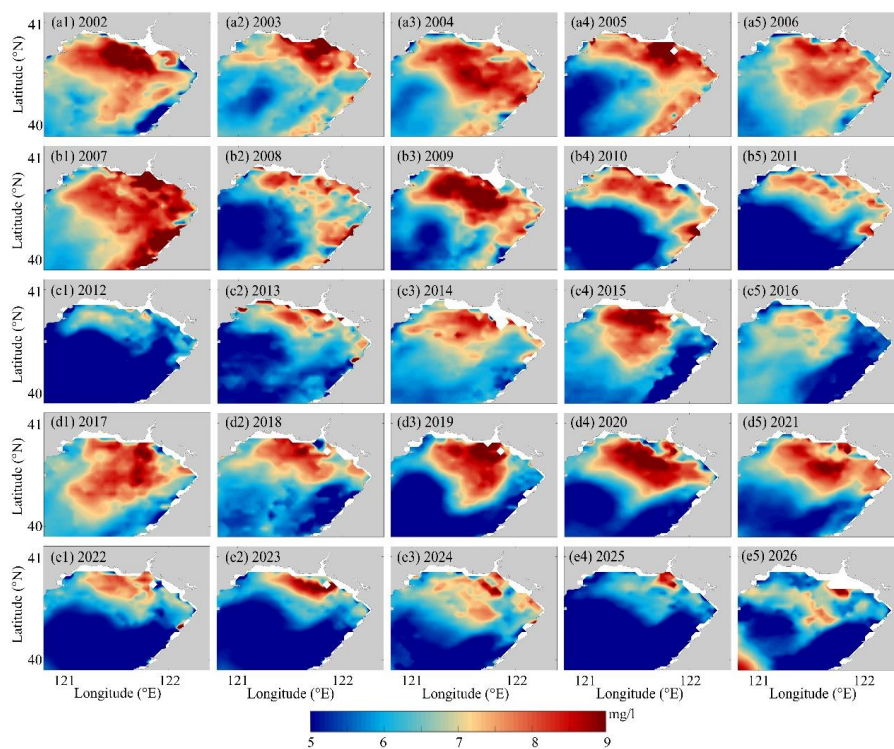


Figure 7. The distributions of SSC from 2002 to 2026. The data is derived from the inversion results of MODIS reflectance.

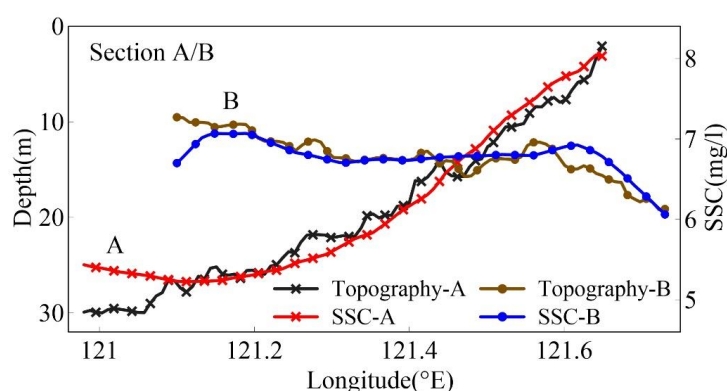
4 Discussion

4.1 Topographic control on the spatial distribution of SSC

The spatial distribution of SSC in LDB exhibits a stepwise offshore decrease closely related to bathymetry, indicating the important role of topography in suspended sediment transport and deposition. To examine this relationship, two representative transects were selected for analysis (Fig. 8). Section A spans the largest depth range, whereas Section B crosses the suspended sediment front in the transitional zone. Along Section A, water depth gradually increases offshore to approximately 30 m,



accompanied by a continuous decline in SSC from 8 to 5 mg/l. In contrast, Section B
 345 traverses the 10–16 m depth interval, where SSC varies by approximately 1.5 mg/l over
 a relatively short distance. Comparison of the two transects suggests that seabed slope
 plays an important role in regulating the spatial distribution of SSC. Gentle slopes are
 associated with gradual SSC changes, whereas steep slopes correspond to pronounced
 SSC gradients and the formation of a suspended sediment front (Fig. 3). In shallow
 350 nearshore waters, strong hydrodynamic forcing may enhance sediment resuspension,
 contributing to elevated SSC. The close correspondence between the sediment front and
 the submarine slope further suggests that topography-induced changes in local
 hydrodynamic conditions may limit the offshore transport of suspended sediment.



355 **Figure 8.** The changes of SSC and topography at Section A and B. The red and black cross lines represent SSC and topography at Section A, respectively. The blue and black dot lines represent SSC and topography at Section B, respectively.

