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Satellite-observed significant improvement in nearshore transparency of the Bohai Sea during pollution control

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Abstract

The Bohai Sea (BS) is the unique semi-closed inland sea of China, characterized by degraded water quality due to significant terrestrial pollution input. In order to improve its water quality, a dedicated action named “Uphill Battles for Integrated Bohai Sea Management” (UBIBSM, 2018–2020) was implemented by the Chinese government. To evaluate the action effectiveness toward water quality improvement, variability of the satellite-observed water transparency (Secchi disk depth, Z_{SD}) was explored, with special emphasis on the nearshore waters (within 20 km from the coastline) prone to terrestrial influence. (1) Compared to the status before the action began (2011–2017), majority (87.3%) of the nearshore waters turned clear during the action implementation period (2018–2020), characterized by the elevated Z_{SD} by 11.6% ± 12.1%. (2) Nevertheless, the improvement was not spatially uniform, with higher Z_{SD} improvement in provinces of Hebei, Liaoning, and Shandong (13.2% ± 16.5%, 13.2% ± 11.6%, 10.8% ± 10.2%, respectively) followed by Tianjin (6.2% ± 4.7%). (3) Bayesian trend analysis found the abrupt Z_{SD} improvement in April 2018, which coincided with the initiation of UBIBSM, implying the water quality response to pollution control. More importantly, the independent statistics of land-based pollutant discharge also indicated that the significant reduction of terrestrial pollutant input during the UBIBSM action was the main driver of observed Z_{SD} improvement. (4) Compared with previous pollution control actions in the BS, UBIBSM was found to be the most successful one during the past 20 years, in terms of transparency improvement over nearshore waters. The presented results proved the UBIBSM-achieved remarkable water quality improvement, taking the advantage of long-term consistent and objective data record from satellite ocean color observation.

Key words: Secchi disk depth, transparency, water quality, nearshore, Bohai Sea, satellite ocean color remote sensing, pollution control

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1 Introduction

The Bohai Sea (BS) is the only semi-enclosed inland sea of China, with an average water depth of about 18 m (Chen et al., 2010) and a coastline length of approximately 3 500 km (Zhang et al., 2020). BS is connected with the Yellow Sea (YS) from the east, and from the other 3 sides, surrounded by three provinces and one municipality (TPOM), i.e., Liaoning (LN), Hebei (HB), Tianjin (TJ, the 3rd largest municipality of China) and Shandong (SD). After decades of rapid development, nowadays the Bohai Rim Economic Belt has become one of the regions with the dense population and active economy (Song, 2017). Meanwhile, the BS has been facing degraded water quality and fragile ecological environment, mainly due to significant terrestrial pollution input along with intensified human activities (Ling and Han, 2021; Pan and Du, 2022; Gao et al., 2014).

To address this issue, the Chinese government implemented two dedicated pollution control actions in the BS during the first decade of 21st century, including “The Plan of Cleaning Bohai Sea” initiated in 2001, and the “The General Plan of Environmental Protection of Bohai Sea” started in 2008. Although many efforts were made during these two actions, the land-based pollution had not been effectively controlled and thus limited improvement in water quality was achieved.

In this context, a new initiative named “Uphill Battles for Integrated Bohai Sea Management” (UBIBSM) was put forward in 2018, aiming at fundamentally reversing the trend of water quality deterioration and comprehensively improving the ecological environment of the BS through three years of action (2018–2020).

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Now, UBIBSM has been completed, and a systematic in-depth scientific evaluation of the action effectiveness is of great importance, in order to answer whether or not (or, to what extent) the water quality has been improved as expected (in other words, marine ecological responses to the terrestrial pollution control), and in which regions the action needs to be strengthened. Albeit important, such a scientific evaluation is lacking.

To this end, in this study, the variability of the satellite-observed water transparency was explored, to evaluate the action effectiveness in terms of water quality improvement. And special emphasis was laid on the nearshore waters (within 20 km from the coastline) of BS, which were prone to terrestrial influence and characterized by pronounced deteriorated water quality. As one of the most important proxies of water quality, transparency (Secchi disk depth, Z_{SD}, m), which refers to the depth of a Secchi disk submerged in water until it is no longer visible to the observer (Preisendorfer, 1986), can comprehensively represent the water clarity (Zhu and Zhao, 1991; He et al., 2017). And thus Z_{SD} is commonly adopted as indicator of water quality variability (Pan and Bai, 2008; Xue et al., 2015; Yin et al., 2020). Satellite-observed, rather than *in situ* measured Z_{SD} was adopted in the study, due to the fact that the former one has advantages of large-scale synoptic, long time series and repeated observations (Lee et al., 2016; Zeng et al., 2020; Liu et al., 2020; Alam et al., 2021) whereas the latter one is inherent with temporal and spatial limitations (Gong, 2012; Lee et al., 2018).

The objectives of this study are two-folds. (1) Characterize the Z_{SD} variability in the BS nearshore waters during UBIBSM action (2018–2020) as compared to the baseline (2011–2017), with special focus on the spatial heterogeneity in terms of administrative regions, as well as comparison with historical pollution control actions. (2) Reveal the mechanisms of the observed Z_{SD} variability in terms of pollution control, and put forward targeted measures and suggestions for future similar actions.

2 Data and methods

2.1 *Data*

In this study, the satellite $R_{rs}(\lambda)$ (monthly products from 2003 to 2020, spatial resolution: 4 km) of Moderate Resolution Imaging Spectroradiometer (MODIS) were used to estimate Z_{SD}, acquired from OceanColor web portal (https://oceancolor.gsfc.nasa.gov/).

To validate the satellite-derived $R_{rs}(\lambda)$ and Z_{SD}, the *in situ* $R_{rs}(\lambda)$ ($N = 7$, purple circles in Fig. 1) and Z_{SD} ($N = 45$, 0.5–4.5 m, purple crosses in Fig. 1), measured in the nearshore waters of the BS in 2005, 2011 and 2013–2016, were collected to match with (temporal window: ±6 h, spatial window: ±3 pixels) MODIS observations.

Validation results (Fig. 2) showed that the medians of the absolute percentage of difference (APDm) of MODIS $R_{rs}(\lambda)$ in the 488–555 nm spectral domain were about 30%, with root mean square error (RMSE) of 0.004 5–0.005 0 sr^{-1}, and R^2 of 0.51–0.71 (Fig. 2a). It's also important to note that the spectral shapes of MODIS $R_{rs}(\lambda)$ were in highly accordance with the *in situ* ones (Fig. 2b). High quality satellite $R_{rs}(\lambda)$ permits reliable Z_{SD} retrievals.

To analyze the driving factors of Z_{SD} changes during UBIBSM, the following data were collected, including pollution discharge, river runoff and sediment transport, wind speed, mixed layer depth (MLD), and dust storm deposition.

(1) Annual statistics of pollutants emissions (e.g., chemical oxygen demand (COD), ammonia nitrogen (NH_4^+-N) and total phosphorus (TP)), was obtained from government report or bulletin, including *Announcement on Environmental Quality of China's Coastal Waters* (2011–2016), *Announcement on Ecologic-*

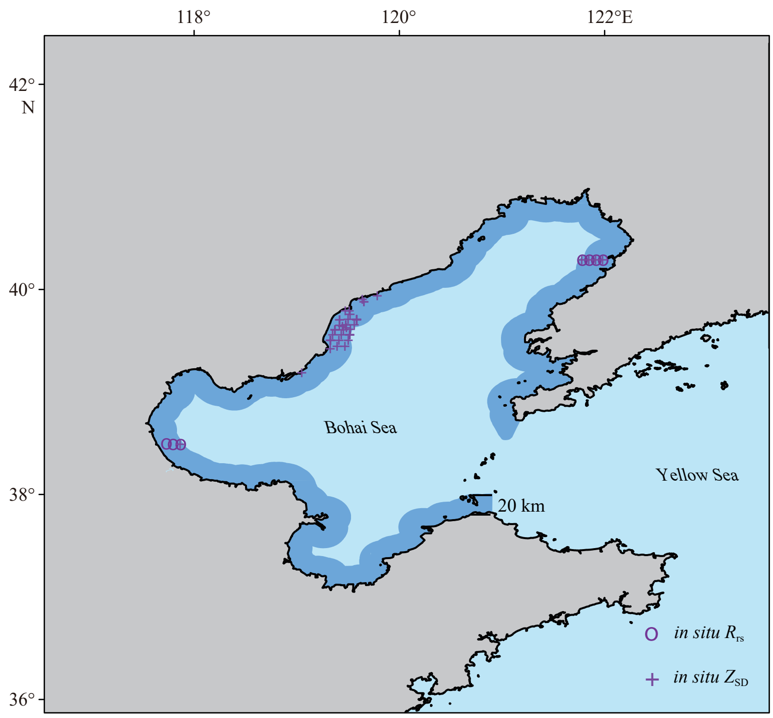

Fig. 1. Location of Bohai Sea and the surrounding TPOM. The study area is nearshore waters (the dark blue region), which is within 20 km from the coastline, with average depth of about 11 m. Purple circles and crosses represent the sites with $R_{rs}(\lambda)$ ($N = 7$) and Z_{SD} ($N = 45$) observations, respectively. It is noted that these 2 measurements are available at 5 stations.

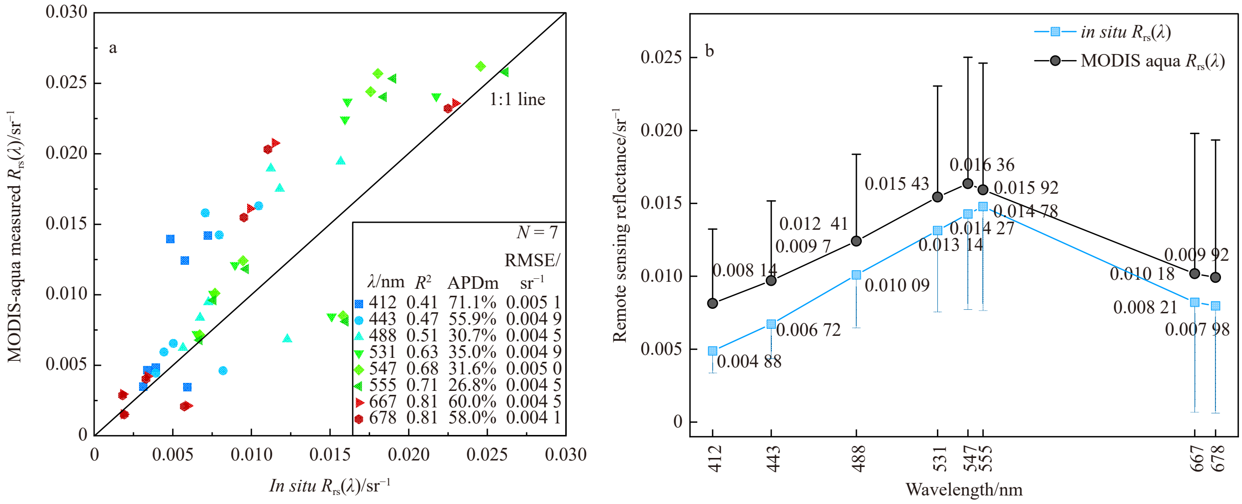

Fig. 2. Validation of MODIS $R_{rs}(\lambda)$ in the nearshore waters of the BS. a. Scatter plot at major ocean color bands; b. comparison of spectral shapes. Error bars denote the standard deviations of multiple observations.

al Environmental Quality of China's Coastal Waters (2017), and *Bulletin of Marine Ecology and Environment Status of China* (2018–2020) (http://www.mee.gov.cn/hjzl/sthjzk/jagb/).

(2) Annual amounts of runoff and sediment discharge from rivers, including the Yellow River, Liaohe River and Haihe River, were obtained from *China River Sediment Bulletin* (an official bulletin annually released by the Chinese government based on routine measurements at hydrological stations along the rivers) (http://www.mwr.gov.cn/sj/tjgb/zghlnsgb/) and used to estimate the concentrations of suspended particulate matter (SPM) from rivers.

(3) Daily wind speed data at coastal meteorological stations in TPOM from 2011 to 2020 were obtained from the SURF_CLI_CHN_MUL_DAY (V3.0) dataset of the China Meteorological Data Service Center (https://data.cma.cn/).

(4) Monthly MLD data from 2011 to 2020, with a spatial resolution of 0.083°, were obtained from Copernicus Marine Environment Monitoring Service (CMEMS) (https://resources.marine.copernicus.eu/).

(5) Annual number of dust storm events in spring (from March to May, when dust storm mainly occurs) was obtained from *Yearbook of Meteorological Disasters in China* (2011–2019) (https://navi.cnki.net/knavi/yearbooks/YQZXH/detail?uniplatform=NZKPT), and *China Climate Bulletin* (2020) (http://www.cma.gov.cn/zfxxgk/gknr/qxbg/202104/t20210406_3051288.html).

2.2 *Methods*

(1) Long-term Z_{SD} record construction

The long-term Z_{SD} records (2003–2020) of the BS were generated using MODIS monthly images and the following model. The flow chart of the Z_{SD} retrieval model is shown in Fig. 3, including roughly 3 steps, with MODIS $R_{rs}(\lambda)$ at bands of 443 nm, 488 nm, 531 nm, 555 nm, and 667 nm as input. This model is detailed in Xiang et al. (2023) and only recalled in brief here.

Step (1): Optical classification. The $R_{rs}(\lambda)$ data were used to calculate the index *f*, which was used to divide seawater into three types: clear water, moderately turbid water, and extremely turbid water.

Step (2): Diffuse attenuation coefficient retrieval $K_d(\lambda)$. For clear water, the quasi-analytical algorithm (QAA) (Lee et al., 2002) was used to estimate absorption coefficient *a* and backscattering coefficient b_b and the diffuse attenuation coefficient $K_d(\lambda)$ was further derived using the Lee et al. (2005) model. For extremely turbid water, the simple semi-analytical (SSA) model (Chen et al., 2014) was adopted to estimate $K_d(490)$, and then $K_d(\lambda)$ was derived with spectral correlations. For moderately turbid water, $K_d(\lambda)$ was obtained as the weighted average of those of clean and extremely turbid waters.