Based on the above spatial differentiation characteristics, the study area can be
 divided from nearshore to offshore into the high-SSC zone, the transitional zone, and
 360 the low-SSC zone, as shown in Fig. 3. The topography and SSC data for three regions
 were quantitatively extracted (Fig. 9), with their spatial extents indicated by the black



boxes in Fig. 1b. Specifically, SSC was around 7–8 mg/l in waters shallower than 10 m (the high-SSC zone), ranged from 6.5 to 7 mg/l at depths of 10–16 m (the transitional zone), and remained generally below 6.5 mg/l at depths exceeding 16 m (the low-SSC zone). Statistical analysis reveals a significant negative correlation between topography (water depth) and SSC, characterized by a rapid decline in SSC with increasing depth. Within the study area, SSC decreases by approximately 1 mg/l on average for every 10 m increase in water depth. This spatial pattern indicates that topography serves as the underlying controlling factor for suspended sediment accumulation.

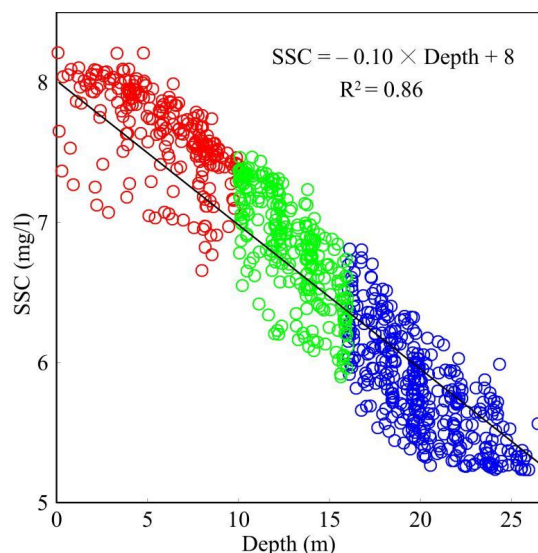


Figure 9. The relationship between SSC and depth. The red circles represent the high-SSC zone (depth < 10 m), the green circles represent the transitional zone (the depth ranges from 10 to 16 m), the blue circles represent the low-SSC zone (depth > 16 m). The black line represents the trend line. The SSC values presented are the long-term averages retrieved from MODIS reflectance data over the 25-year period from 2002 to 2026.

4.2 Temporal dynamics of SSC at hourly and interannual scales

In tide-dominated estuaries and coasts, short-term SSC variations are typically



directly modulated by tidal oscillations (Lin et al., 2025). To quantitatively characterize this process, the 7 mg/l SSC contour was adopted as the boundary of the high-SSC zone.

380 The offshore distance of this boundary was extracted from hourly GOCI retrievals to examine its response to tidal level variations (Fig. 10). The results reveal that during the ebb tide, the offshore distance of the boundary decreased markedly, indicating shoreward retreat and areal contraction of the high-SSC zone. Conversely, during the flood tide, the offshore distance increased, reflecting seaward expansion. This periodic

385 boundary migration driven by tidal alternation further confirms the dominant role of tidal forcing in short-term suspended sediment transport in LDB. Remote sensing observations during morning and evening hours may contain uncertainties due to variations in radiation intensity and solar zenith angle. Future analyses could benefit from incorporating additional imagery from other acquisition times to enhance the

390 reliability.

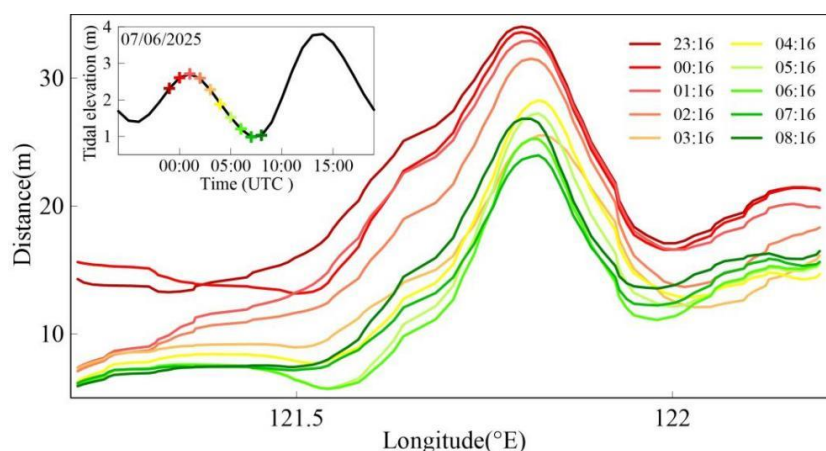


Figure 10. Hourly variations in offshore distance of the 7 mg/L SSC contour on July 6, 2025, derived from GOCI-II retrievals. Colors distinguish the hourly variations. The inset in the upper left shows the corresponding tidal levels.