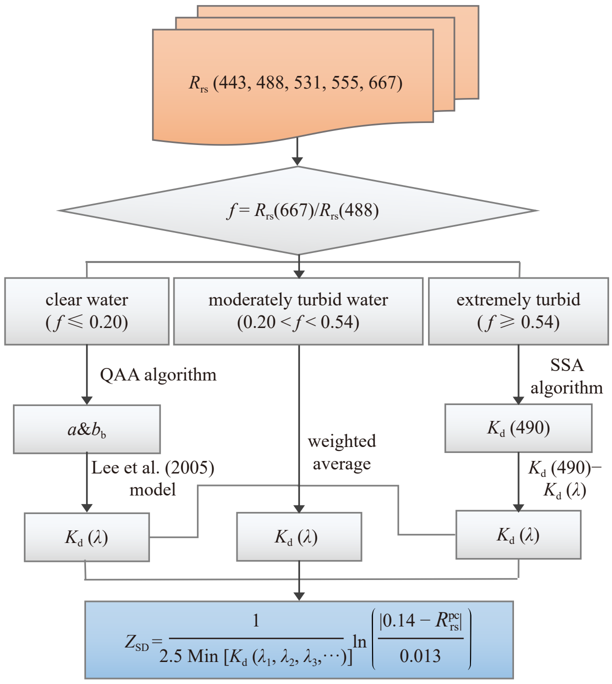

Fig. 3. Diagram of Z_{SD} retrieval model. In the blue box, Min $[K_d(\lambda_1, \lambda_2, \lambda_3, \cdots)]$ represents the minimum at these bands and R_{rs}^{pc} is the remote sensing reflectance of the corresponding wavelength.

Step (3): Z_{SD} derivation. With $K_d(\lambda)$ and $R_{rs}(\lambda)$ as input, the Lee et al. (2015) model was used to retrieve Z_{SD}.

The model was applied to satellite images and validated with concurrent *in situ* Z_{SD} in the BS coastal waters ($N = 45$, Fig. 1), showing a reasonable accuracy (APDm = 32.7%, RMSE = 1.01 m, $R^2 = 0.53$, Fig. 4).

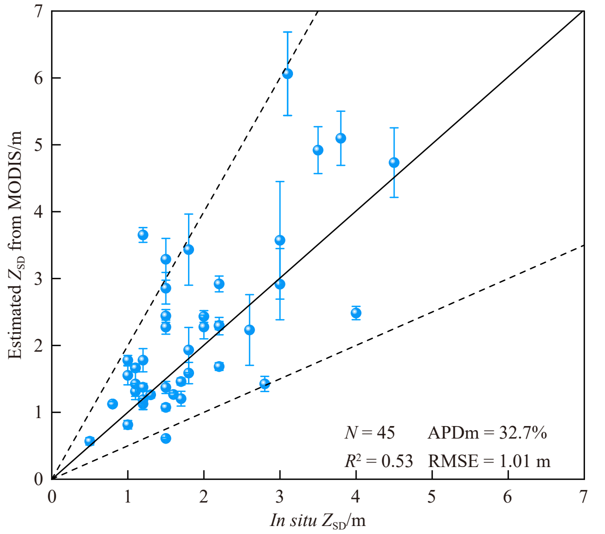

Fig. 4. Comparison between satellite-derived Z_{SD} and *in situ* measurements. Solid line is the 1:1 line. Dashed lines are the 1:2 and 2:1 lines.

The Data Interpolating Empirical Orthogonal Function (DINEOF) (Beckers and Rixen, 2003) was further used to reconstruct the missing data in the optical images due to cloud cover. The cross-validation (Alvera-Azcárate et al., 2005) dataset (Z_{SD} equals 0 m to10 m, N = 1 812) was compiled to validate the reconstructed accuracy of Z_{SD} maps in the nearshore waters. The result (Fig. 5) indicated that the reconstructed Z_{SD} were in good agreement with the satellite-observed data, with an APDm, RMSE, and R^2 of 19%, 0.49 m, and 0.82, respectively.

(2) Z_{SD} variability quantification

Variability of the satellite-observed Z_{SD} was quantified to evaluate the action effectiveness toward water quality improvement. It is noted that the analysis focused only on the nearshore waters (within 20 km from the coastline), not the whole BS, due to the fact that the nearshore waters were prone to terrestrial influence and the emphasis of water quality improvement.

Specifically, for each pixel of the nearshore waters, the Z_{SD} variability (P) during the pollution control action was calculated

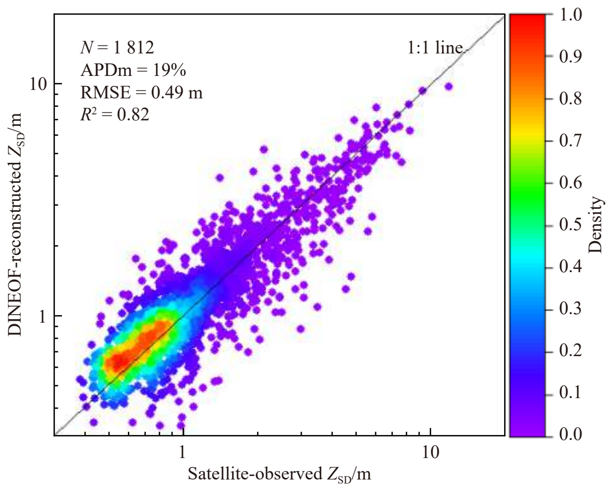

Fig. 5. Scatter plot of satellite-observed and DINEOF-reconstructed Z_{SD} based on cross-validation dataset compiled from the nearshore waters of the BS.

as the percentage difference (Eq. (1)) between the three-year average (B) during UBIBSM (2018–2020) and the multi-year average (A) before UBIBSM (2011–2017). For the significance test of the variability, the U test was adopted (Wei, 2007).

$$P = \frac{B - A}{A} \times 100\%. \quad (1)$$

Besides, the BEAST method (Zhao et al., 2019) was used to analyze the long-term trend of monthly Z_{SD} from 2011 to 2020, in order to detect trend change point, that is, the time when a significant upward/downward trend of Z_{SD} occurred.

3 Results

3.1 Z_{SD} *Overall improvement*

Compared to the status (average Z_{SD} = 1.27 m ± 0.04 m) before the action began (2011–2017), majority (87.3%) of the nearshore waters turned clear (Z_{SD} = 1.44 m ± 0.03 m) during the action implementation period (2018–2020), characterized by the higher (11.6% ± 12.1%) transparency. And the coverage percentage of nearshore waters with significant Z_{SD} improvement (p < 0.05) amounted to 27.9% (blue regions in Fig. 6a).

Besides, the largest water quality improvement with Z_{SD} increase >20% were mainly distributed in the cities of Qinhuangdao (QHD), Dalian (DL) and Yantai (YT) (blue regions in Fig. 6b), which was generally consistent with the spatial distribution of "clearer" nearshore waters with annual average (2011–2017) Z_{SD} greater than 1.5 m (blue regions in Fig. 6c).

BEAST-based long-term change trend analysis from 2011 to 2020 further indicated that during UBIBSM (highlighted in shadow in Fig. 7), the overall trend of the Z_{SD} of BS nearshore waters exhibited an upward trend (Fig. 7), with the change point of Z_{SD} improvement appearing in April 2018, which agreed with the initiation time of UBIBSM action (June 2018) (Ecological Environment Department et al., 2018).

Further extending the analysis to all the years during which MODIS Aqua observations are available (starting August 2002), it can be found that before UBIBSM (2003–2017), Z_{SD} maximum (1.38 m) appeared in 2003, followed by fluctuation in the range of 1.14–1.34 m, with an average of 1.26 m (Fig. 8). In contrast, during UBIBSM period, Z_{SD} significantly bounded to 1.42–1.48 m, with an average of 1.44 m, and the highest transparency was achieved in 2020 for nearly the past two decades (Fig. 8).

In this context, UBIBSM can be regarded as the most successful dedicated pollution control action in the BS, at least in terms of transparency improvement over nearshore waters, when compared with previous ones during the past 20 years, including "The Plan of Cleaning Bohai Sea" and "The General Plan of Environmental Protection of Bohai Sea".

3.2 *Comparison between administrative regions*

Albeit overall Z_{SD} improvement in the nearshore waters of the BS, the improvement during UBIBSM was not spatially uniform. Specifically, higher (>10%) Z_{SD} improvements were achieved in provinces of Hebei, Liaoning, and Shandong (13.2% ± 16.5%, 13.2% ± 11.6%, 10.8% ± 10.2%, respectively), and lower one was in Tianjin municipality (6.2% ± 4.7%) (Fig. 6a).

In provinces of Liaoning, Hebei and Shandong, coverage percentages with elevated Z_{SD} by more than 10%, 20%, and 30% amounted to 25.1%–30.1%, 13.9%–21.7%, and 3.9%–18.1%, respectively. In Tianjin municipality, the proportion of sea area with Z_{SD} improvement of >10% accounted for 13.9%, but no Z_{SD}

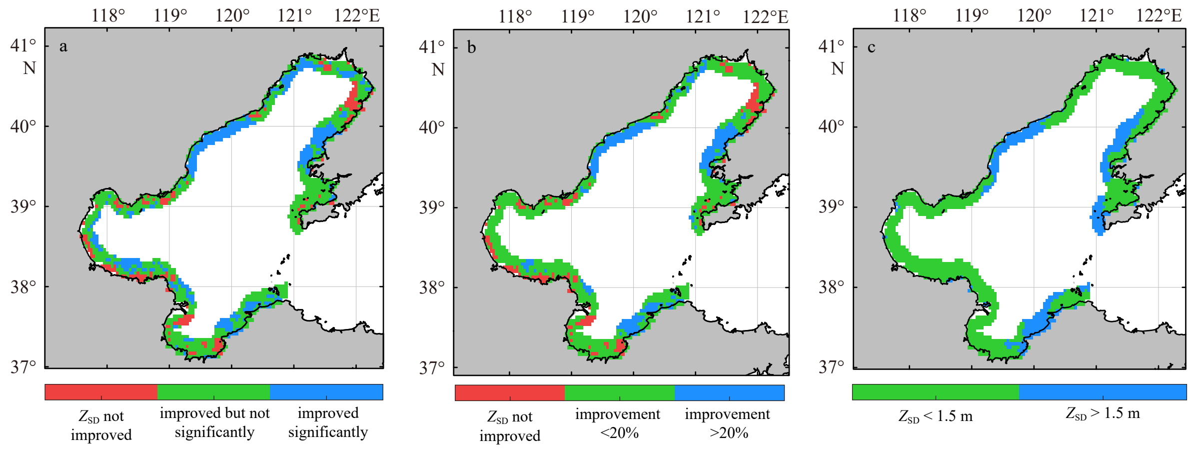

Fig. 6. Spatial distribution of Z_{SD} variability over BS nearshore waters during 2018 and 2020, as compared to that during 2011 and 2017, Z_{SD} improvement of Liaoning, Hebei, Shandong and Tianjin were 13.2% ± 11.6%, 13.2% ± 16.5%, 10.8% ± 10.2%, and 6.2% ± 4.7%, respectively (a); spatial distribution of nearshore waters during 2018 and 2020 with Z_{SD} increase of higher than 20% (in blue) and lower than 20% (in green), respectively (b); and average Z_{SD} during 2011 and 2017 (c). The "improved significantly" refers to Z_{SD} improvement satisfying 95% significance level.

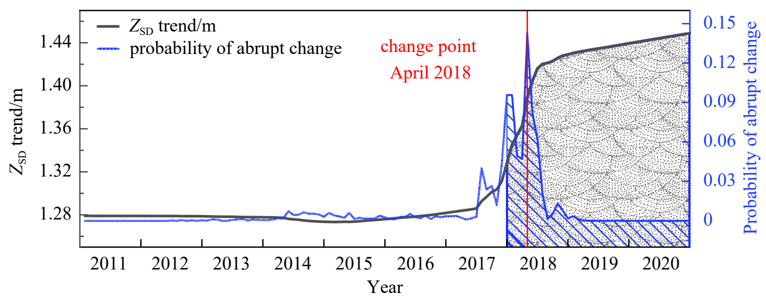

Fig. 7. BEAST-derived change trend (black line) of the Z_{SD} over the BS nearshore waters from 2011 to 2020 and the detected change point with the highest probability of abrupt change. The shaded part highlights the UBIBSM duration, and the red line indicates the detected change point.

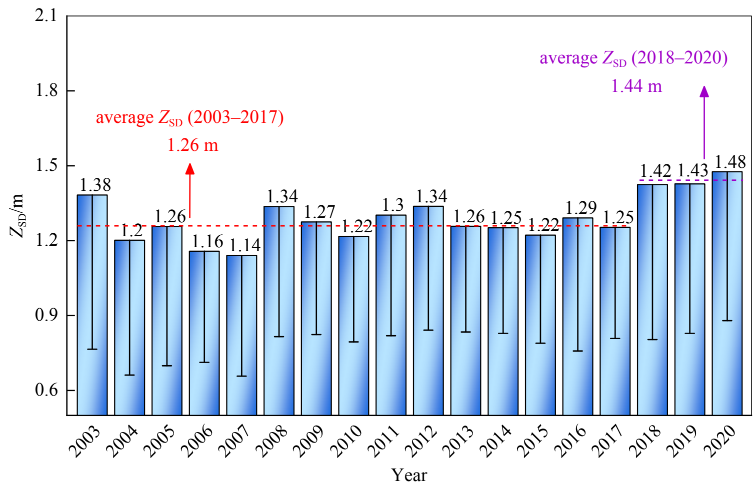

Fig. 8. Annual averaged Z_{SD} of the BS nearshore waters from 2003 to 2020. Error bars denote the standard deviations of monthly transparency.

improvement higher than 20% was found (Fig. 9).

For each province, the distribution of nearshore waters without Z_{SD} improvement was also analyzed. Specifically, these waters in the Hebei, Shandong and Liaoning Provinces were mainly found in the city of Tangshan (TS) (70.3%), Dongying (DY) (54.8%) and Yingkou (YK) (43.1%), respectively.

From the city's perspective, among the 13 coastal cities around BS, Qinhuangdao showed the highest Z_{SD} improvement (33.8% ± 18.8%), followed by Huludao (HLD) (16.5% ± 13.3%), Dalian (16.3% ± 10.3%), and Yantai (16.0% ± 11.5%). The other 9

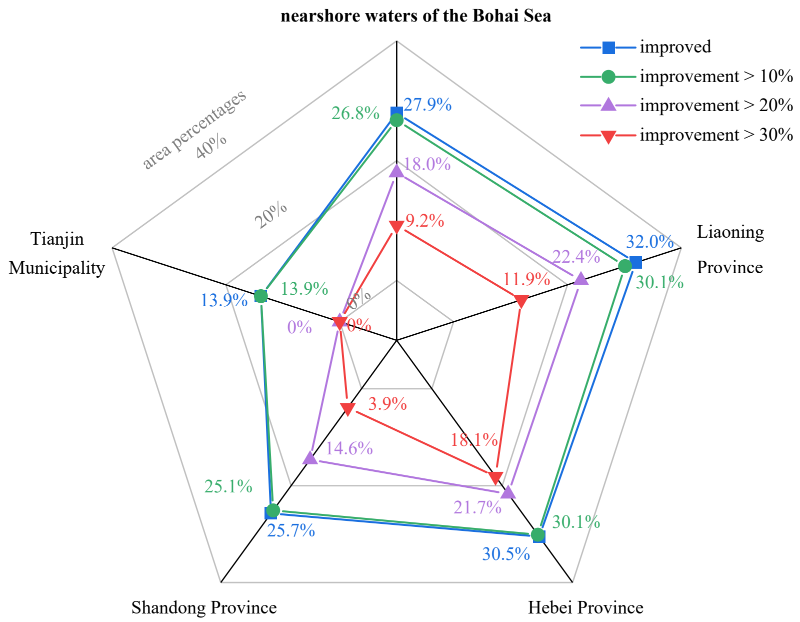

Fig. 9. Coverage percentage of nearshore waters with improved Z_{SD} (2018–2020) for the entire BS and TPOM.

cities exhibited lower Z_{SD} improvement (2.0%–11.3%) than the regional average (11.6% ± 12.1%), requiring more efforts in future pollution control actions (Fig. 10).