395 Interannual variations can effectively remove the noise from short-term factors,
thereby revealing the long-term SSC trend with greater clarity. To better visualize this
interannual signal in LDB, the present study performed time-series analysis at P1, P2,
and P3, which are situated in the high-SSC zone, the transitional zone, and the low-SSC
zone, respectively (Fig. 11). Annual mean SSC data retrieved from 2002 to 2026 were
400 employed for characteristic analysis, with the 2026 value averaged over January–June.
A decreasing trend in SSC was observed at all three positions from 2002 to 2026, albeit
with notable spatial differences in the extent of reduction (Fig. 11). Among them, the
P1 point located in the high-SSC zone witnessed the most significant decline, with the
SSC dropping by more than 3 mg/l over a period of 25 years. In contrast, the station P2
405 in the transitional zone and the site P3 in the low-SSC zone experienced relatively
smaller reductions, both at about 2 mg/l. These differences suggest that interannual
variations in SSC in the LDB exhibit notable spatial difference. The high-SSC zone
responds more markedly to decreased river-derived sediment inputs and dynamic
variability, while the low-SSC and transitional zones show relatively weaker
410 responsiveness to these factors. Furthermore, the interannual variability of SSC is not
characterized by a strictly linear decline. Instead, a periodic oscillation superimposed
on the decreasing trend is observed, with a dominant period of approximately 5–6 years.
SSC in 2026 exhibits a rising fluctuation. Based on the historical variation patterns, it
can be inferred that SSC may enter a new phase of sustained decline over the next four
415 to five years. This cyclical pattern implies that the long-term evolution of SSC is
modulated by both secular environmental changes and recurring natural processes on



multi-year scales, such as climatic oscillations or cyclic variations in terrestrial sediment supply (Che et al., 2026).

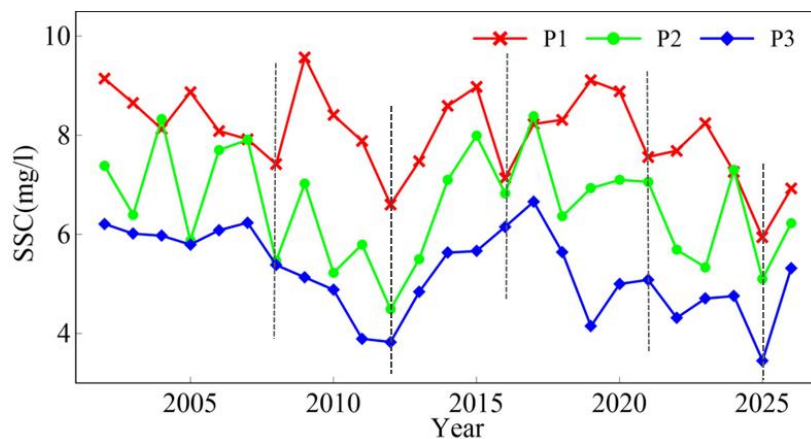


Figure 11. The changes of SSC at different positions from 2002 to 2026. The red line represents the positions of P1, the green line represents the positions of P2, and the blue line represents the positions of P3. The positions of P1, P2, and P3 are shown in Fig. 1b.

4.3 Contributions of dynamic factors to SSC variability

Temporal variations in SSC are influenced by multiple environmental factors (Liu et al., 2025; Tu et al., 2025). Five factors, including current velocity, wind speed, river sediment discharge, SST, and significant wave height, were selected to assess their relative contributions to SSC variability in LDB (Fig. S3). These factors represent the major processes of sediment supply, resuspension, transport, and water-column stratification and mixing. Although the regression does not account for all potential influences, it provides an assessment of the dominant factors associated with SSC variability. As shown in Fig. 12, their relative contributions differ markedly between monthly and interannual timescales.

The contribution of different factors to SSC variation over the monthly cycle was



examined using 2025 as a case study (Fig. 12a). Four major dynamic factors were
 435 considered in this study, including wind, waves, current, and SST. The results show that
 SST is the dominant influencing factor, accounting for 53.3%. SST is an important
 indicator of vertical mixing in seawater (Bernardello et al., 2016). This suggests that on
 monthly scale, SSC variation is primarily driven by the resuspension of bottom
 sediments. Current was the second largest contributor, with a contribution of 31.4%.
 440 Wave contributes 9.3%, and wind contributes 6.0%. These findings suggest thermal
 stratification (indexed by SST) and hydrodynamic conditions (current) are the primary
 controls on SSC dynamics.