For the Liaoning Province, Z_{SD} in 5 cities of Huludao, Dalian, Panjin (PJ), Jinzhou (JZ), and Yingkou along the BS, improved during UBIBSM by 16.5% ± 13.3%, 16.3% ± 10.3%, 11.3% ± 10.6%, 5.2% ± 5.4%, and 2.0% ± 6.0%, respectively (Fig. 11a), ranking the 2nd , 3rd , 5th , 11th , and 13th respectively, among all the 13 cities (Fig. 10). Besides, in terms of the percentages of sea areas with improved Z_{SD}, Jinzhou and Panjin also fell behind the other 3 cities (Fig. 11b).

For the Hebei Province, Z_{SD} in 3 cities of Qinhuangdao, Tangshan, and Cangzhou (CZ), improved during UBIBSM by 33.8% ± 18.8%, 5.9% ± 6.8%, and 5.8% ± 5.2% respectively (Fig. 12a), ranking the 1st , 9th, and 10th, respectively, among all the 13 cities around the BS (Fig. 10). The percentage of sea areas with improved Z_{SD} in Qinhuangdao was also much higher than those of Tangshan and Cangzhou (Fig. 12b).

Finally, for the Shandong Province, Z_{SD} in 4 cities of Yantai, Dongying, Weifang (WF), and Binzhou (BZ), improved during UBIBSM by 16.0% ± 11.5%, 8.7% ± 8.5%, 6.2% ± 5.0%, and 3.9% ± 8.4% respectively (Fig. 13), ranking the 4th , 6th , 8th , and 12th , respectively, among all the 13 cities around the BS (Fig. 10).

4 Discussion

4.1 *Mechanism of Z_{SD} improvement*

Seawater Z_{SD} is influenced by both the natural and human factors (Ye et al., 2022). Previous studies have found that wind speed (Ding et al., 2022; Zhang et al., 2015), sediment transport from river runoff (Mao et al., 2018; Li et al., 2022), mixed layer depth (Li et al., 2020) and dust storm deposition (Chen et al., 2016; Tan et al., 2012) are the possible factors of Z_{SD} variability in the study areas. Therefore, the mechanism analysis is firstly focused on the influences from the above four natural factors.

Strong wind may cause Z_{SD} decrease through triggering resuspension of sediments (Shi et al., 2018; Yin et al., 2021). In order to analyze the possible effects of wind field on the observed

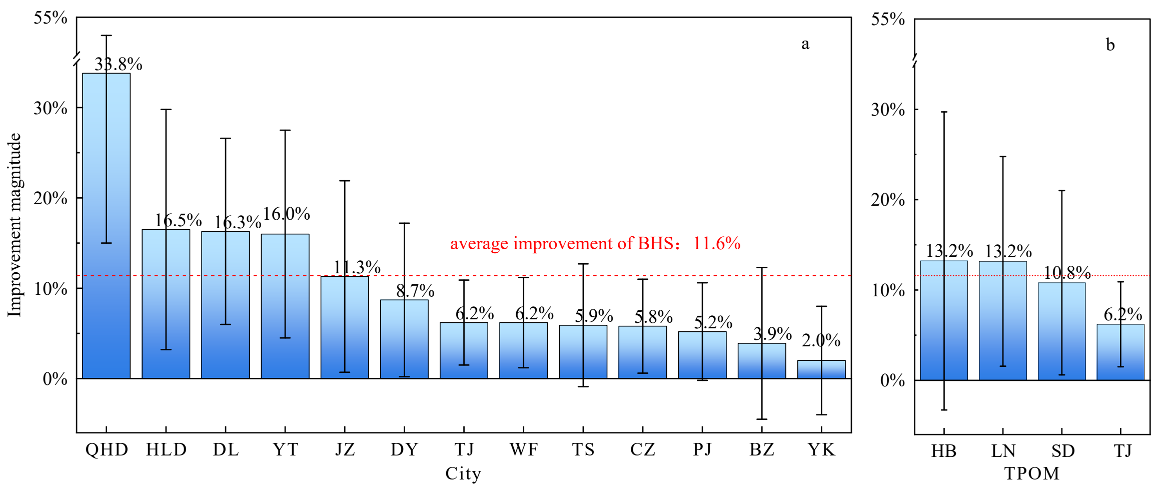

Fig. 10. Z_{SD} improvement for the 13 coastal cities (a) and TPOM around the BS (b).

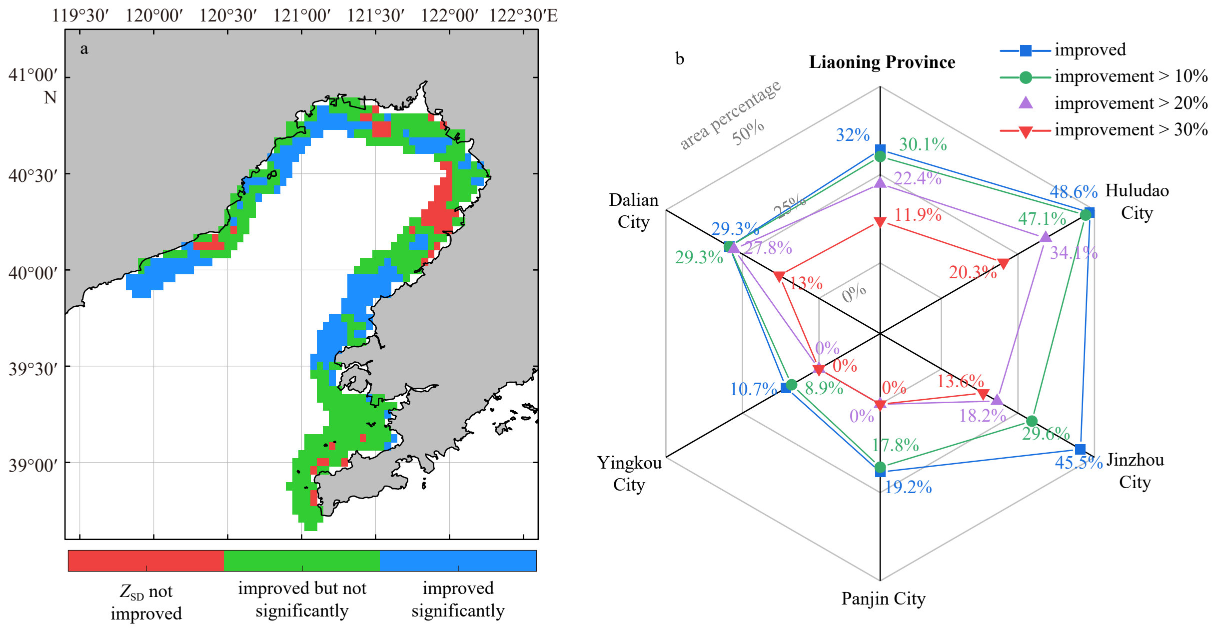

Fig. 11. Spatial distribution of Z_{SD} variability over the BS nearshore waters of Liaoning Province during 2018 and 2020, as compared to that during 2011 and 2017 (a) and coverage percentages of BS nearshore waters with improved Z_{SD} (2018–2020) for cities of the Liaoning Province (b).

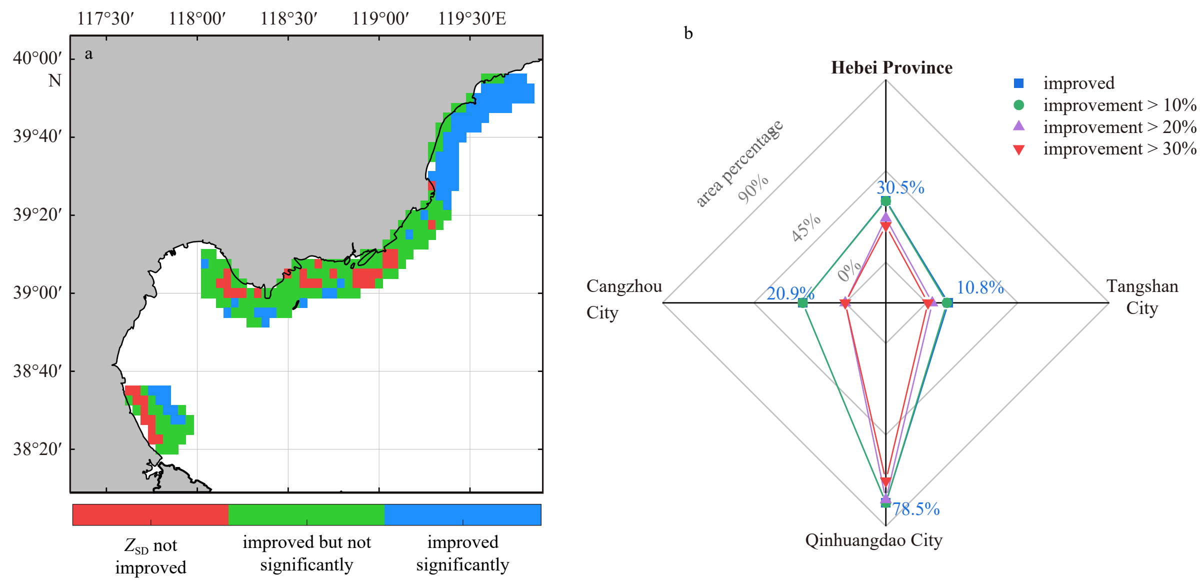

Fig. 12. Spatial distribution of Z_{SD} variability over the BS nearshore waters of Hebei Province during 2018 and 2020, as compared to that during 2011 and 2017 (a) and coverage percentages of BS nearshore waters with improved Z_{SD} (2018–2020) for cities of the Hebei Province (b).

Z_{SD} improvement, wind speed data from TPOM coastal meteorological stations ($N = 15$) during 2011 and 2020 were collected. The statistics showed no significant ($p > 0.1$) variability in the wind speed averaged over 2018–2020 as compared to 2011–2017 (Fig. 14a), implying that wind field is not the main reason for the observed Z_{SD} improvement, although an insignificant weak negative correlation ($R^2 = 0.23$, $p > 0.1$) exists between these two parameters (Fig. 14b).

In order to analyze the possible influences of terrestrial SPM input on the Z_{SD} during UBIBSM, data of river runoff, sediment transport, and SPM concentration of major rivers flowing into the BS (including the Yellow River, Liaohe River, and Haihe River) were collected. The statistics showed that during UBIBSM (2018–2020), SPM concentrations from river runoff had not significantly decreased, as compared to those from 2011 to 2017 (Fig. 15). As SPM decrease corresponds to Z_{SD} increase (Mao et al., 2018; Fei, 1986; Guo et al., 2003), the observed improvement of Z_{SD} cannot be attributed to the river sediment input variability. Previous studies (Li et al., 2021, 2022; Zhao et al., 2022) have found that the effect of SPM on Z_{SD} is spatially confined to the small range within several kilometers of the estuary due to sediment rapid deposition. Therefore, the river-transported SPM has rather limited effect on the general Z_{SD} pattern over the BS nearshore waters as a whole.

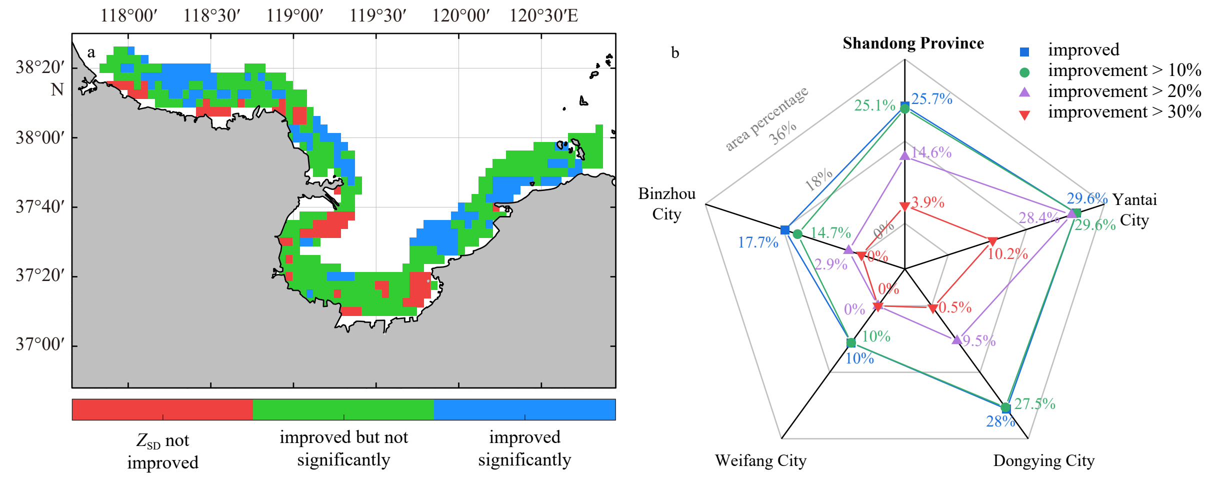

Fig. 13. Spatial distribution of Z_{SD} variability over the BS nearshore waters of Shandong Province during 2018 and 2020, as compared to that during 2011 and 2017 (a) and coverage percentages of BS nearshore waters with improved Z_{SD} (2018–2020) for cities of the Shandong Province (b).