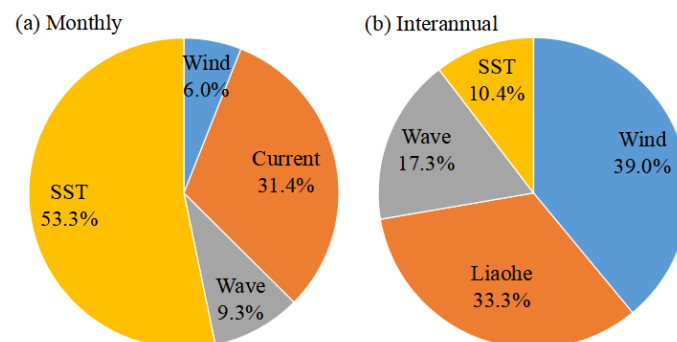


Figure 12. The contributions of different environmental factors in monthly and interannual scale.

445 At the interannual scale, moderate collinearity was identified involving current
 velocity. To minimize multicollinearity, four factors were retained for assessing their
 relative contributions to SSC variability (Fig. 12b), including sediment discharge, wind
 speed, waves, and SST. Wind speed (39.0%) and sediment discharge (33.3%) exhibited
 the largest contributions, followed by waves (17.3%) and SST (10.4%). The dominant
 450 contribution of wind is consistent with its role in enhancing sediment resuspension and
 transport through vertical mixing, wave generation, and wind-driven circulation (Liu et



al., 2025). The comparable contribution of sediment discharge highlights the importance of terrestrial sediment supply, particularly from the Liaohe River. The pronounced decline in SSC at Station P1 in the high-SSC zone (approximately 3 mg/l) over the 25-year period (Fig. 10) is consistent with the influence of reduced riverine sediment input. These results suggest that wind forcing and sediment discharge are the primary factors associated with interannual SSC variability in LDB. However, the contribution of wind at the monthly scale is lower than those of SST and current velocity, indicating that the relative importance of SSC drivers varies with temporal scale.

5 Conclusion

Based on satellite-derived SSC data from 2002 to 2026, this study investigated the multi-scale spatiotemporal variability of SSC and its associated controlling factors in LDB. Spatially, a fan-shaped high-turbidity water body is observed, with SSC decreasing from nearshore to offshore areas, forming three distinct zones: high-SSC, transitional, and low-SSC zones. A distinct suspended sediment front is also identified, and the boundary of the high-SSC zone exhibits pronounced seasonal variations. Published in situ observations further reveal vertical variations in SSC, with concentrations generally increasing toward the seabed. Temporally, hourly SSC variations are closely associated with tidal phases, while seasonal SSC is generally lower in summer and higher in winter. At the interannual scale, SSC exhibits an overall declining trend with quasi-periodic fluctuations of approximately 5–6 years.

Topography plays a key role in shaping the spatial distribution of SSC, whereas



the relative influence of environmental factors varies across timescales. At the monthly scale, SST, serving as an indicator of stratification and vertical mixing, and current
475 velocity are the leading factors, with estimated relative contributions of 53.3% and 31.4%, respectively. At the interannual scale, wind speed and river sediment discharge become dominant, contributing approximately 39.0% and 33.3%, respectively. These findings highlight the timescale-dependent relationships between SSC variability and environmental forcing, providing insights into coastal sediment dynamics and
480 supporting sediment transport modeling and coastal management.

Nevertheless, this study is limited by the availability and temporal resolution of observational data, particularly for vertical SSC distributions and short-term processes. Future studies integrating more comprehensive in situ measurements and higher-resolution datasets could further improve the quantification of environmental
485 contributions and understanding of SSC variability across multiple timescales.

Data availability. MODIS-Aqua Level 3 data are available from the NASA (<https://oceancolor.gsfc.nasa.gov/>). GOCI-II data are available from the KOSC (<https://nosc.go.kr/>), and Landsat-8 data from USGS (<https://earthexplorer.usgs.gov/>). ERA5 data are available through the Copernicus Climate Data Store
490 (<https://cds.climate.copernicus.eu/>), and ocean-current data through the CMEMS (<https://data.marine.copernicus.eu/>). Tidal and topographic data were obtained from NMDIS (<https://oceanknowledge.nmdis.org.cn/>; <https://mds.nmdis.cn/>). River sediment discharge data were compiled from the *China River Sediment Bulletin* issued by the Ministry of Water Resources of China.



495 *Author contributions.* In this manuscript, Lu Zhang was responsible for writing this paper. Xinwei Chen provided supervision, conducted final review and approval of the manuscript. Sichen Zhang collected some hydrodynamic data. Jun Song, Yanzhao Fu and Weimin Huang reviewed and revised the final manuscript.

Competing interest. The authors declare no competing interests.

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