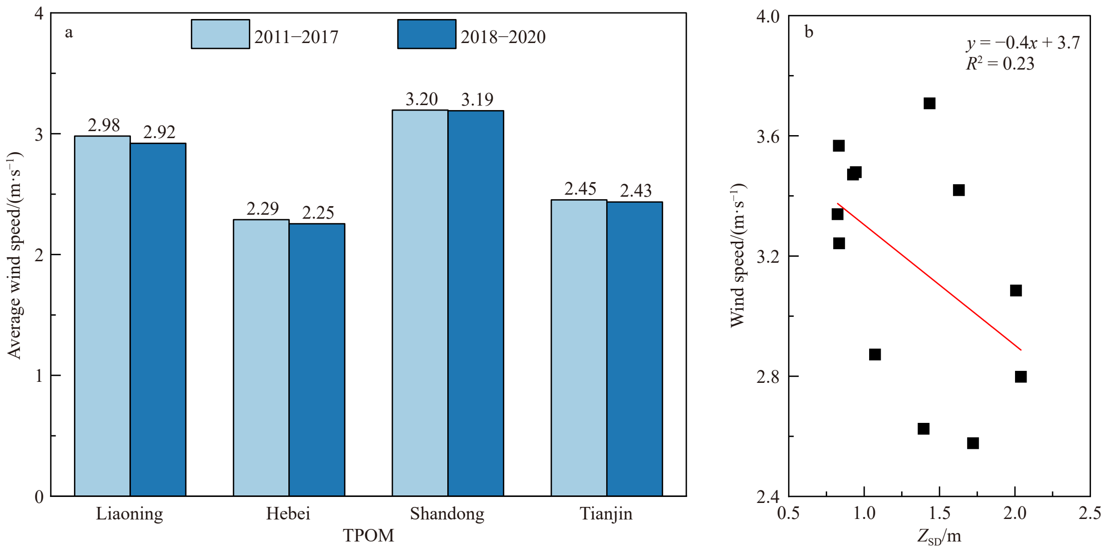

Fig. 14. Comparison of wind speed averaged over 2018–2020 and 2011–2017 (a) and scatter plot of *in situ* measured monthly wind speed and satellite-derived Z_{SD} over the BS nearshore waters (b).

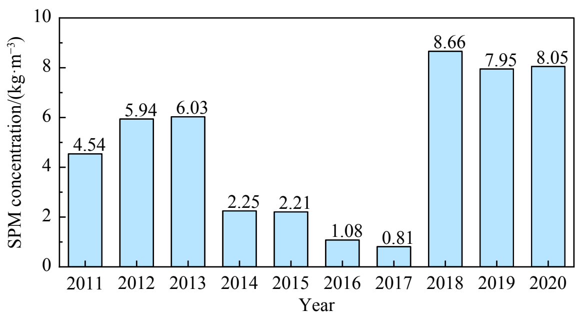

Fig. 15. SPM concentrations (the ratio of total sediment discharge to runoff) of major rivers flowing into the BS, including the Huanghe River, Liaohe River and Haihe River. The Huanghe River contributes the majority of the sediment discharged into the BS.

The MLD indicates the mixing degree of upper seawater. The deeper the MLD is, the stronger the seawater mixing is, corresponding to a decrease in Z_{SD} (Li et al., 2020). In order to characterize the water dynamics and its potential impact on Z_{SD}, annual average MLD from 2011 to 2020 was calculated and the statistics showed that the MLD of BS nearshore waters from 2011 to 2020 remained stable and almost unchanged (the average MLD is 9.61 m in 2011–2017 and 9.69 m in 2018–2020). Therefore, Z_{SD} improvement of BS nearshore waters cannot be attributed to MLD variability.

Dust deposition is a potential factor that may directly or indirectly change the optical properties of waters (Chen et al., 2016; Tan et al., 2012; Claustre et al., 2002). The number of dust storm events from 2011 to 2020 was analyzed to explore the possible influences of dust deposition on Z_{SD}. And the results showed no significant increasing/decreasing trend during the past decade (Fig. 16). Therefore, dust deposition may not be a key factor of the Z_{SD} variability.

Above results indicate that natural factors may not be the main reason for the Z_{SD} improvement of the nearshore waters of the BS, implying that human factors might play an important role. The above deduction is supported by independent data of water quality of rivers entering the BS and the official statistics of pollution discharge as follows.

(1) Statistics based on *in situ* data from the state-monitored river cross-sections indicated that the water quality of rivers entering the BS from TPOM had been significantly improved during UBIBSM. Specifically, as of 2020, the river cross-sections with the poorest water quality class (worse than Class Ⅴ) had been completely eliminated (red parts in Fig. 17). Meanwhile, the proportions of river sections with favorable water quality (Classes Ⅱ–Ⅲ) in provinces of Liaoning, Hebei, and Shandong increased to 88.9%, 50%, and 37.9%, respectively (Fig. 17).

(2) During 2018–2020, the amount of pollutant directly discharged into the BS through sewage outlets steadily met the emission standard. And discharge of COD, NH_4^+-N, and TP decreased by 43.0%, 75.7%, and 69.6%, respectively, during UBIBSM compared with the average between 2011 and 2017 (Fig. 18).

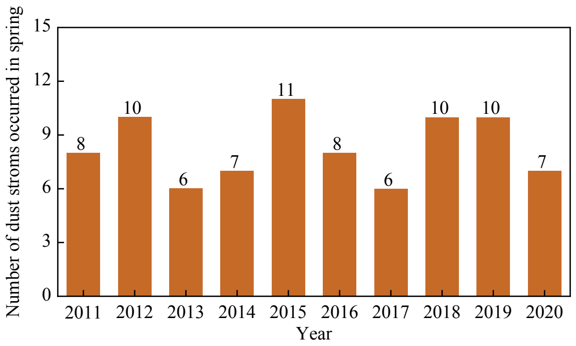

Fig. 16. Number of dust storm events in spring (March to May) over China mainland from 2011–2020.

The above-described substantial reduction in pollutants entering the sea through rivers and sewage outlets will undoubtedly help improve the Z_{SD} and water quality. In summary, it is the pollutant reduction during UBIBSM action, rather than the natural factors, that significantly improves the Z_{SD} in nearshore waters of the BS. This statement is also supported by the BEAST-based change point of Z_{SD}, which independently indicates the significant UBIBSM influence on the observed Z_{SD} improvement.

4.2 *Implication and perspective*

The elevated transparency in the nearshore waters of the BS during UBIBSM, indicated that the water quality of the BS was improved and the water became clear. The achievements of pollution control are hardwon and worth appreciating, especially in view of its semi-enclosed peculiarity, significant impact of intensive human activities, strong influences from many large rivers, and weak water exchange of the BS.

Nevertheless, it should be noted, the achieved transparency improvement was spatially unbalanced across TPOM (Figs 6, 9 and 10), with many areas exhibiting low level of (or limited) improvement, calling for persistent efforts for a long-term steady promotion in water quality. For example, for the river transects in Tianjin (Fig. 17), although the worst water quality class (>Class

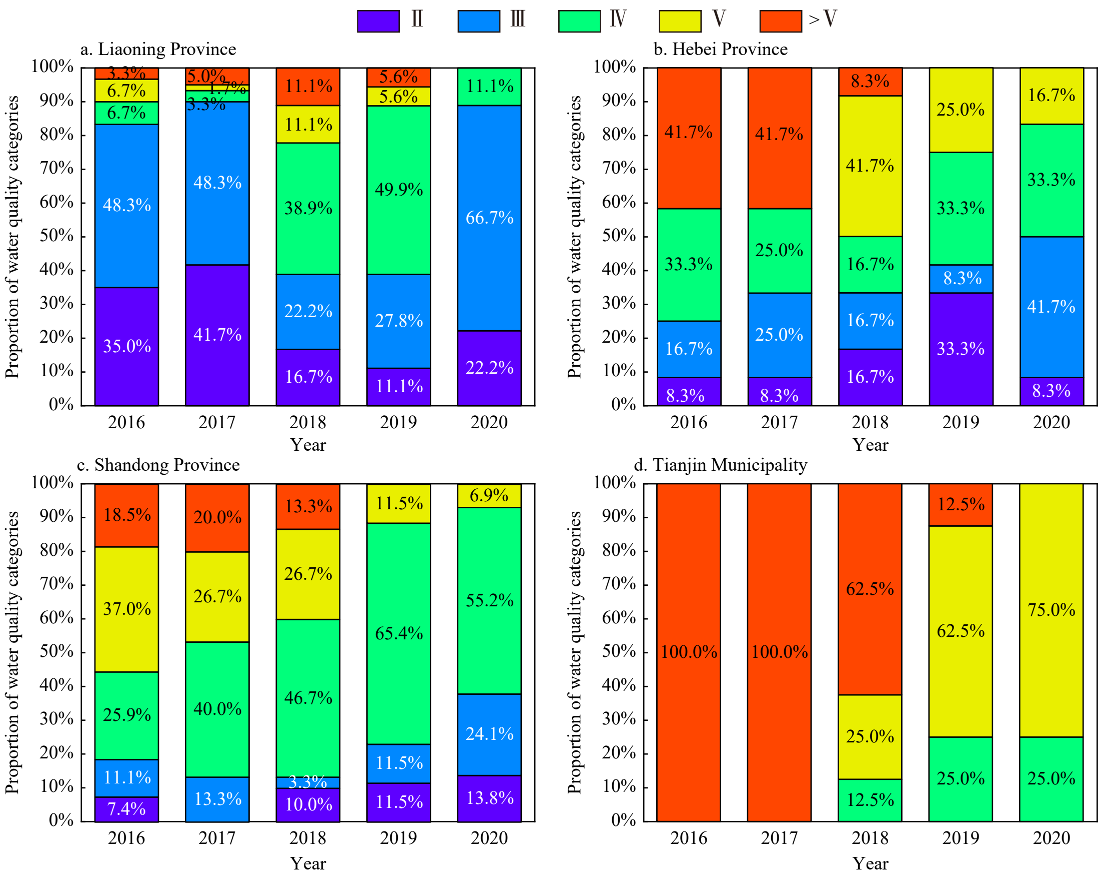

Fig. 17. Percentages of water quality classes at state-monitored cross-sections of rivers entering the BS from Liaoning Province (a), Hebei Province (b), Shandong Province (c), and Tianjin Municipality (d) during 2016–2020. Note that in the study area there is no waters belonging to Class Ⅰ.

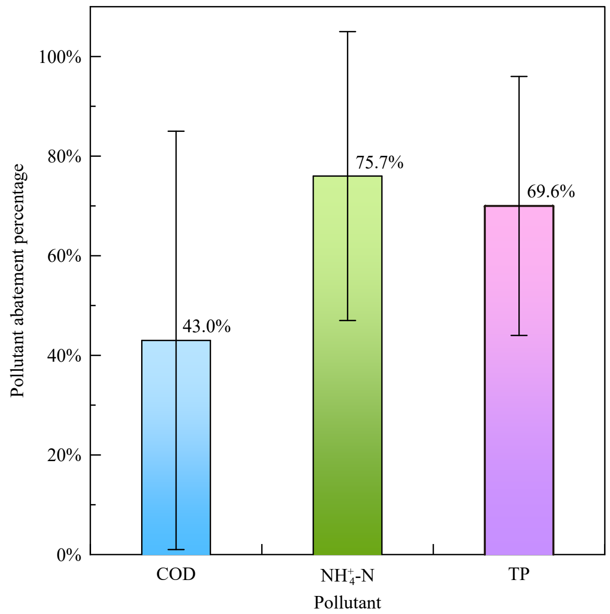

Fig. 18. Percentage of reduced pollutants directly discharged into seawater through sewage outlets in TPOM during 2018–2020 compared with the average during 2011–2017.

Ⅴ) was not found any longer until 2020, the overall water quality grade there is still low, as indicated by the dominated Classes Ⅳ and Ⅴ. It is suggested to optimize measures and strengthen the weak links in the following pollution control actions, especially considering the problem of cross-watershed pollution.

It is noted that only the nearshore waters of Bohai Sea (within 20 km from the coastline) were analyzed in this study, which were more seriously affected by the land-based input. In the future, analysis will be extended to the whole Bohai Sea. On the basis of UBIBSM, in February 2022, seven departments of the Chinese government jointly issued "The Plan of Tough Battle of Key Sea Areas Comprehensive Management", aiming at improving the water quality in 3 key areas, including the BS, the Changjiang (Yangtze) Estuary-Hangzhou Bay, and the Zhujiang (Pearl) River Estuary (Ecological Environment Department et al., 2022). For these ongoing pollution control actions, the methods and results of this study may provide references. Specifically, as demonstrated in this study, satellite remote sensing may play an important role in the near real-time water quality monitoring (Pan et al., 2001), comprehensive evaluation of pollution control effectiveness, and providing guidance for optimization of measures, based on its unique technical advantage of large-scale, quasi synchronous, and long-term repeated observations (Qing et al., 2012; Chen et al., 2007; Liu et al., 2020).

In further space-based evaluations of pollution control effectiveness, in addition to Z_{SD} as a proxy of water clarity, more water quality parameters may be incorporated in the analysis, including ocean color (Wang et al., 2019), SPM (Doxaran et al., 2014; Shen et al., 2014; Tavora et al., 2020) and trophic level (Duan et al., 2008), to achieve more comprehensive and evaluation results. Besides, reliable remote sensing results call for the further development and extensive validation of robust and advanced remote sensing algorithms, for reliable atmospheric correction (Pan and Mao, 2001; Caballero et al., 2014; Bulgarelli and Zibordi, 2018) and accurate in-water retrievals (Kuhn et al., 2019; Cui et al., 2010) to address the technique challenges of satellite ocean color remote sensing over turbid waters (Bailey and Werdell, 2006; McClain, 2009).

5 Conclusions

Based on long term satellite observations, this study analyzed the water quality responses to dedicated pollution control action UBIBSM (2018–2020), with the transparency (Secchi disk depth, Z_{SD}) as proxy and special emphasis on the nearshore waters (within 20 km from the coastline). The main findings are as follows.

(1) Compared to the status before the action began (2011–2017), majority (87.3%) of the nearshore waters turned clear during the action implementation period (2018–2020), characterized by the elevated Z_{SD} by 11.6%±12.1%.

(2) The improvement was not spatially uniform, with higher Z_{SD} improvement in provinces of Hebei, Liaoning, and Shandong (13.2% ± 16.5%, 13.2% ± 11.6%, 10.8% ± 10.2%, respectively) followed by Tianjin municipality (6.2% ± 4.7%).

(3) Bayesian trend analysis indicated the abrupt Z_{SD} improvement in April 2018, which coincided with the initiation of UBIBSM, implying the water quality response to pollution control. More importantly, the independent statistics of land-based pollutant discharge also proved that the significant reduction of terrestrial pollutant input during the UBIBSM action was the main driver of observed Z_{SD} improvement.

(4) Compared with previous pollution control actions in the BS, UBIBSM was found to be the most successful one during the past 20 years, in terms of transparency improvement over nearshore waters.

In summary, UBIBSM was proved to achieve remarkable results, and the water quality of BS nearshore waters has been improved to a large extent. In the future, pollution control efforts are suggested to be maintained or further strengthened, especially focusing on areas with limited improvement, in order to achieve consistent improvement of water quality in the future. In this respect, satellite ocean color remote sensing may provide key evidence on the effectiveness of pollution control measures.

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